MICROBIAL FOULING OF DRIP IRRIGATION EQUIPMENT IN WASTEWATER REUSE SYSTEMS

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Doctor of Philosophy

by

HUW DAVID TAYLOR

Department of Genetics and Microbiology
The University of Liverpool
United Kingdom

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To my parents
John and Enid Taylor

ABSTRACT

This study set out to investigate the processes that lead to emitter fouling in wastewater reuse systems. The susceptibilities of several emitter designs to clogging were compared and the role of phytoplankton in the clogging process and in the development of algal mats was investigated.

Emitter design was found to be an important factor controlling the degree of clogging. Those designs that operated most efficiently used a long-path narrow labyrinth to control emitter output and encourage turbulent flow. Simpler designs that controlled flow by small sponge inserts or by stitched tubing were found to be unsuitable for use with treated wastewaters.

The most common cause of clogging was found to be sand particles in the size range 360 µm to 1080 µm, trapped within the narrow channels of emitters. The sand contaminated the entire irrigation system from the potable water supply in July 1987, before a screen filter was installed in the water supply line. Emitter clogging under these circumstances was a problem, to varying degrees, for all emitter designs and for all water qualities. Emitters supplied with WSP effluent generally clogged to a greater degree than those supplied with potable water and the principal cause of clogging was shown to be sand particles. However, no statistically significant difference was recorded in the discharge characteristics of the most efficient emitter design between different water qualities. Thorough cleaning of the irrigation laterals in 1987 and replacement of emitters in 1988 failed to eradicate the sand contamination problem. Examination of clogged emitters by electron microscopy showed that organic material encased the sand particles in clogged emitters from laterals supplied with WSP effluent, thereby sealing the water channel. This mass was shown to be comprised of dead microalgae and invertebrate animals such as *Daphnia* spp. on which bacteria developed. Microalgae did not multiply in the dark environment of the emitter interiors.

External algal mats were detected on less than 5 percent all emitters supplied with WSP effluent and were absent on all emitters supplied with potable water. Emitter C, which was the design that presented the largest wetted surface to sunlight, developed the greatest number of mats and covering these emitters with black polythene prevented mat development. The mats were shown to comprise of predominantly filamentous cyanobacteria (*Oscillatoria* spp. and *Lyngbya* spp.) and filamentous green algae (*Microcystis* spp.). Although these organisms were also detected on the walls of the maturation pond, they were not detected in grab samples of pond effluent which contained predominantly planktonic algal genera such as *Euglena* spp. and *Chlorella* spp. Short decaying filaments of *Oscillatoria* spp. were, however, detected within the irrigation laterals and on the surfaces of sand particles within clogged emitters and no degree of filtration would guarantee their complete removal from the pond effluent. It was hypothesised that their development on the outer surfaces of emitters was a result of colonization of a well-illuminated, wet and nutrient-rich environment and that the source of the inoculum was as likely to be the soil as to be the maturation pond. Studies of greenhouse irrigation systems in the UK revealed that algal mats were a consequence of applying inorganic nutrients to the crop in the irrigation water: their development can be prevented in greenhouses by chlorination of the water supply.

It was concluded that clogging results from a combination of physical, chemical and biological factors. Sand particles can be efficiently removed from the water supply by incorporating a simple screen filter, with a mesh size of at least 120, that allows microalgae to pass through the system to the soil. Clogging by sand particles was exacerbated by chemical precipitation of calcium carbonate and by the development of a organic material over the surface of the sand particles in emitters supplied with pond effluent. Biological growth alone was not shown to cause emitter clogging. It was also shown that the development of algal mats over the outer surface of emitters supplied with pond effluent were not a result of an accumulation of pond algae at this point but represented an opportunistic colonization of a well illuminated nutrient-rich environment by microorganisms from the atmosphere and/or soil. Algal mats had no adverse effect on the operation of emitters in WSP reuse irrigation.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

ABBREVIATIONS

BOD	Biochemical oxygen demand
cm	Centimetres
COD	Chemical oxygen demand
ds	Decisiemens
g	Acceleration due to gravity
h	Hours
HRTF	High rate trickling filter(s)
kg	Kilogrammes
l	Litres
M	Moles (molar)
m	Metres
mg	Milligrammes
ml	Millilitres
mm	Millimetres
µg	Microgrammes
nm	Nanometres
SAR	Sodium absorbtion ratio
WSP	Waste stabilization pond(s)

CHAPTER 1

1. INTRODUCTION

1.1 Definitions of Irrigation

The most commonly used definition of irrigation is the application of water to the soil for the purpose of supplying the moisture necessary for plant growth. However, irrigation schemes are set up for such a variety of reasons that this narrow definition of irrigation is often inadequate. A broader and more inclusive definition of irrigation would be the application of water to the soil for any of the following reasons (Hansen *et al.*, 1979):

1. to add water to the soil in order to supply the moisture essential for plant growth;
2. to provide crop insurance against short-term droughts;
3. to cool the soil and atmosphere, thereby producing a more favourable environment for plant growth;
4. to reduce the hazards of frost;
5. to washout or dilute salts in the soil;
6. to reduce the hazard of soil piping;
7. to soften tillage pan clods; or
8. to delay bud formation by evaporative cooling.

When treated wastewater is reused for irrigation purposes, a number of additional objectives are achieved. In such circumstances irrigation may be additionally defined by the following aims:

1. Utilization of dissolved compounds in wastewater as plant nutrients. Compared with potable water, treated wastewaters generally contain a high proportion of dissolved plant nutrients such as nitrogen, phosphorus, potassium and trace elements. These nutrients exist both as covalent molecules and as charged ions and may be utilised either directly by crops or may be made available to them by chemical and biological processes within the soil. For example, under normal conditions of irrigation, treated municipal wastewater can be used to provide all the phosphorus and a major part of the nitrogen required to grow high yields of good quality sunflowers and sorghum (Papadopoulos and Stylianou 1988; 1991). The requirement for additional fertilizer is therefore reduced substantially (Shuval *et al.*, 1986).

2. Utilization of the microorganisms present in wastewaters as "slow-release fertilizers". Treated wastewaters contain high levels of bacteria, and in the case of waste stabilization pond effluents, high levels of microalgae. Following application to the soil during irrigation, these organisms become entrapped between soil particles where they are slowly decomposed by the natural chemical and biological processes which allow cytoplasmic elements to become available for plant uptake. This steady release of nutrients is a more efficient means of supplying fertilizers to the crop than bulk application to the soil because excessive leaching of the nutrients away from the root zone is avoided.

3. Utilization of the microorganisms and other suspended solids present in wastewater as soil stabilisers. Microorganisms have long been known to have major effects on soil structure. Such effects include microbial aggregation and physical entanglement (Harris *et al.*, 1966), processes that increase the average pore size between soil particles and thereby increase percolation and infiltration of water through the soil. Bachs *et al.* (1971)

showed that the suspended solids fraction of wastewater also improves soil moisture holding capacity. More recent work has shown that algae in WSP effluent act as soil conditioners (Puskas and Esen, 1989).

4. Additional treatment of the wastewater. Land treatment is an established method of sewage treatment and was developed in Europe in the second half of the nineteenth century when pollution of many rivers was deemed to have reached unacceptable levels (Metcalf and Eddy, 1979). The three principle processes of modern land treatment of wastewater are irrigation, rapid infiltration and overland flow. Of these, irrigation is the predominant land treatment process in use today because in addition to treating the wastewater as it seeps through the soil, its resource value for the cultivation of crops is utilised.

Today, irrigation plays an essential role in the agricultural economies of the arid climate regions of the world. It is not, however, limited to such regions. In many areas, such as North East Brazil and western and southern parts of Africa, annual rainfall is considerable but limited to certain wet seasons; other parts of the year have practically no rainfall. Even in ostensibly humid climates, rainfall rarely coincides completely with crop requirements and irrigation has a part to play in increasing agricultural efficiency. It is therefore becoming a basic part of well developed agriculture throughout the world.

1.2 Present Day Irrigation Technology

Until the twentieth century, irrigation technology had developed little since the days of ancient Egypt and indeed, even today, low-technology approaches to irrigation such as flood and furrow methods predominate throughout the developing world. These methods have advantages over

modern techniques such as low capital costs and energy requirements. They are not, however, very efficient in their use of available water, a large proportion being lost as evaporation into the atmosphere or via drainage channels designed to remove excess water.

In the early part of this century, a novel method of irrigation was developed that applies water to the soil and plant in the form of a spray. Sprinkler irrigation, as it became known, offered several advantages over traditional methods of irrigation, including better water application efficiency and less interference with cultivated land. In addition, sprinkler irrigation could be used for frost protection, crop cooling during hot periods, and as a means of applying fertilizers and pesticides efficiently to the crop. Today, sprinkler irrigation technology is well developed and may be semi-permanent or portable depending on the needs of the farmer.

The next major development in the evolution of irrigation design was the introduction of trickle or drip systems. These designs were originally introduced for irrigation of high cash crops in areas with limited conventional water sources as a means to save water (Oron *et al.*, 1991). The forerunners of the present day designs were introduced into British greenhouses in 1948 and similar systems were used for field crops in Israel, Australia and the USA from the early sixties.

Trickle or drip irrigation (terms which shall be used synonymously in this thesis) consists of a network of polythene or PVC pipes laid on or below the surface of the soil. Water is delivered to the root zone of crops from emitters (drippers) spaced at regular intervals along these laterals. Emitters are designed to deliver a low and controlled discharge of water directly to the soil. Depending on crop water requirements, between two and ten litres of water per hour are applied by means of a narrow orifice or an internal long

flow path. The emitters thereby reduce water pressure and control emitter output.

Trickle irrigation technology offered several advantages, both over low-technology techniques such as furrow irrigation, and over the more advanced sprinkler method. The most important advantages are summarised below.

1. Increased water application efficiency. Water savings of thirty to fifty per cent over sprinkler irrigation are often achieved (Hansen *et al.*, 1979) since water is applied directly to the soil and evapotranspiration losses are cut to a minimum. Water losses from run-off and deep percolation are also reduced (Black, 1976).

2. Reduced labour costs. Trickle irrigation systems can easily be automated using timing devices to activate pumps and solenoid pumps (Bucks *et al.*, 1982). Capital costs, however, remain much higher than those of furrow irrigation.

3. Reduced contact between crops and irrigation water. In wastewater irrigation schemes, trickle methods have the advantage of reducing the chance of crop contamination by wastewater pathogens (Shuval *et al.*, 1986).

The most serious potential problem of trickle irrigation systems is clogging of the narrow channels within the emitters (Bucks *et al.*, 1977; Pelleg *et al.*, 1974). In early systems this became a major problem, but improvements to equipment design, such as the introduction of novel emitters in which water flow is turbulent rather than laminar, have significantly improved system operation efficiency (Wilson, 1972, 1977; Solomon, 1977). Other approaches to the reduction of emitter clogging

have concentrated on improving the quality of water before it reaches the emitter (Bucks *et al.*, 1982). Methods of preventing emitter clogging are discussed in greater detail in section 1.6.

1.3 The History of Wastewater Reuse

The utilization of human waste material for agricultural purposes has a long history. Night soil has been used to fertilize crops in China and other parts of Asia since ancient times (Shuval *et al.*, 1986) and with the introduction of integrated sewage disposal systems in nineteenth century Europe, land application became an increasingly important way of minimising pollution of rivers and other freshwater resources. Sewage farms had already operated successfully in Germany since 1531 (Gerhard, 1909), and from about 1650 in many of the major cities in Britain. In 1865 the First Royal Commission on Sewage Disposal in England reported that "the right way to dispose of town sewage is to apply it continually to the land and it is by such application that pollution of rivers can be avoided".

Broad irrigation with sewage continued to be developed throughout Europe and the USA into the early years of the twentieth century and most of the sewage farms that were developed around Paris between 1890 and 1920 still operate (Dean, 1978). Many projects were later abandoned for a variety of reasons including the encroachment of growing cities into irrigated areas and concern about the possibility of disease transmission via crops. This concern for public health grew alongside the development of new technologies for the treatment of sewage by biological processes such as the trickling filter and activated sludge processes (Shuval *et al.*, 1986).

These methods involve complex mechanical components but do not require as much space as land infiltration and flood farming.

Attitudes to the land application of sewage gradually changed again in the fifties as the potential benefits of greater water resource efficiency and the important role of land application in preventing pollution of freshwater resources were more fully appreciated (Shuval *et al.*, 1986). These developments were encouraged by renewed scientific research into public health aspects of reuse (Rudolf *et al.*, 1951) .

1.4 The Rationale of Effluent Reuse

1.4.1 Water Resource Management

The annual water balance of any region is the difference between its annual water inflow - mainly precipitation, and annual water outflow - irrecoverable losses that consist of roughly two thirds to the atmosphere and one third to the oceans or other regions (Pettygrove *et al.*, 1984). In regions where demand for potable water exceeds that available, the reuse of industrial and domestic wastewater for purposes that do not require potable water, will reduce demand on freshwater supplies through source substitution (Papadopoulos, 1992). However, unless this water would otherwise have been lost to the atmosphere or carried by rivers out of the area in question, such reuse will not actually increase the net amount of water available. It will however ease water supply difficulties associated with temporal or spatial dificiencies. It is important to note that wastewater reuse only leads to a reduction in total costs to the community when it enables deferment of major capital expenditure for augmentation of water sources, water supply infrastructure or sewage treatment works (Burgess, 1991)

Since a large proportion of treated wastewater eventually returns to freshwater supplies and is therefore in effect reused, it is important at this stage to distinguish between intentional and incidental reuse. The term intentional shall in this case be used to describe the planned use of effluents that would otherwise be discharged without being put to direct use.

Treated wastewater is not the only marginal water source available for irrigation in arid and semi-arid regions. In addition, the reuse of stormwater (Oron *et al.*, 1980) may play an important part in the water balance of areas that receive irregular rainfall. Treated wastewater is, however, the most plentiful and reliable source of marginal water available for reuse.

Land application of urban wastewater is a well-established practice in California. In 1977 for example, wastewater was reclaimed at over 200 treatment works and utilised at over 360 locations (Ling, 1978). Treated wastewater constitutes an increasing fraction of the water used for irrigation in the state. Of the 42.2 million acre-feet (MAF) of water used in California in 1980, 84 percent was used for agriculture and 14 percent for urban (both industrial and domestic) use. Of the latter, 41 percent was lost in evapotranspiration and deep percolation before primary use, leaving 49 percent (3.4 MAF) as the total amount of urban wastewater generated annually (Department of Water Resources, 1983). The volume of reclaimed water used for irrigation in California is now approaching ten percent of the states total wastewater output (State of California, 1990).

Table 1.1 demonstrates the fate of this wastewater in 1980. It shows that whereas 18 percent of wastewater was reused incidentally after discharge to the freshwater system, only 7 percent was put to intentional reuse. Obviously the opportunity exists for even greater use of this resource in the future.

Table 1.1 Fate of treated municipal wastewater in California in 1980

	Volume	
	MAF / Year	%
Discharge to saline water	2.44	72
Evaporation and evapotranspiration	0.10	3
Intentional use of reclaimed wastewater a	0.25	7
Incidental use of treated wastewater b	0.61	18
Total municipal wastewater	3.40	100

a Intentional - planned use of treated effluent that would otherwise be discharged without being put to direct use.

b Incidental - use of treated effluent after it is discharged to the freshwater system, so that its subsequent use is unplanned and is merely incidental to wastewater treatment and disposal.

Source: Department of Water Resources (1983)

1.4.2 Pollution Control

Many arid and semi-arid regions of the world have few flowing streams with an adequate water volume to act as the safe repository of even well treated municipal sewage (Shuval *et al.*, 1986). In such places, land application may serve a useful purpose as a final form of sewage treatment and thereby prevent large-scale pollution of waterways.

Land treatment of wastewater is achieved by a variety of physical, chemical and biological processes in the soil. Fine pores and biological slimes effectively filter out most microorganisms within the top metre of the soil by adsorption onto the surfaces of soil particles (Dean and Lund, 1981). Human pathogens are then destroyed in the soil by a combination of physicochemical parameters such as sunlight, unsuitable pH levels, desiccation, nutrient depletion and microbial action (Costa-Vargas, 1988; Gerba *et al.*, 1975). Soil contains a diverse range of microorganisms many of which may act antagonistically against each other, and against the pathogens present in human waste, by the action of antimicrobial compounds. Soil actinomycetes are particularly active in this regard, and streptomycin, chloramphenicol, cyclohexamide, and chlortetracycline are but a few of the important chemotherapeutic substances synthesised by them under laboratory conditions (Alexander, 1977). However, the ecological function of antibiotics in the soil environment is less well understood (Stolp, 1988). Organic matter is efficiently removed by biological oxidation under aerobic conditions. Nitrogen is removed by denitrification in the soil and by plant uptake and harvest, and promotion of these processes prevents groundwater contamination by nitrates. The major phosphorus removal processes in land treatment systems are chemical precipitation and absorption, although plants do take up small amounts of this element (Metcalf and Eddy, 1979).

1.5 Public Health Considerations in Wastewater Reuse

The successful reintroduction of wastewater reuse projects in recent years has to a large extent been the result of scientific monitoring of the potential hazards of such systems. Whereas epidemiological evidence has suggested that uncontrolled use of untreated sewage may present public health problems, in the majority of instances in which care has been taken to ensure that effluent quality is of a sufficiently high level, projects have operated successfully with no evidence of genuine health risks to field workers or consumers (Shuval *et al.*, 1986 and 1989).

However, since the majority of communicable diseases in tropical countries are excreta-related, the irrigation of edible crops with waste material does carry potential risks that should not be underestimated. It is clear that a wide spectrum of pathogenic microorganisms are present even in wastewater that has been treated and that these organisms are capable of survival in the soil and on crops from periods of just a few hours to several months depending upon the type of organism and environmental conditions. Regulatory controls related to the use of reclaimed water are therefore principally directed at protection of public health (Crook, 1991).

It is, however, difficult to prove an indefatigable link between human infection and the handling or consumption of such produce. A number of additional factors must be taken into account in any epidemiological study such as the degree of immunity within the affected community, the level of simultaneous infection from other sources, and the minimal infective dose of the pathogen under study (Bradford-Hill, 1965). A detailed study of the various causative agents of disease present in wastewaters is outside the scope of this introduction and is well documented in other works (Feachem *et al.*, 1983; Feachem and Blum, 1985). The public health risks associated with the major disease causing organisms present in domestic sewage are outlined in Table 1.2. Table 1.3 summarises present WHO guidelines for the safe application of wastewaters to crops by irrigation.

Table 1.2 Major pathogens egested in fæces

Organism	Disease	Reservoir
Viruses:		
Adenoviruses	Numerous conditions	Man
Enteroviruses		
Polioviruses	Poliomyelitis, paralysis and other conditions	Man
Echoviruses	Numerous conditions	Man
Coxsackieviruses	Numerous conditions	Man
Hepatitis A virus	Infectious hepatitis	Man
Reoviruses	Numerous conditions	Man and animals
Rotaviruses, Norwalk agent and other viruses	Diarrhœa	Probably man
Bacteria:		
Campylobacter fœtus ssp. jejuni	Diarrhœa	Man and animals
Pathogenic *E. coli*	Diarrhœa	Man
Salmonella		
S. typhi	Typhoid fever	Man
S. paratyphi	Paratyphoid fever	Man
Other salmonellae	Food poisoning and other salmonelloses	Man and animals
Shigella spp.	Bacillary dysentery	Man
Vibrio		
V. cholerae	Cholera	Man
Other vibrios	Diarrhœa	Man
Yersinia enterocolitica	Diarrhœa and septicæmia	Man and animals
Protozoa:		
Balentidium coli	Diarrhœa, dysentery, and colonic ulceration	Man and animals (pigs and rats)
Entamoeba histolytica	Colonic ulceration, amoebic dysentery and liver abscesses	Man
Giardia intestinalis	Diarrhœa and malabsorption	Man and animals
Cryptosporidium parvum	Cryptosporidiosis	Man and animals
Helminths:		
Ancylostoma duodenale	Hookworm	Man - soil - man
Ascaris lumbricoides	Ascariasis	Man - soil - man
Fasciola hepatica	Fascioliasis	Sheep - aquatic snail - aquatic vegetation - man
Schistosoma	Schistosomiasis; bilharziasis haematobium	Man - aquatic snail-man
Taenia saginata	Taeniasis	Man - cow - man
Taenia solium	Taeniasis	Man - pig (or man) - man

Modified from Feachem *et al.* (1983)

Table 1.3 Recommended microbiological quality guidelines for wastewater use in agriculture[a]

Category	Reuse Conditions	Exposed Group	Intestinal nematodes[b]	Fæcal Coliforms[c]	Wastewater Treatment Expected to Achieve the Required Microbiological Quality
A	Irrigation of crops likely to be eaten uncooked; sports fields, public parks	Workers, consumers, public	≤ 1	≤ 1000 d	A series of WSP designed to achieve the microbiological quality indicated; or equivalent treatment
B	Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees	Workers	≤ 1	No standard recommended	Retention in WSP for 8-10 days or equivalent helminth and fæcal coliform removal
C	Localised irrigation of crops in category B if exposure of workers and the public does not occur	None	Not applicable	Not applicable	Pretreatment as required by the irrigation technology, but not less than primary sedimentation

a In specific cases, local epidemiological, sociocultural and environmental factors should be taken into account and the guidelines modified accordingly.
b *Ascaris* and *Trichuris* species and hookworm. Arithmetic mean per litre during the irrigation period.
c Geometric mean per 100 ml during the irrigation period.
d A more stringent guideline (≤200 fæcal coliforms per 100 ml) is appropriate for public lawns such as hotel lawns, with which the public may come into contact.
e In the case of fruit tree, irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used.

Source: WHO (1989)

1.6 Clogging Problems in Drip Irrigation

Since the inception of drip irrigation technology, three major problems have come to light (Keller and Karmeli, 1975). These are:

1. salinity increase;
2. poor soil moisture distribution; and
3. emitter clogging.

The last of these represents the main obstacle to the low rate application of wastewater in reuse schemes (Alon and Adin, 1981). It constitutes a potential problem in all drip irrigation systems and is a direct result of the utilization of narrow channels to reduce water flow. It is hence a function of water quality and of emitter design.

1.6.1 Water Quality and Emitter Clogging

Bucks *et al.* (1979) group the causes of emitter clogging into three categories (Table 1.4) - physical (suspended solids), chemical (precipitation) and biological (bacteria and algae). The relative importance of each of these contributors to emitter clogging will depend on the nature of the water supply used and attempts have been made to rate the clogging effect of the biological, chemical and physical characteristics of water sources on trickle irrigation schemes (Table 1.5). Such numerical ratings are arbitrary but do allow different water sources to be compared.

For any given source of water, each of the three factors (physical, chemical and biological) may be quantified and allocated a rating of one to ten according to Table 1.5. A combined value of 0-0-0 represents a water source of excellent quality whereas a value of 10-10-10 is poor. Within

these extreme values, if the sum of the three factors totals ten or less, little problem is anticipated, whereas a total of ten to twenty indicates some problem, and twenty to thirty, a severe problem. For water sources that fall within the latter two ranges, water filtration and preventative measures are suggested.

Emitter clogging is rarely found to be the result of purely physical, chemical or biological processes in isolation. It is usually the result of two or more of these parameters working in combination to plug the flow of water (Nakayama *et al.*, 1978). It is, however, useful to summarise the role of the individual causes of emitter clogging.

1.6.2 Physical Causes of Emitter Clogging

Inorganic particles exist in all potential sources of irrigation water including potable water supplies. Water from rivers and unlined storage reservoirs often contains silts and clays while water from wells and bores may contain larger sand particles. Irrigation water taken from municipal potable water supplies will generally have undergone some form of pretreatment including filtration which will have reduced the concentration of these particles to negligible levels. Water sources that have not undergone such pretreatment generally need to be filtered at the irrigation site (Adin, 1987).

An alternative source of larger particles, which may cause emitters to become clogged, originates from the drip irrigation equipment itself: the construction of an interlocking pipeline network can result in the intrusion into the pipes of soil grains and plastic particles. These remnants of pipe manipulation may in some cases represent a serious clogging problem (Gilbert *et al.*, 1981).

Table 1.4 Principal physical, chemical and biological contributors to the clogging of trickle systems

Physical (Suspended solids)	**Chemical** (Precipitation)	**Biological** (Bacteria & Algae)
Inorganic particles:	Calcium or magnesium carbonate	Filaments
Sand		
Silt		Slimes
Clay	Calcium sulphate	
Plastic		Microbial Depositions:
	Heavy metal hydroxides,	Sulphur
Organic particles:	carbonate, silicates &	Iron
Aquatic plants (phytoplankton/algae)	sulphides	Manganese
Aquatic animals (zooplankton)	Oil or other lubricants	
Bacteria	Fertilizers: Phosphate, aqueous ammonia	
	Iron, zinc, manganese	

Source: Bucks *et al.* (1979)

Table 1.5 System for classifying irrigation waters used in trickle systems

Arbitrary Rating	Physical	Chemical *		Biological
	Suspended Solids	Dissolved Solids **	Iron and/or Manganese	Bacterial *** Population
0	<10	< 100	0.1	<100
1	20	200	0.2	1000
2	30	300	0.3	2000
3	40	400	0.4	3000
4	50	500	0.5	4000
5	60	600	0.6	5000
6	80	800	0.7	10,000
7	100	1000	0.8	20,000
8	120	1200	0.9	30,000
9	140	1400	1.0	40,000
10	> 160	> 1600	> 1.1	> 50,000

Physical and chemical values represent maximum in mg per litre.

Bacterial population in numbers per ml.

* Tentative chemical classification is based on the highest rating for either dissolved solids, soluble iron, or manganese

** If the pH level of water is 7.5 or greater, rating is increased by 2

*** If water is known to contain an abundant reproductive snail population, rating is increased by 4.

Source: Bucks *et al.* (1979)

1.6.3 Chemical Causes of Emitter Clogging

The principal causes of chemical clogging are calcium and magnesium carbonates and calcium sulphate. These dissolved salts may lead to emitter clogging in three different ways (Abbott, 1985):

1. by evaporation at the external surface of the emitter;
2. within the emitter - this is especially prevalent when mineral fertilizers are injected into the water supply; or
3. at the beginning of the emitter water path - usually caused by the breaking off of carbonate scales from the internal walls of the irrigation lateral.

Calcium carbonate has been found to present a potential clogging problem when the calcium carbonate saturation index of the irrigation water is above 0.5 and calcium hardness above 200 mg per litre (Awad, 1982). The presence in the water of hydrogen sulphide, however, may prevent the precipitation of carbonate deposits following its bacterial oxidation to sulphuric acid (Ford, 1984). In controlled studies, 3 mg per litre of hydrogen sulphide in flowing waters completely dissolved coatings of calcium carbonate (Ford, 1978).

1.6.4 Biological Causes of Emitter Clogging

The susceptibility of a given irrigation scheme to clogging by microbial growth will depend upon the nutritional characteristics of the irrigation water and upon the nature of the microenvironment in which the blockage occurs. No two situations are identical, but by analyzing the chemical and

microbiological composition of the irrigation water and by studying the overall irrigation scheme design, fairly accurate predictions of potential microbial growth problems may be made. Since the microbial causes of emitter clogging represent a major part of this research project, the subject is treated in greater detail in Section 1.7.

1.6.5 Prevention and Treatment of Clogged Emitters

The key to solving emitter clogging lies primarily in good system design because it is cheaper and more effective to design an irrigation system that functions efficiently with the water supply available than to attempt to clean emitters that have become clogged (Ayers and Westcot, 1985). The quality of potential water sources varies tremendously and therefore the type and degree of water treatment will differ for each water source. System designers should take account of the physical, chemical and biological characteristics of the water source before initiating an irrigation scheme and adapt components of the system accordingly. This may be done by rating the water source according to its characteristics as shown in Table 1.5 (Bucks *et al.*, 1979). Using this information, the most efficient strategy to reduce clogging can be formulated. In addition to system design, efficient field monitoring is essential in order to identify equipment failure such as filter overload, pipeline leaks, and to spot reductions in the wetted zone surrounding individual emitters (Abbott, 1985).

The three most important elements of drip irrigation systems that may prevent or minimise emitter clogging are filtration and chemical treatment of the water supply and emitter design.

Filtration. This is an essential part of all drip irrigation designs and remains the major method of dealing with physical clogging by suspended

solids. Inadequate filtration may lead to the need for expensive emitter reclamation procedures in order to prevent a reduction in crop yield. However, both the capital and labour costs of the operation increase with increasing levels of filtration and so excessive filtration should be avoided. There are two major types of filter used in drip irrigation - media (or granular) and screen (or strainer).

Media filters generally consist of sand, gravel or synthetic foam packed within a tank. Water usually passes from top to bottom through the medium which removes suspended material by a combination of entrapment and adsorption. This method is capable of removing large amounts of suspended particles provided that flow rate is reduced for more turbid waters and that the system is backwashed at regular intervals. If such measures are not taken, the filter may provide conditions favourable for bacterial growth. As the filter becomes blocked, pieces of the attached microbial "cake" tend to break off and may cause emitter clogging by their shear mass. Correctly operated, however, media filters represent a reliable means of minimising emitter clogging. The relatively high capital and labour costs of media filters compared with simpler means of filtration can be justified in high investment agricultural practices where accurate control of water and plant feed is essential. They are therefore used extensively in British commercial greenhouses.

Media filters are particularly effective when the suspended material in the water source is chiefly organic. They effectively remove the microalgae present in waters obtained from open tanks and reservoirs and successfully remove long narrow organisms such as filamentous algae and diatoms since there is a greater chance of withholding such particles in a multilayered filter than on a single screen surface (Wilson, 1972). Laboratory studies have shown that fine sand filters can, under optimum

conditions of operation, remove over 97 percent of the alga *Scenedesmus quadricauda* from water supplies heavily inoculated with this organism (Naghavi and Malone, 1986).

Screen filtration, where the main filtration mechanism is straining, is the minimum form of filtration required for drip irrigation systems (Alon and Adin, 1981). Even when media filters are used, a screen filter is installed "downstream" in order to avoid sand and detached solids contaminating the system during backwashing operations (Wilson, 1972). The screen may be made of steel, plastic or nylon, the pore size of which is chosen to correspond with the size of suspended solids present in the water supply and the smallest diameter of the water path within the emitter. The maximum acceptable particle size for different emitter orifice sizes has not been defined but a ratio of 1 to 10 has been suggested (Pelleg *et al.*, 1974). Table 1.6 compares screen filter measurements with equivalent particle sizes using soil classification categories.

Filter screens are generally less efficient than media filters at removing colloidal and submicronic particles (Adin, 1978), but such particles may be retained on the screen filter by the filter cake formed on the screen surface (Adin and Alon, 1986). Indeed, filtration by screen filters is dependant on two simultaneous processes (Alon and Adin, 1981):

1. Deposition of material within the pores of the screen and filter cake, thus contracting the passage of the suspension.
2. Deposition of material at a constant rate on the surface of the screen and later of the filter cake. Thus a perforated spongelike filter cake is formed, the pores of which retain a constant diameter which correspond to the pores on the filter screen.

Chemical treatment. Mechanical filtration is often not sufficient to prevent emitter clogging and a number of different chemical treatments have been

used in drip irrigation to control the problem. For the long term operation of trickle systems, chemical water treatment is considered by some researchers to be essential for controlling the build-up of sediment, precipitates, and microbial slime (Nakayama *et al.*, 1978). The choice of chemical to be used will depend on the nature of the clogging material.

Chlorination is an efficient means of controlling limited microbial growth by chemical means. Chlorine may be added to the irrigation water as sodium hypochlorite, calcium hypochlorite or chlorine gas. Of these, sodium hypochlorite is the generally preferred form being safer to use than chlorine gas. It also avoids the possibility of calcium precipitation which may occur when calcium hypochlorite is applied. McElhoe and Hilton (1974) found that improving filtration, in order to remove particles greater than 25 microns in diameter rather than 90 microns, reduced the amount of emitter blockage, over a period of eighty days, from 92 to 78 percent. Intermittent chlorination of water filtered to 90 micron, at a concentration of 10 mg per litre for 20 minutes per day, reduced the incidence of emitter blockage from 92 to 10 percent.

Most pathogenic bacteria and viruses are inactivated by a free residual chlorine concentration of 1 mg per litre when the contact time is between 10 and 30 minutes (Nakayama, 1982). At much higher concentrations (100 - 1000 mg per litre) it can oxidise suspended organic matter as well as highly reduced dissolved molecules such as hydrogen sulphide. In addition to its disinfecting properties, chlorination therefore reduces BOD levels (Linsley and Franzini, 1979). It may be added to the irrigation water either at a continuous low rate or injected intermittently at much higher concentrations (McElhoe and Hilton, 1974).

In any injection procedure it is the residual free chlorine concentration in the system that should be monitored and maintained at a suitable level for it is only such free residual chlorine that will be available for bactericidal action. This parameter is therefore dependent on the concentration of oxidisable matter in the irrigation water. As chlorine is added, readily oxidisable substances such as Fe^{2+}, Mn^{2+}, H_2S, and organic matter, react with the chlorine and reduce most of it to the chloride ion (Metcalf and Eddy, 1979). Following satisfaction of this immediate demand, chlorine continues to react with ammonia to form chloro-organic compounds and chloramines. Higher concentrations of chlorine cause some chloramines to be converted to nitrogen trichloride, the remaining chloramines will be oxidised to nitrous oxide and nitrogen, and the chlorine will be reduced to the chloride ion. Continued addition of chlorine leads to a break point when most of the chloramines are oxidised. Further addition of chlorine past the break point will result in a directly proportional increase in the free available chlorine (unreacted hypochlorite).

Chlorination practices vary widely. In commercial greenhouses in the UK, where chlorination is used, sodium hypochlorite is generally injected continuously into the water supply so as to achieve a residual chlorine concentration of about 5 mg per litre (North West Growers, *pers. comm.*). In other parts of the world farmers attempt to maintain a residual chlorine concentration of 1 mg per litre (Abbott, 1985). McElhoe and Hilton (1974) reported that continuous treatment of filtered reservoir water with 1 mg per

litre of residual chlorine or intermittent treatment with 10 mg per litre residual for 20 minutes daily prevented plugging of emitters.

Badly fouled irrigation systems may be treated with high residual concentrations of chlorine which are left in the irrigation laterals for twenty four hours in an attempt to oxidise organic matter. Nakayama *et al.* (1977) reclaimed flushable emitters clogged with biological slime by treating the system for about 24 hours with 100 mg per litre of chlorine and adding sulphuric acid to lower the pH to 2. The discharge rates were increased from as low as 50 percent back to between 90 and 95 percent of original design. In such instances, it is important to maintain a high level of residual chlorine as lower levels would leave small particles of organic material that would continue to clog the system. Following the treatment period, the whole system should be fully flushed with unchlorinated water, taking care to avoid contamination of the crop with a potentially lethal concentration of chlorine.

Chlorination is less successful when added to partially treated wastewaters. The higher concentrations of organic matter in such waters necessitate high concentrations of chlorine and long contact periods. Chlorination therefore increases costs and technology requirements and is therefore avoided where possible, especially in developing countries (Mara and Cairncross 1987). Since its action is unpredictable and it does not remove helminths and protozoa, chlorination is never a substitute for adequate wastewater treatment (Feachem *et al.*, 1983)

Table 1.6 Filter screen size equivalents

Standard Soil Particle Category	Microns	Inches	Screen Mesh *
Very coarse sand	1000 - 2000	0.0393 - 0.0786	18 - 10
Coarse sand	500 - 1000	0.0197 - 0.0393	35 - 18
Medium sand	250 - 500	0.0098 - 0.0197	60 - 35
Fine sand	100 - 250	0.0039 - 0.0098	160 - 60
Very fine sand	50 - 100	0.0020 - 0.0039	270 - 160
Silt	2 - 50	0.00008 -0.0020	>400 - 270
Clay	Less than 2	Less than 0.00008	---

* Using market grade wire cloth

Source: Wilson (1977).

Acidification is primarily used to control carbonate precipitation (Nakayama, 1982). The tendency for a water supply to precipitate calcium carbonate depends on its pH level, its calcium and dissolved solids concentration and its alkalinity. A theoretical pH can be calculated from these parameters and related to the measured pH (Bower *et al.*, 1965), a positive value indicating a tendency for calcium carbonate to precipitate from solution. Acidification of the water supply results in a lowering of this value and therefore a decrease in the tendency to precipitate calcium carbonate. The clogging of emitters by chemical precipitates is dealt with in greater detail in Chapter 3.

Acidification of irrigation water is generally achieved by the continuous injection of sulphuric or hydrochloric acid at concentrations sufficient to achieve a water pH level of 6 to 6.5. An additional advantage of acidification is that at these lower pH levels the activity of injected chlorine is increased because the concentration of hypochlorous acid, the active component in chlorination, is increased. Acid is therefore often used in combination with sodium or calcium hypochlorite (Bucks *et al.*, 1982). At pH levels lower than 6 however, corrosion of system components may occur.

In addition to chlorination and acidification, a number of additional compounds have been used in the past to prevent or remove biological masses with varying degrees of success. These compounds include chelated copper sulphate, iodine, hydrogen peroxide and acrolein. Ford (1978) considered acrolein to be too toxic for use in irrigation lines and found that under certain conditions it formed deposits. Copper sulphate is effective against algae and is usually injected into irrigation water at copper concentrations of 5 mg per litre (Round, 1973).

Emitter design. The development of improved emitter designs over the last thirty years has markedly increased the water application efficiency of

drip irrigation systems. Early models reduced water flow at the emitter by means of a tiny orifice as small as 0.75 mm in diameter (Abbott, 1985) and were therefore highly susceptible to all forms of clogging. Today, a wide selection of emitter designs that use a variety of methods to minimise emitter clogging are available. These include short-path, long-path, short-orifice, vortex, pressure compensating, self-flushing, perforated single- and double-chamber tubing, as well as porous tubing emitters (Solomon, 1977).

The flow regime of most emitter designs can be characterised by the Reynolds number (Re), which is defined as (Bucks *et al.*, 1982):

$$Re = v\ d / v$$

where v is the emitter flow velocity (metres per second), d is the emitter diameter (metres), and v is the kinematic viscosity (m^2 per second). If Re is less than 2100, the flow is laminar; if over 3000, the flow is turbulent; between these values a transitional type of flow exists (Linsley and Franzini, 1979).

Of the designs presently available, the most commonly used are the long path emitters which encourage turbulent water flow and thereby reduce water pressure by increasing losses caused by friction. Such designs allow a wider water pathway and additionally reduce siltation by the turbulent motion of the irrigation water itself.

In Chapter 4 the discharge uniformities of a variety of emitter designs, using waste stabilization pond effluent and potable water, are compared and the relationship between emitter design and the degree of clogging is discussed.

1.7 The Role of Microorganisms in Emitter Clogging

1.7.1 The Microbial Colonization of Surfaces

The adhesion of microorganisms to solid surfaces leads to the formation of a biofilm (McCoy *et al.*, 1981). Such biofilms are a product of the natural microflora of the aqueous phase and of its nutritional qualities. Hence biofilm communities vary greatly in their structure and mass depending on the environment in which they develop.

The processes that lead to microbial adherence to solid surfaces and the eventual formation of a biofilm community are complex and need to be studied initially in terms of the thermodynamic parameters involved. This aspect of microbial adhesion has been well documented by other workers (Neumann *et al.*, 1980; Zisman, 1964; Shafrin, 1966; Good and Girifalco, 1960; Fowkes, 1962, 1964; Good, 1979; Dexter, 1979).

It was not until the late sixties that the manner in which solid surfaces are colonised by microorganisms in aquatic environments began to be investigated actively. Until that time, the traditional methods of microbial research had hindered the understanding of the nature of natural microbial communities for the following reasons:

1. The use of in vitro axenic cultures stimulates the development of mutants incapable of producing extracellular polysaccharides, an energetically expensive phenomenon unnecessary for the survival of microorganisms within the protected environment of a pure culture containing no antibacterial factors. Hence, those naturally occurring mutants that do not produce polysaccharide present a competitive advantage over the polysaccharide possessing wild-type (Costerton *et al.*, 1985). Indeed,

animal passage is often necessary before wild-type organisms can be reobtained from such cultures. Alternatively, if bacterial adhesion is to be studied, the use of antibiotics (Govan and Fyfe, 1978), or surfactants (Govan, 1975) has been shown to promote external polysaccharide production.

2. Extracellular polysaccharides do not attract the heavy metal stains traditionally used in electron microscopy and so their ecological ubiquity was not appreciated for many years. However, with the development of poly-anion specific stains such as ruthenium red and alcian blue (Fletcher and Floodgate, 1973), external polysaccharides were visualised for the first time in electron micrographs. Later developments in electron microscope technology using stabilising lectins (Birdsell *et al.*, 1975) and specific antibodies (Mackie *et al.*, 1979; Chan *et al.*, 1982) preserved the structure of these highly hydrated polymers.

The nature of microbial extracellular polymers is as complex as the polymers are varied and many terms have been used in the past to describe them, including slime layers, capsules and microcapsules . Costerton *et al.* (1981) proposed the term *glycocalyx* to define "those polysaccharide containing structures of bacterial origin, lying outside the integral elements of the outer membrane of Gram negative cells and the peptidoglycan of Gram positive cells". The term glycocalyx is considered by some to represent an oversimplification of the complex nature of the polymers involved, suggesting as it does, an essentially polysaccharide character to all such structures (Wicken, 1985). In reality this is not always the case since some genera, notably *Bacillus*, are able to produce extracellular polypeptide polymers especially under conditions of excess nitrogen. The term is, however, widely used nowadays by researchers in this field of study and has therefore successfully unified nomenclature on the subject. Costerton *et al.* (1985) divide the glycocalyx into two basic types:

1. S-layers. Regularly structured surface arrays of glycoprotein subunits. These subunits are able to self-assemble, driven by minimum free energy using information contained within the glycoprotein subunits (Sleytr, 1978). They are attached to the cell surface by electrostatic forces alone.

2. Capsules. Fibrous structures at the cell surface to which one or more of the following descriptions may be applied:

(a) Rigid - a classical capsule of sufficient structural coherence to exclude particles (as demonstrated by negative staining.)

(b) Flexible - a deformable structure that does not exclude particles and is therefore not delineated by negative staining.

(c) Integral - a capsule closely associated with the cell surface.

(d) Peripheral - a loosely associated capsule that may be released into the milieu under certain circumstances.

Detailed chemical analysis of the wide variety of capsules produced by different bacteria, and the means by which these capsules lead to adherence, is still at an early stage (Marshall, 1985), but it is already known that a single bacterial species will utilise differing chemical modes of interaction depending on the nature of the surface to which it adheres (Fletcher, 1980). With certain exceptions such as *Bacillus*, capsules are generally polysaccharide in composition. Corpe (1970) isolated an extracellular polymer of *Pseudomonas atlantica* that contained mannose, glucose and galactose in addition to glucuronic acid and pyruvate. This polymer was, however, obtained from the bacterium in an unrealistically rich medium and such studies must be treated with caution because of the genetic differences between bacteria cultured *in vitro* in laboratory cultures and those that are actually responsible for adhesion to solid surfaces in the natural environment.

1.7.2 The Major Microbial Groups Associated with Clogging

Microorganisms have never been demonstrated to block irrigation equipment solely by an accumulation of cells. Clogging problems associated with microorganisms are thought to be the result of microbial production of extracellular material, which acts as a polyelectrolyte flocculant (Pavoni *et al.*, 1972; Sharp, 1956), adhering organic silt and chemical precipitates to form a clogging mass. A large variety of microbial groups are able to attach themselves to solid surfaces by the mechanisms described previously: a smaller number of these organisms have been implicated in the fouling of irrigation equipment. These groups are summarised below.

Bacteria. The prokaryotic kingdom contains organisms with highly diverse metabolic characteristics. Such diversity allows certain groups to populate ecological niches unavailable to other organisms. When their nutritional requirements are available at sufficiently high concentrations, these organisms may multiply to such an extent that the biofilm produced may cause severe restriction and may ultimately clog irrigation equipment. In many cases the cause of clogging will be a combination of the microbial biofilm itself and certain end products of the organisms metabolism. This type of biological growth may occur when the irrigation water contains high concentrations of reduced iron, manganese salts or hydrogen sulphide.

Iron deposits (ochre) have caused major emitter clogging problems in drip irrigation systems in the past (Ford and Tucker, 1975). These deposits are produced by the activity of the iron bacteria - a taxonomically diverse group of organisms which appear to obtain their energy from the oxidation of

ferrous compounds. Two important genera of iron bacteria have been studied in detail but their metabolism is still not fully understood. *Sphaerotilus* is a rod-shaped obligatorily aerobic Gram-negative organism (Singleton and Sainsbury, 1978). Cells may occur singly but are often observed as unbranched sheathed filaments. These organisms are chemoorganotrophic although inorganic electron donors may be used by some strains. *Sphaerotilus* may become coated with ferric oxide when ferrous salts are present in their environment. *Gallionella* on the other hand, is thought to be strictly chemolithotrophic. It is a Gram-negative aerobic organism of uncertain taxonomic affiliation. Its cells, which may be reniform, bacilliform or coccoid, produce a long stalk which contains ferric hydroxide (Singleton and Sainsbury, 1978). Other bacteria that have been associated with emitter clogging are the filamentous organisms *Leptothrix*, *Toxothrix* and *Crenothrix* and the capsule forming aerobes *Pseudomonas* and *Enterobacter* (Ford, 1978). In irrigation lines, either of these organisms may cause emitter clogging when the Fe (II) concentration in the water supply is at or above 0.1 mg per litre (Abbott, 1985). Manganese slimes are also caused by chemolithotrophic action of bacteria and may become a problem when the manganese content of water exceeds 0.1 mg per litre (Ford, 1977a).

Aerobic sulphur slimes may represent a potential clogging hazard when the hydrogen sulphide concentration of the irrigation water is greater than 0.5 mg per litre (Abbott, 1985). The slimes are produced by the action of sulphur oxidising bacteria of the Beggiatoa -Thiothrix group. Winogradsky, in his pioneering work on chemoautotrophy, showed that these organisms

are able to oxidise hydrogen sulphide and can accumulate large quantities of intracellular elemental sulphur which is further oxidised to sulphate (Stanier *et al.*, 1976). Study of these organisms has, however, been hindered by the practical problems of growing the organisms aerobically at the expense of hydrogen sulphide. Slimes caused by sulphur oxidising bacteria are easily controlled, and generally the presence of hydrogen sulphide in irrigation water is advantageous to the control of emitter clogging as it leads to inhibition of ochre development and other microbially produced slimes following its oxidation to sulphuric acid (Ford, 1974).

Bacterial slime production is not limited to the chemoautotrophs. Certain common chemoorganotrophic organisms too are able to clog irrigation equipment by the development of copious quantities of extracellular polysaccharide, especially if such slimes are able to cement together sand grains or other suspended matter. Examples of bacteria implicated in this process in the past include *Pseudomonas* and *Enterobacter* (Ford, 1977a).

Algae. It may be assumed that planktonic algae will exist in all water supplies drawn from open tanks and reservoirs (Linsley and Franzini, 1979). These organisms are considered a potential clogging hazard and filtration is therefore used to remove algae and other suspended solids in most drip irrigation designs (Alon and Adin, 1981).

Generally, eutrophication of a water body results in increased numbers of microalgae but decreased taxonomic diversity (Pearson, 1987). Oligotrophic water sources may therefore contain a low concentration of algal biomass but a wide variety of different planktonic algal genera such as *Chlorella*, *Scenedesmus*, and *Pediastrum*, and blue-green algae (cyanobacteria) such as *Gloeocapsa*, *Synechococcus* and *Anacystis* (APHA,

1985). In addition, filamentous sessile algae from the walls of reservoirs may be present to a lesser extent. The eutrophicated waters of waste stabilization ponds contain a particularly high concentration of algal biomass. In studies of experimental WSP in the Northeast of Brazil, the algal standing crop in efficiently operating primary facultative ponds frequently reached values of 2,500 µg per litre chlorophyll *a* or even higher, while in maturation ponds with a BOD_5 loading of less than 50 kg per hectare per day, values from 100 to 1000 µm per litre chlorophyll *a* were recorded (Mara *et al.*, 1983; König, 1984). Since species diversity in ponds generally decreases as the organic loading increases, fewer species are found in facultative ponds than in maturation ponds. Flagellate algae such as *Chlamydomonas*, *Euglena* and *Pyrobotrys* are the dominant genera found in the turbid waters of facultative ponds, whereas in the clearer waters of maturation ponds a variety of nonmotile genera such as *Scenedesmus*, *Chlorella* and *Micractinium* predominate (Pearson, 1987).

Although heterotrophic growth of some algae, such as *Euglena gracilis*, is possible in the absence of light (Round, 1973), no evidence exists of algal multiplication within irrigation lines and emitters. Algal growth is more likely to occur in those parts of the irrigation system exposed to sunlight, such as the external orifices of drip emitters. No scientific investigation into the composition of such algal mats is reported and it has been assumed from operational evidence that they represent a simple accumulation of the algal cells present in the water supply. Investigations into the biological structure, origin, and role of these mats in emitter clogging, are described in Chapter 5.

1.8 Introduction to Research Work

Despite continued improvements in the design and operation of drip irrigation systems, the successful application of this technology in developing countries is still limited by the need for expensive procedures that prevent or limit the clogging of emitters. The Planning and Design Preparatory Group of the Overseas Development Unit Research Colloquium on Research Needs in Third World Irrigation (Overseas Development Unit, 1987), pinpointed the need to "develop design procedures for developing country applications, and to improve the design of emitters to prevent, or at least reduce clogging without resorting to expensive filtering or water treatment."

The combined use of waste stabilization ponds and drip irrigation, as a means of safely reusing valuable water resources, offers enormous benefits to agriculture in developing countries. If such schemes can be designed so as to minimise the need for a complex technological input, it can be hoped that reuse will eventually benefit even the least developed parts of the world. The research work described herein investigates the processes that lead to emitter clogging in such schemes, one of the major stumbling blocks in the development of wastewater reuse. Based on the results of this research, practical suggestions are made that will enable reuse schemes to be better designed without resorting to expensive measures to prevent clogging.

Because of the dearth of previous interdisciplinary research, the role of biological processes in the clogging of emitters is little understood. There has been a tendency to treat microorganisms as inert particles rather than as living organisms which influence, and in turn are influenced by, the

environment in which they exist. Such attitudes have limited responses to the problem. For example, the classic solution to the presence of suspended particles in bodies of water is to filter the water through porous screens or to infiltrate it through a large volume of a granular medium such as sand. Although this is often a very efficient means of removing the bulk of biotic as well as abiotic particles, it does not counteract the regrowth of microorganisms "downstream" of the filter. Therefore, assuming that filtration of irrigation water will not remove every microorganism within it, the possibility of microbial regrowth and eventual plugging of the system remains. Whether such regrowth occurs at any point in the system will depend on a number of environmental parameters, none of which will be counteracted by filtration. These parameters include:

1. the nutrient quality of the irrigation water;
2. the pH level of the irrigation water;
3. the concentration of dissolved oxygen in the irrigation water;
4. the concentration and nature of metabolic toxins in the irrigation water;
5. the temperature within the irrigation laterals and its diurnal fluctuations;
6. interactions between microorganisms;
7. moisture availability within the irrigation laterals; and,
8. the presence or absence of sunlight.

Only by considering these environmental influences on microbial growth can the phenomenon of microbial clogging in drip irrigation systems be understood and a logical approach to its prevention be formulated.

CHAPTER 2

2. MATERIALS AND METHODS

2.1 Field Experiments - Évora, Portugal 1986

The first field trials were conducted in Évora, in the semi-arid province of Upper Alentejo, Portugal, during September and October 1986. The experimental wastewater irrigation site was situated on land adjacent to the Évora municipal sewage treatment plant (Figure 2.1), which treats predominantly domestic sewage from the city of Évora. The plant is of the conventional biological trickling filtration type and comprises screening, grit removal, primary settling, secondary treatment by high rate trickling filter and secondary settling tank, anaerobic digesters and sludge drying beds.

2.1.1 Site Design

Prior to 1985 the irrigation site had not been cultivated for at least ten years. In 1985 the area was cleared of stones and prepared by deep tilling for a reuse trial involving spray (Costa-Vargas and Mara, 1987), and furrow irrigation (Marecos do Monte *et al.*, 1988). The first pilot drip irrigation system of this project was designed and set up in September 1986 (Figure 2.2), on the site previously occupied by the spray irrigation experiments. It consisted of a simple design to demonstrate the susceptibility to clogging of the two drip irrigation emitters most commonly used in the Alentejo region of Portugal, and to compare their efficiency of operation using a potable water supply with that achieved using treated final effluent from the Évora sewage treatment plant.

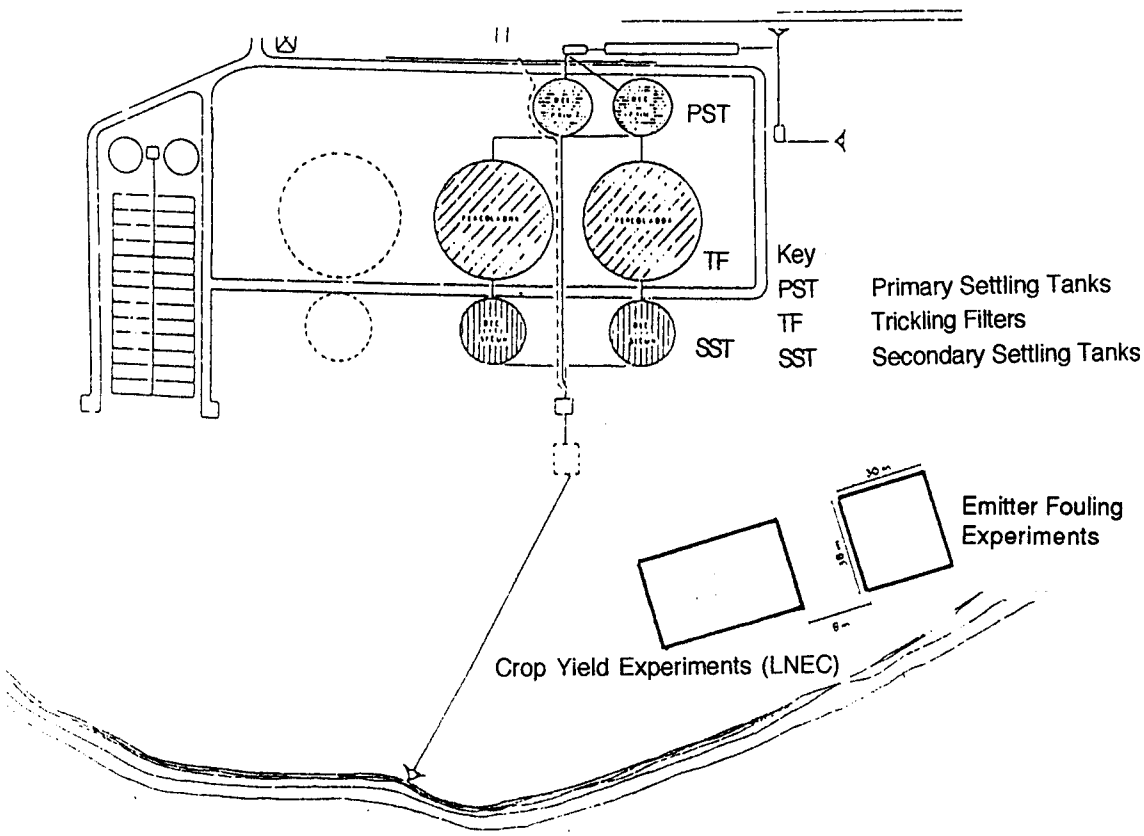


Figure 2.1 Plan of Évora Sewage Treatment Works and wastewater reuse experiments 1986. Scale: 1:2610

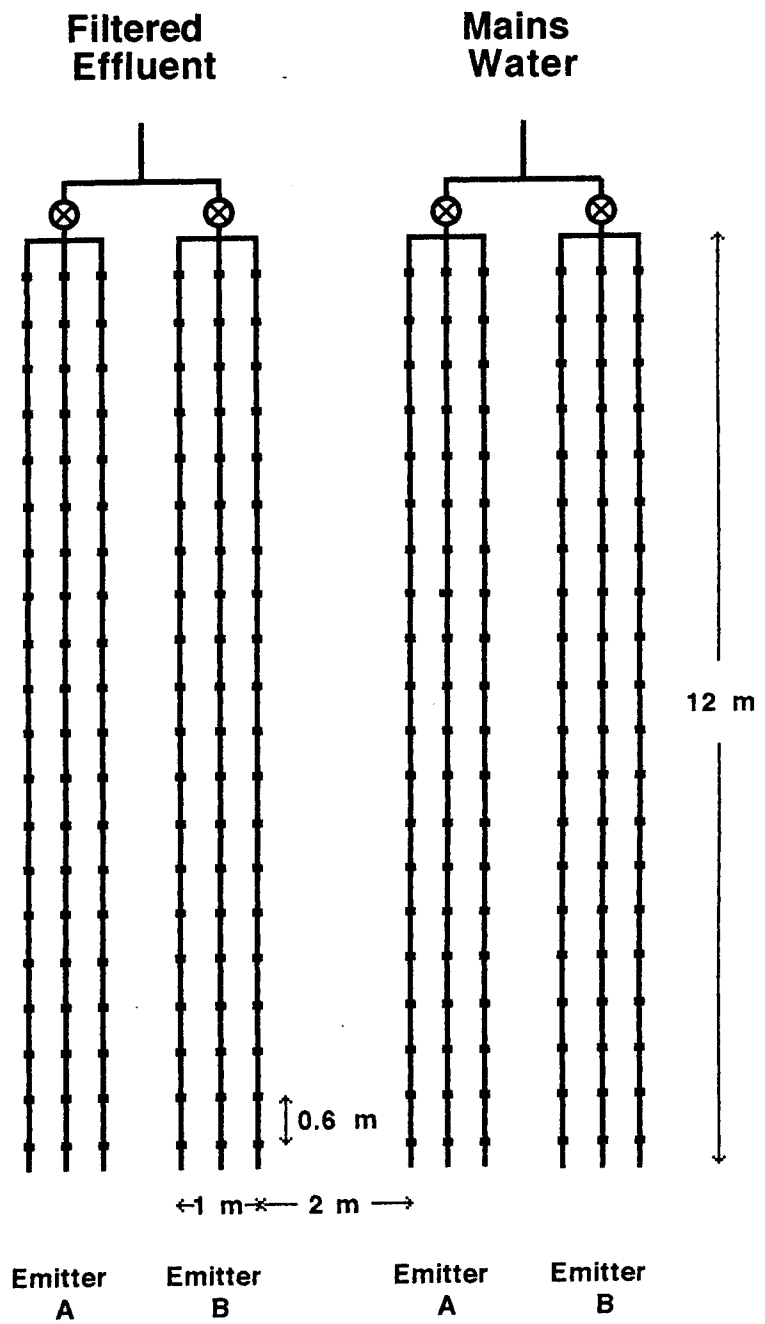


Figure 2.2 Pilot drip irrigation system layout

Évora 1986

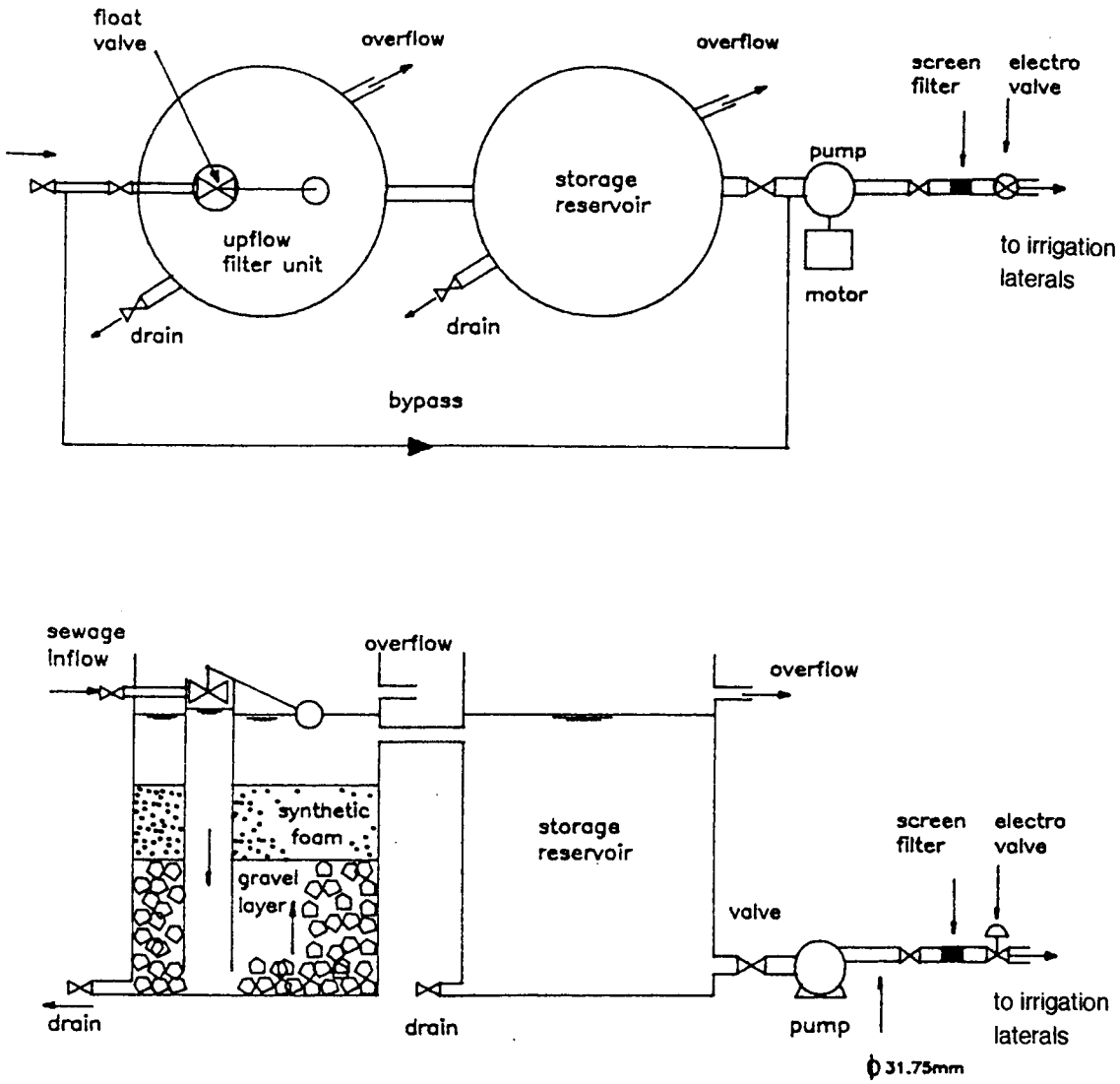


Figure 2.3 Treated wastewater filtration system

Plan and cross section, Évora 1986

2.1.2 Design of Emitter Clogging Experiments

The drip irrigation reuse system formed part of a larger experimental reuse research programme set up during the 1986 growing season. To evaluate the impact of wastewater irrigation on crop yield and pathogen contamination, maize, sorghum and sunflower were furrow irrigated with final effluent from the treatment works. The spray irrigation studies, which were completed in July 1986, were carried out by Costa-Vargas (1988) of the University of Leeds. The furrow irrigation studies, which ran concurrently with the drip irrigation study, were operated and monitored by research workers from the Laboratório Nacional de Engenharia Civil (LNEC), Lisbon.

Two replicate plots were set up within the area used for previous spray irrigation studies (Figure 2.2). One plot was supplied with filtered final effluent from the HRTF system and the other was supplied with unfiltered potable water. Each plot consisted of six 12 metre long black polythene lateral tubes (12 mm diameter), placed 50 cm apart in parallel, and supplied from a single mainline. The efficiencies of two emitter designs were investigated. Three laterals were fitted with Emitter 1 and the other three laterals were fitted with Emitter 2, at a spacing of 60 cm, a total of 60 emitters of each design per plot.

The treated final effluent was coarsely filtered through an up-flow reticulate foam filter (10 ppi), followed by a 18 mesh stainless steel screen filter (Figure 2.3). The filters were back-washed manually every seven days. Both treated effluent and potable water were supplied at a pressure of 1.5 kg cm^{-2}, this pressure being controlled by an automatic flow adjustment valve. Irrigation was carried out automatically, by means of an electrical timer, for two hours each day between 09.00 hrs. and 11.00 hrs., for a period of thirty five days from 11 October to 14 November 1986.

2.1.3 Emitter Designs

Two emitters were chosen for this initial pilot scale study, following consultations with local farmers and agricultural engineers. The chosen emitters were those most commonly used by farmers in drip irrigation systems using potable water in the semi-arid province of Upper Alentejo. The two emitters utilise radically different methods to reduce the flow of water within the emitter to the required "drop-by-drop" level of output:

1. Emitter 1 (Figure 2.4) was the TB In-line™ nylon emitter supplied by Access Irrigation Ltd. of Crick, UK. Its design is of the type used in large scale outdoor drip irrigation schemes in several countries. It has a design output of two litres per hour at an operating pressure of 1.5 kg cm^{-2}. It achieves the required reduction in flow within the emitter by means of a long path internal labyrinth that reduces water velocity by causing turbulent flow thereby eliminating the need for the very small orifices used in the past. The emitter is unobtrusive and therefore irrigation laterals can be easily coiled up and stored between growing seasons.

2. Emitter 2 (Figure 2.5) was a simple design, also with a design output of 2 litres per hour at an operating pressure of 1.5 kg cm^{-2}, and was the emitter design most commonly observed in the Upper Alentejo in 1986. Flow reduction in this case was achieved by a small piece of plastic foam sponge within the emitter which decreased the water pressure at this point by increasing surface friction. Although this is a crude method of reducing flow, the design has the advantage of being easily opened *in situ* so as to replace the foam insert should clogging occur.

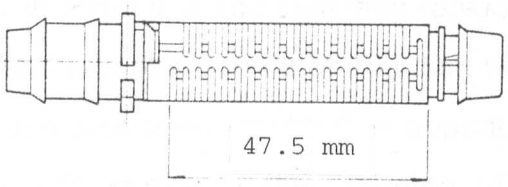


Figure 2.4 Emitter 1, Évora 1986

(Emitter D, Santo André 1987)

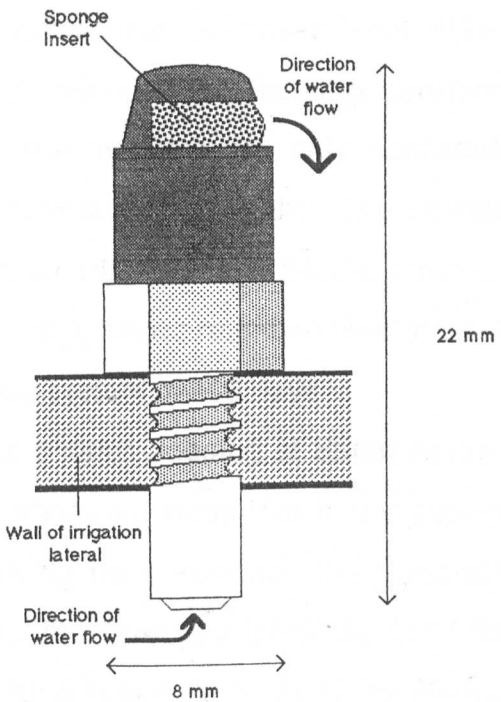


Figure 2.5 Emitter 2, Évora 1986

2.2 Field Experiments - Santo André, Portugal 1987

Following the preliminary studies in Évora, using the effluent from a HRTF sewage treatment plant, a pilot scale study that would utilise the effluent from a waste stabilization pond system was designed. WSP are the treatment of first choice in many arid and semi-arid regions of the world and are therefore an important potential source of irrigation water in such water scarce areas. The second pilot study provided an opportunity to investigate the role of planktonic microalgae in the clogging of drip emitters in wastewater reuse systems. In May 1987 the new pilot scale drip irrigation system was set-up in Santo André in the district of Setúbal, on the south west coast of Portugal.

The WSP system is situated one kilometre from the centre of Santo André. The system comprises two ponds linked in series. The first pond has a surface area of 10,700 square metres, a water depth of three metres and a theoretical hydraulic retention time of 46 days. It was designed to be an aerated lagoon system rather than a conventional WSP. The lagoon is aerated mechanically by means of four floating aerators, but in order to minimise energy costs, the aerators are only operated for a period of between two and four hours during the night. The second pond acts as a facultative lagoon. It has a surface area of 24,200 metres, a water depth of 1.8 metres and a theoretical hydraulic retention time of 62 days giving a total retention time for the whole system of 108 days.

The investigations into emitter clogging at Santo André during 1987 and 1988 were part of a collaborative study into many aspects of wastewater reuse for irrigation involving from Portugal; the Laboratório Nacional de Engenharia Civil (LNEC), the Direcção Geral da Qualidade do Ambiente (DGQA), and the Laboratório Ribelo da Silva of the Portuguese Ministry of Agriculture; and from the U.K., the Universities of Liverpool and Leeds.

2.2.1 Site Design

In June 1987 an experimental trickle irrigation system was set up adjacent to the Santo André WSP. The land was divided into three sectors (Figure 2.6).

Sector 1 was controlled and operated by LNEC and was set-up to study the yield response of crops to irrigation with pond effluent compared to the yield of identical crops irrigated with potable water. The three crops chosen for study were maize, sunflower and sorghum. Sector 2 was used to study bacterial contamination of soil and crops in order to evaluate present guidelines for the safe reuse of treated wastewater in agriculture (WHO, 1989). The salad crops lettuce and radish were chosen for analysis because they are eaten raw and therefore pose a greater risk of infection to consumers. Sector 3 was used to investigate emitter clogging (Figure 2.7)

Facultative pond effluent for the irrigation plots was supplied from a small storage reservoir. This reservoir was designed to store the final pond effluent before it is pumped at night, to a site 500 metres from the WSP site, for ground water infiltration. The irrigation pump, manometers and filtration equipment (Figure 2.8) were housed in a small annex, constructed specifically for this purpose, adjacent to the existing pump house. The irrigation pump inlet was protected from large suspended solids by a large-mesh nylon gauze and suspended into the reservoir at mid-depth (0.5 metres). Effluent filtration was achieved using a 120 mesh (80 μm pore size) nylon screen filter which was manually cleaned after each daily irrigation cycle. Mains water was supplied *via* the pump house and each section of the overall system could be operated independently from the pump house annex. In the case of the clogging studies, irrigation with potable water and pond effluent was carried out each morning for a period of one hour at a supply pressure of 1.5 kg m-2 from 12 August to 20 October 1987 (a total of seventy hours of irrigation).

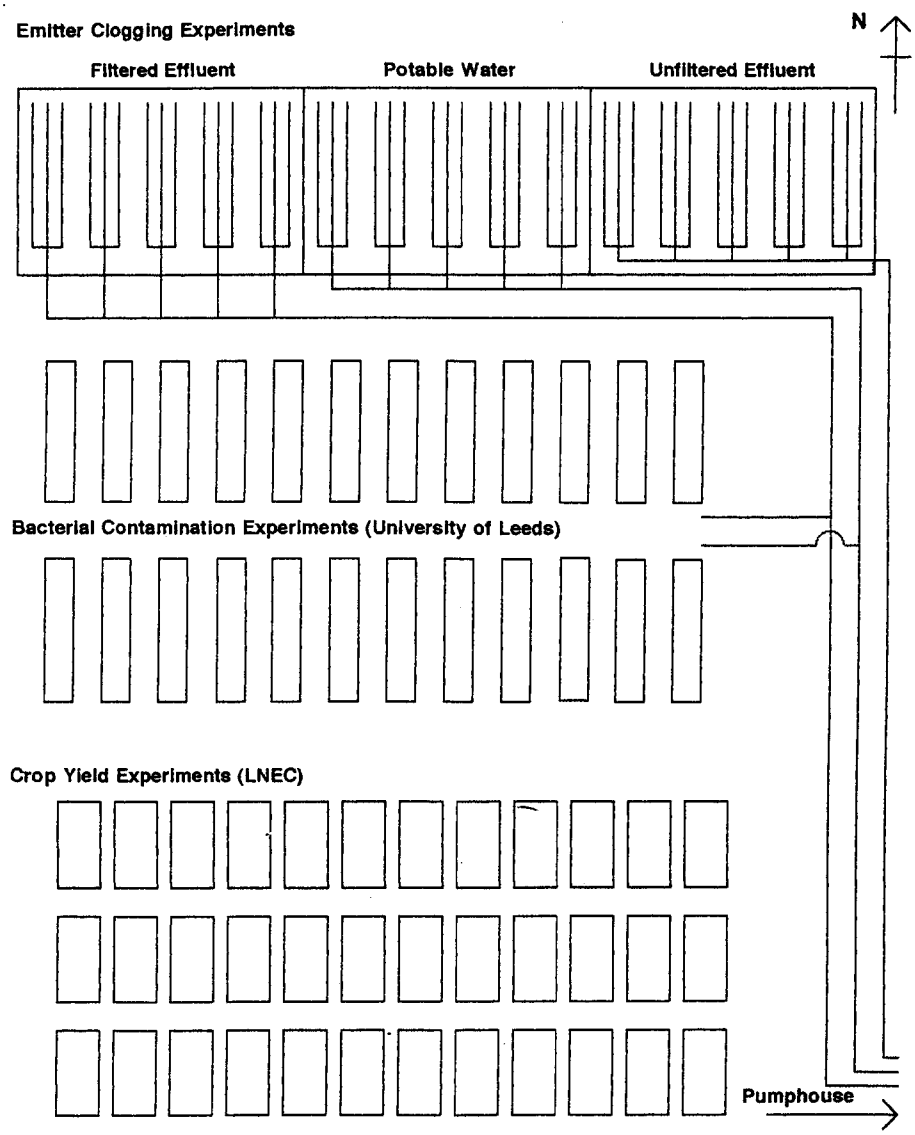


Figure 2.6 Plan of WSP effluent reuse site, Santo André 1987

Plate 2.1 The facultative pond at Santo André

Plate 2.2 The irrigation site at Santo André

May 1986

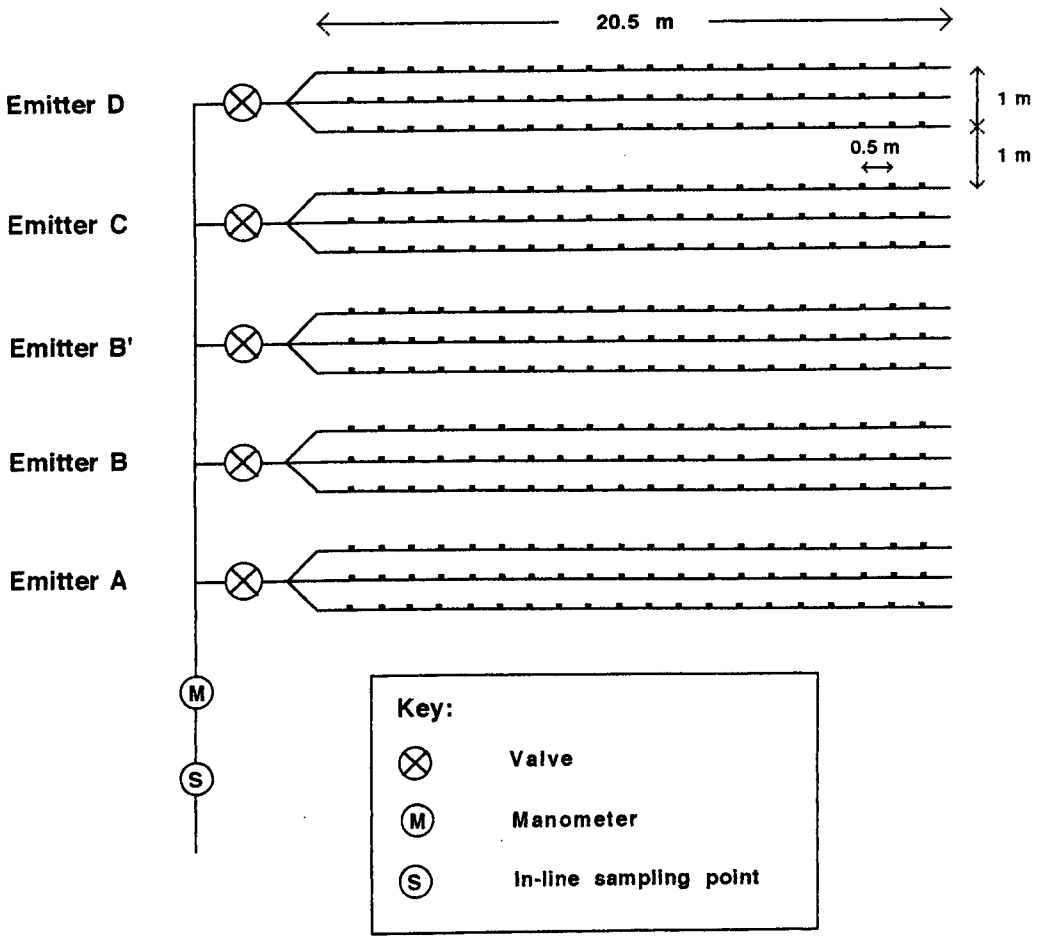
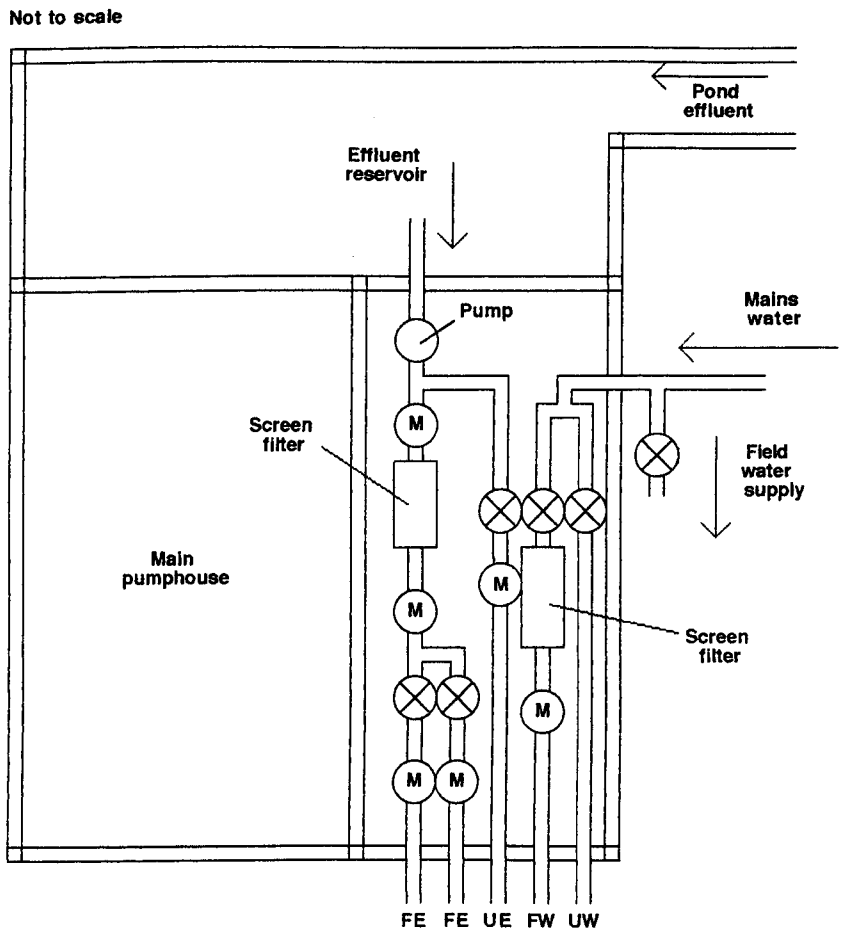


Figure 2.7 Plan of single plot from emitter clogging experiments

(plot designs were identical for all three water sources)

Santo André 1987



Key:

⊗	Valve
M	Manometer
FE	Filtered effluent supply to (a) LNEC plots (b) Bacteriology and clogging plots
UE	Unfiltered effluent supply to clogging plots
FW	Filtered water supply to bacteriology and clogging plots
UW	Unfiltered water supply to LNEC plots

Figure 2.8 Schematic representation of pump house equipment

Santo André 1987

2.2.2 Design of Emitter Clogging Experiments

Sector 3 was divided into three plots, each of which were each supplied with a water source of a different quality. These sources were:

1. unfiltered mains water;
2. unfiltered facultative pond effluent; and
3. filtered facultative pond effluent.

The plots were divided into five subplots (Figure 2.7) each containing three 10.5 metre long black polythene laterals (12 mm diameter), laid down in parallel at a spacing of 50 cm. Each subplot was fitted with a different emitter design, fitted into or onto the laterals depending on design, at a spacing of 50 cm. Hence each subplot contained three lines fitted with twenty identical emitters, a total of sixty identical emitters per subplot.

2.2.3 Emitter Designs

Emitter designs were chosen to reflect the diversity of emitters available for both outdoor and greenhouse irrigation systems. They included designs that could be manually punched onto the irrigation laterals *in situ* using a mechanical hole punch (so called "on-line" emitters), and designs that are pre-fitted into the laterals either by the manufacturer, or *in situ* prior to setting up the system ("in-line" emitters). Each type offers certain advantages to the farmer: the former can be easily replaced should clogging problems occur

whereas the latter type presents no protruding external parts and therefore allows laterals to be rolled up and stored between growing seasons, a distinct advantage in large scale outdoor systems.

Of the two emitter designs used in Évora during 1986, Emitter 1 was further investigated at the Santo André site but was redesignated Emitter D in order to simplify nomenclature in the second phase of the study. On the basis of the Évora results it was decided that Emitter 2 was unsuitable for irrigation using marginal water sources and therefore studies on this design were discontinued. The emitter designs studied in 1987 are described below.

Emitter A (Figure 2.9). This emitter was supplied by Twin Drops™ Iberica s.a. It is an "in-line" design with a design discharge rate of three litres per hour at an operating pressure of 1.2 kg cm^{-2}. The rate of water discharge is controlled by a long-path internal matrix that leads to two openings on opposite sides of the lateral. This emitter is of the type commonly found in large outdoor irrigation systems but has the added advantage that it can be opened and cleaned *in situ* if required. Emitter A was used throughout Sectors 1 and 2 for yield and contamination studies.

Emitter B (Figure 2.10). This design was the K2™ (DLK) emitter supplied by Access Irrigation Ltd in the UK. It is a turbulent flow "on-line" emitter that attaches to the side of the polythene laterals. It was specifically designed for greenhouse and nursery applications and has a design discharge rate of 2 litres per hour at an operating pressure of 1.0 kg cm^{-2}. Flow reduction is achieved by a long narrow (0.65 x 0.65 mm) water path.

Emitter B' (Plate 2.3). This was an adaptation of the above design in which a 30 cm length of 3 mm diameter black polythene hose was attached to the emitter outlet and inserted into a 10 cm length of 12 mm diameter lateral tubing, inserted vertically into the soil surface. This successfully excluded sunlight from the emitter opening.

Emitter C (Plate 2.4). This was the Netafim Button Dripper™ with a design discharge rate of 2 litres per hour at an operating pressure of 1.0 kg cm^{-2}. This "on-line" emitter was designed primarily for orchards and field crops. It is of a similar design to the Netafim Pot Dripper™ used extensively in nurseries, gardens and greenhouses. Flow path dimensions of this emitter are as follows: depth 0.889 mm; width 0.762 mm; and, length 50.80 mm.

Emitter D (Emitter 1). This was the TB In-line™ emitter supplied by Access Irrigation Ltd. and is of a similar design to Emitter A. It does not, however, allow for opening *in situ*. Design discharge rate is 2 litres per hour at an operating pressure of 1.5 kg cm^{-2} (Figure 2.4).

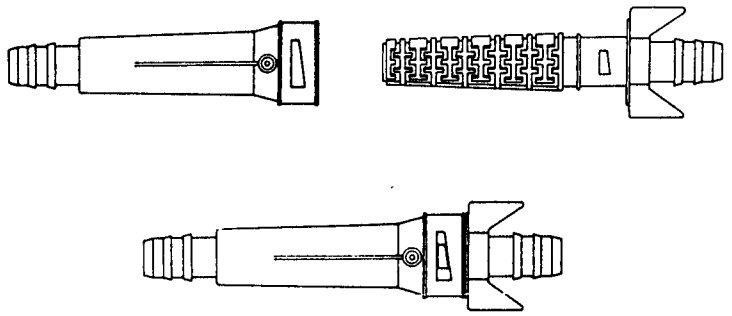


Figure 2.9 Emitter A

Emitter Dimensions

a	26 mm
b	38 mm

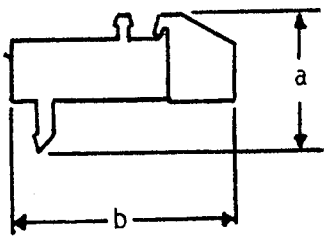


Figure 2.10 Emitter B

Plate 2.3 Emitter B' in operation

Plate 2.4 Emitter C

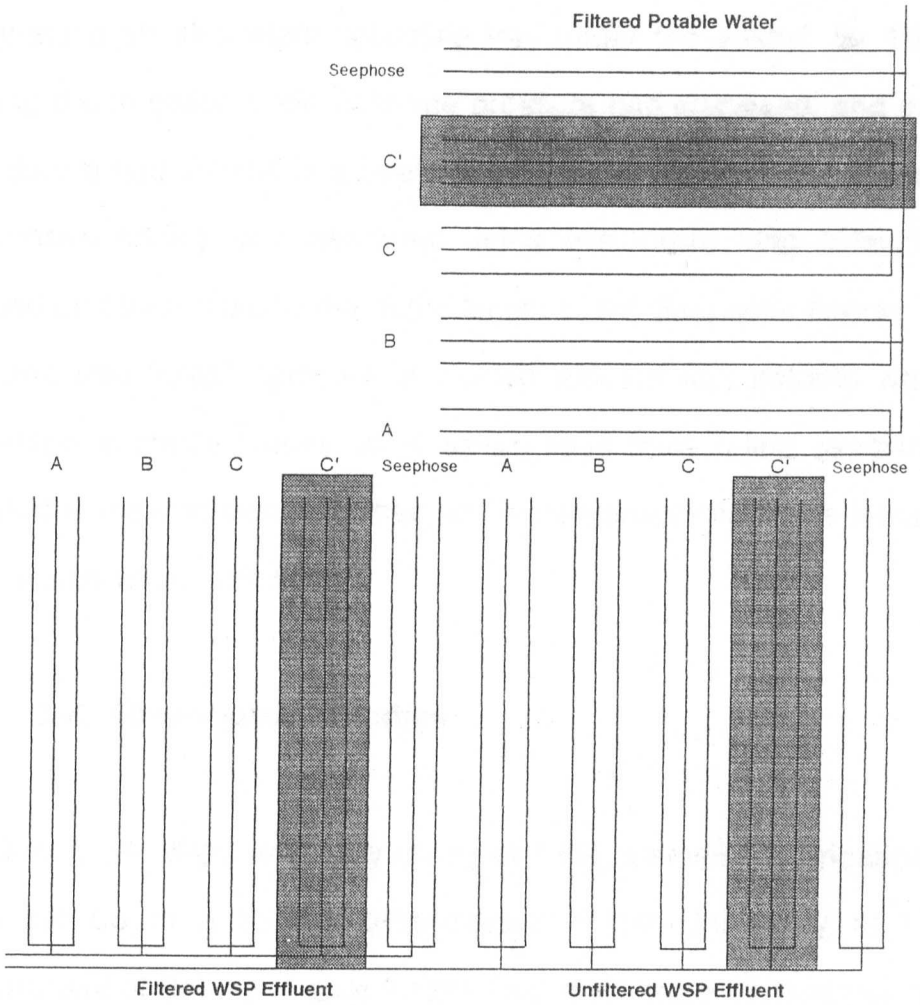
(L, internal labyrinth)

2.3 Field Experiments - Santo André, Portugal 1988

Field work was resumed at Santo André in May 1988 when a similar system to that of the previous year was set up. However, certain adaptations were made in order to develop the experiments in the light of the findings during the previous years.

Studies of Emitter D and the adaptation of Emitter B (Emitter B') were discontinued in 1988 whereas studies of Emitters A, B and C were further developed. In addition to plots containing Emitter C exposed to sunlight, additional plots were adapted by covering the laterals and emitters with black polythene sheeting to prevent the access of sunlight to the external emitter orifice. Emitters in these adapted plots were designated Emitter C'.

The efficiency of a low pressure design was also investigated in 1988. Seephose tubing is a simple low cost design which is only recommended by the manufacturers for use with a well filtered water supply. However, since this design can be operated at an in-line pressure as low as 0.5 kg cm^{-2}, it may offer the opportunity of supplying WSP effluent to crops without the need for expensive pumping equipment. It was therefore investigated in 1988 as a possible means of reducing the technological requirements of wastewater reuse schemes. Unlike the other emitter designs, which consist of individual emitters on or within polythene lateral lines, the Seephose system consists of a flexible, "lay flat" polythene tube stitched along one edge to form a continuous low emission emitter along the entire length of the tubing. It is manufactured by Access Irrigation Ltd. in the UK.



Key:

A, B, C, C' and Seephose	Emitter designs
Shaded areas	Laterals covered by black polythene

Figure 2.11 Plan of emitter clogging experimental plots, Santo André 1988. Scale 1:167

2.4 Sampling Techniques

Emitter discharge of selected emitters was monitored every seven days by placing an aluminium collecting tray under the emitter for 10 minutes during the irrigation cycle after line pressure had stabilised, and measuring the discharged volume in a one litre measuring cylinder. The output of the Seephose tubing was measured using one metre long collecting trays placed end-to-end below the entire length of the Seephose lateral.

One litre "grab" samples of treated effluent and potable water were collected in sterile bottles every seven days from in-line sampling points located in the irrigation mainlines and were transported to the laboratory for processing within one hour.

2.5 UK Greenhouse Studies

During the winter and early spring of 1988, a small drip irrigation system was set up in a heated greenhouse in the University of Liverpool Department of Botany (Figure 2.12). This small scale system was designed to compare the microbiological aspects of emitter fouling in a "clean water system" that contained dissolved inorganic plant fertilizers with the microbiological fouling phenomenon observed during wastewater reuse field trials in Portugal.

Plate 2.5 Equipment used for measuring emitter output

Plate 2.6 Measuring emitter output

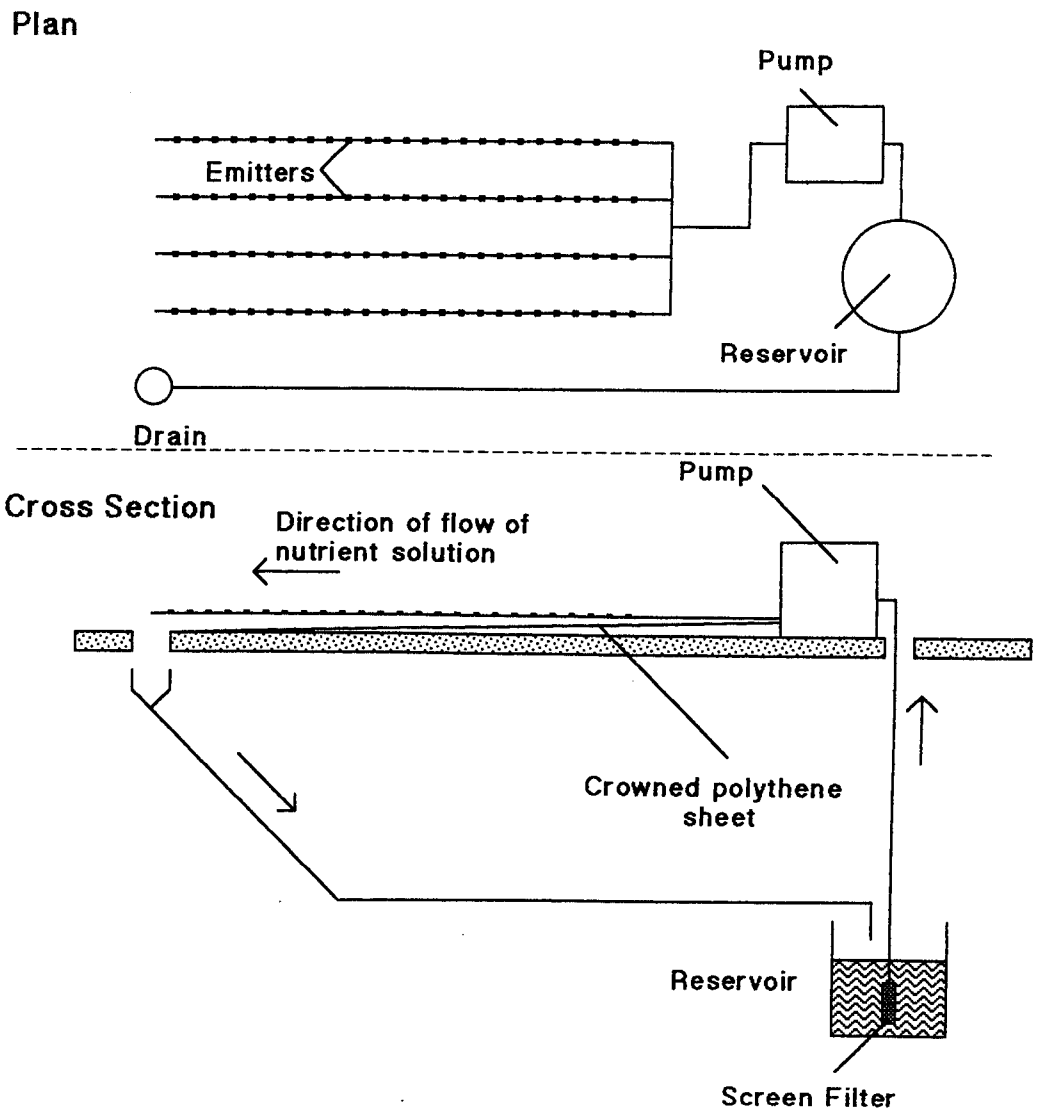


Figure 2.12 Schematic diagram of small scale greenhouse experiment Liverpool 1988

The system consisted of one hundred Type C emitters inserted into four 1 metre length black polythene laterals (diameter 12 mm), laid down in parallel on a polythene sheet (Figure 2.12). The emitters were inserted at a spacing of 4 cm (ie., 25 emitters per line). All four laterals were supplied with a solution of inorganic plant fertilizer (Vitax Foliar Feed) at an in-line pressure of 1.5 kg cm^{-2}, through a single main line using an electric centrifugal pump. The system was operated for one hour each day from 09.00 hrs. to 10.00 hrs. for a period of fifty days. The dissolved plant feed was stored in a 100 litre capacity reservoir and was circulated through the system to reduce plant feed requirements. The reservoir was drained every seven days and a fresh supply of plant feed prepared. Details of the plant feed composition are given in Chapter 5.

2.6 **Laboratory Procedures**

2.6.1 Bacteriological Techniques

Samples of final effluent and potable water were collected in sterile one litre bottles and transferred to the laboratory for processing within one hour. The samples were mixed by inverting the sample bottles several times and all dilutions were prepared in sterile $^1/_4$ strength Ringers solution (Oxoid BR5).

The multiple tube technique, also known as the most probable number (MPN) technique, was used for the enumeration of salmonellae in effluent samples. The MPN method is a means of estimating the most probable number of a particular type of viable microorganism within a sample. A series of tubes containing a medium selective for the growth of the particular

organism in question are inoculated with measured volumes of the original sample in solution, so as to establish a dilution series. Assuming that one or more of the organism is present in the inoculum of a particular tube then that tube will show a positive result following incubation (PHLS and SCA, 1983). Providing that the original dilution series was sufficient to produce both positive and negative results, the most probable number of the selected organism in the original sample may be estimated by reference to statistical tables (Swaroop, 1938).

Tenfold dilutions of effluent were prepared using 1/4 strength Ringers solution and pipetted into bottles of double and single strength Selenite F Broth. Muller-Kauffman Tetrathionate Broth was used in preference to Selenite F Broth from June 1987 for the enumeration of *Salmonella* spp. following recommendations for the cultivation of salmonellae by Oragui (pers. comm.). The inoculated enrichment medium was incubated for twenty four hours at 37°C. A loopful from each bottle was then streaked onto freshly prepared Xylose Lysine Desoxycholate Agar (XLD) and incubated at 37°C to detect the presence of *Salmonella* spp. Presumptive positive colonies were confirmed using Lysine Iron Agar. Final confirmation of presumptive *salmonella* colonies was carried out using serological techniques by agglutination with polyvalent 'O' and 'H' antisera.

The membrane filtration technique was used for the enumeration of fæcal coliforms. This is a direct means of enumerating bacteria and as such offers distinct advantages in accuracy and ease of operation over the indirect MPN technique. However, no satisfactory procedure exists for counting *Salmonella* spp. by this method. The method used for faecal coliforms was that described in Report 71 of the PHLS and SCA (1983), using a vacuum

pump and manifold connected to sterile filtration equipment. All samples were processed in triplicate.

Membrane Lauryl Sulphate Broth (m-SLS) was used for the presumptive enumeration of total and fæcal coliforms. The sterile broth was added to sterile absorbent pads placed on the base of sterile 9 mm diameter plastic petri dishes, so as to saturate the pad. Following sample filtration, the membrane filter (Millipore HAWG 047 S1) was placed aseptically onto the saturated pad prior to incubation. Plates were incubated for 18 to 24 hours at 44^{0}C.

Presumptive colonies of fæcal coliforms were confirmed using Tryptone Water and Lactose Peptone Water. Tryptone Water is used to test for the ability of an organism to produce indole from tryptophan. After inoculation of the medium with the sample, the tubes were incubated for 24 hours at 44^{0}C, and 0.2-0.3 ml of Kovac's reagent were added. The presence of indole is indicated by a deep reddening of the reagent. Lactose Peptone Water is used to demonstrate the production of acid and gas from lactose at 44^{0}C. After inoculation of the broth and incubation at 44^{0}C for 24 hours, a positive result is indicated by the production of acid (medium changes from red to yellow) and the evolution of gas as shown within the inverted Durham tubes.

Plate Count Agar (PCA) is recommended by APHA (1985) for total heterotrophic counts. Using this agar, the total numbers of heterotrophs in the irrigation waters were estimated every seven days, by the spread plate technique. Dilution series were prepared using sterile Ringers solution, and three replicate plates from each dilution were spread and incubated at 37^{0}C for 24 hours. Replicate plates were also incubated at 24^{0}C for five days.

2.6.2 Algal Techniques

The algal biomass content of pond effluents was estimated indirectly by measuring chlorophyll *a* concentrations. This method is considered a more appropriate means of measuring algal biomass than counting algal numbers (Dust and Shindala, 1970). This is because all algae contain essentially the same proportion of chlorophyll *a* i.e. approximately 1.5 percent of the dry organic mass (APHA, 1985). Microalgal cell volumes may, however, vary enormously especially between different genera: large *Euglena* may be three to four times larger than small *Euglena* and eighty five times larger than *Chlorella* (Pearson, 1986). The procedure used and described below is an adaptation of those described by Marker *et al.* (1980a) and Pearson (1986).

1. 1 ml of 0.1 percent magnesium carbonate suspension was filtered through a 7 cm^3 Whatmann GFC glass fibre filter. The entrapped magnesium carbonate aids retention of algal cells on the filter, but more importantly, it prevents the transformation of chlorophyll *a* into its degradation products (such as phæophytin *a*) by acidification.
2. A known volume of the sample was filtered to entrap all the algal cells on the filter surface. The maximum volume filterable without clogging was used to obtain a sufficient chlorophyll a concentration for a spectrophotometric reading within the Lambert-Beer range of proportionality (0.2 - 0.8).
3. The filter pad was placed in boiling tubes and 10 ml of 90 percent methanol were added. The sample was then boiled for two minutes to aid extraction.

4. The extract was centrifuged at 500 *g* for ten minutes to remove filter debris and the extract volume corrected to 10 ml by the addition of more 90 percent methanol.
5. A proportion of the extract was then transferred to a 4 cm glass cuvette and its absorbence read at 663 nm and 750 nm against a 90 percent methanol blank, the higher wavelength being a correction for turbidity.

Readings were then corrected for the presence of phaeophytin *a* (a means of estimating the percentage of viable cells) using the following procedures:

6. 0.2 ml of 0.6 M HCl were added to the extract in the cuvette, mixed and left for one minute.
7. 0.2 ml. of 0.6 M dimethyl-aniline in 90 percent methanol were added, mixed and left for a further minute.
8. Absorbence of the extract was re-read at 663 and 750 nm.

Concentration of chlorophyll *a* can then be calculated using the following equation:

$$\text{Chl. } a \ (\mu g \ l^{-1}) = X \ (A_b - A_a) \ k. \ v \ / \ V. \ l$$

where; Chl. *a* = Concentration of chlorophyll *a*
X = R/(R-1) where R is the max. acid ratio in 90% methanol
A_b = Absorbence at 665 nm less the abs. at 750 nm before acidification
A_a = Absorbence at 665 nm less the abs. at 750 nm after acidification
k = 103/a where a is the specific absorbence coefficient for chlorophyll *a* in 90% methanol
v = Volume of solvent in millilitres
V = Volume of sample filtered in litres
l = Path length in centimetres

Using the values given by Marker *et al.* (1980_b) of 1.58 for the maximum acid ratio, R, in 90 percent methanol, and 77 for the specific absorption coefficient, a, of chlorophyll *a* in 90 percent methanol, and assuming a path length of 1 cm, the equation simplifies to:

Chlorophyll *a* (µg per litre) = 35.32 (Ab - Aa). v / V

Finally, all chlorophyll *a* values must be multiplied by 1.033 to correct for dilution by acid and base.

2.6.3 Physicochemical Analyses

All physicochemical analyses of the irrigation waters were carried out in accordance with the recommendations of APHA (1985) using the following methods.

1. Total suspended solids (TSS) were determined using Whatman GF/C glass fibre filters. The filters were dried at 105°C.

2. Chemical oxygen demand (COD) was determined using the closed reflux titrimetric method.

3. Biochemical oxygen demand (BOD_5) was determined by the dilution test at 20°C for five days.

4. Sodium, magnesium and calcium were determined by the inductively coupled plasma atomic emission spectroscopy method following sample filtration through Whatman GF/C glass fibre filters.

2.6.4 Microscopy and Photography

1. Low power light microscopic photographs of emitters were taken with a Nikon SMZ 10 stereoscopic microscope with a x 2.5 projection lens and a x 1/2 auxiliary lens and Nikon FG SLR camera. Illumination was achieved with a Schott KLI 500 fibre optic illuminator and Nikon microflex UF x11 photomicrographic attachment.

2. Microscopic examination and measurements of emitter clogging particles were carried out on a stereoscopic light microscope using a calibrated eyepiece graticule.

3. Samples of irrigation equipment for scanning electron microscopy were dehydrated in ethanol at -20 ^{0}C and critical point dried using carbon dioxide. The samples were then coated with 60 percent gold : 40 percent palladium, glued onto stubs and viewed on a Philips 501 B Scanning Electron Microscope using an accelerating voltage of between 7.2 and 15 kV.

CHAPTER 3

3. WATER QUALITY AND PREDICTION OF EMITTER FOULING

3.1 Introduction

Scarcity of potable water in many arid and semi-arid areas of the world has necessitated the utilization of water from less desirable sources for irrigation (Oron *et al.*, 1979). Use of such waters requires adequate planning in order to avoid adverse affects on crop yield and irrigation equipment. Ayers and Westcot (1985) divide the major problems associated with water quality into four groups.

1. Salinity which may affect yield by reducing water availability to the crop.
2. Water infiltration rate. High sodium or low calcium levels, in the soil or irrigation water, reduce infiltration of the water into the soil so that insufficient water may become available to the crop.
3. Specific ion toxicity. Certain sensitive crops may accumulate specific ions such as boron, sodium or chloride, to such an extent that the crop is damaged.
4. Miscellaneous. This group includes excessive nutrients which may reduce yield or quality, and constituents that produce unsightly deposits on the crop and those that corrode or clog irrigation equipment.

Domestic and industrial wastewaters are a potential source of irrigation water where potable water is scarce. In many arid and semi-arid regions of the world potable water supplies have been reserved for human consumption while irrigation has been extended by the utilization of treated wastewaters.

Various guidelines for wastewater quality in reuse schemes have been prepared by national governments. The latest WHO guidelines (WHO, 1989) are based on cause and effect observations in existing irrigation systems (Table 1.3): these guidelines will probably be modified in the light of further research and as predictive capability is improved.

3.1.1 Water Quality in Effluent Reuse Systems

The composition of treated wastewaters used for irrigation depends on the composition of the raw wastewater, and the nature and degree of treatment. The composition of a particular wastewater will vary with time. Local conditions, such as seasonal rainfall and diurnal patterns in water use by the community for example, control both the flow and concentration of raw wastewater. Typical data on the composition of untreated domestic wastewater are reported in Table 3.1.

The aim of wastewater treatment is to accelerate and contain the natural purification processes under controlled conditions within a treatment facility (Metcalf and Eddy, 1979). Such processes decrease the oxygen demand on receiving water bodies and accelerate the die-off of pathogenic organisms. Wastewater facilities are therefore a means to isolate and reduce risks to the environment and to public health. In addition, wastewater treatment can now be considered a means of producing water suitable for irrigation. The composition of the two types of treated effluents used in the experimental work, ie. the high rate trickling filter process and waste stabilization ponds, are considered here.

The trickling filter process, which was first developed in the UK in the late nineteenth century, is a method of oxidising carbonaceous and nitrogenous pollutants thereby minimising the eutrophication of receiving water bodies. Pathogen removal was not a primary objective of its design and it is therefore more commonly used in those countries where the protection of the environment is the most important goal. Raw wastewater is screened to remove gross solids before passing into a primary sedimentation tank where sedimentation and microbial oxidation removes 20 to 40 percent of the unstable organic matter originally present in the wastewater (Linsley and Franzini, 1979).

The trickling filter process is a means of further purifying the effluent of a primary sedimentation tank. Degradation of organic material is achieved by a complex microbial community on the surface of stones or whatever inert material comprises the contact bed. Settled sewage is applied to the surface of the filter by a rotary distributor and allowed to trickle through to the outlet at the base. The provision of nutrients in the wastewater leads to the development of a microbial slime on the surfaces of the contact bed containing bacteria, fungi, algae and protozoa as well as higher animals including snails, insect larvae and worms (Metcalf and Eddy, 1979). Table 5.2 lists the major organisms commonly found in trickling filters. The effluent from trickling filters generally enters a secondary sedimentation tank in which residual solids sediment out and are combined with the sludge from the primary sedimentation tank for anaerobic digestion. The final effluent from an efficient trickling filter process contains the inorganic products of aerobic oxidation (water, salts of nitrogen, phosphorus and sulphur, and carbon dioxide) and is suitable for discharge into rivers and streams (Higgins and Burns, 1975).

Waste stabilization ponds (WSP) are often the treatment process of first choice wherever sufficient sunlight and suitable land are available. They are particularly effective at removing intestinal pathogens including nematode eggs, bacteria and viruses (Pearson, *et al.*, 1987). They operate successfully throughout the world and are an efficient low cost, low technology method of wastewater treatment particularly suitable for use in developing countries that possess a warm climate (Pearson, 1987). WSP are shallow basins into which wastewater flows and from which treated effluent is discharged (Mara and Pearson, 1986). They require no input of energy other than sunlight and, if well designed, they will operate effectively with minimum maintenance. Experimental ponds in the Northeast of Brazil are reported to have virtually eliminated pathogens and to have substantially reduced BOD_5 and suspended solid loadings (Mara *et al.*, 1983). A detailed discussion of the design of WSP and the biological processes that lead to wastewater treatment are outside the remit of this study: further details are reported by Mara (1976), Mara and Pearson (1986), and Curtis (1990).

The final effluent from the WSP process differs markedly from the effluent of other conventional treatment processes such as trickling filter systems. Because planktonic algae play a pivotal role in the treatment process, they are usually present in large numbers in the final effluent. These algae increase the level of suspended solids and can prevent the effluent from meeting those discharge criteria for wastewater treatment systems that state a maximum level for suspended solids. However, algal cells do not

constitute the same pollution risks as those associated with the suspended solid component of the trickling filter and activated sludge processes, and may offer benefits as a source of plant fertilizers and soil conditioners in any subsequent agricultural reuse scheme.

The risk of disease among consumers of crops that are contaminated by wastewater pathogens has resulted in the development of water quality guidelines in which levels of pathogens (or pathogen indicators) are the primary criterion for the suitability of a particular wastewater as a source of irrigation water for a particular crop (Crook, 1991). Early guidelines (WHO, 1973) were based on a limited amount of data from existing reuse schemes. These tended to overestimate the risks involved and are these days generally considered too conservative for many situations. Also, the degree of wastewater treatment necessary to attain such standards is impracticable in many applications especially in the developing world. Recently, less stringent quality criteria (IRCWD, 1985; WHO, 1989) have better reflected the potential risks of effluent reuse (Table 1.3). These guidelines are based on survival times of selected enteric pathogens in the soil and on crops (Feachem *et al.*, 1983) and on systematic epidemiological evidence from actual cases of infections linked to human exposure to wastewater such as those reported in India (Krishnamoorthi et al., 1973), Israel (Shuval *et al.*, 1986) and the USA (Clarke *et al.*, 1981) .

Recent studies have concentrated on options for health protection that include crop restriction, localised application methods and control of human

exposure in addition to waste treatment. Blumenthal *et al.* (1989) have presented a generalised model to show the effectiveness of each option in reducing health risks to agricultural workers and consumers of the crops grown.

Aspects of wastewater quality other than those associated with health have received less attention. Agronomic suitability of a potential water source is of great importance whether the water is potable or a treated wastewater, and therefore salinity, permeability and ion toxicity should be considered prior to the instigation of all reuse schemes.

The presence of dissolved organic substances in wastewaters used for irrigation can theoretically deplete the available oxygen in the plant root zone. However, irrigation with water supplies containing high levels of dissolved organic material has been practised in many countries without problems (Bouwer and Idelovitch, 1987). Little information is available on the effect of pesticides and other synthetic organic substances in wastewater on crops and no limits have been established for reuse schemes but it has been recommended by the US Environmental Protection Agency (1977) that pesticide and carcinogenic polynuclear aromatic hydrocarbons should not greatly exceed the WHO International Standards for Drinking Water (1972).

Plant nutrient levels in treated wastewaters are usually higher than those in potable water supplies but the level of specific nutrients will depend on the type and the efficiency of the treatment process used. Wastewater used for irrigation therefore possesses a 'fertilizing potential' in addition to its

basic 'water value' (Papadopoulos, 1992).

Of the three macronutrients present in wastewaters (ie. phosphorus, potassium and nitrogen), phosphorus and potassium are well absorbed by the soil and relatively high levels can be accommodated by a combination of soil absorption and crop uptake without causing damage to the crop or contaminating the groundwater. A review of available literature from field studies in which wastewater irrigation has been practised for extended periods showed only infrequent occurrences of phosphorus penetration into subsoil layers (Hook *et al.*, 1973).

The levels of nitrogen in irrigation waters are of greater agricultural importance. Nitrogen is a significant constituent of most municipal wastewaters and is usually considered beneficial to plants (Vazquez Montiel, 1991). The concentration of nitrogen and the ratio of its molecular forms (NH_4-N, NO_3-N, NO_2-N and organic-N) depend on the degree and type of treatment (UNEP/FAO 1991). The nitrogen in reclaimed wastewater essentially replaces fertilizer nitrogen requirements under most conditions (Papadopoulos, 1992). However, when it is present in significant amounts in irrigation water, care must be taken to control the application rate so as to avoid leaching of nitrates into the groundwater and vegetative growth, delays in maturation and damage to the crop caused by excess uptake of nitrate and ammonium ions.

3.1.2 The Effect of Effluent Quality on Emitter Clogging

The basic causes of emitter clogging as described by Bucks *et al.* (1979), can be classified as physical, chemical or biological (Table 1.4). Each of these categories plays a part in the clogging of emitters but the importance of each depends on the nature of the water supply used for irrigation.

Suspended solids in wastewaters are generally considered to be the major cause of emitter clogging in wastewater trickle irrigation schemes (Shuval *et al.*, 1986). Some authors suggest that as much suspended material as is possible should be removed before sewage effluent is used for irrigation (Bouwer and Idelovitch, 1987). However, removal of solids constitutes an additional wastewater treatment process which increases costs and removes water constituents rich in plant nutrients. The nature of the suspended solids within a given effluent will depend on the nature and degree of treatment. For example, the high suspended solids fraction in waste stabilization pond effluents results from algal growth. In Israel WSP effluent is usually pretreated prior to its use in drip irrigation. The most common form of pretreatment is filtration by strainers with a pore size of between 20 and 200 mesh (Shuval *et al.*, 1986). Back washing of filters is considered essential to prevent filter blockages and the escape of large organic aggregates into the laterals but clogging of emitters is still reported in Israeli reuse drip irrigation systems using such filtration (Adin, 1987). More recently, media filtration units have been used. These utilise a bed of

sand or gravel rather than a screen and can, with proper maintenance, remove a far greater proportion of suspended material including microalgae. Media filters are commonly used in UK greenhouses to remove the algae from water reservoirs. Removal of microalgae from irrigation waters does, however, remove an important source of plant nutrients and soil conditioners. In this project minimum screen filtration of treated wastewaters was used in order to ascertain whether the algal fraction could be applied to plants without causing emitter blockages.

In assessing potential clogging risks it is important to note that the simple classification of the causes of emitter clogging as physical, chemical or biological does not take into account the environmental conditions that may lead to microbial growth within an irrigation system. Microbial growth will occur wherever the nutritional and environmental requirements of a particular organism are satisfied. Enumeration of microorganisms in the irrigation water cannot, therefore, accurately predict the occurrence of biofouling problems. Previous assessments have not taken into account the role of microbial nutrients in irrigation waters and the nature of the habitat of irrigation equipment. The nature of variations in the habitat of trickle irrigation laterals and emitters that may affect microbial growth and thereby cause blockages are described in Section 3.3.

Table 3.1 Typical composition of untreated domestic wastewater

Constituent	Concentration		
	Strong	Medium	Weak
Solids, total:	1200	720	350
Dissolved, total	850	500	250
Fixed	525	300	145
Volatile	325	200	105
Suspended, total	350	220	100
Fixed	75	55	20
Volatile	275	165	80
Settleable solids, ml per litre	20	10	5
BOD_5, 20 °C	400	220	110
Total organic carbon (TOC)	290	160	80
COD	1000	500	250
Nitrogen (total as N):	85	40	20
Organic	35	15	8
Free ammonia	50	25	12
Nitrites	0	0	0
Nitrates	0	0	0
Phosphorus (total as P):	15	8	4
Organic	5	3	1
Inorganic	10	5	3
Chlorides *	100	50	30
Alkalinity (as $CaCO_3$)	200	100	50
Grease	150	100	50

All values except settleable solids are expressed in mg per litre

* Values should be increased by amount in domestic water supply

Source: Metcalf and Eddy (1979)

Table 3.2 Estimated performance data for trickling filter and waste stabilization pond treatment processes

Process	SS	BOD_5	COD	N	NH_3	P
(Incoming wastewater	225	200	450	40	25	10)
Trickling filters:						
low rate	25	18	100	25	1	7
high rate	30	20	100	30	25	7
Stabilization ponds*:						
algal surface layer	420	40	160	20	1	4
aerated surface layer	80	25	140	20	4	4

* Without solids removal
All values are expressed in mg per litre

Adapted from Tchabanoglous (1974)

3.2 Results of Monitoring Studies of Irrigation Water

The quality of the water supplies used for irrigation was monitored every seven days during the 1986 and 1987 irrigation seasons as described in Chapter 2. In 1988 physicochemical data on the WSP effluent were supplemented by more detailed experiments into changes in the levels of the following parameters within the irrigation laterals:

i. total suspended solids;
ii. chlorophyll *a* ;
iii. dissolved oxygen; and
iv. temperature.

The physicochemical composition of the trickling filter final effluent that was used for the initial pilot irrigation scheme is presented in Table 3.3a. The results of additional analyses of the effluent, taken from the in-line sampling points within the irrigation system, are presented in Table 3.3b. These results demonstrate that the trickling filter treatment system at Évora was not operating successfully during the 1986 growing season. Data for the raw municipal wastewater at Évora is not available but assuming an average raw wastewater strength, as defined by Metcalf and Eddy (1979), BOD_5 removal averaged 73 percent, COD 53 percent and suspended solids 77 percent. The final effluent was of poor microbiological quality: fæcal coliform levels averaged 1.2×10^6 per 100 ml, considerably higher than the recommended maximum of 10^3 per 100 ml suggested by the WHO (1989) for unrestricted irrigation. Salmonellae were detected in all samples of final effluent. The poor quality of the treated effluent can be explained by poor maintenance of the trickling filters and overloading of the system.

The method suggested by Bucks *et al.* (1979) for classifying irrigation waters used in trickle systems can be used to rate the emitter clogging potential of the HRTF effluent used in Évora. Comparing the mean values for suspended solids, dissolved solids and total bacteria obtained from the irrigation lines with those given in Table 1.5, the HRTF effluent gives a rating of 3-7-10 for unfiltered effluent and 1-7-10 for unfiltered effluent. According to Bucks *et al.* (1979) combined values between 10 and 20 represent some problem and those between 20 and 30 represent a severe problem.

Closer analysis of the Évora HRTF effluent quality data suggests that clogging of emitters by organic aggregates was a potential problem if the effluent were to be used for drip irrigation. The suspended solid fraction of the effluent mainly comprised undegraded fæcal material that had bypassed the successive treatment stages because the system was overloaded. Media filtration of the final effluent reduced the mean suspended solids concentration by fifty percent but large organic aggregates were still routinely observed in the filtered effluent. The appearance of large solids between 5 and 10 millimetres in diameter suggested that they had broken away from the filter cake and were entering the irrigation laterals. These solids may aggregate within the laterals and cause blockages in the narrow channels within the emitters.

In addition to high levels of suspended materials, the final effluent from the Évora HRTF plant contained high concentrations of dissolved nutrients. High values for BOD_5 and high concentrations of the major forms of nitrogen suggest that heterotrophic microorganisms may multiply on the internal surfaces of the irrigation equipment in a similar manner to the biofilm on the trickling filter media bed. Other factors controlling the degree and nature of microbial growth within the laterals and emitters are temperature and the availability of oxygen. Phototrophic growth within the black laterals is prevented by the absence of light.

The composition of the Santo André WSP effluent differed markedly from that of the Évora HRTF. Pathogen levels in the WSP effluent were lower (Table 3.5), with a mean fæcal coliform level in the final effluent of 4.28 x 10^3 per 100 ml in 1987. Salmonellae were undetected in most 100 ml samples. Levels of suspended solids were similar to those of the HRTF effluent, but microscopic analysis of the two effluents revealed the nature of the suspended material to be very different. Visible aggregates of solids were rare in the WSP effluent and the suspended material was primarily composed of planktonic microalgae. Microscopic analysis of the WSP effluent revealed the predominant alga to be Euglena with average cell dimensions of approximately 50 x 10 μm. Qualitative studies of the algal population of the WSP effluent are described in Chapter 5.

Chlorophyll *a* was measured routinely in the WSP effluent in 1987, from the in-line sampling points in the filtered and unfiltered effluent mainlines, using a technique adapted from those of Pearson (1987); and Marker *et al.* (1980b), as described in Chapter 2. Chlorophyll *a* estimation is a recommended means of expressing the algal component of water bodies (APHA, 1985) and because algae play a pivotal role in the operation of WSP, it is used to verify that ponds are functioning properly. Variations in the levels of chlorophyll *a* between weekly samples of filtered and unfiltered WSP effluent are shown in Figure 3.2: the mean values were 252 μg per litre of filtered effluent, and 308 μg per litre of unfiltered effluent.

Chlorophyll *a* levels can also be used to estimate the total dry weight of algae. Assuming that chlorophyll *a* represents approximately 1.5 percent of the ash free dry weight of all oxygenic phototrophs (ie., cyanobacteria and eukaryotic microalgae), an estimation of the total biomass of these organisms in terms of suspended solids can be made. Dividing this value by the total concentration of suspended solids in the same samples gives a rough estimate of the contribution of these organisms to the level of

suspended solids in the sample. The basic chlorophyll *a* method does not distinguish between active cells and those that are partially degraded. This is because both chlorophyll *a* and its major degradation product, phæophytin *a* contribute to the spectrophotometric absorbence reading. A simple modification of the method can be used to measure only metabolically active algae. This is achieved by acidifying the sample and measuring the absorbence of the phæophytin *a* produced. The results of analyses of chlorophyll *a*, suspended solids and bacteria in the filtered and unfiltered WSP effluent in 1987 are summarised in Table 3.5.

Differences between the composition of the WSP effluent and that of the Évora HRTF effluent suggest that the causes of any clogging problems that occur may also be different. Applying the prediction technique of Bucks *et al.* (1979) to the WSP effluent data of 1987 gives a value of 3-10-10 (the rating for dissolved solids being increased by 2 because the mean pH level of the pond effluent is higher than 7.5.

Although this method of predicting the clogging potential of an irrigation water may be of use in those situations where a more detailed investigation is not possible, it gives a highly simplified impression of water quality. A simple measurement of the dry weight of suspended material per litre does not distinguish between inorganic particles such as sand, single celled microorganisms, and larger aggregates of organic matter. Although WSP effluents usually contain high levels of microalgae, they are unlikely to survive and multiply within the laterals and emitter interiors: sand particles and organic aggregates represent a more likely cause of blocking narrow water paths. Therefore, microscopic analysis of the irrigation water source is as important as suspended solid measurements when designing a new trickle irrigation system.

Table 3.3a Physicochemical characteristics of the final effluent of the HRTF plant, Évora (August to October 1986)

Constituent	Mean	Range
Solids:		
Dissolved, total	1073.09	916 - 1162
Filterable	596.46	474 - 644
Volatile	476.64	438 - 518
Suspended, total:	50.14	23.0 - 83.0
Filterable	43.18	19.5 - 74.0
Volatile	6.96	0.0 - 21.0
BOD_5	60.45	32 - 155
COD	234.27	159 - 389
Nitrogen:		
Organic	9.03	3.1 - 33.2
Free ammonia	12.51	0.0 - 22.4
Nitrates	4.35	0.0 - 33.5

All values are expressed in mg per litre
Data provided by DGQA Laboratório de Santo André, Portugal

Table 3.3b Composition of waters used for irrigation, Évora Additional data from irrigation lines (September to October 1986)

Parameter	Filtered Effluent	Unfiltered Effluent	Potable Water
Suspended solids	22	44	0.5
Total plate count*	$1.2x10^7$	$4.0x10^7$	ND
Faecal coliforms	-	$1.2x10^6$	ND
Salmonellae	-	56	ND

Values for suspended solids are arithmetic means of 10 weekly samples and are expressed in mg per litre
Values for bacteria are geometric means of 10 weekly samples and are expressed in numbers per 100 ml
ND Not detected in 1 ml samples

Table 3.4 Physicochemical characteristics of filtered final effluent of the waste stabilization ponds, Santo André

Constituent	1987 Mean	1987 Range	1988 Mean	1988 Range
BOD_5, 20 °C	27	20 - 75	50	35 - 70
COD	85	19.4 - 132.9	122	118 - 137
Solids				
Suspended, total	26.6	6.0 - 48.5	ND	
Dissolved, total	1132	1054 - 1368	ND	
Nitrogen (totals as N)				
Free ammonia	22.6	12.3 - 30.8	30.0	24 - 39
Organic	7.27	6.00 - 18.70	8.97	7.8 - 10.3
Nitrates	0.92	0.40 - 2.41	0.42	0.4 - 0.5
Nitrites	0.678	0.055 - 1.563	ND	
Sulphates	101.44	77.50 - 229.41	ND	
Potassium	32.4	31 - 34	36.7	21 - 40
Calcium	74.22	66.21 - 80.95	76.8	68 - 82
Magnesium	31.24	28.69 - 35.74	30.7	27 - 36
Sodium	149	141 - 153	145.7	142 - 149
SAR	3.6		3.5	
Alkalinity (as CaCO3)	387	286 - 487	ND	
pH	8.3	7.9 - 8.6	8.1	7.8 - 8.5
Total hardness	87.22	77.50 - 106.50	ND	
Conductivity (ds/m)	1.49	1.39 - 1.80	1.51	1.38 - 1.95
Ortho-Phosphates	18.92	11.22 - 43.02	9.34	1.4 - 27
Chlorides	150	125 - 208	ND	
Iron	0.11	0.05 - 0.20	ND	

Data provided by DGQA Laboratório de Santo André
All values are expressed in mg per litre except pH and where units are noted.
ND Not determined

Table 3.5 Composition of filtered and unfiltered WSP effluent. Additional data from in-line sampling points (1987)

Parameter	Filtered Effluent	Unfiltered Effluent
Fæcal coliforms	-	4.28×10^3
Salmonellae	-	0.1
Total plate count*	-	6.07×10^6
Total suspended solids (mg/l)	40.27	43.96
Chlorophyll a (µg/l)**	251.7	308.2
Total algal biomass*** (mg/l)	17	21

* Total microbial heterotrophs, incubated at 25 °C for five days.
** Corrected for phæophytin *a* content
*** Estimation calculated from chlorophyll *a* measurements

Bacterial values expressed in numbers per 100 ml

Table 3.6 The physicochemical composition of the potable water supply. Santo André 1988.

Parameter	Mean	Range
pH	7.6	7.5 - 7.6
Conductivity (ds/m)	0.81	0.76 - 1.61
NO_3 - N	0.35	0 - 2
Calcium	79.0	78 - 81
Magnesium	29.2	24 - 29
Sodium	111.3	132 - 151
SAR	2.7	

All values expressed in mg per litre except pH and where units are noted

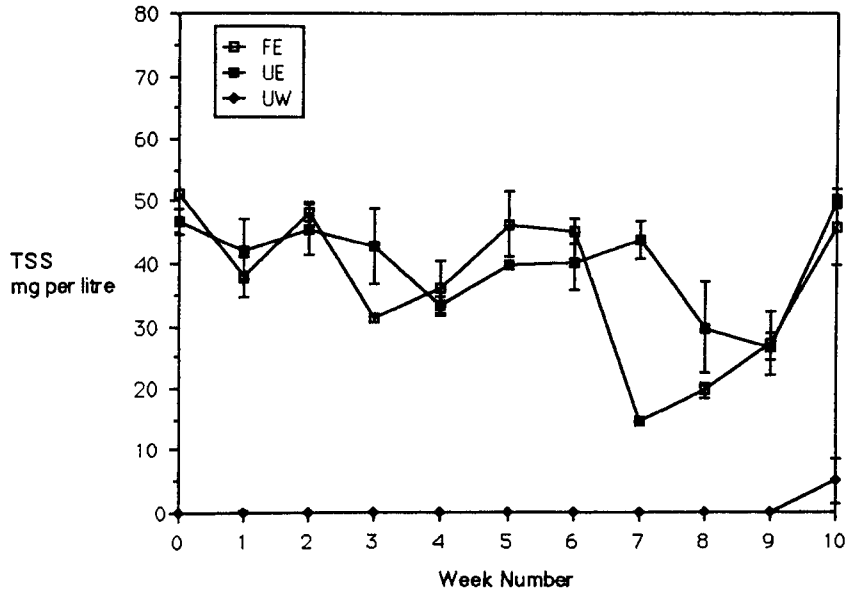


Figure 3.1 Levels of suspended solids in WSP effluent - filtered (FE) and unfiltered (UE) - and potable water (UW) during the 1987 irrigation season

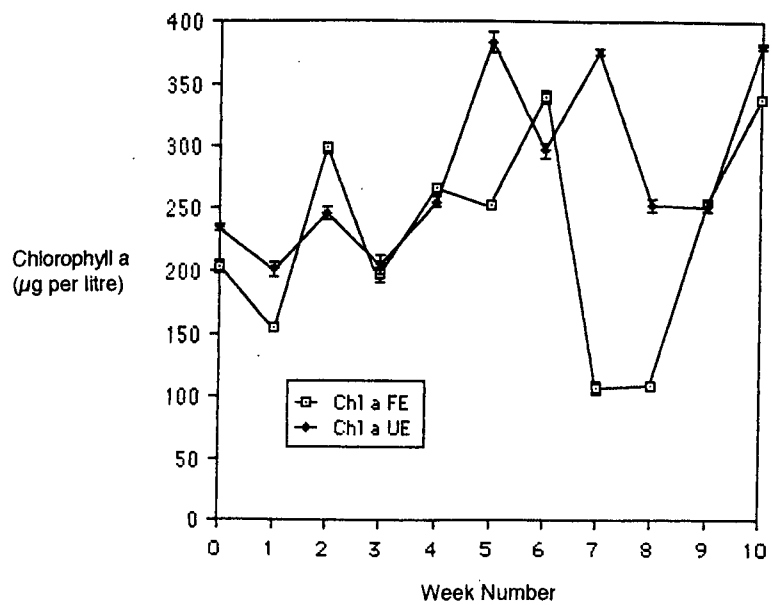


Figure 3.2 Levels of chlorophyll a in filtered (FE) and unfiltered (UE) WSP effluent during the 1987 irrigation season

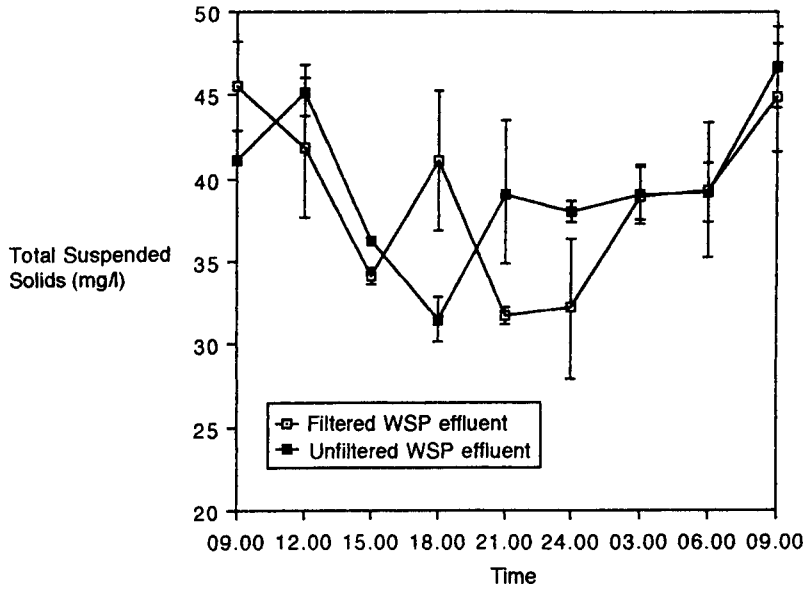


Figure 3.3 Diurnal variations in the levels of suspended solids in filtered and unfiltered WSP effluent, 05.10.87

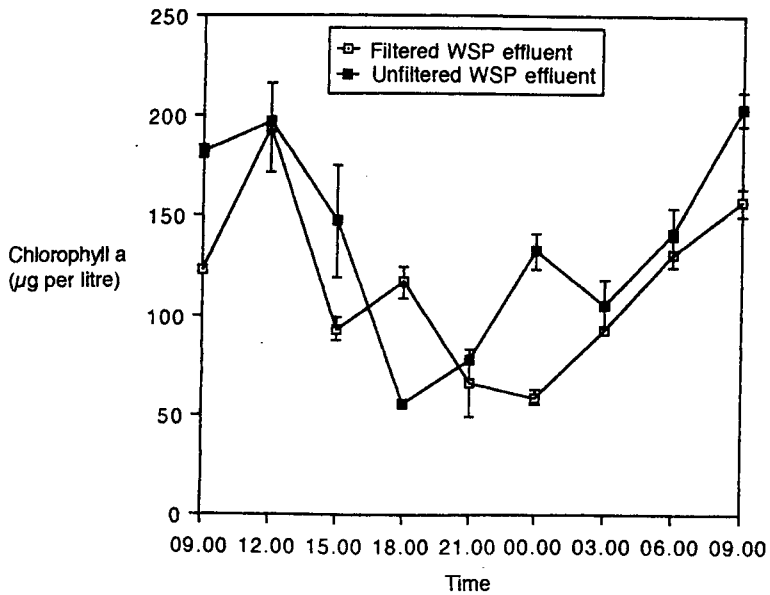


Figure 3.4 Diurnal variations in the levels of chlorophyll *a* in filtered and unfiltered WSP effluent, 05.10.87

The algal component of WSP effluents represents a potential source of "slow release fertilizers" in reuse systems. In facultative WSP, algae stratify in daylight hours into a narrow band some 20 cm thick, which moves up and down the water column in response to changes in levels of radiation and disperses at night (Mara and Pearson, 1986). This phenomenon can cause large diurnal variation in the quality of facultative pond effluents (Mara *et al.*, 1983). It was therefore considered important to monitor diurnal variations in algal levels of the final effluent at Santo André in order to investigate the effect of altering irrigation times on water quality. To estimate diurnal changes in algal concentration and levels of suspended solids, the irrigation system was switched on every three hours over a period of twenty four hours between 09.00 hours on 5 October 1988 and 09.00 hours the following morning, and triplicate samples of filtered and unfiltered were taken from the in-line sampling points for analysis. On each occasion the system was allowed to run for fifteen minutes before the samples were taken in order to flush out residual effluent in the irrigation lines.

The results of this twenty four hour profile are presented in Figures 3.3 and 3.4. Both parameters reached their peak during the day (194 µg of chlorophyll *a* and 42 mg of solids per litre of filtered WSP effluent at mid-day). Lowest levels were recorded between during the night (59 µg of chlorophyll *a* and 32 mg of solids per litre of filtered WSP effluent at midnight). Such variations in levels of algae in the final effluent can be accounted for by stratification of algae in the facultative pond during the day. During the night algae disperse throughout the water column. The outlet of the facultative pond at Santo André is positioned at the top of the water

column and therefore more algae are taken when effluent is taken off during the day than if irrigation takes place during the night. The effects of algal stratification are however reduced at Santo André because final effluent is stored in a small covered tank from which the irrigation water is taken. If WSP effluent is taken directly from pond outlets for irrigation, algal stratification should be taken into account when estimating concentrations of algae and plant nutrients.

3.3 Variations in Water Quality within Laterals

The results of the regular monitoring of irrigation water quality, carried out in 1987, may be used to predict causes of equipment blockages. However, such analyses do not demonstrate the changes in water quality that occur within the irrigation laterals. Between each daily irrigation cycle, irrigation water remains within the laterals. During this period changes occur in the habitat of the irrigation lateral interiors that affect physical, chemical and biological components of the irrigation water and may subsequently cause emitter blockages. In 1988 several experiments were carried out in order to investigate these changes during and between irrigation cycles.

Wastewaters contain a high proportion of reduced organic material. Oxidation of this material by heterotrophic microorganisms consumes dissolved oxygen, and unless sufficient oxygen is available from the atmosphere or from oxygenic photosynthesis by eukaryotic algae and cyanobacteria, the wastewater will rapidly become anoxic. The concentration of material available for biological oxidation in a water body is

often measured in terms of the amount of oxygen consumed during its oxidation by microorganisms. An important parameter of a raw or treated wastewater is its Biochemical Oxygen Demand. The BOD_5 test measures the oxygen consumed (in mg) per litre of wastewater, or a known dilution of wastewater, during five days at 20 ^{0}C (APHA, 1985). Treatment of wastewater reduces its BOD_5 by encouraging the microbial oxidation of organic material. Oxygen is provided by increased contact with the atmosphere in the case of trickling filters and by oxygenic photosynthesis in the case of WSP. The BOD_5 level of a treated wastewater will depend on the efficiency of the treatment process.

Within black irrigation laterals phototrophic activity by microalgae is prevented and the supply of oxygen from the atmosphere is limited. Since WSP and trickling filter effluent contain suspended and dissolved organic material, the aerobic oxidation of this material by microorganisms will continue in the irrigation laterals between irrigation cycles until the available oxygen is depleted. Figure 3.5 presents the results of investigations carried out in 1988 into dissolved oxygen concentrations within the irrigation laterals. Samples of the three irrigation water qualities were taken every ten minutes from the in-line sampling points at the irrigation plots. Care was taken to avoid aerating the sample. Dissolved oxygen was measured immediately using a YSI oxygen meter (Model 54 ARC/230). The experiment was carried out on three occasions during the growing season.

Figure 3.5 presents the mean values for dissolved oxygen within the irrigation laterals. The results show that when treated wastewater was left to

stand in the irrigation laterals conditions rapidly become anoxic. The consumption of oxygen may cause a "metabolism shift" by the microflora within the laterals: strict aerobes are suppressed and alternative sources of oxidising energy such as nitrates and sulphate are utilised by other organisms. The reduction of sulphate by sulphate reducing bacteria (SRB) releases hydrogen sulphide, which is toxic to many microorganisms. Conditions rapidly become aerobic again when fresh WSP effluent is reapplied to the system during the next irrigation cycle. This pattern of oxygen levels did not occur in laterals supplied with potable water in which little reduced organic material was present and in which microbial activity was consequently limited.

The pattern of dissolved oxygen concentrations in the laterals was probably far more complex than that shown in Figure 3.5. Within the sedimented material on the base of laterals, areas probably exist that remain anaerobic at all times: oxygen concentrations at the solid/liquid interface are dependent on the provision of aerated WSP effluent. A complex community of aerobes, facultative and obligate anaerobes are therefore able to grow within close proximity. Possible mechanisms of microbial community development within the laterals are discussed in Chapter 4 and summarised in Figure 6.1.

The temperature within the irrigation laterals showed a far greater diurnal variation than ambient temperatures (Appendix 1). During times of direct sunlight the black polythene laterals absorbed a great amount of heat and internal temperatures as high as 57 ^{o}C were recorded. Figure 3.6 shows the variations in ambient air temperature and the temperature of filtered effluent

within the irrigation laterals between 08.00 hrs. and 20.00 hrs. on 10 September 1988. Similar results were recorded for unfiltered effluent lines and for potable water lines. During the morning and early afternoon the in-line temperature rose more rapidly than the ambient air temperature, reaching a maximum of 30.0 ^{0}C at 16.00 hours compared to an air temperature of 26.7 ^{0}C. Irrigation was carried out on this occasion between 16.00 hours and 17.00 hours in order to demonstrate how in-line temperatures were rapidly reduced by the introduction of fresh WSP effluent into the laterals.

The rate of microbial growth is proportional to environmental temperature over a limited range. Above this range cell destruction results from thermal inactivation of cell proteins. Diurnal variations in the temperature of the irrigation water within irrigation laterals will therefore affect the level and composition of the microbial population. Those that are able to cause biofouling within the laterals must be able to tolerate high temperatures for several hours each day. Less thermotolerant organisms will be destroyed during these periods and their contribution to any biofouling problem will therefore be limited.

Drip irrigation emitters use a narrow water path to reduce the flow of water to the plant. The emitter therefore acts as a filter preventing the passage of particles of diameters greater than the internal diameter of the emitter. Since the internal diameter of all the drip irrigation emitters used was greater than the diameter of the screen used to filter the WSP effluent (120 mesh), all suspended particles (such as microalgae), that pass through the screen, should also pass freely through the emitters to the soil.

However, between irrigation cycles suspended material in the irrigation waters settles to the bottom of the laterals. This is the first stage of the colonization of the internal surfaces by microorganisms and the subsequent production of a biofilm.

Development of the attached biofilm leads to a change in the nature of suspended material within the laterals. Fresh WSP effluent is largely composed of unicellular microalgae. Between irrigation cycles these organisms settle to the base of the laterals where they decompose in the dark as a result of bacterial activity. Occasionally, pieces of the attached biofilm are "sloughed off" by the shear forces caused by the flow of effluent. Such pieces, measuring between approximately one and ten millimetres in diameter, were observed in the irrigation laterals at Santo André. They pose a risk of clogging the narrow channels of trickle emitters unless they are periodically removed by opening the ends of the laterals and flushing out the contents. This was carried out at Santo André every seven days throughout the two irrigation seasons.

Figure 3.7 shows how the level of suspended solids in the laterals supplied with WSP effluent rapidly drops when irrigation begins. A proportion of the suspended material passes through the emitters to the soil but unless the laterals are flushed out grosser solids will continue to accumulate in the laterals. Screen filtration did not make any significant difference to the levels of suspended solids, within the laterals.

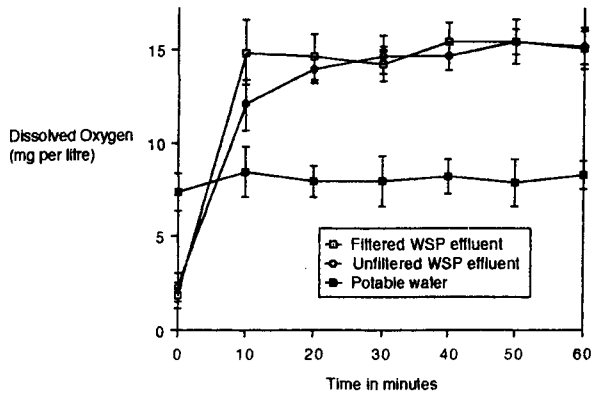


Figure 3.5 Changes in levels of dissolved oxygen within the irrigation laterals during irrigation

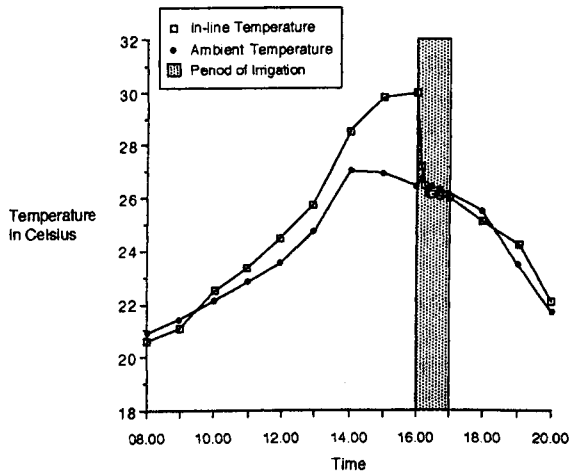


Figure 3.6 Temperature changes within irrigation laterals over a period of twelve hours (10.09.88)

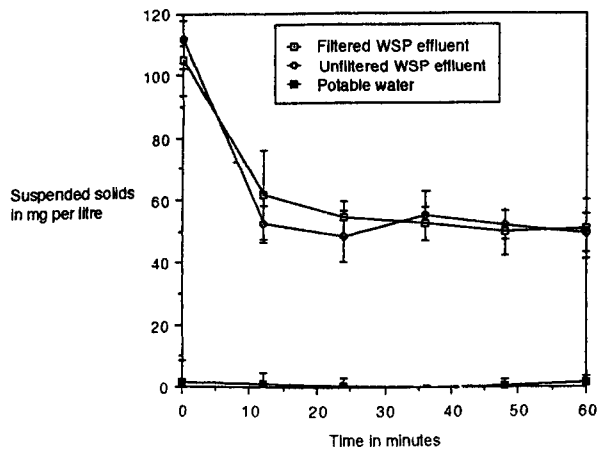


Figure 3.7 Changes in levels of suspended solids within the irrigation laterals during irrigation

At the end of the 1988 growing season, a short section of one of the polythene laterals supplied with filtered WSP effluent was dehydrated in ethanol in order to examine the deposited material on the internal surface by scanning electron microscopy. Plate 3.1 shows the surface of this biofilm. Short sections of *Oscillatoria* can be seen, embedded in a matrix of decomposing organic matter. Clearly short trichomes of this organism occasionally passed through the 120 mesh filter, even though they were not detected in weekly "grab" samples of the filtered WSP effluent. A space is visible between each trichome and the surrounding matter suggesting the presence of an extracellular glycocalyx which would have been destroyed by dehydration of the sample. Since only short trichomes were detected within the laterals, it would appear that they are not actively growing in this environment, as was the case in the biofilms detected on the external surfaces of emitters (Plate 5.11). None of the unicellular algal genera commonly found in samples of pond effluent were detected in the biofilm.

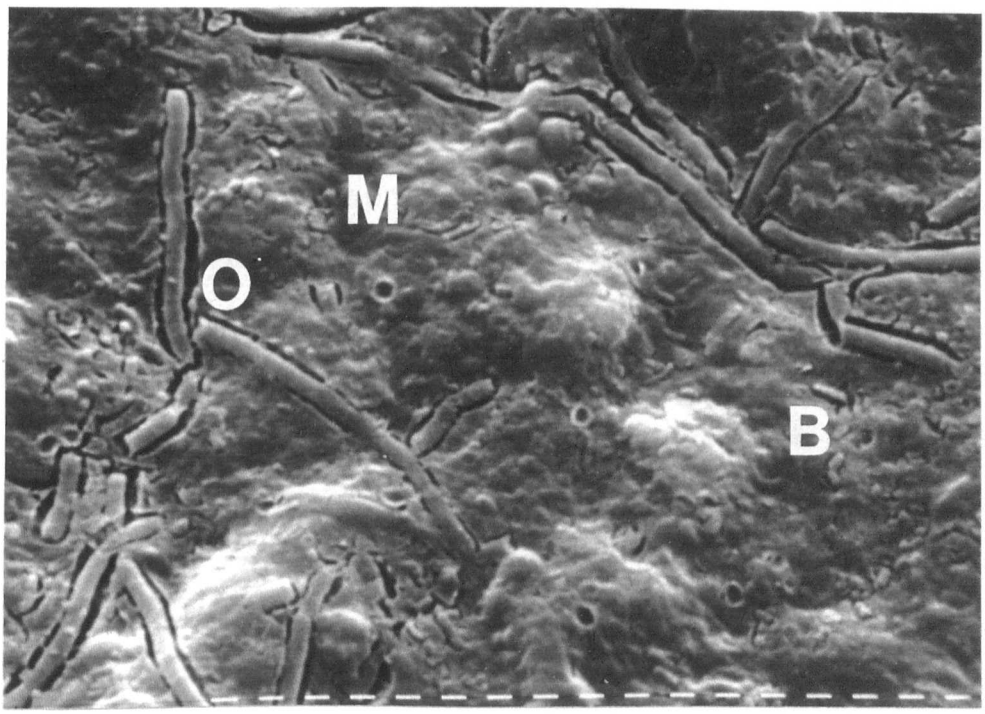


Plate 3.1 The surface of the biofilm on the internal surfaces of irrigation laterals supplied with WSP effluent. O *Oscillatoria* trichome; B bacteria; M matrix of decomposing organic matter. Scale: 1 bar = 1 μm

CHAPTER 4

4. EMITTER DISCHARGE VARIATION - QUANTITATIVE AND QUALITATIVE STUDIES OF THE CLOGGING PHENOMENON

4.1 Introduction

Emitter discharge efficiency is a prerequisite of all successful drip irrigation systems. Failure of individual emitters is often difficult to spot in large systems and crops may be irreparably damaged before the emitters are cleaned or replaced. Prevention of emitter clogging is therefore a better alternative to remedial action during operation of the system. It can be achieved by improvements to the design of drip irrigation components, particularly the emitters themselves. As yet, no emitter designs have been developed specifically for use with marginal water resources such as treated wastewater, and design improvements have concentrated on filtration and water treatment. Improvements in the design of emitters so as to facilitate their successful application in reuse schemes requires a fuller understanding of the factors causing emitter clogging in such situations and further studies into the suitability of those emitters presently available.

Although the mechanisms of emitter clogging have been studied by several researchers, few have measured the discharge efficiencies of presently available designs using marginal water resources. Research projects that have attempted to quantify emitter efficiency using such waters are summarised in Table 4.1.

One project, in Arizona, USA, studied the problems associated with the use of Colorado River water in trickle irrigation schemes. In a series of papers (Bucks *et al.*, 1979; Gilbert *et al.*, 1979 and 1980; Nakayama, 1982), the operational characteristics of a variety of emitter designs in combination

with river water were investigated. The river water was pre-treated with various combinations of screen and media filtration, and chemical additions such as sodium hypochlorite and sulphuric acid. Field trials over a period of four years led to the conclusion that all emitter designs require filtration of some form, and that this filtration should be to such a level as to deal adequately with peak loads of suspended solids in the river water. In most cases, chemical treatment was also considered to be necessary in order to maintain adequate emitter performance. Of the emitter designs investigated, those that contained moving parts or membranes were more susceptible to emitter clogging than "static" devices (Gilbert *et al.*, 1981). Only one design (a "long-path, spiral-grooved, manual flush" emitter) performed efficiently with 50 mesh screen filtration alone (Gilbert *et al.*, 1980).

In Israel, Oron *et al.* (1979; 1982) studied the performance of drip irrigation emitters in reuse schemes utilising the effluent from high-rate algal ponds and WSP. The authors found that no emitter clogging occurred when using a WSP effluent containing suspended solids in the concentration range 50 -250 mg per litre. The only water treatment used in this instance was filtration with a 50 mesh screen. Other workers in Israel, (Adin and Sacks, 1987), recorded fluctuations in emitter discharge rates of greater than 30 percent within a period of 72 hours. This was attributed to the phenomenon of emitter clogging and self-cleaning during a single irrigation cycle.

Laboratory studies in the United States (Janney, 1980) were used to analyse the performance of four emitter designs supplied with water containing measured grit particles in suspension. It was found that the emitters clogged even when the grit containing water was filtered to manufacturers specifications. Long-path emitters in particular demonstrated a poor ability to either pass or flush grit particles.

Table 4.1 Previous investigations into emitter discharge efficiency

Authors	Water Qualities	Water Treatments	Emitter Designs
Solomon (1977)	"Clean water"	Not recorded	12 designs including orifice, long path, short path and line source devices
Oron *et al.* (1979)	1. HRAP effluent	1. Clarification by alum flocculation and flotation	Netafim labyrinth-type "in-line" emitter
	2. Trickling filter effluent	2. Filtration by 50 mesh screen filter	
	3. Potable water	3. None	
Janney (1980)	Potable water "seeded" with measured grit particles	None	1. "Orifice-vortex emitter" 2. "Flexible orifice in series 3. "Long path" 4. "Groove and flat short path
Gilbert *et al.* (1981)	Colorado River water	Sand and screen filtration plus in some instances, treatment with hypochlorite and/or acid	1. Long-path capillary tubing 2. Long-path, spiral-grooved 3. Diaphragm, expandable orifice 4. Single vortex
Oron *et al.* (1982)	WSP* effluent	Filtration by 120 mesh screen filter	Netafim labyrinth-type "in-line" emitter
Taylor *et al.** (1989)	1. WSP effluent	1. Filtration by 120 mesh screen filter	Netafim "on-line" button dripper and Access TB "in-line" labyrinth-type emitter
	2. Potable water	2. None	
Adin and Sacks (1991)	WSP effluent stored in seasonal reservoir	Gravel filtered and unfiltered	Two non-regulated long-path labyrinth designs and one self regulating diaphragm design

* Preliminary report on the study presented in this thesis

4.2 Causes of Emitter Clogging

Factors that may lead to emitter blockages are considered in previous chapters. In this section the causes of emitter malfunction in previous trickle irrigation studies are reviewed. The primary causes of emitter clogging are classified by Bucks *et al.* (1979) as physical, chemical or biological: which of these groups presents the greatest risk of emitter clogging depends upon the nature of the water source. Emitter clogging is directly related to the quality of the irrigation water (Gilbert *et al.*, 1979) and for this reason, the main cause of clogging problems will vary from system to system.

In studies of citrus grove trickle irrigation systems in Florida, USA, the fundamental cause of most emitter clogging problems was bacterial slimes (Ford, 1978). Of these, the most serious problem was caused by filamentous sulphur bacteria slimes, although filamentous iron deposits also caused problems (Ford and Tucker, 1975). However, few authors report bacterial slimes to be a major problem. In a four year study of a trickle irrigation system in Arizona using Colorado River water, the predominant cause of emitter clogging was physical particles; next, and minor in comparison was the development of biological and chemical deposits (Gilbert *et al.*, 1981). The responses of national committees to an international survey suggested that physical factors are the main cause of emitter clogging in most trickle irrigation systems (Abbott, 1985).

More recently, emitter clogging has been investigated in wastewater reuse schemes. The presence of high levels of microorganisms, dissolved salts and suspended solids in such waters suggests that clogging is potentially a serious problem. Suspended solids are thought to be the main

cause of emitter blockages in such schemes. Because of their elasticity, the organic particles present in wastewaters may penetrate orifices smaller than their original size and they may also encourage bacterial growth (Alon and Adin, 1981). Particles ranging from 60 - 300 μm are reported to contribute greatly to clogging and microalgae have been found to contribute by deposition on existing sediment in emitters (Adin and Sacks, 1987).

Whatever the primary cause, emitter clogging in all systems is usually the result of a combination of factors, eg., clay and corrosion products entrapped within a biological mass cemented together with precipitated calcium carbonate (Adin and Alon, 1986). Although clogging continues to pose serious problems in many reuse schemes, with efficiently maintained screen filtration (120 mesh), it has been shown that reservoir water containing WSP effluent can be used for drip irrigation with no clogging of emitters (Oron *et al.*, 1982).

4.3 Emitter Discharge Studies

This chapter deals with emitter discharge studies carried out in Portugal between September 1986 and October 1988. It presents the measured discharge characteristics of various emitter designs when used in conjunction with the following water sources:

1. potable mains water;
2. final effluent from a high-rate trickling filter sewage treatment plant; and
3. final effluent from a waste stabilization pond system

4.3.1 Methods of Assessing Emitter Discharge Efficiency

Having measured the discharge rate of individual emitters as described in Chapter 2, the discharge values (expressed in litres per hour) can be treated in a number of different ways in order to compare the efficiency of different emitter designs with various qualities of irrigation water. The results of each single operational condition (e.g. filtered WSP effluent and Emitter A), were pooled and emitter efficiency of each group or population expressed in terms of the following statistical concepts:

1. Mean discharge rate - the simple arithmetic mean of the discharge rates of all emitters within a particular group.
2. Percentage of clogged emitters. This is the simplest and most commonly used measure of emitter efficiency. It is expressed as the percentage of all emitters within a group discharging less than fifty percent of the emitter design discharge rate.
3. Variance. This the average of the *n* squared deviations. It is also known as the mean square and is defined by the following equation:

$$\text{Variance} = \frac{\sum y^2}{n}$$

4. Standard deviation. This is the most commonly used measure of dispersion in any statistical treatment of populations. It is equivalent to the positive square root of the variance and is therefore represented by the following equation:

$$s = \frac{\sum y^2}{n - 1}$$

where s is the standard deviation of the mean, $\sum y^2$ is the sum of the squares and n is the number of observations.

5. Coefficient of variation. This allows comparisons of the variation within several populations with different means and is simply the standard deviation of the population expressed as a percentage of the mean (Nakayama and Bucks, 1983). It is defined by the following equation:

$$CV = \frac{s \times 100}{Y}$$

where CV is the coefficient of variation, s is the standard deviation of the mean, and Y is the sample mean.

6. Field Emission uniformity (EU). This concept considers the relationship between minimum and average emitter discharge rates within a system and was developed by Merrium and Keller (1978). The concept is defined by the following equation:

$$EU = 100\ q_n / q_a$$

where EU is the emission uniformity as a percentage, q_n is the average of the lowest quarter of the emitter discharge rates and q_a is the average of all the emitter flow rates.

4.3.2 Methods of Assessing the Causes of Emitter Blockages

Following each growing season, clogged emitters were labelled and transferred to the laboratory where they were opened and the emitter interior studied by light microscopy. The nature of clogging particles, and their dimensions, were recorded and examples of clogged emitters were dehydrated in ethanol for further analysis by scanning electron microscopy.

4.3.3 Emitter Performance in a HRTF Reuse System

The first drip irrigation pilot scheme of this research project was a simple design to assess the degree of emitter clogging in a HRTF reuse system and to formulate methods of monitoring the phenomenon throughout the course of a single irrigation season. Details of the system layout are described in Chapter 2. Quantitative analysis of emitter performance was limited to weekly measurements of the discharge rates of emitters 6, 12 and 18 of each lateral (nine emitters per water supply:emitter design combination), in an attempt to monitor an expected gradual decrease in emitter efficiency. The results of these analyses are reported in full in Figures 4.1 and 4.2

Emitter 1. Two of the nine monitored emitters supplied with filtered HRTF effluent became clogged within fourteen hours of operation. After seventy hours of operation, a further two emitters had become clogged. Observations of the wetted zones around each emitter after seventy hours suggested that 35 percent of emitters were clogged to some extent. Of the nine emitters that were monitored in laterals supplied with potable water,

only one became clogged. Of all emitters supplied with potable water only 8 percent appeared to be clogged at the end of the irrigation season.

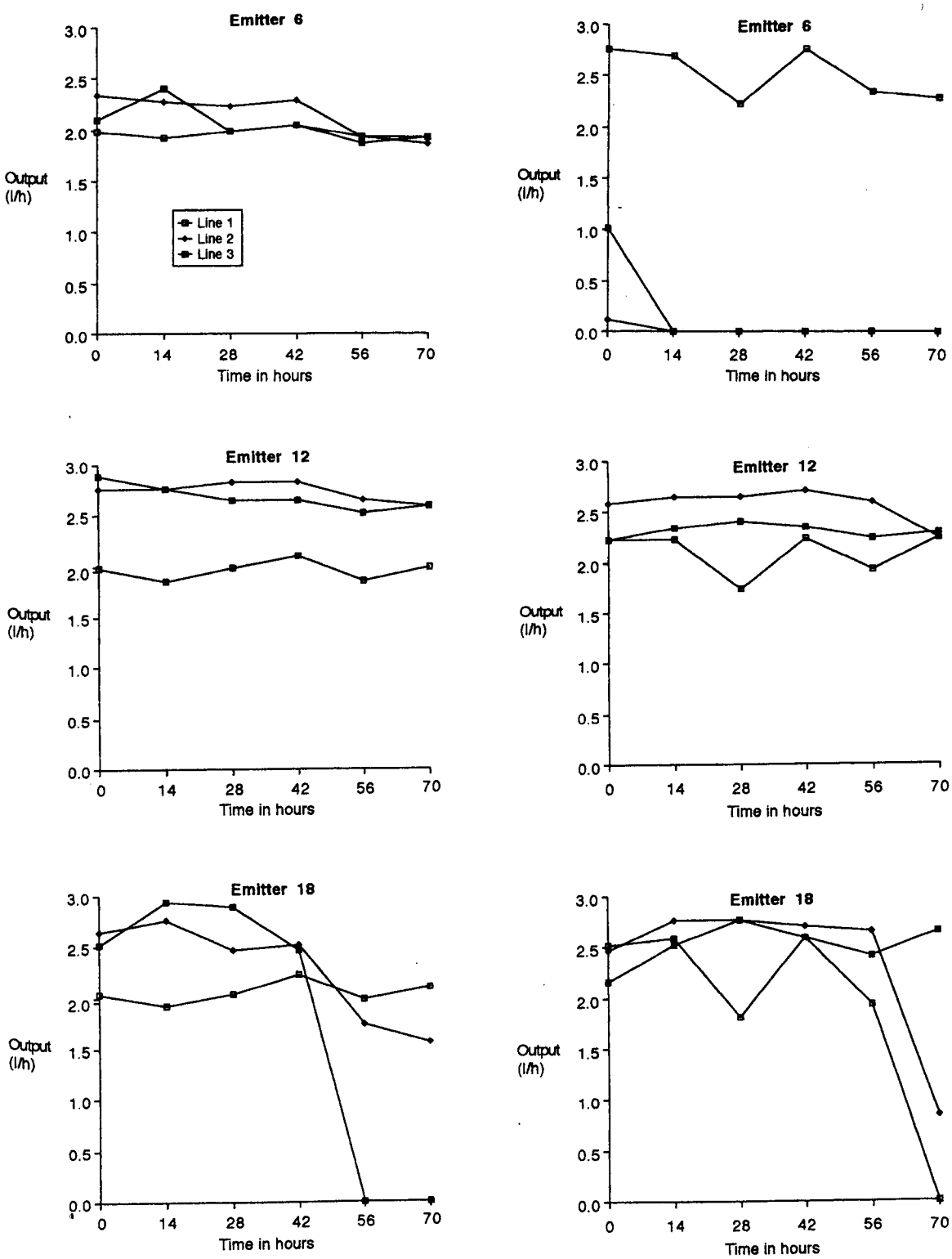
Emitter 2 performed extremely poorly with filtered HRTF effluent (Figure 4.2). All nine emitters studied in the laterals supplied with effluent became clogged within two weeks of operation and 80 percent of all emitters were clogged by the end of the growing season. No such problems were encountered in emitters supplied with potable water, of which only 7 percent became clogged.

Microscopic examination of a proportion of the clogged emitters at the end of the growing season revealed the cause of clogging in emitters supplied with filtered HRTF effluent to be organic matter deposited within the narrow water paths of the emitter interiors. The large aggregates of organic matter that were observed in the effluent were clearly the cause of emitter failures. These aggregates were a consequence of the treatment plant being overloaded; a high flow reduced the retention time of the system and resulted in organic matter passing into the final effluent. Detachment of solids from the "filter-cake" that accumulated on the foam filter and subsequent aggregation in the emitter laterals may also have exacerbated the problem. In Emitter 1 organic solids accumulated within the long-path labyrinth of the emitter. In Emitter 2 organic matter accumulated within the small piece of foam sponge that controlled flow. The mucoid consistency of clogged sponges suggested that bacterial growth also contributed to the reduction in flow.

Examination of those emitters supplied with potable water that became clogged revealed the cause to be inorganic particles such as sand, silt and

in one case, a small shaving of polythene that had entered the lateral when the system was set up. Organic matter did not appear in any of these emitters.

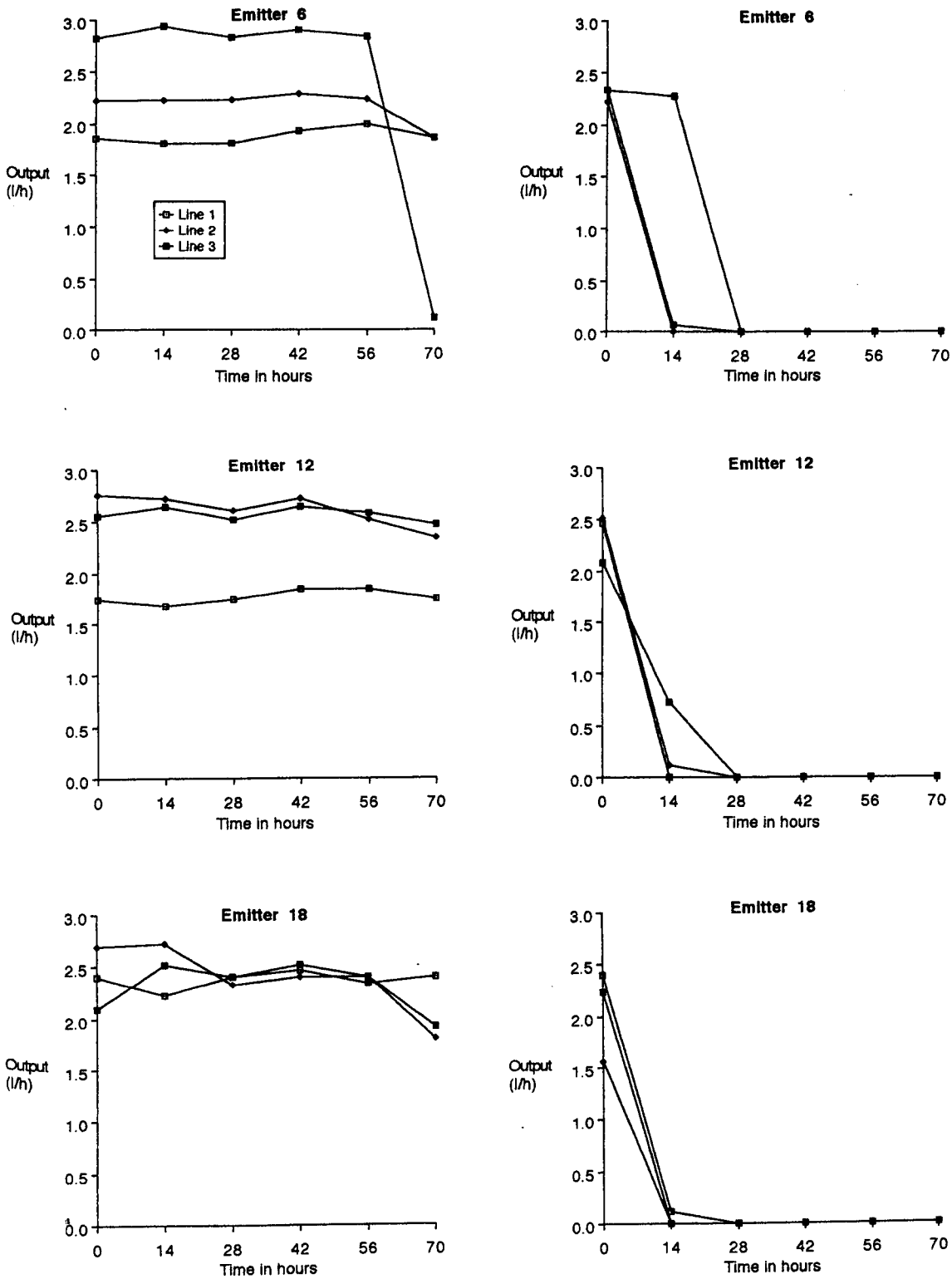
It was concluded that successful reuse of the Évora HRTF effluent in trickle irrigation would require a greater degree of filtration than was achieved with the foam media filters (Figure 2.3). A series of sand filters with adequate back-washing facilities would probably reduce the clogging problem considerably. Effluents from efficiently operated HRTF contain less suspended solids than the effluent of the Évora plant (Table 3.2), and more importantly dimensions of suspended particles are smaller. The simple design of Emitter 2 was inadequate for its successful application in effluent reuse systems and its study was therefore discontinued in subsequent studies. Emitter clogging appeared to be an immediate phenomenon, emitter output decreasing from design rate to zero spontaneously rather than over the course of several days or weeks. The information provided by this limited investigation was of use in designing subsequent studies using WSP effluent.



Potable Water

Filtered HRTF Effluent

Figure 4.1 Output characteristics of the sixth, twelfth and eighteenth emitter in each lateral of the HRTF reuse system - **Emitter 1**



Potable Water Filtered HRTF Effluent

Figure 4.2 Output characteristics of the sixth, twelfth and eighteenth emitter in each lateral of the HRTF reuse system - **Emitter 2**

4.3.4 Emitter Performance in a WSP Reuse System

The pilot scheme established in the summer of 1987 is described in detail in Chapter 2. At the end of the 1987 growing season (after seventy hours of irrigation), a full analysis of the discharge performance of every emitter was carried out in order to obtain statistically significant emitter performance data for all the designs. The results of these analyses are summarised in Tables 4.2; 4.4; 4.8; 4.9 and 4.16; and presented in the form of contingency groups in Figure 4.5.

The reuse system set up in 1988 was an adaptation of the previous years pilot scheme with certain modifications to facilitate the study of alternative emitter designs and adaptations of previously studied designs. A full description of the system is given in Chapter 2. Discharge performances of all emitters were measured after fifty, seventy and ninety hours of irrigation. The results of these measurements are summarised in Tables 4.3; 4.5 to 4.7; and 4.10 to 4.15; and in the form of contingency groups in Figures 4.6 to 4.8.

Emitter A. In 1987 Emitter A operated successfully only in combination with potable water (Figure 4.2). After seventy hours of operation, only one emitter supplied with potable water demonstrated a discharge rate lower than 1.5 litres per hour (50 percent of the design discharge rate). Emission uniformity for all emitters supplied with potable water was 66.95 percent.

Emitters supplied with WSP effluent functioned less efficiently than those supplied with potable water. After seventy hours of operation, 45.00 percent of emitters in the filtered WSP effluent lines, and 51.67 percent of emitters in the unfiltered WSP effluent lines, had become sufficiently clogged to reduce

their discharge rate to less than 50 percent of the manufacturers design rate. In the case of emitters supplied with unfiltered WSP effluent, variance in discharge rate between emitters was sufficient to reduce emission uniformity to zero.

In 1988 the emitters were monitored for a second season. As in the crop yield and bacterial contamination studies, the same emitters were used as in 1987. It was therefore possible to ascertain the performance characteristics of Emitter A during a second season of use. Performance with all water qualities was found to be much reduced compared to the results of the previous summer and emission uniformity in both the filtered and unfiltered WSP effluent lines was reduced to zero after seventy hours. In 1988 the performance of emitters supplied with potable water was severely reduced and after seventy hours of operation only 26.66 percent of these emitters were shown to discharge greater than 50 percent of the emitter design output (Table 4.3).

Emitter B. When laterals containing Emitter B were supplied with WSP effluent in 1987, much higher rates of emitter clogging were recorded compared with those laterals supplied with potable water. The greatest degree of emitter clogging was recorded in lines supplied with filtered effluent (41.67 percent), and this was sufficient to reduce emission uniformity to zero for all emitters within the three replicate laterals. Surprisingly, those emitters supplied with unfiltered WSP effluent demonstrated better performance characteristics than those supplied with filtered effluent: only 5 percent of these emitters demonstrated a discharge rate less than 1 litre per hour after seventy hours of operation and emission uniformity was therefore

comparable with those emitters supplied with potable water at 72.41 percent.

In 1988 the performance of Emitter B was investigated for a second season using new emitters. Discharge of all emitters was measured after fifty, seventy and ninety hours of operation (Tables 4.5 to 4.7). During this irrigation season the potable water supply was filtered with a 80 mesh screen and the accuracy of pressure measurements was increased by the siting of manometers at the head of each plot, in addition to those sited at the pump house.

Emitters supplied with the filtered potable water operated more successfully than those supplied with WSP effluent in 1988, although clogging of these emitters was far higher than in 1987. One third of emitters supplied with filtered potable water discharged less than one litre per hour after fifty hours of operation but this fraction did not increase significantly after seventy and ninety hours. The greater degree of emitter clogging was reflected by a much lower emission uniformity to that recorded in 1987 (2.58 percent after ninety hours).

Those emitters supplied with WSP effluent performed less efficiently than those supplied with filtered potable water, but in 1988 the performance efficiency of emitters supplied with unfiltered effluent and those emitters supplied with filtered effluent was not significantly different. The percentage of emitters discharging less than 1 litre per hour increased from 46.66 percent to 68.33 percent in filtered effluent lines, and from 48.33 percent to 65.00 percent in unfiltered lines between measurements at seventy and ninety hours after the commencement of irrigation operation. This degree of

emitter clogging was sufficient to reduce emission uniformity to zero in all replicate laterals supplied with WSP effluent.

Emitter B'. This adapted form of Emitter B, which excluded light from the external orifice of the emitter, demonstrated similar performance characteristics to the unadapted form (Table 4.8). Performance was again related to the quality of the water supply with potable water producing the best conditions for emitter uniformity (67.96 percent), and only 3 emitters (5 percent) discharging less than 1 litre per hour after seventy hours of operation. Emitters supplied with unfiltered WSP effluent operated only marginally less successfully with an emission uniformity of 63.19 percent. Emitters supplied with filtered WSP effluent performed the least successfully, with an emitter uniformity 31.18 percent, although the percentage of clogged emitters after seventy hours of operation varied greatly between each replicate lateral (from 15 to 50 percent of emitters).

Emitter C. In 1987 Emitter C operated relatively well with all three qualities of water supply (Table 4.9). After seventy hours of irrigation, only five of these emitters demonstrated a discharge rate of less than 1 litre per hour and emission uniformity was consistently high for all three water qualities. Those emitters supplied with unfiltered WSP effluent recorded a total emission uniformity of 91.18 percent, the highest discharge uniformity recorded for any emitter design during the study.

In 1988 the measured efficiency of Emitter C was significantly lower than in 1987 (Tables 4.10 to 4.12). The percentage of clogged emitters was higher on all three dates that emitter discharge was measured in 1988, compared with the results of the previous year. Efficiency was particularly

high in those emitters supplied with filtered potable water, but the number of clogged emitters in filtered water lines only increased by one during the course of the three successive emitter discharge measurements. Total emission uniformity in filtered water lines decreased from 13.87 percent after fifty hours of operation to 1.52 percent after ninety hours.

Emitters supplied with WSP effluent performed more efficiently than those supplied with filtered potable water during the 1988 season. Emitters in the unfiltered lines were the least efficient with an emission uniformity for all such emitters of 5.64 percent after fifty hours, 2.53 percent after seventy hours and 1.44 percent after ninety hours; which corresponded to 30.00 percent of emitters discharging less than 1 litre per hour at the end of the irrigation season.

When Emitter C was supplied with filtered WSP effluent, the design performed marginally better than those supplied with the unfiltered effluent. Emission uniformity of all replicates was 42.38 percent after fifty hours and remained at a similar level (43.74 percent) after seventy hours of irrigation. However, after ninety hours the percentage of clogged emitters rose by 10 percent and emission uniformity subsequently dropped to 2.56 percent.

In 1988 an adaptation of Emitter C (**Emitter C'**), was monitored for emitter performance in addition to the unadapted design (Tables 4.13 to 4.15). The replicate laterals into which Emitter C' was inserted, were covered with black polythene sheeting in order to exclude light from the external orifice of the emitter. Overall, the emission uniformities of the covered emitters were similar to those recorded for the uncovered emitters with certain differences. Type C' Emitters supplied with filtered potable

water functioned more efficiently than the uncovered emitters supplied with the same water supply. After ninety hours of irrigation only 20 percent of these emitters demonstrated a discharge rate less than 1 litre compared with 30 percent of the uncovered emitters. However, in both cases the performance characteristics of the emitters varied little between the three dates on which emitter discharge was measured.

The percentage of emitters discharging less than 1 litre per hour increased in those laterals supplied with unfiltered effluent from 18.33 percent to 40.00 percent between the first and last dates of performance analysis, whereas the same parameter increased only from 30 percent to 35 percent in lines provided with filtered effluent during the same period. In both instances emitter clogging was sufficient to reduce emission uniformity to zero in all replicate laterals containing Emitter C' and supplied with WSP effluent.

In 1987 the performance characteristics of Emitter 1 using WSP effluent was investigated (Table 4.16). To simplify nomenclature the emitter was designated **Emitter D**. Of all the emitter designs investigated during 1987, this design was demonstrated to be the least efficient: 35.00 percent of those emitters supplied with unfiltered potable water were found to be clogged, i.e., discharge rate was less than 1 litre per hour, after seventy hours of operation. Emitter clogging was sufficient in those emitters supplied with WSP effluent (50.00 percent for filtered effluent and 40.00 percent for unfiltered effluent) to reduce emission uniformity to zero in the filtered lines and 0.50 in the unfiltered lines.

The Seephose system constitutes a radically different means of applying water to the soil, compared with the other designs analysed during the reuse studies. The system operates at a pressure of only 0.5 kg cm^{-2} and emits water to the soil surface through the stitched seam of its flexible lateral tubing. In 1988 this system was monitored for emission efficiency using filtered potable water; and filtered and unfiltered WSP effluent. The system was operated for one hour each day and pressure was controlled manually at the head of each set of lateral replicates using a valve and the vertical sight tube provided by the manufacturers. Pressure was set at 0.5 kg cm^{-2}, as recommended by the manufacturers.

The system was operated for a total of 25 days from 3 to 22 September 1988. The discharge rate from the laterals was measured on the first and last days of operation using the technique outlined in Chapter 2. The results of these studies are shown in Figures 4.3 and 4.4, which demonstrate the discharge rate of consecutive one metre sections in each 12 metre lateral. As in the case of Emitter 2, the results clearly indicate the unsuitability of this design in such a reuse scheme. After twenty five hours of irrigation, mean discharge per metre was reduced; from 8.77 litres per hour to 0.16 litres per hour in the filtered WSP effluent lines; and from 8.86 litres per hour to 0.37 per hour in the unfiltered WSP effluent lines. These results represented reductions to 1.82 and 4.18 percent of original discharge rates respectively. Only in the case of filtered potable water lines did the system continue to operate effectively throughout the course of study, although a decrease in mean discharge from 12.86 per hour to 8.76 per hour was recorded in these lines.

Table 4.2 Summary of emitter performance results
Emitter A after a total of 70 hours irrigation (Santo André 1987)

Water	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	3.22 ± 0.16	1.08	4.50	0.54	0.73	22.70	70.81	5.00
Line 2	2.99 ± 0.17	1.74	3.96	0.60	0.77	25.90	67.83	0.00
Line 3	3.53 ± 0.15	1.68	4.44	0.43	0.66	18.50	74.45	0.00
All Lines	3.25 ± 0.10	1.08	4.50	0.55	0.75	22.90	66.95	1.67

Filtered Effluent	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.30 ± 0.21	0.00	2.64	0.91	0.95	72.90	23.08	60.00
Line 2	1.64 ± 0.21	0.30	2.70	0.86	0.93	56.40	29.27	45.00
Line 3	1.73 ± 0.21	0.06	2.58	0.87	0.93	54.10	20.81	30.00
All Lines	1.56±0.12	0.00	2.70	0.88	0.94	60.30	23.59	45.00

Unfiltered Effluent	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.32 ± 0.34	0.00	3.60	2.24	1.50	64.10	2.59	30.00
Line 2	1.56 ± 0.39	0.00	3.72	3.11	1.76	113.0	0.00	55.00
Line 3	1.00 ± 0.35	0.00	3.48	2.45	1.57	157.0	0.00	70.00
All Lines	1.63 ± 0.22	0.00	3.72	2.81	1.68	103.0	0.00	51.67

Min., minimum recorded output; Max., maximum recorded output; Var., variance; S.D., standard deviation; C.V., coefficient of variation; E.U., emission uniformity; % Clogged, percentage of emitters with an output less than 50 percent of design output. Mean, minima and maxima values are shown in litres per hour.

Table 4.3 Summary of emitter performance results
Emitter A after a total of 140 hours irrigation (Santo André 1988)

Water	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	0.92 ± 0.31	0.00	3.84	1.85	1.36	148.0	3.92	80.00
Line 2	1.93 ± 0.36	0.00	3.84	2.59	1.61	83.50	3.11	45.00
Line 3	0.41 ± 0.18	0.00	3.66	0.64	0.80	193.0	0.00	95.00
All Lines	1.09 ± 0.18	0.00	3.84	2.04	1.43	131.0	1.10	73.33

Filtered Effluent	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.66 ± 0.35	0.00	3.42	2.45	1.57	94.60	0.00	50.00
Line 2	0.90 ± 0.29	0.00	3.42	1.68	1.30	144.0	0.00	75.00
Line 3	0.59 ± 0.24	0.00	3.24	1.18	1.09	185.0	0.00	85.00
All Lines	1.05 ± 0.18	0.00	3.42	1.92	1.38	132.0	0.00	70.00

Unfiltered Effluent	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.49 ± 0.31	0.00	3.00	1.95	1.40	94.00	0.00	45.00
Line 2	1.71 ± 0.32	0.00	3.00	2.06	1.43	84.10	0.00	40.00
Line 3	0.91 + 0.29	0.00	2.94	1.67	1.29	142.0	0.00	70.00
All Lines	1.37 ± 0.18	0.00	3.00	1.94	1.39	102.0	0.00	51.67

Table 4.4 Summary of emitter performance results
Emitter B after a total of 70 hours irrigation (Santo André 1987)

Water	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.10 ± 0.11	0.84	2.52	0.25	0.50	24.00	65.14	10.00
Line 2	2.22 ± 0.08	1.14	2.52	0.12	0.35	15.80	77.84	0.00
Line 3	2.24 ± 0.05	1.74	2.40	0.04	0.20	9.03	86.78	0.00
All Lines	2.19 ± 0.05	0.84	2.52	0.14	0.37	17.00	75.25	3.33

Filtered Effluent	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.24 ± 0.15	0.00	1.74	0.46	0.677	54.80	4.84	25.00
Line 2	0.86 ± 0.17	0.00	1.68	0.61	0.780	90.30	0.00	50.00
Line 3	0.91 ± 0.17	0.00	1.68	0.55	0.741	81.80	6.59	50.00
All Lines	1.00 ± 0.10	0.00	1.74	0.55	0.741	73.90	0.00	41.67

Unfiltered Effluent	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.18 ± 0.11	0.36	2.55	0.24	0.49	22.70	72.11	5.00
Line 2	2.07 ± 0.16	0.00	2.40	0.53	0.73	35.30	56.81	10.00
Line 3	2.23 ± 0.05	1.74	2.52	0.05	0.21	9.50	87.17	0.00
All Lines	2.16 ± 0.07	0.00	2.55	0.27	0.52	24.00	72.41	5.00

Table 4.5 Summary of emitter performance results
Emitter B supplied with filtered potable water (Santo André 1988)

50 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.25 ± 0.20	0.00	2.88	0.82	0.90	40.10	58.13	15.00
Line 2	1.57 ± 0.27	0.00	2.76	1.46	1.21	77.20	14.52	40.00
Line 3	1.25 ± 0.24	0.00	2.58	1.18	1.09	86.60	27.84	45.00
All Lines	1.69 ± 0.15	0.00	2.88	1.29	1.14	67.20	5.44	33.33

70 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.68 ± 0.23	0.06	3.30	1.09	1.05	39.10	48.81	15.00
Line 2	1.83 ± 0.30	0.00	3.36	1.78	1.33	73.10	12.46	45.00
Line 3	1.57 ± 0.24	0.00	3.12	1.14	1.07	67.90	22.16	40.00
All Lines	2.03 ± 0.16	0.00	3.36	1.52	1.23	60.90	16.16	33.33

90 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.07 ± 0.20	0.00	2.70	0.76	0.87	42.10	40.58	15.00
Line 2	1.46 ± 0.28	0.00	3.00	1.52	1.23	84.30	0.00	40.00
Line 3	1.13 ± 0.23	0.00	2.58	1.07	1.04	91.30	9.56	60.00
All Lines	1.55 ± 0.14	0.00	3.00	1.23	1.11	71.40	2.58	38.33

Table 4.6 Summary of emitter performance results
Emitter B supplied with filtered WSP effluent (Santo André 1988)

50 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.33 ± 0.23	0.00	2.58	1.03	1.02	76.30	0.00	40.00
Line 2	0.89 ± 0.23	0.00	2.46	1.04	1.02	115.0	0.00	65.00
Line 3	1.41 ± 0.23	0.00	3.06	1.04	1.02	72.10	0.00	35.00
All Lines	1.21 ± 0.13	0.00	3.06	1.06	1.03	84.90	0.33	46.66

70 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	0.99 ± 0.21	0.00	2.22	0.85	0.92	92.90	0.00	50.00
Line 2	0.58 ± 0.20	0.00	2.04	0.81	0.90	154.0	0.00	70.00
Line 3	0.88 ± 0.21	0.00	2.10	0.90	0.95	108.0	0.00	55.00
All Lines	0.82 ± 0.12	0.00	2.22	0.86	0.93	113.0	0.00	58.33

90 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	0.77 ± 0.23	0.00	2.28	1.06	1.03	133.0	0.00	65.00
Line 2	0.64 ± 0.20	0.00	2.28	0.83	0.91	142.0	0.00	75.00
Line 3	0.68 ± 0.19	0.00	2.40	0.75	0.87	127.0	0.00	65.00
All Lines	0.70 ± 0.12	0.00	2.40	0.85	0.92	132.0	0.00	68.33

Table 4.7 Summary of emitter performance results
Emitter B supplied with unfiltered WSP effluent (Santo André 1988)

50 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	0.70 ± 0.21	0.00	1.98	0.89	0.94	136.0	0.00	65.00
Line 2	0.73 ± 0.21	0.00	2.04	0.84	0.92	126.0	0.00	60.00
Line 3	1.54 ± 0.15	0.00	2.04	0.44	0.66	42.80	0.00	20.00
All Lines	0.99 ± 0.12	0.00	2.04	0.85	0.92	93.40	0.00	48.33

70 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	0.83 ± 0.23	0.00	2.34	1.07	1.03	124.0	0.00	60.00
Line 2	0.67 ± 0.24	0.00	2.40	1.11	1.05	157.0	0.00	70.00
Line 3	1.15 ± 0.23	0.00	2.28	1.07	1.03	89.80	0.00	45.00
All Lines	0.89 ± 0.14	0.00	2.40	1.09	1.04	118.0	0.00	58.33

90 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	0.93 ± 0.27	0.00	2.70	1.49	1.22	131.0	0.00	65.00
Line 2	0.61 ± 0.21	0.00	2.58	0.88	0.94	154.0	0.00	75.00
Line 3	1.07 ± 0.24	0.00	2.88	1.12	1.06	99.30	0.00	55.00
All Lines	0.87 ± 0.14	0.00	2.88	1.16	1.08	124.0	0.00	65.00

Table 4.8 Summary of emitter performance results
Emitter B' after a total of 70 hours irrigation (Santo André 1987)

Water	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.71 ± 0.15	0.06	3.24	0.45	0.67	24.60	75.28	5.00
Line 2	2.98 ± 0.14	2.10	5.16	0.38	0.61	20.60	84.56	0.00
Line 3	2.38 ± 0.19	0.00	3.24	0.75	0.87	36.50	47.40	10.00
All Lines	2.69 ± 0.10	0.00	5.16	0.57	0.75	28.10	67.96	5.00

Filtered Effluent	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.44 ± 0.10	0.24	1.74	0.21	0.45	31.40	59.44	15.00
Line 2	1.05 ± 0.13	0.00	1.80	0.33	0.57	54.50	32.00	50.00
Line 3	1.32 ± 0.13	0.00	1.74	0.32	0.57	42.90	36.36	20.00
All Lines	1.27 ± 0.07	0.00	1.80	0.30	0.55	43.30	31.18	28.33

Unfiltered Effluent	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.15 ± 0.11	0.30	2.55	0.26	0.51	23.60	72.00	5.00
Line 2	1.99 ± 0.16	0.00	2.70	0.51	0.71	35.80	57.29	10.00
Line 3	2.07 ± 0.15	0.00	2.49	0.46	0.68	32.60	60.09	10.00
All Lines	2.07 ± 0.08	0.00	2.70	0.40	0.63	30.50	63.19	8.33

Table 4.9 Summary of emitter performance results
Emitter C after a total of 70 hours irrigation (Santo André 1987)

Water	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.54 ± 0.16	0.30	3.12	0.52	0.72	28.30	70.39	10.00
Line 2	2.59 ± 0.12	0.48	3.30	0.27	0.52	20.10	82.93	5.00
Line 3	2.67 ± 0.02	2.58	2.82	0.00	0.07	2.47	96.63	0.00
All Lines	2.60 ± 0.07	0.30	3.30	0.26	0.51	19.60	83.23	5.00

Filtered Effluent	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.97 ± 0.05	1.14	2.34	0.06	0.24	11.90	88.32	0.00
Line 2	1.88 ± 0.10	0.00	2.22	0.20	0.45	24.00	79.79	5.00
Line 3	2.07 ± 0.06	1.92	3.18	0.08	0.28	13.60	92.75	0.00
All Lines	1.97 ± 0.04	0.00	3.18	0.12	0.34	17.20	87.31	1.67

Unfiltered Effluent	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.30 ± 0.07	0.96	2.46	0.11	0.33	14.20	86.61	5.00
Line 2	2.42 ± 0.03	2.10	2.58	0.01	0.11	4.57	95.21	0.00
Line 3	2.40 ± 0.02	2.22	2.70	0.01	0.10	4.21	95.50	0.00
All Lines	2.38 ± 0.03	0.96	2.70	0.05	0.21	8.89	91.18	1.67

Table 4.10 Summary of emitter performance results
Emitter C supplied with filtered potable water (Santo André 1988)

50 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.63 ± 0.22	0.00	2.70	0.96	0.98	60.10	19.14	30.00
Line 2	2.30 ± 0.13	0.42	2.82	0.31	0.56	24.30	68.35	5.00
Line 3	1.28 ± 0.26	0.00	2.64	1.30	1.14	89.10	3.75	55.00
All Lines	1.73 ± 0.13	0.00	2.82	1.01	1.00	57.90	13.87	30.00

70 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.08 ± 0.27	0.00	3.36	1.40	1.18	57.00	9.23	25.00
Line 2	2.62 ± 0.16	0.00	3.18	0.53	0.73	27.90	66.41	5.00
Line 3	1.40 ± 0.29	0.00	2.94	1.66	1.29	92.00	2.57	55.00
All Lines	2.03 ± 0.15	0.00	3.36	1.41	1.19	58.40	8.47	28.33

90 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.60 ± 0.25	0.00	2.64	1.21	1.10	68.90	0.75	30.00
Line 2	1.96 ± 0.21	0.00	2.58	0.86	0.93	47.50	24.49	15.00
Line 3	1.19 ± 0.23	0.00	2.46	1.04	1.02	85.60	0.00	45.00
All Lines	1.58 ± 0.14	0.00	2.64	1.10	1.05	66.40	1.52	30.00

Table 4.11 Summary of emitter performance results
Emitter C supplied with filtered WSP effluent (Santo André 1988)

50 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.96 ± 0.15	0.00	2.34	0.46	0.66	34.50	63.06	10.00
Line 2	1.73 ± 0.19	0.00	2.40	0.72	0.85	49.10	20.81	20.00
Line 3	1.86 ± 0.18	0.00	2.46	0.66	0.82	43.80	42.58	15.00
All Lines	1.85 ± 0.10	0.00	2.46	0.60	0.78	41.90	42.38	15.00

70 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.80 ± 0.14	0.00	2.10	0.39	0.62	34.50	61.33	10.00
Line 2	1.62 ± 0.19	0.00	2.22	0.70	0.84	51.50	22.96	20.00
Line 3	1.70 ± 0.16	0.00	2.10	0.54	0.74	43.20	45.18	15.00
All Lines	1.71 + 0.09	0.00	2.22	0.53	0.73	42.60	43.74	15.00

90 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.77 ± 0.23	0.00	2.58	1.02	1.01	57.20	5.42	25.00
Line 2	1.88 ± 0.22	0.00	2.58	0.97	0.98	52.20	17.23	20.00
Line 3	1.63 ± 0.25	0.00	2.52	1.23	1.11	68.10	0.00	30.00
All Lines	1.76 ± 0.13	0.00	2.58	1.05	1.02	58.10	2.56	25.00

Table 4.12 Summary of emitter performance results
Emitter C supplied with unfiltered WSP effluent (Santo André 1988)

50 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.48 ± 0.22	0.00	2.22	0.93	0.96	65.20	0.00	30.00
Line 2	1.49 ± 0.20	0.00	2.16	0.80	0.90	60.00	5.64	30.00
Line 3	1.71 ± 0.18	0.00	2.22	0.65	0.81	47.10	29.47	20.00
All Lines	1.56 ± 0.11	0.00	2.22	0.78	0.88	56.50	5.64	26.67

70 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.54 ± 0.23	0.00	2.28	0.11	0.10	66.80	0.00	30.00
Line 2	1.46 ± 0.23	0.00	2.34	0.11	0.10	71.30	0.00	35.00
Line 3	1.75 ± 0.20	0.00	2.28	0.81	0.90	51.60	20.00	20.00
All Lines	1.58 ± 0.13	0.00	2.34	0.97	0.98	62.10	2.53	28.33

90 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.80 ± 0.24	0.00	2.64	1.16	1.08	59.80	0.67	25.00
Line 2	1.62 ± 0.25	0.00	2.58	1.29	1.14	70.00	2.96	35.00
Line 3	1.57 ± 0.23	0.00	2.64	1.09	1.05	66.40	0.76	30.00
All Lines	1.67 ± 0.14	0.00	2.64	1.15	0.11	64.40	1.44	30.00

Table 4.13 Summary of emitter performance results
Emitter C' supplied with filtered potable water (Santo André 1988)

50 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.96 ± 0.18	0.00	2.58	0.62	0.79	40.10	41.02	15.00
Line 2	1.83 ± 0.21	0.00	2.58	0.88	0.94	51.11	22.95	20.00
Line 3	2.01 ± 0.19	0.00	2.70	0.71	0.84	41.90	38.21	15.00
All Lines	1.93 ± 0.11	0.00	2.70	0.72	0.85	43.70	30.67	16.67

70 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.16 ± 0.25	0.00	3.12	1.27	1.13	52.30	18.89	20.00
Line 2	2.26 ± 0.23	0.00	3.30	1.09	1.04	46.20	28.14	15.00
Line 3	2.24 ± 0.22	0.00	3.48	0.95	0.98	43.60	33.21	20.00
All Lines	2.22 ± 0.13	0.00	3.48	1.07	1.03	46.60	25.59	18.33

90 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.78 + 0.22	0.00	2.58	0.93	0.96	54.20	12.13	20.00
Line 2	1.95 ± 0.19	0.00	2.52	0.72	0.85	43.70	30.15	20.00
Line 3	1.84 ± 0.21	0.00	2.46	0.91	0.95	51.60	17.61	20.00
All Lines	1.86 ± 0.12	0.00	2.58	0.83	0.91	49.10	22.15	20.00

Table 4.14 Summary of emitter performance results
Emitter C' supplied with filtered WSP effluent (Santo André 1988)

50 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.66 ± 0.21	0.00	2.46	0.85	0.92	55.40	10.84	25.00
Line 2	1.79 ± 0.17	0.00	2.28	0.59	0.77	43.00	36.20	20.00
Line 3	1.30 ± 0.25	0.00	3.30	1.21	1.10	84.50	0.92	45.00
All Lines	1.58 ± 0.12	0.00	3.30	0.90	0.95	59.80	5.06	30.00

70 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.41 ± 0.19	0.00	2.04	0.75	0.87	61.20	8.51	30.00
Line 2	1.38 ± 0.21	0.00	2.10	0.87	0.93	67.50	0.00	30.00
Line 3	1.08 ± 0.22	0.00	2.10	0.99	0.99	91.90	0.00	45.00
All Lines	1.29 ± 0.12	0.00	2.10	0.86	0.93	71.80	0.00	35.00

90 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.63 ± 0.24	0.00	2.64	1.12	1.08	65.90	1.47	30.00
Line 2	1.68 ± 0.25	0.00	2.70	1.20	1.09	65.20	0.00	30.00
Line 3	1.25 ± 0.25	0.00	2.58	1.29	1.14	91.00	0.00	45.00
All Lines	1.52 ± 0.14	0.00	2.70	1.21	1.10	72.40	0.00	35.00

Table 4.15 Summary of emitter performance results
Emitter C' supplied with unfiltered WSP effluent (Santo André 1988)

50 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.84 ± 0.14	0.00	2.34	0.42	0.65	35.10	52.17	10.00
Line 2	1.55 ± 0.22	0.00	2.40	1.01	1.00	64.80	0.00	30.00
Line 3	1.81 ± 0.18	0.00	2.40	0.65	0.81	44.60	37.79	15.00
All Lines	1.73 ± 0.11	0.00	2.40	0.66	0.83	47.80	26.13	18.33

70 Hours

	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.54 ± 0.21	0.00	2.28	0.89	0.94	61.00	4.68	30.00
Line 2	1.51 ± 0.23	0.00	2.28	1.03	1.02	67.40	0.00	30.00
Line 3	1.67 ± 0.20	0.00	2.28	0.78	0.88	52.60	12.93	25.00
All Lines	1.59 ± 0.12	0.00	2.28	0.83	0.91	57.20	7.04	28.33

90 Hours

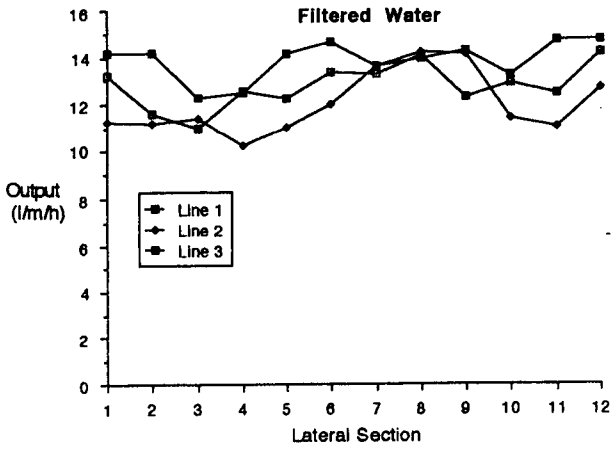
	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.51 ± 0.23	0.00	2.40	1.08	1.04	68.70	0.80	40.00
Line 2	0.98 ± 0.22	0.00	2.34	0.93	0.96	98.00	0.00	50.00
Line 3	1.46 ± 0.23	0.00	2.40	1.02	1.01	69.00	0.00	30.00
All Lines	1.32 ± 0.13	0.00	2.40	1.03	1.02	77.00	0.00	40.00

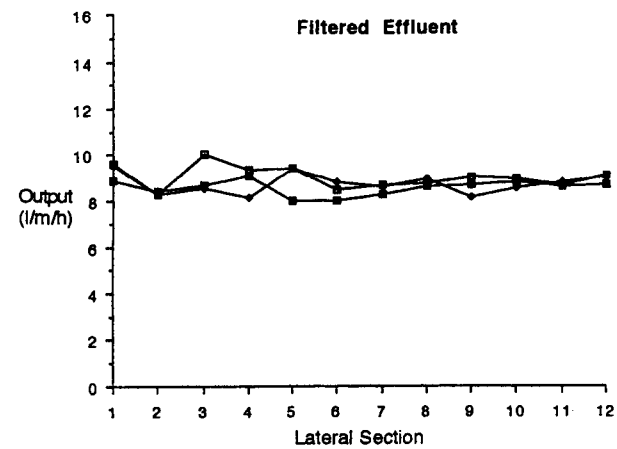
Table 4.16 Summary of emitter performance results
Emitter D after 70 hours (Santo André 1987)

Water	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	2.30 ± 0.21	0.66	3.72	0.92	0.96	41.60	41.74	15.00
Line 2	1.60 ± 0.26	0.00	3.60	1.36	1.17	72.90	25.00	40.00
Line 3	2.23 ± 0.21	0.66	3.60	0.85	0.92	41.30	34.98	50.00
All Lines	2.04 ± 0.14	0.00	3.72	1.11	1.05	51.50	31.50	35.00

Filtered Effluent	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.38 ± 0.22	0.00	2.40	1.00	1.00	72.30	0.00	40.00
Line 2	0.94 ± 0.24	0.00	2.34	1.14	1.07	114.0	0.00	60.00
Line 3	1.11 ± 0.23	0.00	2.34	1.10	1.05	94.20	0.00	50.00
All Lines	1.14 ± 0.13	0.00	2.40	1.08	1.04	90.70	0.00	50.00

Unfiltered Effluent	Mean	Min.	Max.	Var.	S.D.	C.V.	E.U.	% Clogged
Line 1	1.95 ± 0.33	0.03	3.36	2.23	1.49	76.70	2.15	35.00
Line 2	2.14 ± 0.32	0.00	3.60	2.07	1.44	67.10	1.12	30.00
Line 3	1.42 ± 0.35	0.00	3.42	2.40	1.55	109.0	0.00	55.00
All Lines	1.84 + 0.19	0.00	3.60	2.25	1.50	81.60	0.50	40.00





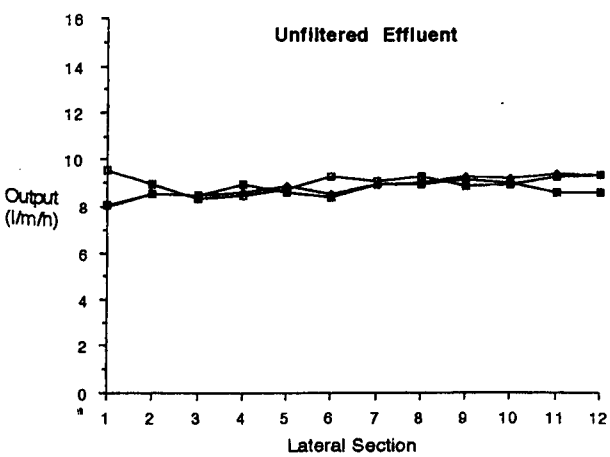
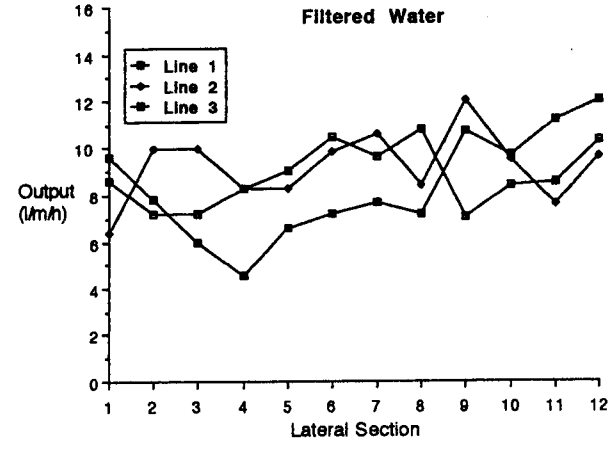
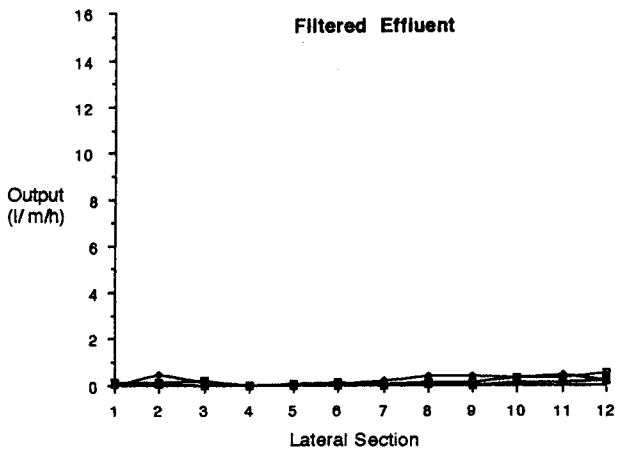


Figure 4.3 Discharge performance of Seephose tubing. Zero Hours (Santo André 1988)





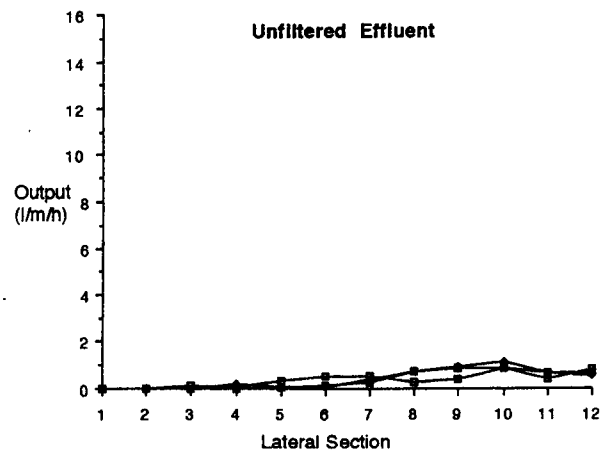


Figure 4.4 Discharge performance of Seephose tubing after twenty five hours (Santo André 1988)

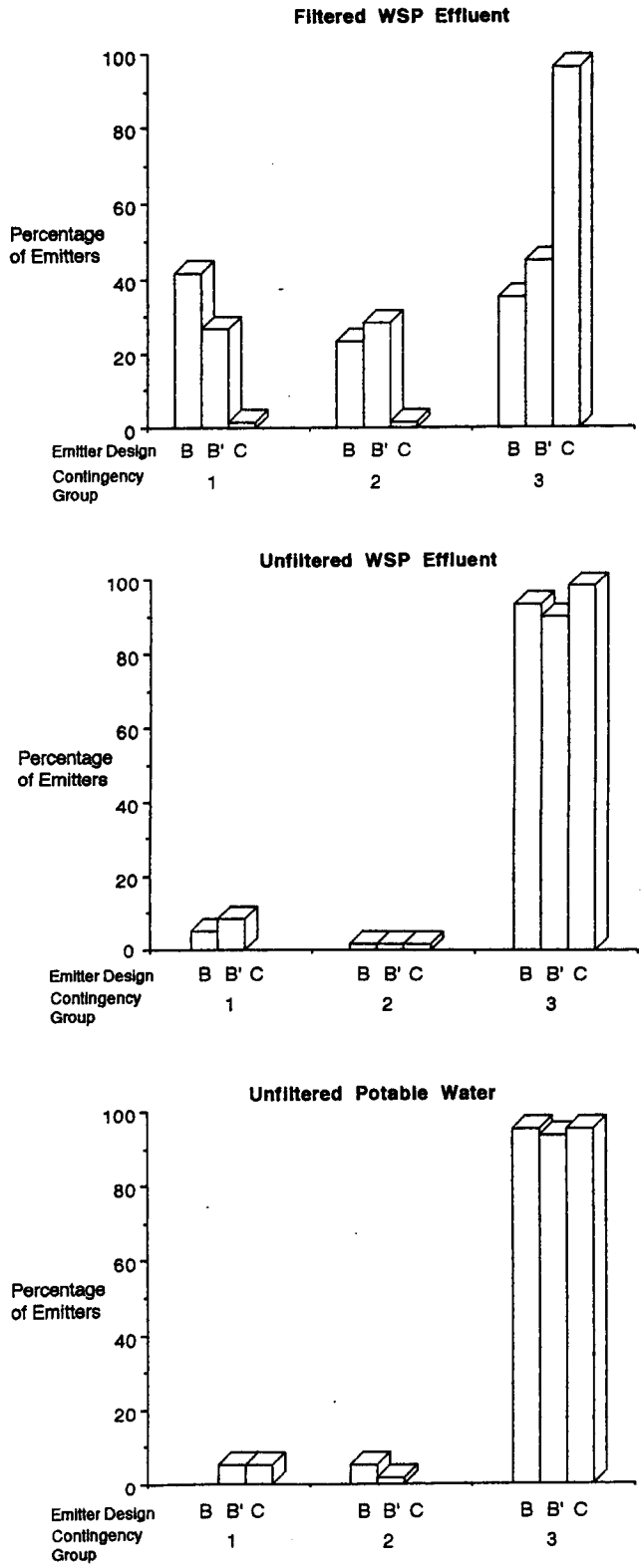


Figure 4.5 Contingency Groups
Emitters B, B', and C (Santo André 1987)
1 = 0-0.96; 2 = 0.96-1.98; and 3 = >1.98 litres per hour

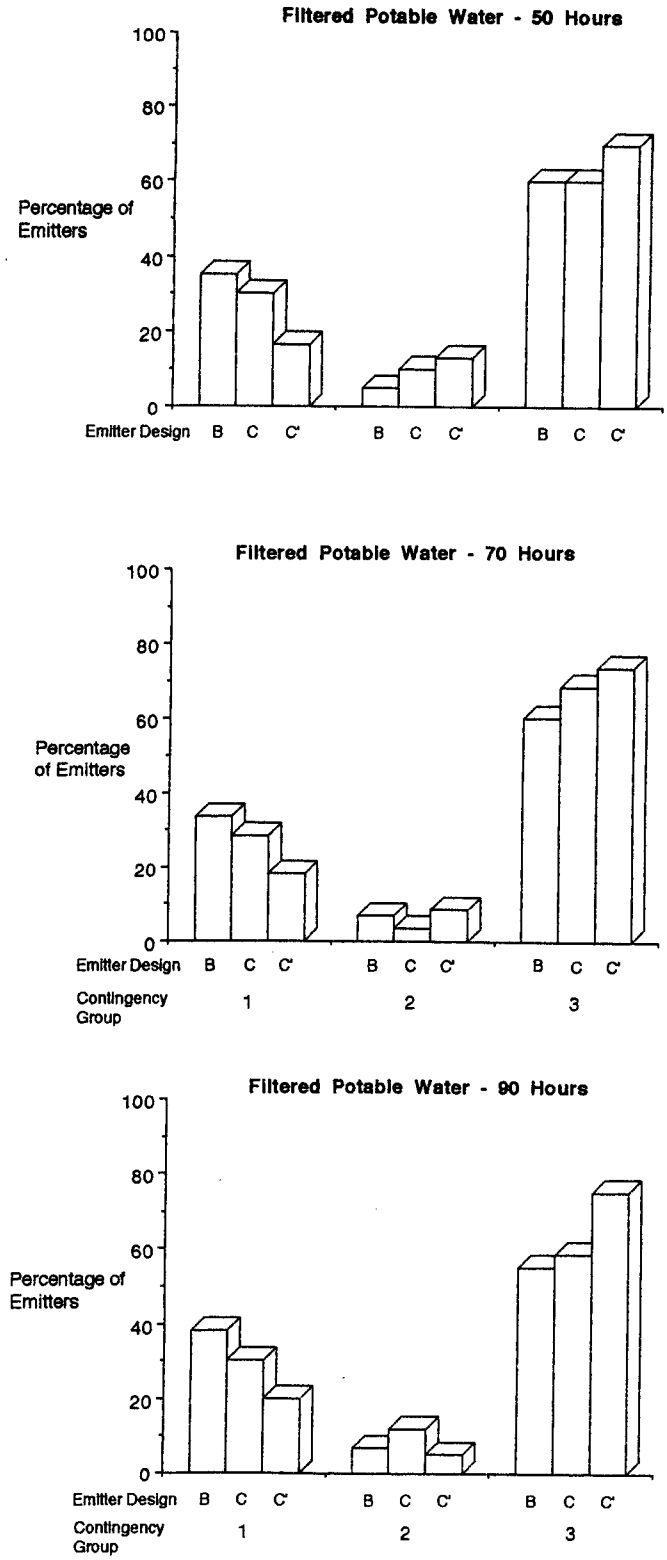


Figure 4.6 Contingency Groups
Emitters B, C and C', Filtered Water (Santo André 1988)
1 = 0-0.96; 2 = 0.96-1.98; and 3 = >1.98 litres per hour

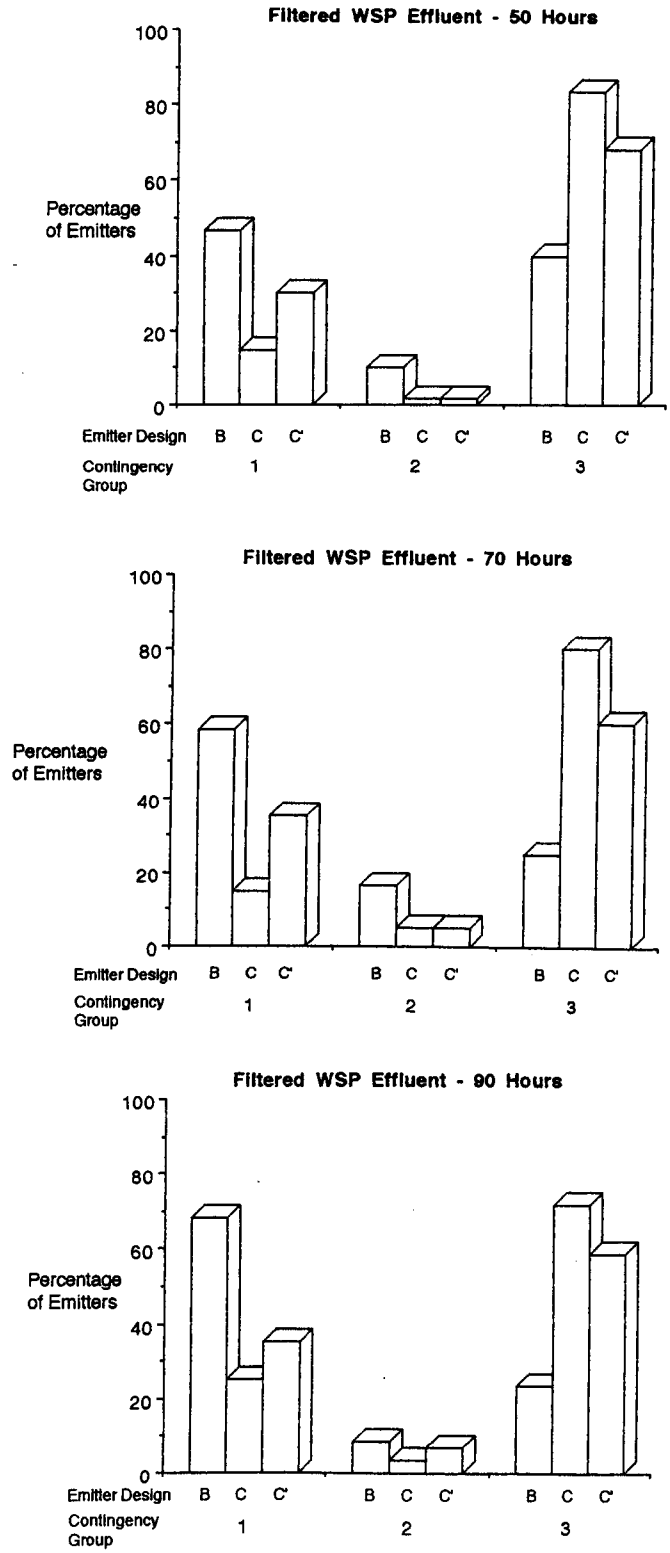
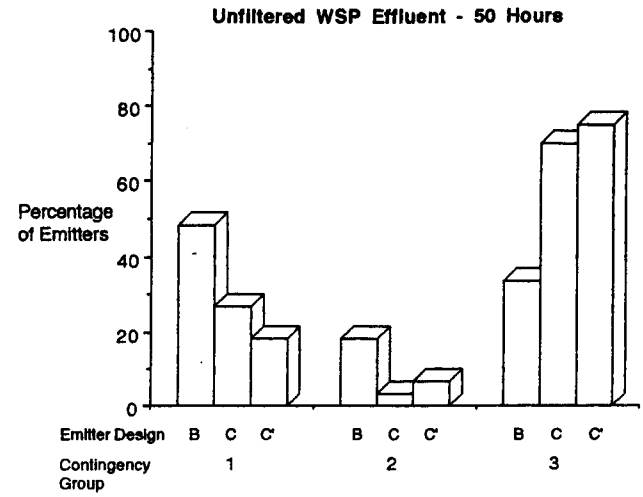
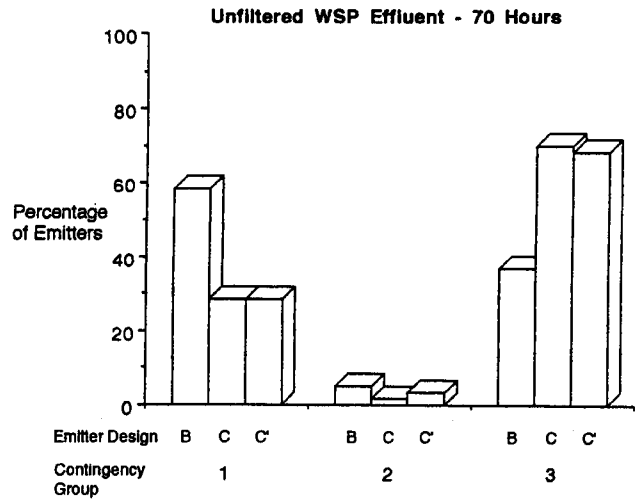


Figure 4.7 Contingency Groups
Emitters B, C and C', Filtered WSP effluent (Santo André 1988)
1 = 0-0.96; 2 = 0.96-1.98; and 3 = >1.98 litres per hour





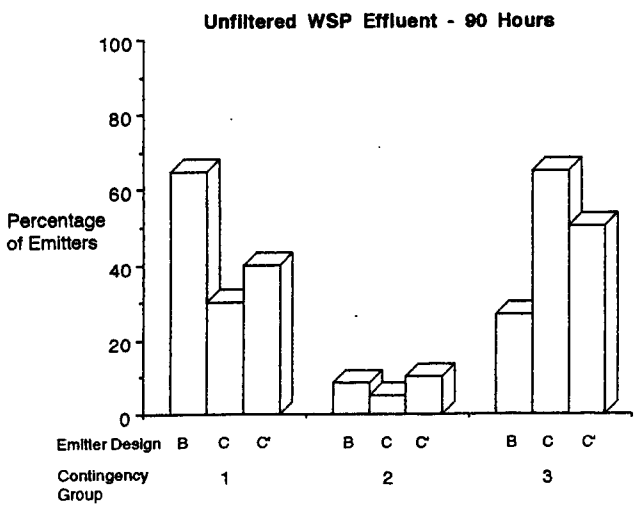


Figure 4.8 Contingency Groups
Emitters B, C and C', Unfiltered WSP effluent (Santo André 1988)
1 = 0-0.96; 2 = 0.96-1.98; and 3 = >1.98 litres per hour

Following the 1988 growing season, clogged emitters were labelled and transferred to the laboratory for examination. Table 4.17 summarises the causes of clogging in Emitters C, C' and D. Sand particles in the diameter range 360 - 1080 μm were the initial cause of clogging in 207 of the 211 clogged emitters examined. In 79 percent of clogged emitters from laterals supplied with filtered potable water, sand particles were the only visible cause of the blockages (Plate 4.1). Of the remaining emitters, calcium carbonate precipitation was shown to cement the sand particles in 6 percent of emitters and the exoskeletons of invertebrate organisms contributed to flow reduction in 8 percent of emitters. In one emitter, *Gomphonema* sp., an epiphytic diatom associated with unpolluted water sources was detected on the surface of clogging sand particles (Plate 4.2).

In clogged emitters from laterals supplied with WSP effluent, the causes of emitter clogging appeared to be more complex. Sand grains alone accounted for only 6 percent of blockages whereas in 90 percent of clogged emitters a biofilm composed of decomposing organic matter, bacteria and in some case, the exoskeletons of *Daphnia* sp., had become deposited on the surface of sand grains (Plates 4.3 and 4.4). This biofilm appeared to adhere to the sand grains causing the water path to seal.

The presence of calcium carbonate precipitation or algal mats on the external surfaces of emitters was not shown to contribute to emitter clogging. Since algal mats have previously been thought to contribute to emitter clogging, their composition and relevance are investigated in Chapter 5.

Table 4.17 Causes of emitter clogging in 1988 Emitters C, C' and D (values are presented as a percentage of all clogged emitters)

Cause of Clogging	Filtered WSP Effluent	Unfiltered WSP Effluent	Filtered Potable Water
Physical			
Sand grains	6	4	79
Plastic particles	0	0	4
Sediment	0	0	0
Body parts of insects and animals	0	0	0
Biological			
Algal mats	0	0	0
Bacterial slimes	0	0	0
Chemical precipitation	0	0	0
Combined			
Physical/biological	68	86	9
Physical/chemical	0	0	6
Chemical/biological	0	0	0
Physical/chemical/ biological	22	10	2
Non-detectable	4	0	0

Table format adapted from Gilbert *et al.* (1981)

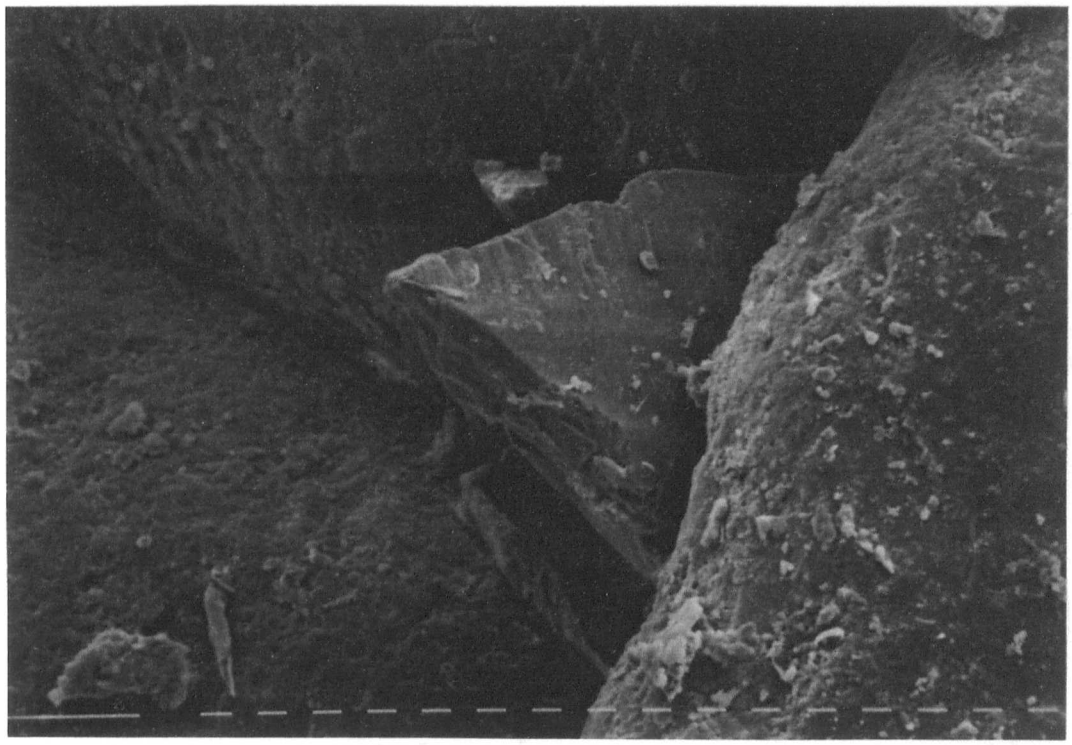


Plate 4.1 The surface of sand grains blocking the water-path of an emitter supplied with filtered potable water. Little organic matter or microbial growth recorded on particle surfaces. Scale: 1 bar = 10μm.

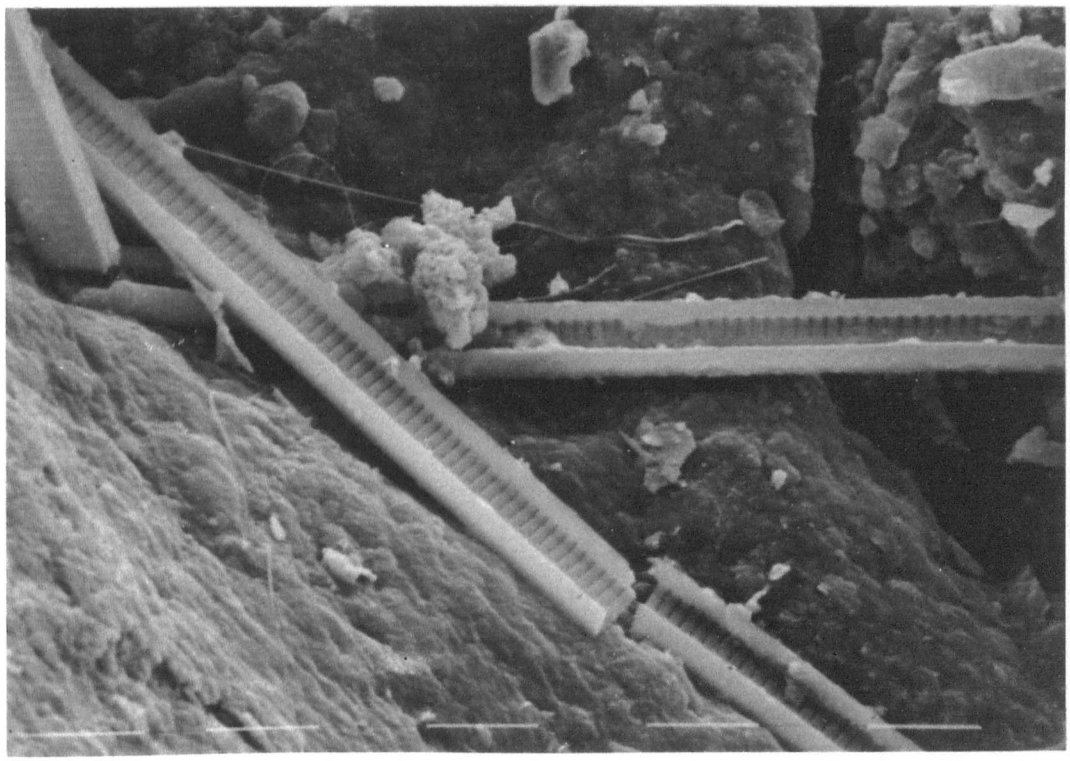


Plate 4.2 Gomphonema sp. on the surface of sand particles supplied with filtered potable water. Scale: 1 bar = 10 μm.

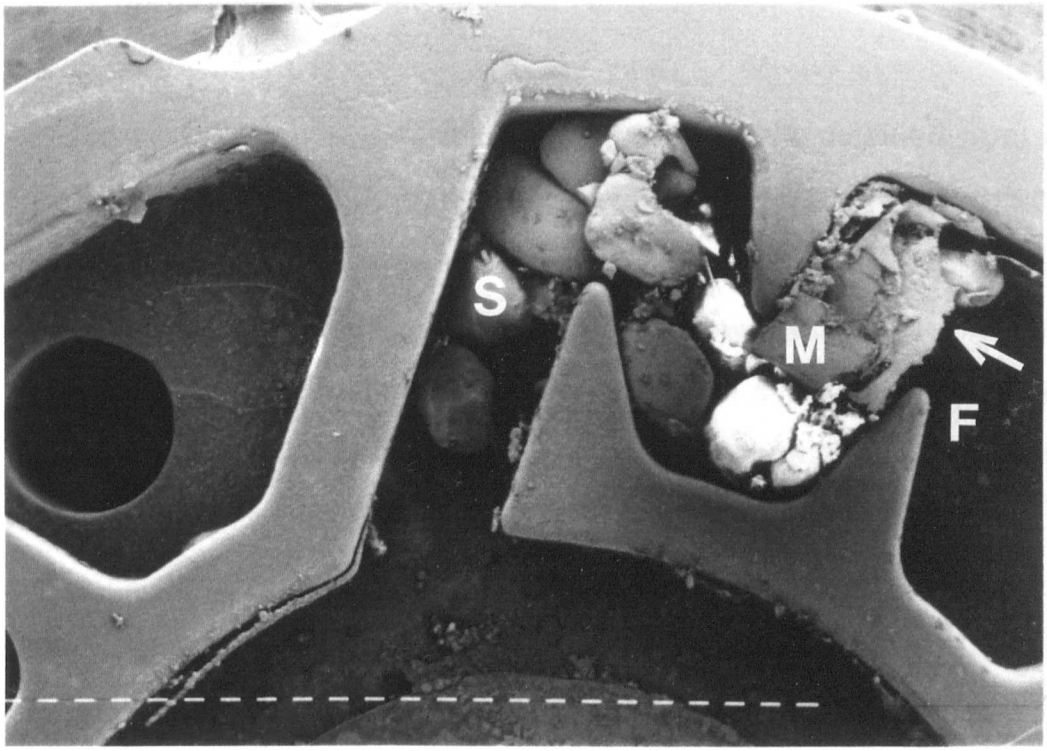


Plate 4.3 Sand particles and organic matter clogging the internal labyrinth of a Type C Emitter: S, sand grains; M, organic matter and microorganisms; F, direction of flow. Scale: 1 bar = 100 μm.

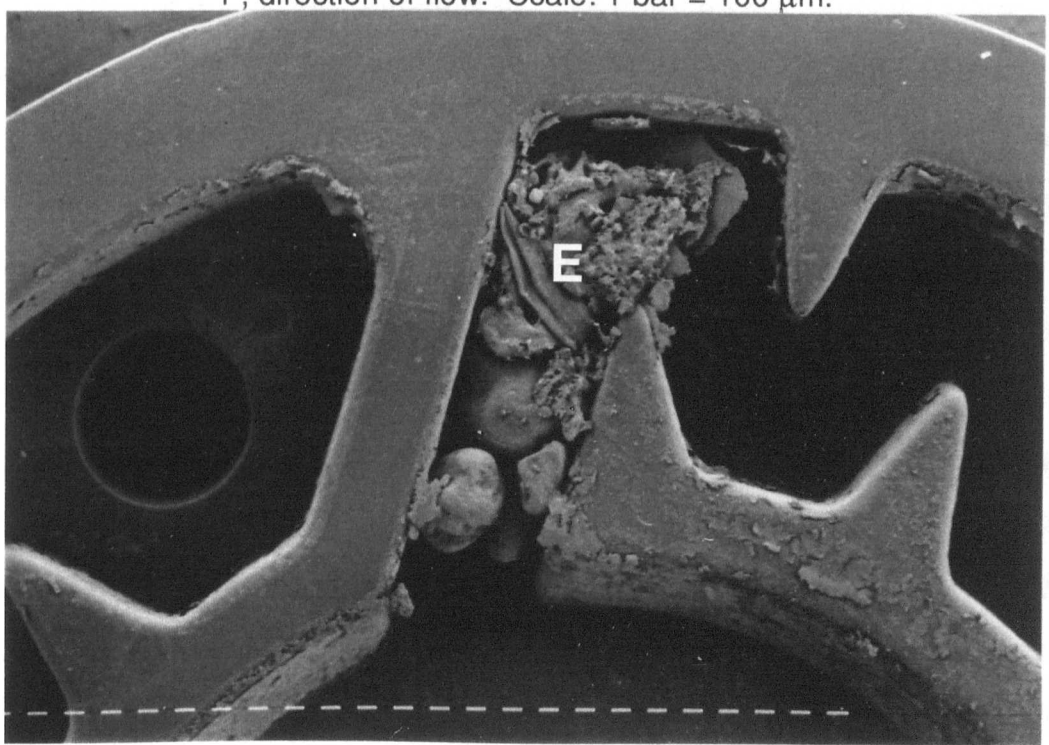


Plate 4.4 Sand particles and organic matter clogging the internal labyrinth of a Type C Emitter: E, exoskeleton of *Daphnia* spp.Scale: 1 bar = 100 μm.

4.4 Discussion

In order to compare the emitter performance data obtained from this research with that obtained by other workers, it is important to take account of all the conditions that were specific to the study. No two water sources have identical characteristics and treated wastewaters in particular vary considerably in their chemical and microbiological characteristics. These differences are related to the nature of the raw sewage and to the method and efficiency of its treatment.

The most important factor to be considered in the case of this particular study was the contamination of the entire system with sand from the municipal potable water supply during the early part of the 1987 growing season. Unfortunately, all water qualities were affected by this contamination via a defective one-way valve between the potable water and WSP effluent mainlines. Attempts to flush out the sand particles were only partly successful and this contamination of the entire system affected emitter performance throughout the two growing seasons, despite the fact that new emitters were installed before the second growing season. All emitter performance results should therefore be considered in the light of this fact.

All emitter design:water quality combinations showed higher performance efficiency in 1987 than in 1988. Although all models other than Emitter A were replaced with new emitters in 1988, and the entire system was flushed-out prior to irrigation, it was not possible to replace main-lines and laterals. Sand contamination therefore continued to present a problem in 1988. "On-line" emitter designs (B, B', C and C') performed more efficiently than "in-line" designs (A and D). Adapted emitter designs in which the light was excluded from the external orifice did not demonstrate improved emitter performance efficiency although they successfully

prevented the growth of microalgae on the external surface of emitters. The phenomenon of algal growth on the exterior surfaces of emitters is discussed in Chapter 5.

Efficiency of operation was linked more closely to emitter design than to water quality. Generally emitters supplied with potable water performed better than those supplied with effluent but the distinction was not clear cut: the most efficient combination during the study was Emitter C supplied with unfiltered WSP effluent during 1987; and one of the least efficient combinations was Emitter A supplied for a second season with potable water in 1988. Treatment of all these results however must take into account the sand contamination of the entire system during 1987. In general, emission uniformity was inadequate under all conditions, the minimum acceptable value of 0.90, suggested by Howell and Hiler (1974) was achieved only by Emitter C.

The potential use of analysis of variance techniques for the emitter discharge data is limited by the fact that, because of practical constraints, all emitters other than the Seephose laterals were operated at a supply pressure of 1.5 kg cm^{-2} rather than the design pressure for each design. Differences in design output between emitter designs (3 litres per hour for Emitter A) also precluded comparison of designs by this technique. A limited Model 1 anova was carried out on the output data obtained for Emitter C after ninety hours of operation as this emitter appeared to be the most successful design studied. The null hypothesis was that there is no added component, caused by differences in water quality, that affects emitter output.

Table 4.18 Anova table for Emitter C after ninety hours of operation

Source of variation	*df*	SS	MS	F_s
Among water qualities	2	0.9620	0.4810	0.4374
Within water qualities	177	194.64	1.0997	
Total	179	195.60		

F0.05[2,120] = 3.07 F0.01[2,120] = 4.79
F0.05[2,∞] = 3.00 F0.01[2,∞] = 4.61

df degrees of freedom; SS sum of squares; MS mean square; F_s sample variance ratio.

Table 4.18 is the anova table for testing this hypothesis using the methodology outlined by Sokal and Rohlf (1981). Comparison of the calculated variance ratio (Fs) of 0.4374 for three water qualities and sixty samples per group, with the conservative critical value of the F-distribution for degrees of freedom v1 = 2 and v2 = 120, (obtained from the statistical tables of Rohlf and Sokal (1981) suggests that the null hypothesis should be retained, ie. for Emitter C output was not affected by differences in water quality.

The phenomenon of emitter clogging appears to be a spontaneous event which leads from full emitter discharge rates to negligible rates within a short period of time. Grouping the discharge rates in the form of contingency graphs (Figures 4.5 to 4.8) shows that very few emitters of any design:water quality combination exhibit discharge rates in the mid-range, i.e., 0.96 -1.98 litres per hour (Group 2). Emitter clogging seems to result in a reduction of

discharge from greater than 1.98 litres per hour (Group 3) to less than 0.96 litres per hour (Group 1) with no intermediate stage. This suggests that the cause of clogging is particles in the water supply that clog the emitter as soon as they become trapped within the emitter labyrinth rather than the gradual growth and replication of microorganisms to form a clogging organic mass. The occasional observation of a reduction in the number of clogged emitters suggested that self-flushing of the particles trapped within emitters had occurred.

Little increase in emitter clogging was observed in 1988 between fifty and ninety hours after the commencement of irrigation. Most clogging occurred before fifty hours of operation. This suggests that solids within the irrigation equipment prior to setting up the system played a more important part in the emitter clogging process than solids within the water supplies used in 1988. It is therefore probable that sand from the line contamination in 1987 was not effectively removed from the system prior to irrigation in 1988.

Examination of clogged emitters proved that sand particles were the cause of clogging with all three qualities of water. These sand particles most probably derived from the municipal potable water supply in 1987 as the long retention time of WSP results in the removal of all settleable solids such as sand. Since no emitters were shown to have been clogged solely by the types of suspended solids normally present in the pond effluent (ie., microalgae, bacteria and small invertebrates), it can be assumed from the data that emitter clogging would not have been a problem using WSP effluent had the sand contamination not occurred. The organic matter present in WSP effluent appears only to be a factor in emitter clogging when sand particles are also present.

CHAPTER 5

5 ALGAE AND WASTEWATER REUSE

5.1 Introduction

5.1.1 Environmental Factors Affecting Algal Speciation

The growth of algae in aquatic environments may be controlled by one or more limiting factors (Mills, 1987). These factors, which have been studied in detail by other authors, include light (Round, 1973), limiting nutrients (Rhee and Gotham, 1980), pH (Pearson *et al.*, 1987), temperature (Butterwick, 1987), dissolved oxygen (Round, 1973), dissolved carbon dioxide (Cole, 1982) and organic pollution (Curtis and Curds, 1971). These factors not only control the extent of algal growth and reproduction but also affect the speciation of the algal community. Each algal species has its own specific nutritional and environmental requirements and tolerance levels. Therefore, in a given habitat, certain algae will flourish while others will not survive.

Experience in Israel (Dor and Benzion, 1980; Benzion and Dor, 1981) has shown that certain bacteria may adversely affect the growth of algae in WSP. The authors investigated the effect of twenty species of sewage bacteria on the growth of *Chlorella vulgaris* and *Scenedesmus obliquus* in monaxenic cultures and found that all bacterial species studied reduced the growth of both algae to some extent. The importance of antialgal activity by bacteria in WSP is not known and may have considerably less significance compared to the stimulatory effect of bacterial carbon dioxide production.

5.1.2 Algae and Wastewater Treatment

Algae (and cyanobacteria) play an important role in the purification of polluted waters in natural environments. Oxygenic photosynthetic eukaryotic algae and prokaryotic cyanobacteria provide the oxygen required by heterotrophic bacteria for the breakdown of organic material which in turn releases the inorganic nutrients required for the growth of phototrophs. The mutualistic relationship between algae and bacteria is exploited in the design of waste stabilization ponds (Figure 5.1). In facultative and maturation WSP a high algal population is essential for the provision of oxygen and the maintenance of a high pH level. Disturbances to the algal population such as those caused by high levels of sulphide or ammonia, rapidly lead to a decrease in the quality of the pond effluent.

Although algae do not play such an important role in the trickling filter process as they do in WSP, they are an integral part of the microbial biofilm on the surfaces of the filter bed (Table 5.1) and oxygenic photosynthesis may provide a considerable proportion of the oxygen required by attached heterotrophic bacteria for the breakdown of organic pollutants. The main factor controlling algal speciation in wastewater treatment systems is the level of organic pollution. At high levels of BOD, algal growth is limited to those that can survive in anoxic environments. As the level of BOD falls, algal diversity increases although total numbers may decrease as wastewater quality improves (Mills, 1987).

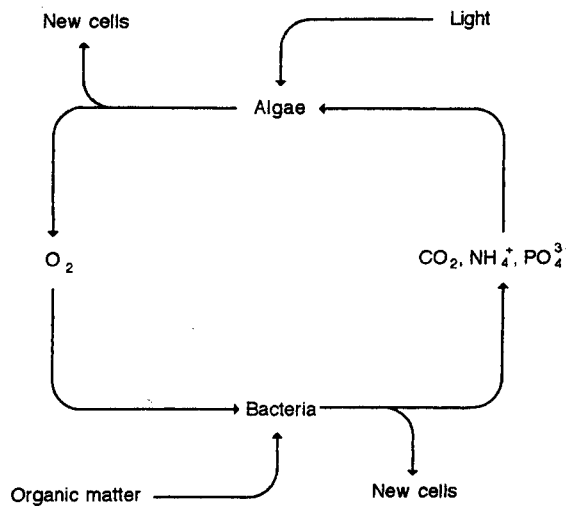


Figure 5.1 Schematic representation of the reciprocal relationship between oxygenic photosynthetic microalgae and heterotrophic bacteria in waste stabilization ponds (Mara and Pearson, 1986)

Table 5.1 The composition of the microbial community commonly found on the media beds of the trickling filter treatment process

Bacteria	Fungi	Algae	Protozoans
Achromobacter	*Fusazium*	*Phormidium*	*Vorticella*
Flavobacterium	*Mucor*	*Chlorella*	*Opercularia*
Pseudomonas	*Penicillium*	*Ulothrix*	*Epistylis*
Alcaligenes	*Geotrichum*		
Sphaerotilus natans	*Sportichum*		
Nitrobacter	The yeasts		

Adapted from Higgins and Burns (1975)

5.1.3 Colonization of Surfaces by Algae

The ability of photosynthetic microorganisms to fix carbon dioxide without the requirement of organic carbon allows them to colonise environments in which strict heterotrophs are unable to survive and they are therefore often the primary colonisers of both aquatic and terrestrial environments. All surfaces that are wet and illuminated will eventually support the growth of an algal population (Cooksey and Cooksey, 1986). Attached growth offers several advantages over a planktonic existence including increased availability of nutrients and the protection against predation from other organisms provided by colonial growth and the production of an extracellular glycocalyx (Costerton *et al.*, 1978). Therefore, in shallow lakes attached algae may make a significant contribution to productivity (Fay, 1983). The tendency of organic molecules to accumulate at surfaces (Zobell, 1943) increases the availability of nutrients for heterotrophic growth (Costerton and Geesey, 1979), and the metabolic rates of attached heterotrophs are therefore often higher than their planktonic counterparts.

The primary colonisers of wetted surfaces are often diatoms which play an important role in the nutrient dynamics of any subsequent biofilm (Characklis and Cooksey, 1983). The majority of diatoms (Bacillariophyta) are unicellular although some colonial and filamentous species exist. Their common characteristic is their silicaceous cell wall (frustule) which consists of two parts (valves) that fit together like a box with an overlapping lid (Singleton and Sainsbury, 1978). As algal mats develop and cells become buried beneath others, the diatoms are the first to disappear, perhaps

because of the sensitivity of these organisms to sulphide (Jørgensen *et al.*, 1988).

Cyanobacteria (blue-green algae) are of considerable importance in natural environments as primary colonisers of sterile environments. Cyanobacterial mats are often recorded in habitats where other phototrophic microorganisms are unable to survive because of low water potential. Resistance to desiccation is a characteristic common to several filamentous cyanobacteria and is thought to be a consequence of the protection provided by thick mucilaginous sheaths (Fay, 1983).

5.2 Algae and the Biofouling of Emitters in a HRTF Effluent Reuse System

The initial experimental reuse system in Évora, Portugal utilised the final effluent of the towns municipal high-rate trickling filter (HRTF) wastewater treatment plant for drip irrigation. The effluent was monitored for total suspended solids and chlorophyll a concentrations. The mean TSS value for the unfiltered effluent was 44 mg per litre, that of the filtered effluent was 22 mg per litre (Table 3.3b). Chlorophyll *a* was not detected in any of the weekly grab samples of final effluent and no algae were observed in microscopic examination of the same samples. Suspended solids appeared to comprise undegraded fæcal material.

Samples of rock from the trickling filters were transferred to the laboratory on five occasions for identification of the attached biological community. It was found to contain most of the organisms listed by Metcalf and Eddy

(1979) as typical components of the attached biological community of trickling filters (Table 5.1). The predominant algae on those stones exposed to sunlight were the filamentous *Ulothrix* and *Microspora*, the filamentous cyanobacteria *Oscillatoria* and *Phormidium* and the diatom *Nitzschia*.

Although algae were not detected in grab samples of the HRTF effluent, it is highly probable that algal cells were occasionally present in the effluent. "Sloughing-off" of the attached microbial community of trickling filters is a natural phenomenon that occurs when microbial growth has reached such a level that insufficient nutrients can be made available to cells within the microbial mass. The death of cells at the substrate : community interface weakens the attachment of the biological mass and it is eventually removed from the substrate surface by hydrodynamic forces.

Secondary sedimentation removes the bulk of this biological mass but it must be assumed that some algal cells will be present in the final effluent. This is particularly true of overloaded HRTF, such as that at Évora, in which the mean hydraulic retention time of the sedimentation tanks is lower than that for which it was designed.

Irrigation was carried out between 09.00 hrs. and 11.00 hrs. each day from 11 October to 14 November 1986 (a total of seventy hours of irrigation over a period of thirty five days). During this period of study, no algal colonization of the two emitter designs under study was detected. Both designs performed poorly and emitter blockage was a serious problem. When emitters were cut open and examined microscopically at the end of the irrigation season, the cause of blockages was shown to be in all cases the result of accumulated undegraded organic material within the emitters

(see Chapter 3). Algae were not detected on either the interior or the exterior surfaces of emitters and were therefore not implicated in the clogging process.

Because the soil at the experimental site was a relatively impervious heavy loam and because intensive rainfall occurred during the irrigation period, waterlogging of the soil occurred. Pools of water rapidly formed around the emitters and remained for several hours after irrigation had ceased. After twelve days, a biological community was found to be developing in these pools. Within twenty days a mass of mucilaginous green growth filled the pools. Microscopic examination of these growths revealed a complex biological community dominated by the filamentous green alga *Microspora* and the filamentous cyanobacterium *Oscillatoria*. The diatoms *Nitzschia* and *Navicula* were routinely detected within the filamentous matrix in addition to invertebrate "grazers" such as *Daphnia* and the metazoan *Rotifera*.

The development of these pool communities cannot be explained by the simple accumulation of organisms present in the HRTF effluent. The constituent organisms appeared to be actively multiplying within the pools. The habitat of the pools therefore provided all the environmental requirements for their growth. The source of the initial inoculum of organisms could have been the filter beds; or, alternatively, it could have been the surrounding environment (ie., the soil and air), and the community could therefore have developed in a similar manner to that of the attached community on the filter beds of a newly commissioned HRTF system.

The controlling factor in the build up of such communities is therefore not

the nature of the initial inoculum but the nature of the habitat. Environmental factors such the availability of light, moisture, nutrients and surfaces for attachment; and interactions between organisms such as competition and predation, are responsible for the composition of the established community. The habitat of the effluent pools around the emitters were very similar to the habitat of the surfaces within the trickling filter beds and the resultant biological communities in the two habitats were therefore similar. In both, a well illuminated substrate (rocks or soil surface) was supplied with water and sufficient organic and inorganic nutrients to support a complex interacting community of heterotrophs and phototrophs.

The biological masses did not interfere with the operational efficiency of the emitters during the short period of irrigation in 1986. However, this initial study did show that algal biofouling of irrigation equipment is a potential problem in cases in which the environmental requirements for the growth of algal blooms are provided. In order to more fully understand the role of algae in the process of emitter clogging in reuse schemes, further field work using waste stabilization pond effluent was carried out during the summer months of 1987 and 1988.

5.3 Algae and the Biofouling of Emitters in WSP Effluent Reuse Systems

Pearson (1986) reported that, in the past, the appearance of algal mats on the surfaces of emitters in WSP effluent reuse systems was assumed to be the result of employing an algal-rich water source. This project attempted

to show that the development of algal mats was a consequence of environmental factors rather than the simple accumulation of WSP phytoplankton in the final effluent.

The WSP reuse experiments in Santo André, Portugal were carried out from 12 August to 20 October 1987, and from 11 July to 27 October 1988. Irrigation occurred between 09.00 hrs. and 10.00 hrs. each day. The experiments were designed to establish the susceptibility of various emitter designs, which are described in Chapter 2, to the algal fouling previously noted in field experience of WSP effluent reuse in Israel.

The concentration of microalgae in the WSP effluent was estimated by measuring the concentration of chlorophyll *a* (the photosynthetic pigment common to eukaryotic algae and prokaryotic cyanobacteria). The presence of dead algae was corrected for by measuring the concentration of phaeophytin *a*, a breakdown product of chlorophyll *a*. Assuming the level of undegraded chlorophyll a to be 1.5 percent of cell mass in all eukaryotic algae and cyanobacteria, an estimation of total active algal biomass can be calculated (APHA 1985). Dividing this value by the concentration of suspended solids in the same samples gives a rough estimate of the contribution of active algae to the level of suspended material in the WSP effluent.

The mean value for chlorophyll *a* in the filtered WSP effluent during the 1987 irrigation season was 252 µg per litre, which corresponds to approximately 17 mg of algal biomass per litre of effluent or 42 percent of the total suspended material according to the above calculations. Measurements of chlorophyll *a* were corrected for the presence of

chlorophyll degradation products. Therefore the calculated concentration of algal biomass accounts only for metabolically active organisms capable of acting as an inoculum. The proportion of the suspended solids of WSP effluent comprising decomposing algal cells is not included in the estimation of algal biomass.

The WSP final effluent was examined microscopically every seven days throughout the two irrigation seasons in order to identify the constituent algal genera. The results showed that the maturation pond effluent was dominated by the genera *Euglena* and *Chlorella* (Tables 5.2; 5.4; 5.6; and 5.8). These two genera, which are found in most facultative and maturation WSP, were detected in all samples of filtered and unfiltered effluent. Other important genera were the diatom *Nitzschia* and the green alga *Scenedesmus* (found in one third of samples), and *Ankistrodesmus* (found in 22 percent of samples). No filamentous algae were detected in these weekly grab samples although examination of the filter screen surface prior to daily washing occasionally revealed short filaments of *Oscillatoria.*

The development of an algal mat on emitter surfaces was linked to emitter design (Tables 5.10 and 5.11). In 1987 Emitter C showed the greatest degree of algal mat development after seventy hours of irrigation (detected on 18.33 percent of emitters supplied with filtered WSP effluent and on 23.33 percent of emitters supplied with unfiltered WSP effluent). In all other designs the percentage of affected emitters did not exceed 10 percent. In 1988 mat development was less prevalent. Emitter C again showed the greatest degree of mat development at the end of the irrigation season (ie., after ninety hours of irrigation). Mats were detected on 33.33

percent of emitters supplied with unfiltered WSP effluent and on 8.5 percent of emitters supplied with filtered effluent.

The development of this biofilm on the surface of Emitter C was thought to be a consequence of the large external surface area that became wetted during irrigation. Emitter C was inserted into the irrigation lateral on site and the angle of the emitter on the lateral influenced the degree of wetting that occurred: those that had a horizontal emitter surface were more prone to wetting and were consequently more likely to develop an algal mat.

The development of algal mats followed a common course on all affected emitters. Water would evaporate from the emitter surface following irrigation while carbon dioxide was absorbed from the atmosphere. These processes would lead to the precipitation of calcium carbonate on the emitter surface. This process occurred on emitters supplied with each of the three water qualities investigated. On those emitters supplied with potable mains water, chemical precipitation was the only form of external fouling to occur. No biological growth was recorded on these emitters and when carbonate precipitation did occur it was not shown to cause a reduction in emitter discharge.

Algal mats were first recorded four weeks after the commencement of irrigation in both 1987 and 1988. The mat development occurred on those emitters supplied with filtered or unfiltered WSP effluent on which carbonate precipitation had been previously recorded. Small pieces of algal mat were removed each week from this point onwards for microscopic analysis. These analyses revealed a microbial community dominated by the filamentous cyanobacteria *Oscillatoria* and *Lyngbya* (Tables 5.3; 5.5;5.7;

and 5.9). Other important components of the mat communities were the filamentous green alga *Microspora* and the diatoms *Nitzschia* and *Navicula*.

Of the two major algal components of the WSP final effluent, *Chlorella* were detected in 50 percent of algal mats and *Euglena* were undetected in all samples. Weekly samples of algal mats were taken two hours after irrigation had ceased. On one occasion, however, small samples of algal mat were examined every twenty minutes following the cessation of irrigation using a small field microscope. In these samples *Euglena* were detected up until forty minutes after irrigation had ceased. It would appear that these green planktonic unicellular organisms were unable to withstand the desiccating conditions of the emitter exteriors.

The distribution and size of mats changed from week to week. Mats often became dislodged from emitters following heavy rainfall or disturbances caused by field practises such as weeding. Development of the mats appeared to be limited and adherence of the algal mat to the emitter surface became weakened within approximately three weeks. The mats then "sloughed off" in a similar way to the biofilms on the inert substrate surfaces within trickling filter treatment systems. In some cases fresh mats developed to replace the mature mat.

Plate 5.1a

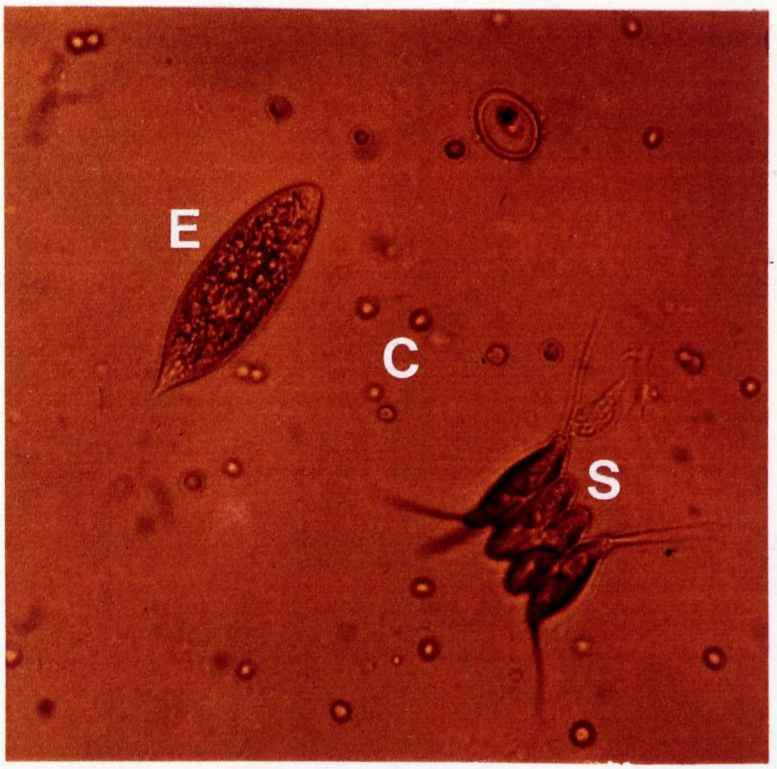
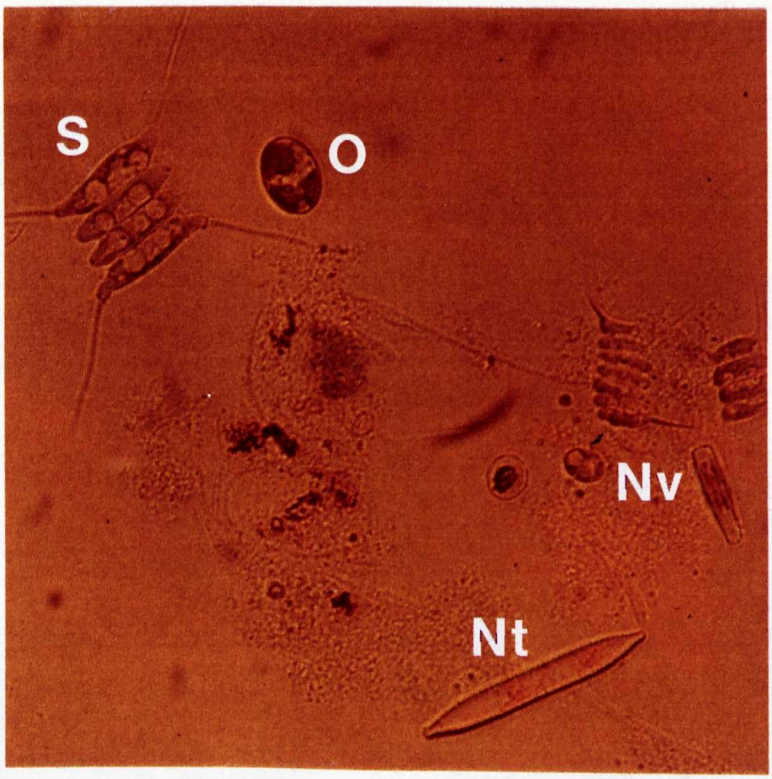


Plate 5.1b



Plates 5.1a and 5.1b. Examples of typical algal genera found in the WSP final effluent, Santo André. E, *Euglena*; C, *Chlorella*; S, *Scenedesmus*; O, *Oocystis*; Nv, *Navicula*; Nt, *Nitzschia*. Scale: 1:650.

Plate 5.2 An example of an uncolonised Type C Emitter in operation

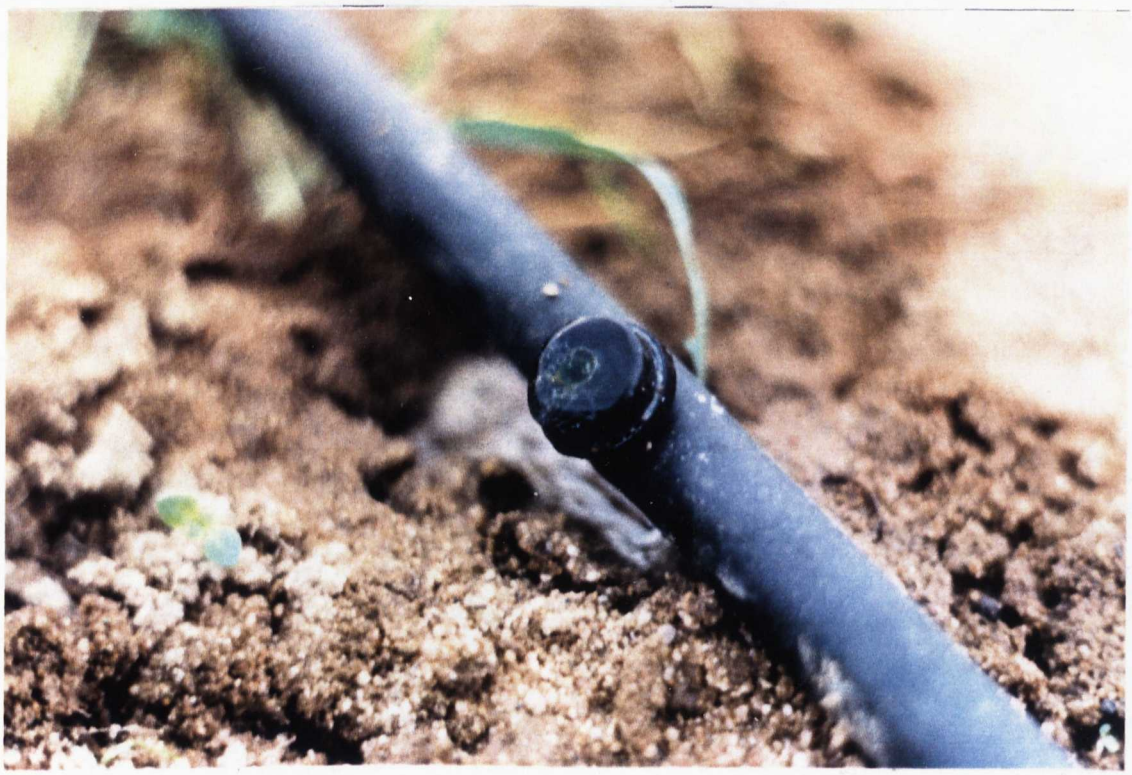


Plate 5.3 An example of Emitter C after colonization by a cyanobacterial mat. Emitter continues to operate efficiently

Plate 5.4 An example of Emitter C in operation showing a cyanobacterial mat and calcium carbonate precipitation

Plate 5.5 Growth of filamentous cyanobacteria on the soil surrounding an emitter discharging WSP effluent

Plate 5.6 Calcium carbonate precipitation on the surface of a Type A Emitter supplied with potable water (emitter discharge efficiency is unaffected)

Plate 5.7 Calcium carbonate precipitation on the surface of a "Seephose" lateral supplied with potable water

Table 5.2 Algal composition of filtered WSP effluent 1987

	Week Number									
	1	2	3	4	5	6	7	8	9	10
Chlorella sp.	+	+	+	+	+	+	+	+	+	+
Euglena sp.	+	+	+	+	+	+	+	+	+	+
Micractinium sp.	+	+	−	−	−	+	−	−	−	−
Oscillatoria sp.	−	−	−	−	−	−	−	−	−	−
Lyngbya sp.	−	−	−	−	−	−	−	−	−	−
Microspora sp.	−	−	−	−	−	−	−	−	−	−
Navicula sp.	−	−	−	−	−	−	−	−	−	−
Nitzschia sp.	−	−	+	−	+	+	−	−	−	+
Ankistrodesmus sp.	+	−	−	+	+	−	−	−	+	−
Chlamydomonas sp.	−	−	−	−	−	−	−	−	−	−
Oocystis sp.	−	−	−	−	−	−	−	−	−	−
Scenedesmus sp.	−	+	−	−	+	+	−	−	−	−
Synedra sp.	−	−	−	−	−	−	−	−	−	−
Gomphonema sp.	−	−	−	−	−	−	−	−	−	−
Chroococcus sp.	−	−	−	−	−	−	−	−	−	−
Microcystis sp.	−	+	+	−	+	−	−	−	+	+
Chamaesiphon sp.	−	−	−	−	−	−	−	−	−	−

Table 5.3 Algal composition of algal mats (filtered WSP lines) 1987

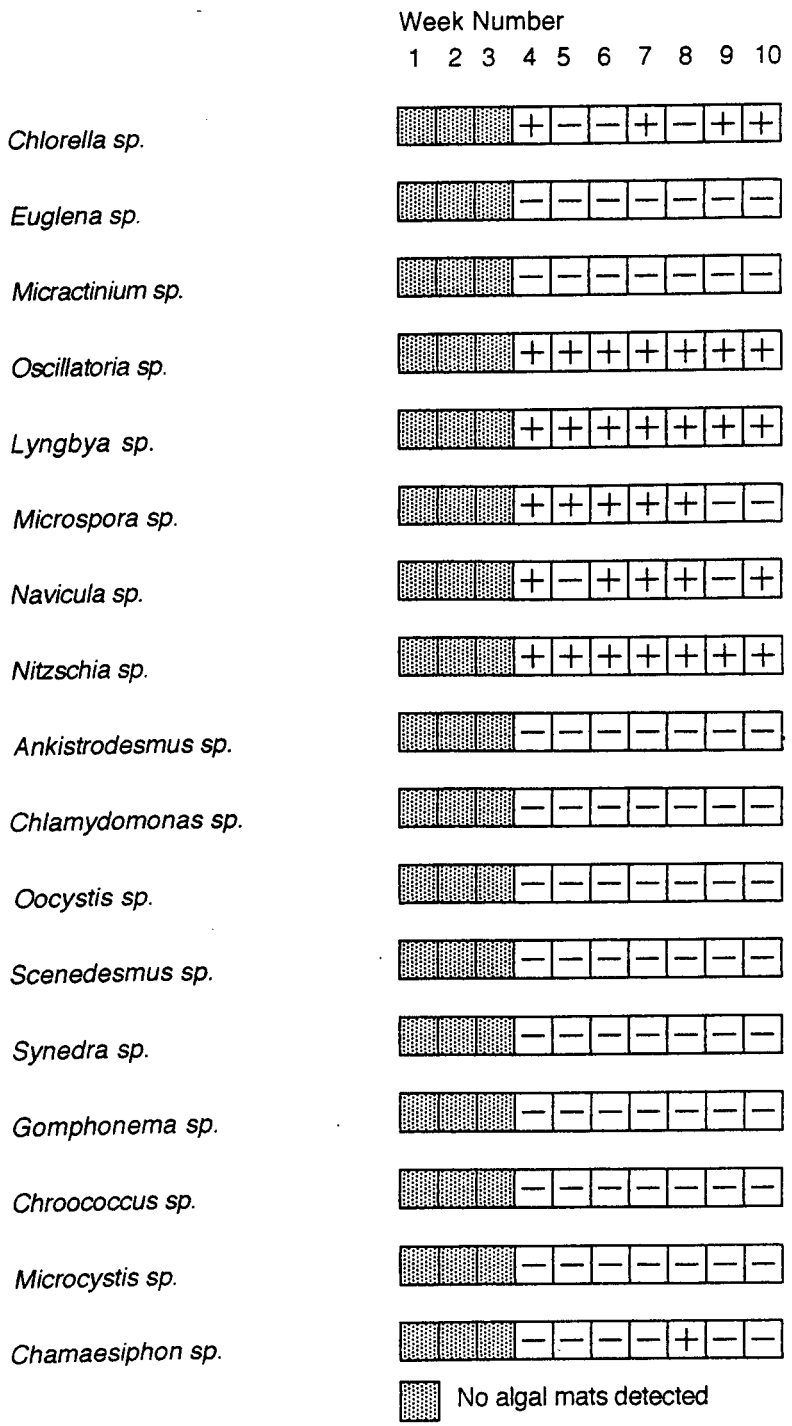


Table 5.4 Algal composition of unfiltered WSP effluent 1987

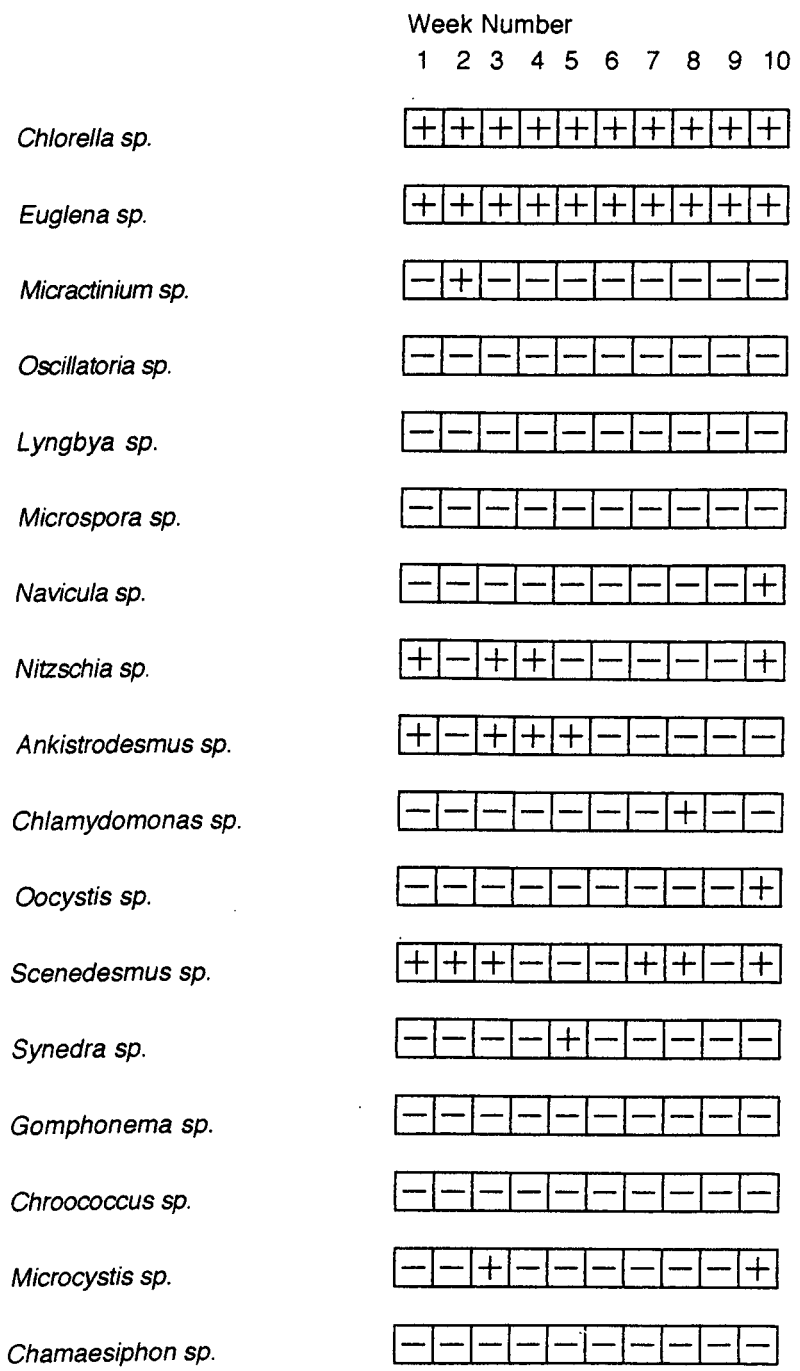


Table 5.5 Composition of algal mats (unfiltered WSP lines) 1987

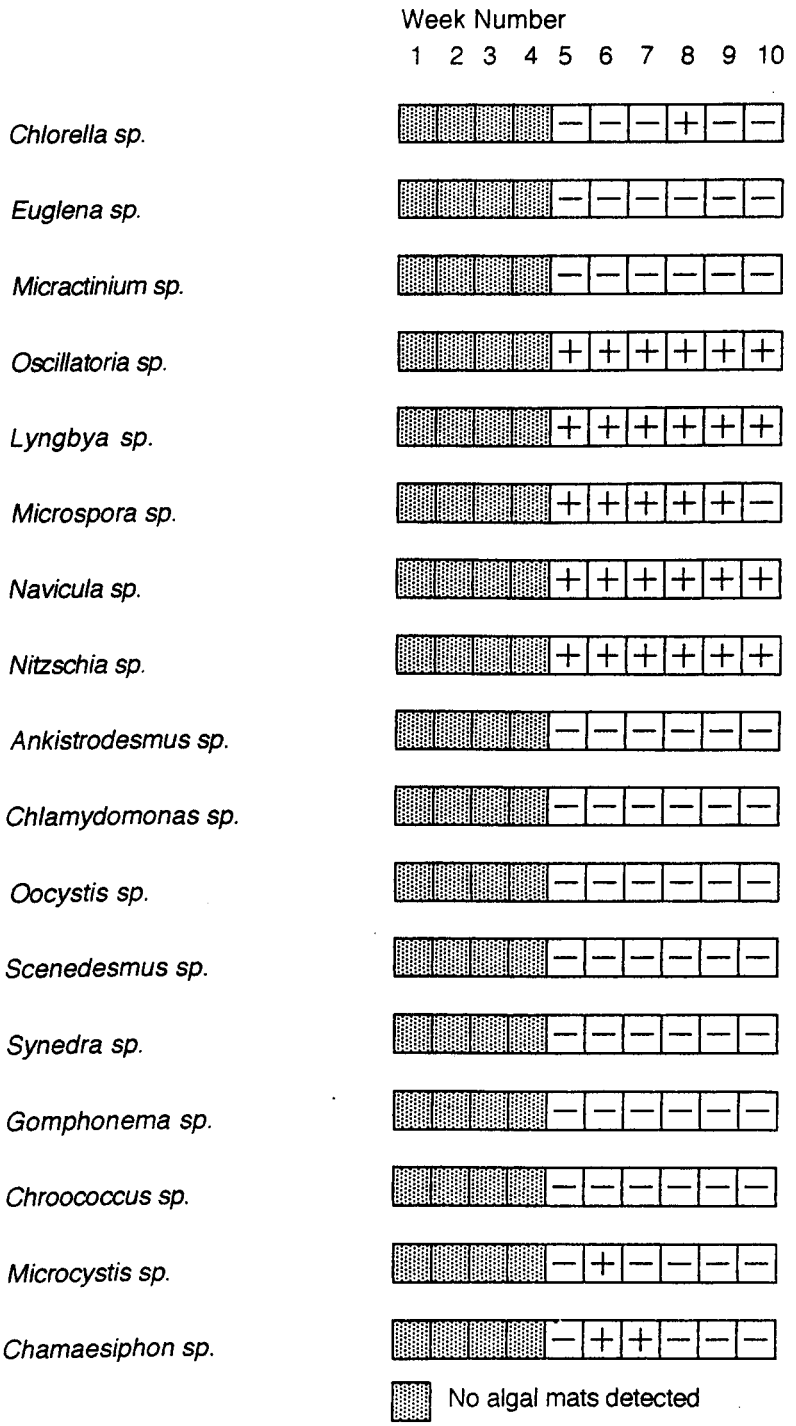


Table 5.6 Algal composition of filtered WSP effluent 1988

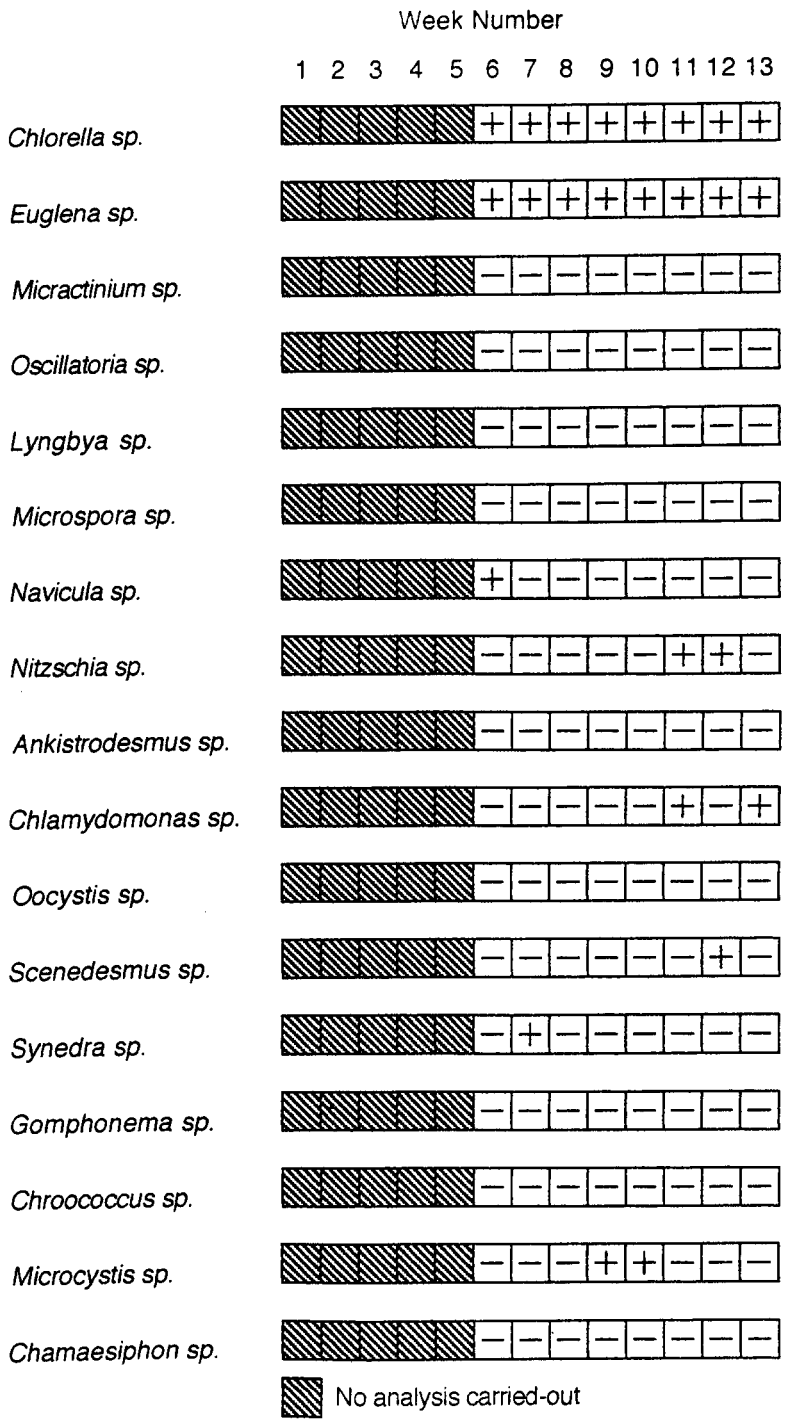


Table 5.7 Composition of algal mats (filtered WSP effluent lines) 1988

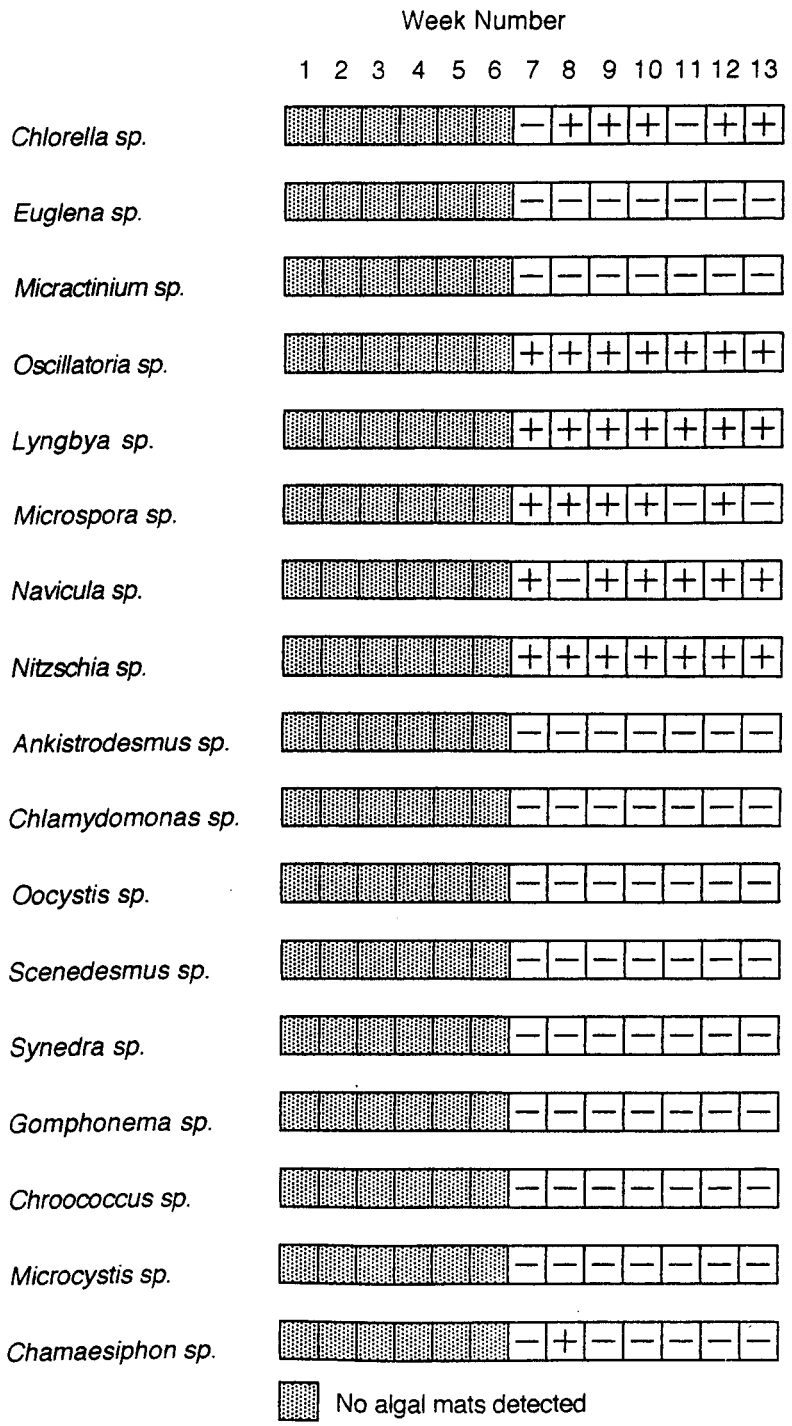


Table 5.8 Algal composition of unfiltered WSP effluent 1988

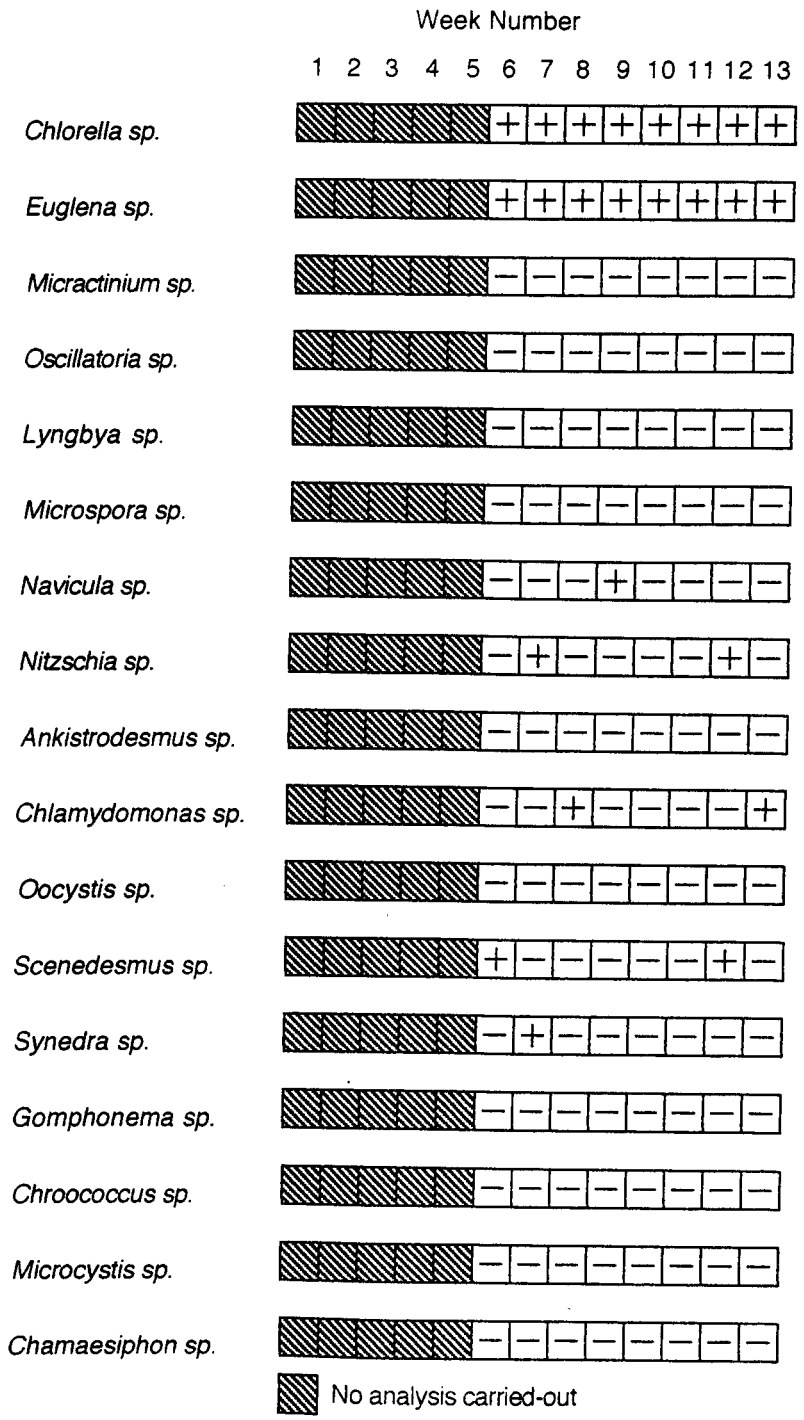
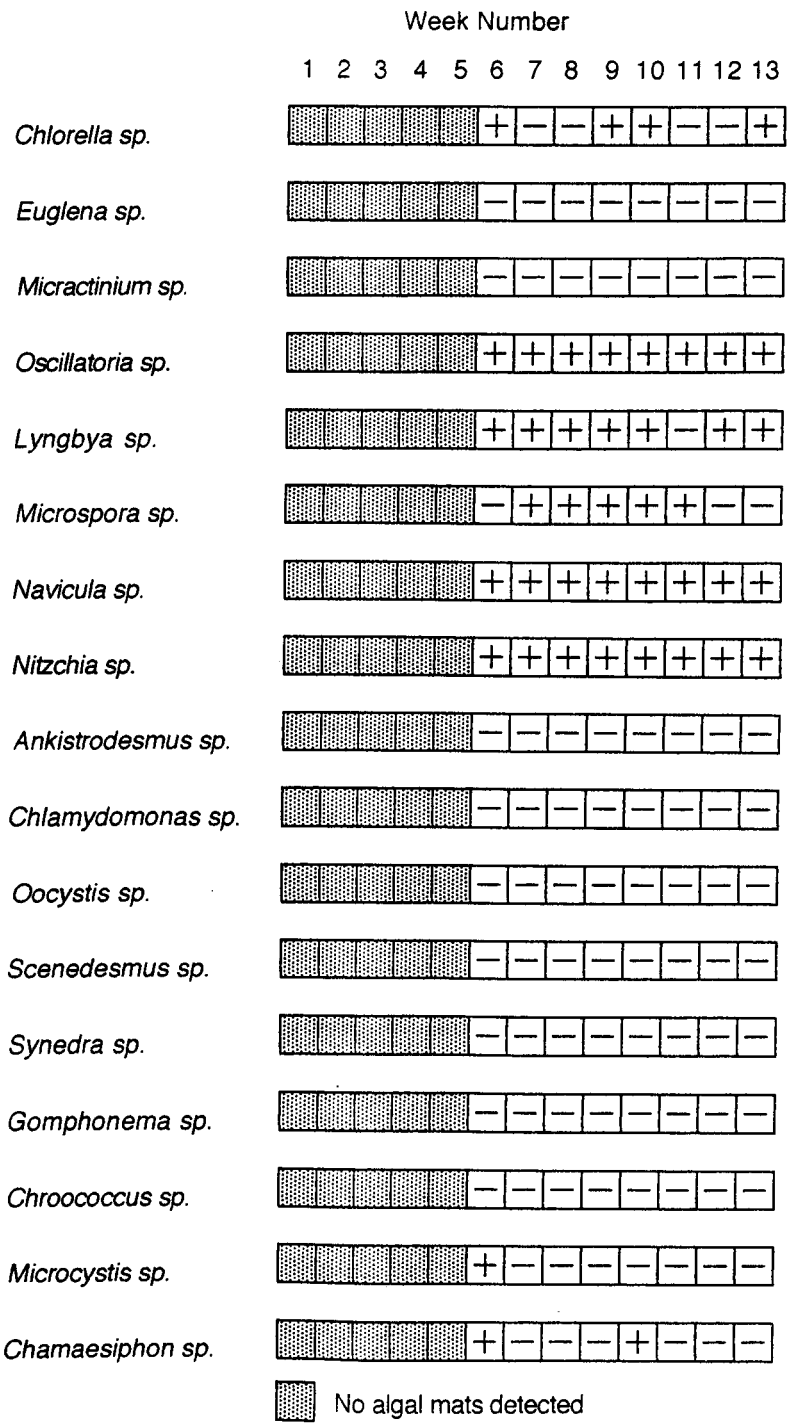


Table 5.9 Composition of algal mats (unfiltered WSP effluent lines) 1988



Following the 1987 irrigation season (ie., after seventy hours of irrigation), the discharge of all emitters was measured (see Chapter 4). No correlation between the presence of algal mats and reduction in emitter discharge was recorded (Figures 5.2; 5.3; and 5.4): those emitters affected by algal growth continued to operate efficiently and no link between the growth of external algal mats and the clogging process could be deduced.

In 1988 emitter discharge of all Type C Emitters was measured after fifty, seventy and ninety hours of irrigation. Again no correlation between algal mat development and emitter blockage was recorded (Figure 5.5). Where mats were present on clogged emitters, the cause of clogging was always found to be accumulated sand particles within the emitter labyrinth.

Adaptations to emitter designs were made during both growing seasons in order to ascertain the influence of light on the development of external algal mats. In 1987 Emitter B was compared with a modification of the same emitter design (Emitter B') in which a black polythene microtube was attached to the emitter orifice (Plate 2.3) and placed into a 30 mm section of 12 mm diameter black irrigation lateral tubing inserted into the soil. In this way the irrigation waters entered the soil without coming into contact with sunlight. Neither the modified, nor the unmodified design were affected by algal mat development because the surfaces of this emitter design did not become wetted during irrigation.

Since the only emitter design to be affected significantly by mat development in 1987 was Emitter C, in 1988 the effect of eliminating light from the surface of this emitter was monitored. Plots containing Emitter C were covered with black polythene (Emitter C') and emitter performance was compared with those in the unmodified plots. Eliminating light from the emitters prevented the growth of algal mats but there was no significant difference in the prevalence of emitter blockage between covered and uncovered plots.

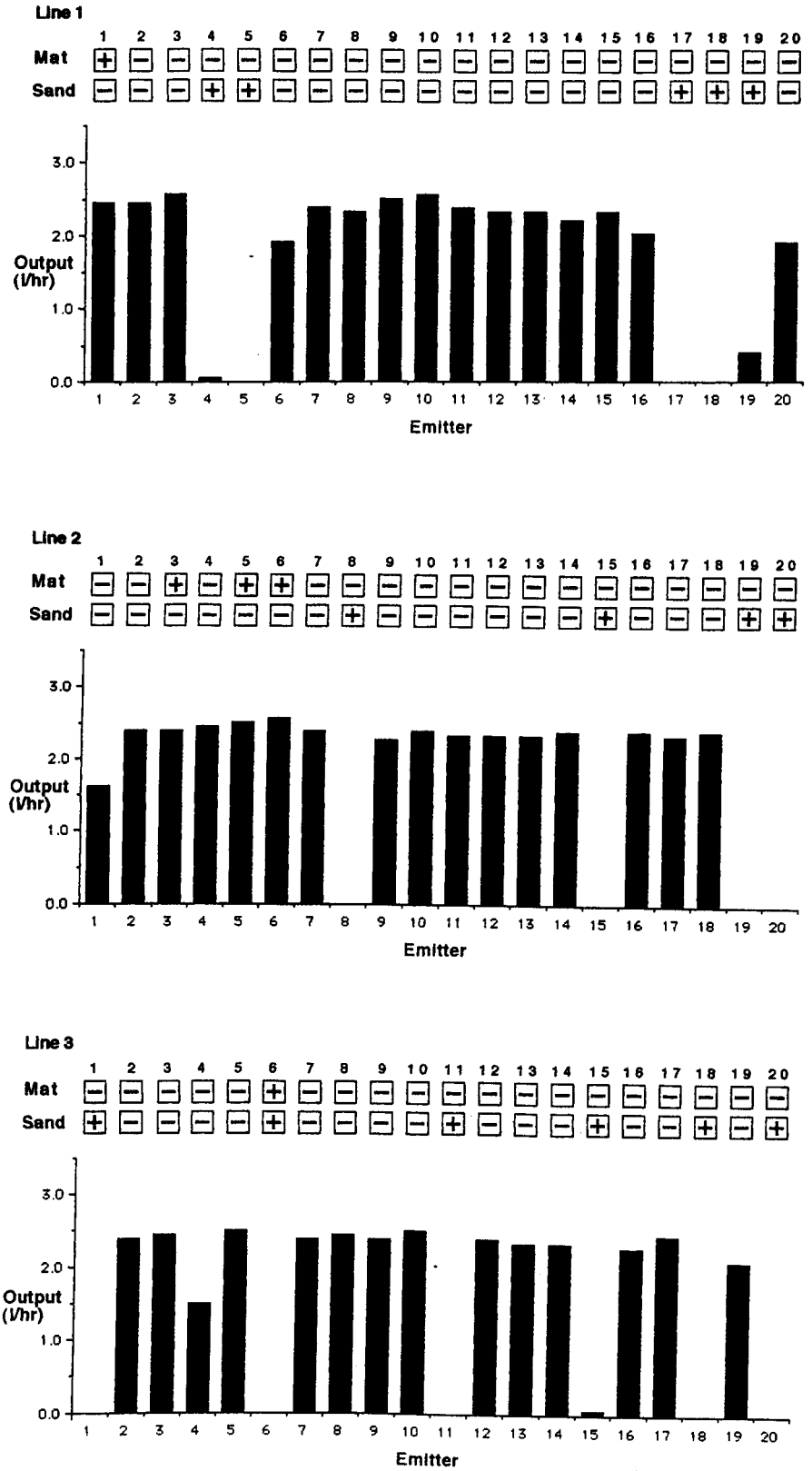


Figure 5.2 The relationship between emitter output, the presence or absence of sand within emitters, and algal mats on emitter surfaces after 90 hours of irrigation (1988)

Emitter C, filtered effluent

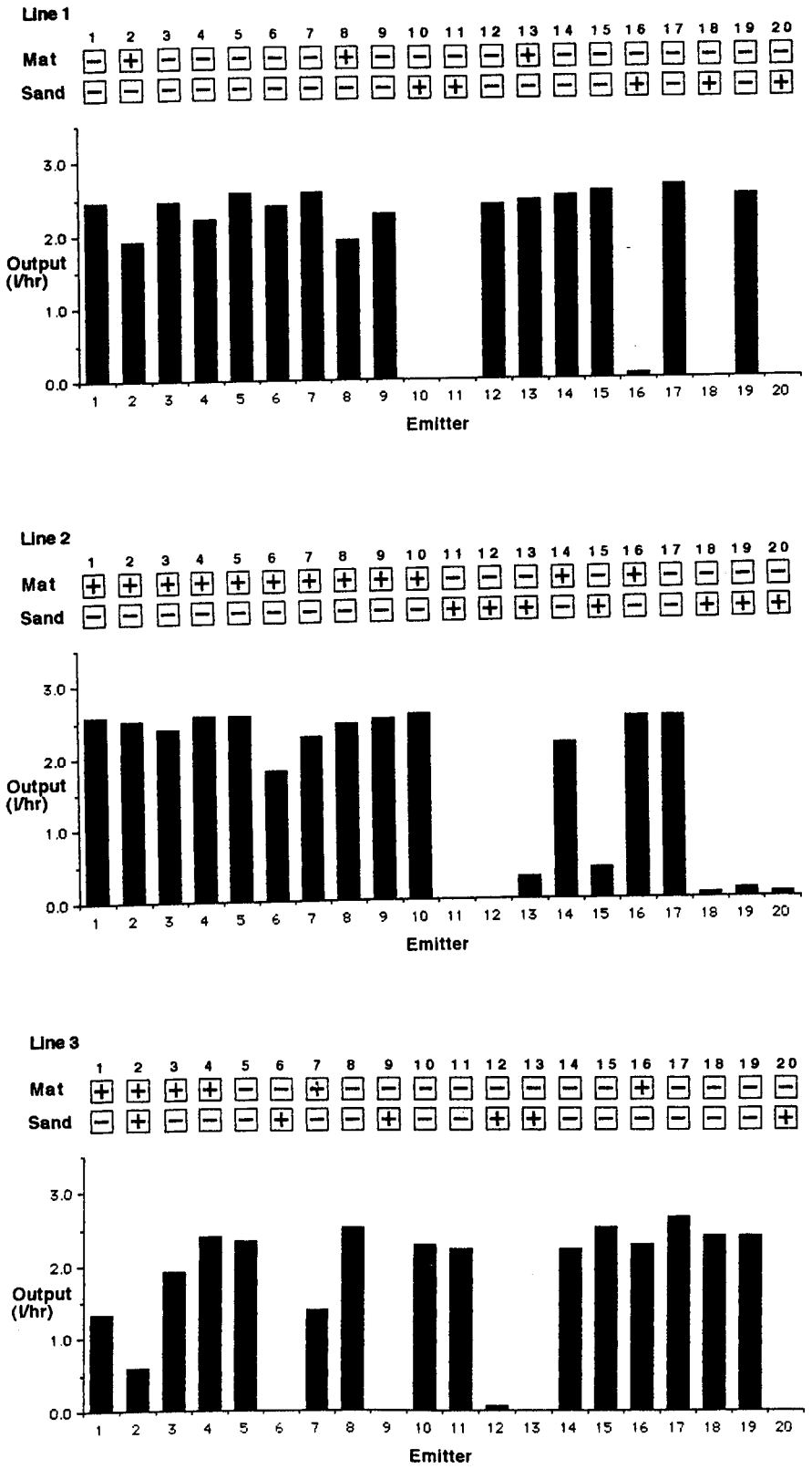


Figure 5.3 The relationship between emitter output, the presence or absence of sand within emitters, and algal mats on emitter surfaces after 90 hours of irrigation (1988)

Emitter C, unfiltered effluent

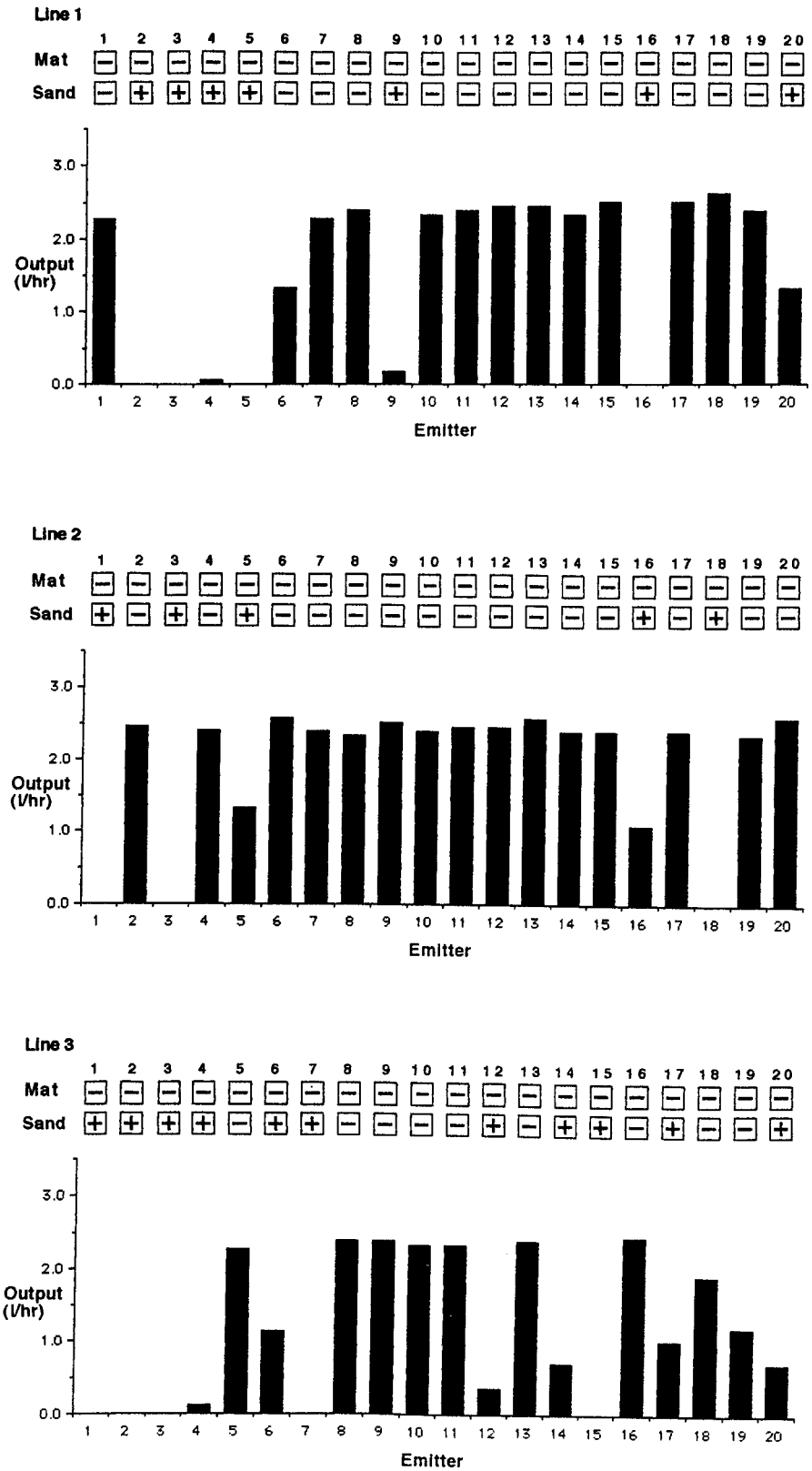


Figure 5.4 The relationship between emitter output, the presence or absence of sand within emitters, and algal mats on emitter surfaces after 90 hours of irrigation (1988)

Emitter C, potable water

Table 5.10 Summary table comparing emitter appearance and emitter output data.
Emitter C after 90 hours of irrigation (1988)

Water Quality	Emitter Appearance	Clogged[1]	Unclogged[2]
Potable Water	Clean [3]	0	62
	Mat only [4]	0	0
	Mat and sand [5]	0	0
	Sand only [6]	30	8
Filtered Effluent	Clean	0	68
	Mat only	0	7
	Mat and sand	2	0
	Sand only	23	0
Unfiltered Effluent	Clean	0	37
	Mat only	0	33
	Mat and sand	2	0
	Sand only	28	0

All values are presented as a percentage of the total number of emitters in each sub-plot
Notes:
1 Output less than 1 litre per hour
2 Output greater than 1 litre per hour
3 No sediments or microbial growths found
4 Algal mat on emitter exterior surface
5 Algal mat on emitter surface and sand grains found within labyrinth
6 Sand grains found in emitter internal labyrinth

Table 5.11 Prevalence of algal mats on emitter surfaces 1987
FE, filtered WSP effluent; UE, unfiltered WSP effluent;
FW, filtered potable water
(Emitter designs A, B, B', C and D)

		Week Number									
		1	2	3	4	5	6	7	8	9	10
A	FE	0	0	0	0	0	0	0	3.3	0	0
	UE	0	0	0	0	0	0	3.3	3.3	0	0
	FW	0	0	0	0	0	0	0	0	0	0
B	FE	0	0	0	0	0	1.7	1.7	1.7	1.7	3.3
	UE	0	0	0	0	0	0	1.7	1.7	1.7	1.7
	FW	0	0	0	0	0	0	0	0	0	0
B'	FE	0	0	0	0	0	0	0	0	0	0
	UE	0	0	0	0	0	0	0	0	0	0
	FW	0	0	0	0	0	0	0	0	0	0
C	FE	0	0	0	0	3.3	5	10	10	15	15
	UE	0	0	0	3.3	8.3	8.3	5	13.3	25	16.7
	FW	0	0	0	0	0	0	0	0	0	0
D	FE	0	0	0	0	0	0	0	0	0	0
	UE	0	0	0	0	0	0	0	0	0	0
	FW	0	0	0	0	0	0	0	0	0	0

All values are presented as a percentage of the total number of emitters in each sub-plot

Table 5.12 Prevalence of algal mats on emitter surfaces 1988
(Emitter designs A, B, C and C')

		Week Number												
		1	2	3	4	5	6	7	8	9	10	11	12	13
A	FE	0	0	0	0	0	0	0	0	0	0	0	3.3	0
	UE	0	0	0	0	0	0	0	0	0	0	0	0	0
	FW	0	0	0	0	0	0	0	0	0	0	0	0	0
B	FE	0	0	0	0	0	1.7	0	1.7	0	3.3	5	5	10
	UE	0	0	0	0	0	0	0	0	0	1.7	0	0	0
	FW	0	0	0	0	0	0	0	0	0	0	0	0	0
C	FE	0	0	0	3.3	5	3.3	5	6.7	6.7	6.7	13.3	8.3	8.3
	UE	0	0	0	1.7	5	10	8.3	13.3	16.7	23.3	25	25	35
	FW	0	0	0	0	0	0	0	0	0	0	0	0	0
C'	FE	0	0	0	0	0	0	0	0	0	0	0	0	0
	UE	0	0	0	0	0	0	0	0	0	0	0	0	0
	FW	0	0	0	0	0	0	0	0	0	0	0	0	0

All values are presented as a percentage of the total number of emitters in each sub-plot

Immediately after the 1988 irrigation season (ie., after ninety hours of irrigation) all emitters were removed to the laboratory for examination. Representative samples of irrigation laterals, clogged emitters and emitters covered with algal mats were dehydrated in freezing 90 percent ethanol and taken to Liverpool University for examination by scanning electron microscope.

The consistency of the algal mats was mucoid owing to the gelatinous sheaths and glycocalyces of the constituent organisms, which are able to retain moisture. Scanning electron microscopy revealed the structure and the biological composition of the mats on the external surfaces of the emitters but the desiccation process destroyed the extracellular mucilaginous material and therefore considerably reduced the volume of the mats.

Plate 5.8 shows the internal labyrinth of a Type C Emitter that had been used in combination with filtered WSP effluent. *In situ* only the central portion of this emitter part is exposed to sunlight. It can be seen that this central part is the only area colonised by algae. The rest of the water path is not exposed to sunlight and no colonisation of these parts by algae was recorded. As the internal labyrinth of this particular emitter did not become clogged by sand particles or any other material, the emitter continued to operate efficiently throughout the experimental period despite the presence of an algal mat at the outer orifice of the emitter.

Plate 5.9 shows the same algal mat at a higher power of magnification. At this scale the mat is seen to consist of a three dimensional matrix of filamentous microorganisms. At higher magnifications (Plates 5.10 and 5.11), the constituent organisms within the mat can be identified. The filamentous matrix is seen to comprise the cyanobacteria *Oscillatoria* and

Lyngbya, actively growing to produce an interlocking three dimensional web. The mat is therefore resistant to the shearing forces that could break-up the mat if the filaments grew in a unidirectional manner. Finer mycelia of actinomycetes are also present in addition to electron light strands that probably represent the remnants of the dehydrated glycocalyx destroyed during the fixation of the samples.

Within the matrix, several unicellular organisms can be seen. Diatoms (*Nitzschia* and *Navicula* spp.) were recorded in all algal mats examined, attached to the filamentous cyanobacteria. Other algal genera commonly found in the WSP were less commonly recorded on the algal mats. *Euglena* spp. were undetected in all electron micrographs and *Chlorella* spp., when observed, had usually lost their original structure and were undergoing decomposition.

Metazoan algal grazers were observed on most mat surfaces. The predominant organism was the rotifer *Monostyla*. Rotifers are ideally suited to the environment of the mat community: they are able to withstand long periods of desiccation and can feed and swim as soon as water becomes available. During periods of drought the rotifers contract in volume and in some cases the organism itself is destroyed but the eggs contained within it survive until moisture returns (Pearse and Buchsbaum, 1987).

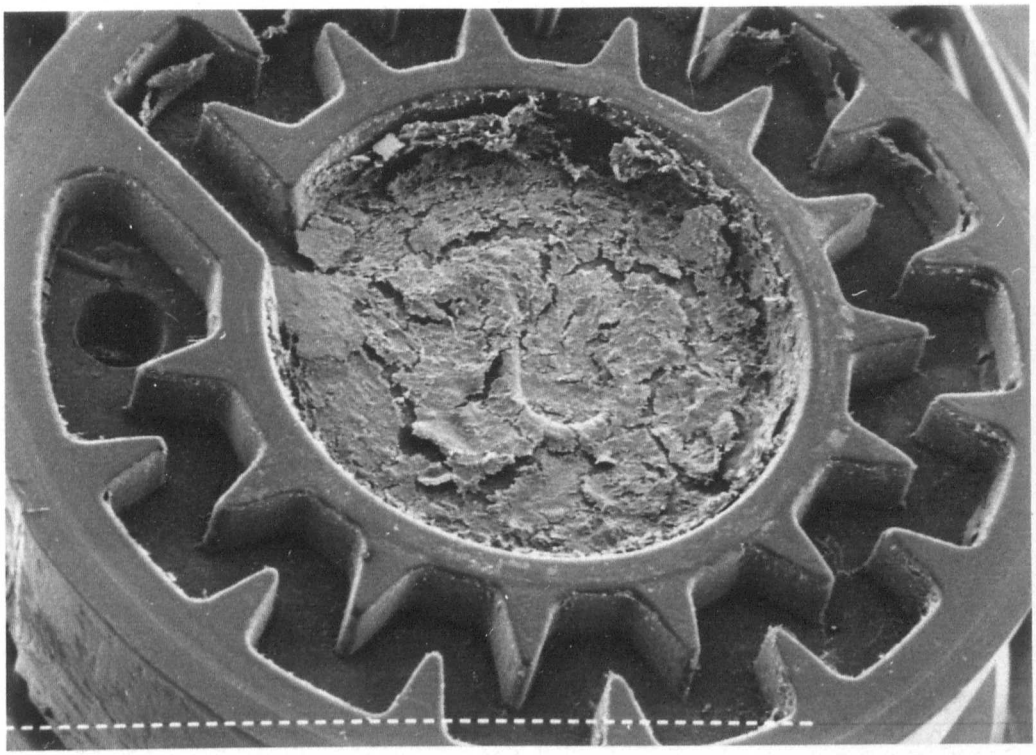


Plate 5.8 Scanning electron micrograph of the internal parts of a Type C Emitter colonised by a cyanobacterial mat. Scale: 1 bar = 100 μm.

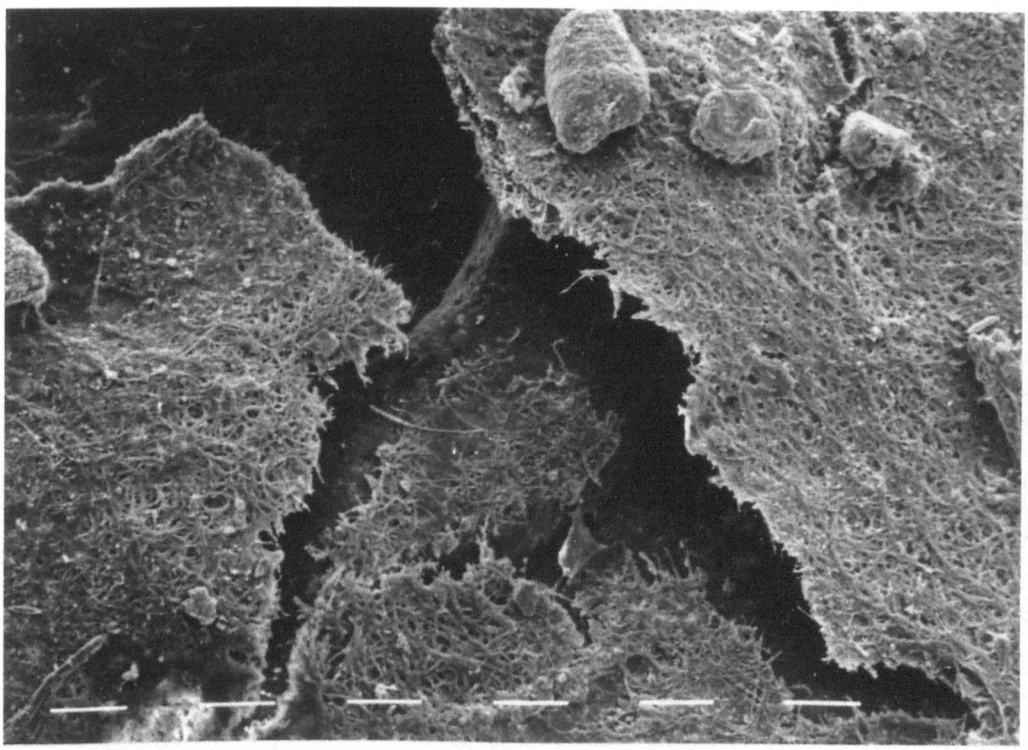


Plate 5.9 Pieces of cyanobacterial mat covering the external orifice of a Type C Emitter. Scale: 1 bar = 100 μm.

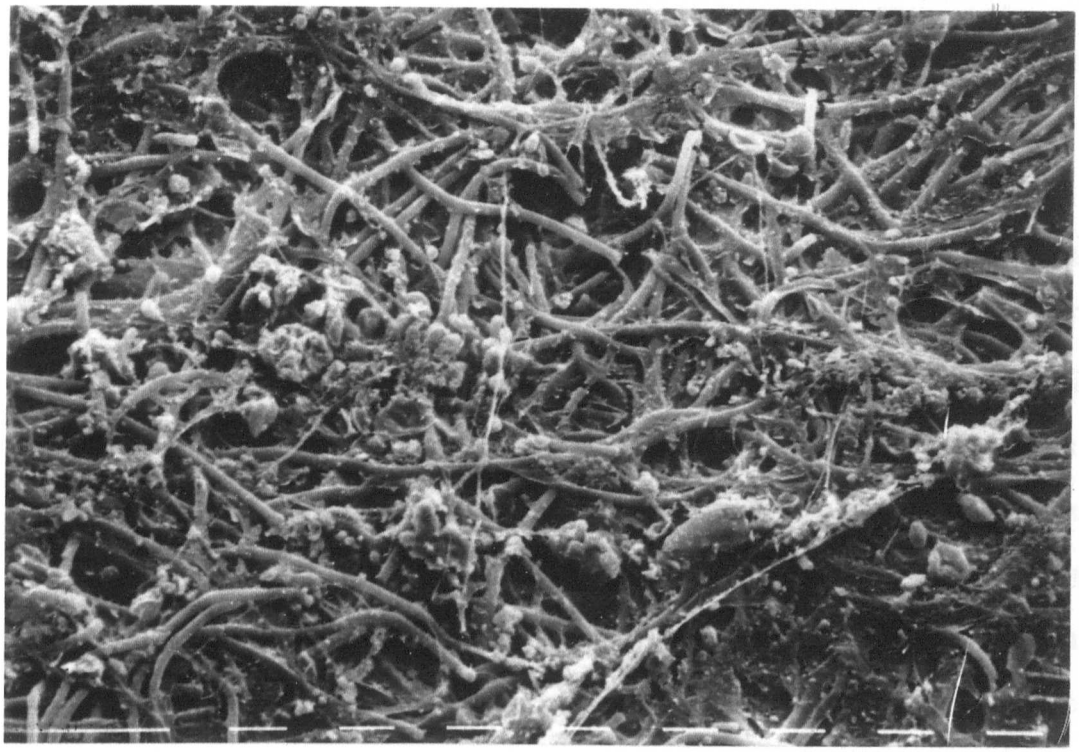


Plate 5.10 Scanning electron micrograph of a cyanobacterial mat on a Type C Emitter. Scale: 1 bar = 10 μm.

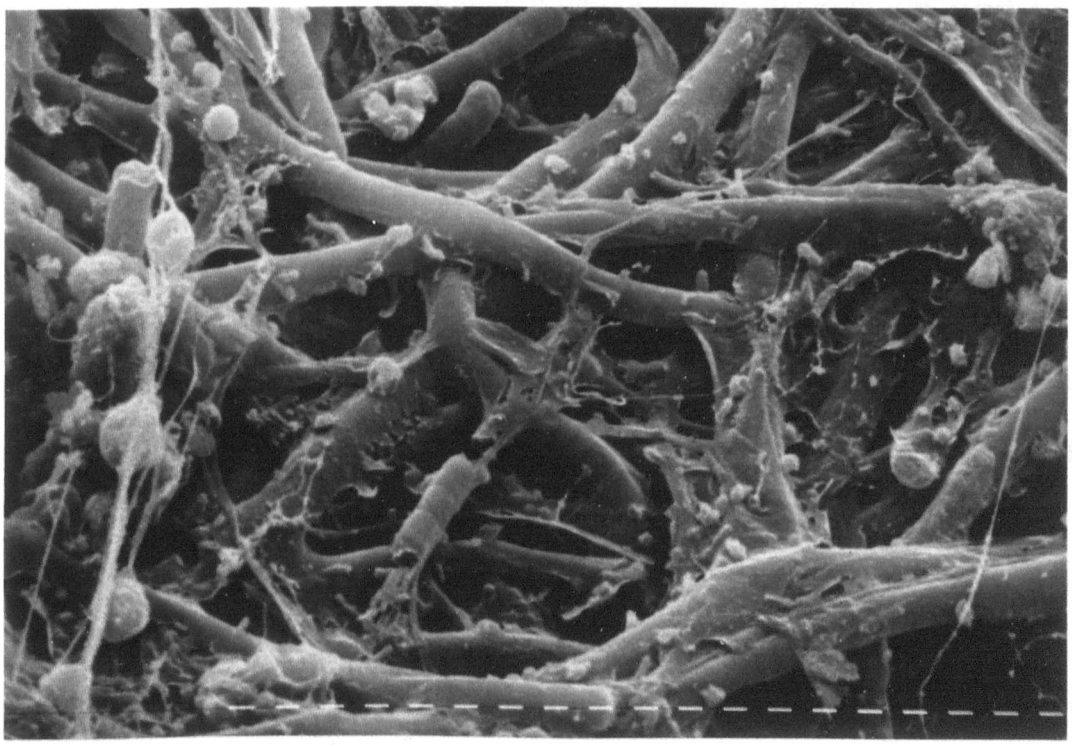


Plate 5.11 Scanning electron micrograph of a cyanobacterial mat on a Type C Emitter showing filaments of *Oscillatoria* and *Lyngbya* spp. Scale: 1 bar = 1 μm.

5.4 Algae and the Biofouling of Emitters in Greenhouse Irrigation Systems

Algae are reported to play a part in the clogging of drip irrigation emitters in greenhouse systems in the UK (Access Irrigation Ltd, pers. comm.). The water quality in such systems is generally good and is usually a combination of potable mains water and storm water run-off collected from the roofs of greenhouses and stored in uncovered reservoirs. The water supply is then filtered using either a simple screen or sand filter. In many of these systems plant nutrients are dissolved in the irrigation water so that plant growth and maturation can be more readily controlled. A similar result is achieved when nutrient-rich wastewaters are used for irrigation. The technique is sometimes referred to as "fertigation". The clogging problems that occur in greenhouse systems using fertigation were therefore studied in order to demonstrate the effect of dissolved nutrients on biofouling in the absence of particulate matter.

An initial survey of a Lancashire greenhouse revealed algal slimes on greenhouse floors which were dominated by diatoms. Occasionally, slimes dominated by filamentous green algae and filamentous cyanobacteria were observed on the external surfaces of emitters. Five UK greenhouse managers were interviewed during the course of this project. Three of these managers considered emitter clogging to be a major problem in their drip irrigation systems. Algae had played a role in the clogging of emitters at some stage in two of the five systems.

System A is a small family horticultural business known as White Knight Gardens in Bishopston, West Glamorgan. A variety of salad crops are grown under approximately two acres of glass. Emitter clogging is a considerable

problem and affects between 10 and 15 percent of all emitters per annum. The cause of clogging is invariably accumulated silt within the internal labyrinths of the emitters. The emitter design used in this system is easily opened and several hours of labour per week are spent renovating clogged emitters. The problem would probably be avoided by using sand filters rather than less efficient in-line screen filters. However, because the system is small, renovative work on the present system may make better economic sense than capital expenditure on new equipment. Algae are not considered to be a cause of emitter blockages in this system. Most of the nutrients for crop growth are obtained from a rich compost and the only nutrient added to the water is small amounts of potash at certain stages of the plants growth. This relative lack of nutrients in the irrigation water may explain why algae do not grow over the surfaces of emitters.

System B is The Copley Nursery, a small family business situated one kilometre from System A, in Murton, West Glamorgan. This greenhouse system contains 5,500 emitters under a covered area of approximately half an acre. Calcium nitrate and potassium nitrate are added to the irrigation water in varying proportions depending on the development stage of the tomato crop. All other nutrients are provided by a rich rooting compost. The main cause of clogging at this site is small shavings of polythene tubing that entered the system when it was first set up and which have never been adequately removed. However, clogging is a minor problem despite the lack of filtration equipment, affecting less than one percent of emitters. Microbial growth has never caused problems, probably because nitrogen is not added to the irrigation water.

System C is Church Farm in Banks, near Southport. The growing area covers two acres and contains 20,000 emitters. Emitter clogging is a greater problem at this site, affecting approximately ten percent of emitters during each growing season. The cause in most cases is thought to be precipitation of nutrient salts within the emitters. This problem is now successfully controlled by periodic flushing with nitric acid. Algal mats are observed on approximately 15 percent of emitters during July and August, but they are thought to reduce emitter discharge only very occasionally. Such reduction could also be explained by salt precipitation within the emitters rather than as a result of algal growth.

System D belongs to Van Heyningen Brothers Ltd., and is situated in Saint Mellons, South Glamorgan. This is the largest irrigation system to have been investigated and is the only one to still experience serious emitter clogging problems caused by microalgae. The present system has been operating for four years and contains approximately 190,000 emitters. Until recently, approximately 1 to 5 percent of emitters became clogged each year. The cause was seen to be the accumulation of a dark green "slime" on the external emitter orifices and over the pegs with which the emitters are attached to the rockwool root holders. In recent years, the problem has decreased. This decrease is thought to be a result of better maintenance of the emitters (eg., flushing with nitric acid between growing seasons). Although emitter blockages are no longer a major problem, algal slimes continue to be observed on up to 5 percent of emitters during each growing season. This is probably due to the high concentration of inorganic nutrients in the irrigation water, all plant nutrients being derived from this source. The problem could be tackled by dosing the water supply with sodium hypochlorite. In such a large scale system, chlorination may considerably reduce the labour costs associated with emitter renovation.

System E is owned by North West Growers at Hesketh Bank in Lancashire. Tomatoes have been grown here using drip irrigation for twenty five years. The site consists of approximately 13.5 acres of greenhouses. Chlorination of the irrigation water was introduced five years ago in order to combat the growth of algae on the surfaces of emitters. Algal growth affected up to 30 percent of emitters prior to the use of chlorination. Sodium hypochlorite is now added to the irrigation water in order to maintain a residual chlorine concentration of approximately 5 mg per litre: pH is maintained at approximately 6.5 by the addition of nitric acid. At this pH precipitation of dissolved salts is prevented and chlorine activity is maximised. Chlorination has effectively prevented the growth of algal mats on emitter surfaces.

In February 1988 a small greenhouse drip irrigation system was set up at the University of Liverpool Department of Botany. This system, which is described in detail in Chapter 2, consisted of one hundred of the emitter design most prone to colonization by an algal mat during the Portuguese field trials (Emitter C). An inorganic plant nutrient solution (Vitax Standard Foliar Feed) was added to mains potable water at a concentration of 400 milligrammes per litre, representing a total nitrogen concentration of 5.71 mM per litre (Table 5.14). Irrigation was carried out for one hour each day from 09.00 hrs. to 10.00 hrs. at an operating pressure of 1.5 kg cm-2 for sixty days. Emitters were punched into the irrigation laterals in a horizontal position so as to encourage "pooling" of irrigation water on the emitter surfaces. The results of this study are summarised in Table 5.15.

The system operated efficiently with no significant reduction in emitter discharge in any of the emitters during the experimental period. Pooling of irrigation waters occurred on all emitters and took approximately three hours to evaporate after each daily irrigation cycle. Within seven days visible precipitation of salts had occurred on 65 percent of emitters and within fourteen days all emitters were similarly affected. After twelve days the first algal mat was noted and consisted of a thin dark green film over the wetted portion of the emitter surface. After twenty two days, algal mats were recorded on 24 emitters (Table 5.15). The polythene sheeting below the emitters also became colonised by algae but no further algal mats developed within sixty days. On two of the colonised emitters the algal mats had developed over the surface of the emitter orifice but no significant differences in the discharge of colonised and uncolonised emitters were recorded.

After 60 days the colonised emitters were removed and their algal mats examined by light microscopy. The mat community was seen to be similar to those seen on emitters in the WSP effluent reuse experiments in Portugal and those from hydroponic greenhouse systems in the UK. The mats were dominated by filamentous green algae and cyanobacteria.

Table 5.13 Summary of emitter clogging problems in five UK greenhouses

System	A	B	C	D	E
Number of emitters	5,000	5,500	20, 000	190,000	130,000
Water source	Mains water	Mains water	Mains and stormwater	Mains and stormwater	Mains and stormwater
Chemical treatment	None	None	None	None	NaOCl
Added plant nutrients	KNO3*	KNO3 Ca (NO3)2*	KPO4 MgSO4 KNO3 Ca(NO3)2	KPO4 MgSO4 KNO3 Ca(NO3)2	KPO4 MgSO4 KNO3 Ca(NO3)2
Form of filtration	Screen	None	S/M	S/M	S/M
Percentage of emitters affected	10 - 15	0<1	10 - 15	1 - 5	0**
Cause of clogging	Silt	Plastic shavings, insects	Ppt. of salts	Algae	-

S/M Screen/media
* All other plant nutrients supplied by rooting compost
** Prior to chlorination of the irrigation water, approximately 30 percent of emitters were affected by algal growth

Table 5.14 Composition of plant nutrient solution used in small scale drip irrigation system (Liverpool, February - April 1988)

Component	Concentration (mg per litre)
Nitrogen	80
Water soluble phosphorus pentoxide	80
Potassium oxide	80
Magnesium	18
Manganese	6.8
Iron	13.2
Copper	1.7
Boron	3.2
Molybdenum	0.12

Plant feed was prepared by dilution of Standard Vitax Foliar Feed

Table 5.15 Prevalence of algal mats on emitter surfaces in a small scale drip irrigation system (Liverpool, February- April 1988)

Parameter	Time in Days						
	0	10	20	30	40	50	60
Precipitation	0	71	100	100	100	100	100
Algal mats	0	0	24	24	24	24	24
Mean output*	2.10	1.94	2.15	2.12	2.19	1.95	2.07
Clogged**	0	0	0	0	0	0	0

* Litres per hour

All other values presented as a percentage of all emitters

** Emitters discharging less than 1.00 litre per hour

5.5 Summary of Principal Conclusions

1. The development of biofilms on the external surfaces of drip irrigation emitters is a consequence of environmental factors that control the habitat and select those organisms able to survive in that habitat. Algal mats are dependent on the presence of sunlight, inorganic nutrients and moisture.

2. Algal mats are not dependent on the provision of an algal inoculum in the irrigation water. In WSP reuse experiments the biological composition of emitter mats was very different to the composition of grab samples of WSP effluent. The composition of algal mats on emitters supplied with WSP effluent and the composition of algal mats on emitters supplied with potable water augmented by inorganic plant nutrients were very similar. The most abundant planktonic algal genera present in the WSP effluent were not able to survive the desiccating conditions that exist on the external surfaces of emitters.

3. Algal mats were not shown to be responsible for reducing emitter discharge rates in WSP reuse studies. However, field experience in greenhouse irrigation systems showed that algal growth could present a clogging problem when sufficient nutrients were available in the irrigation water.

4. The growth of algal cells in emitter mats is not dependent on the provision of an algal inoculum in the irrigation water. If sufficient nutrients are available in the water supply, algal colonization from the soil and air will occur.

CHAPTER 6

6. DISCUSSION

Seasonal shortages of potable water in many arid and semi-arid regions of the world have necessitated the utilization of alternative water resources for irrigation. This practice reduces demand on potable water supplies and allows expansion of clean water provision to those who were previously without adequate supplies. In this way wastewater reuse for irrigation can result in an improvement in the health of many people in those developing countries with hot climates in which inadequate potable water provision is a major cause of disease transmission.

If the problems of biofouling can be minimised schemes, drip irrigation presents a practical way of reducing crop contamination by intestinal nematode eggs, bacteria and viruses in wastewater reuse systems. It is also a more efficient means of using available water resources than methods such as furrow and spray irrigation as losses from evaporation and run-off are reduced to a minimum.

The conclusions that can be drawn from this research project have ramifications for the future design of all drip irrigation systems. More specifically, they suggest how waste stabilization pond effluent can be utilized successfully for drip irrigation and they disprove certain misconceptions about the risks of emitter clogging in wastewater reuse irrigation.

Although contamination of the WSP reuse system by sand particles led to a higher degree of emitter clogging than would otherwise have occurred in a better maintained system, the conclusions from this study about the influence of emitter design and the role of microalgae in emitter fouling, increase our understanding of the mechanisms of emitter fouling and provide a theoretical basis for improving the design of drip irrigation systems. The clogging problems associated until now with the use of WSP effluent for drip irrigation can accordingly be reduced to a minimum.

The finding that sand particles were the predominant cause of blockages, both with WSP effluent and potable water, supports the findings of Adin and Sacks (1991), who found that inorganic particles were a more serious threat to the operation of drip irrigation systems that microbial films or chemical precipitates. From the field observations and laboratory analyses described in previous chapters, and drawing on results of other such studies, a model for the emitter fouling process can be deduced. Inorganic particles in the size range 360 μm to 1080 μm were the initial components of the emitter clogging mass. Their presence within the irrigation laterals led to their subsequent entrapment in the narrow channels of the emitter interiors. Entrapment of inorganic particles was followed by deposition of organic matter over their surfaces. This organic material therefore played an auxiliary role in emitter clogging: no examples of emitters in which organic matter alone had caused clogging were observed.

Simple screen filtration, while able to remove gross solids, did not significantly affect the mean level of suspended solids in the WSP effluent. Microalgae, particularly the unicellular forms common to all WSP, were able

to pass through both the screen filter and the emitters and consequently contributed to the fertilizing potential of the irrigation water. Media filtration of the WSP effluent, which would significantly reduce the concentration of microalgae, would not however solve the problem of particle agglomeration within the laterals.

Figure 6.1 is a schematic representation of the structure of the biofilm that formed within the irrigation laterals supplied with filtered or unfiltered WSP effluent. Between irrigation cycles irrigation water remained within the laterals and solids that had been held in suspension by hydraulic forces during irrigation were able to settle to the base of the polythene lateral. Heterotrophic bacteria utilized the nutrients released from decaying algae in the sedimented material to form a complex biofilm.

The composition of the biofilm was controlled by the nature of the habitat of the lateral interiors. Only those bacteria that were able to survive the high temperatures that occurred during the hottest part of the day would be able to contribute significantly to the development of the biofilm. Spatial and temporal differences in oxygen levels must also have affected the development of the biofilm: aerobic respiration rapidly decreased oxygen levels in the laterals following each irrigation cycle and therefore anaerobic processes such as sulphate reduction probably had an important effect on the habitat. However, the ecology of the lateral interiors was obviously far more complex than the limited data of this study could explain and within microhabitats the conditions may have existed for bacteria with differing nutritional requirements to grow.

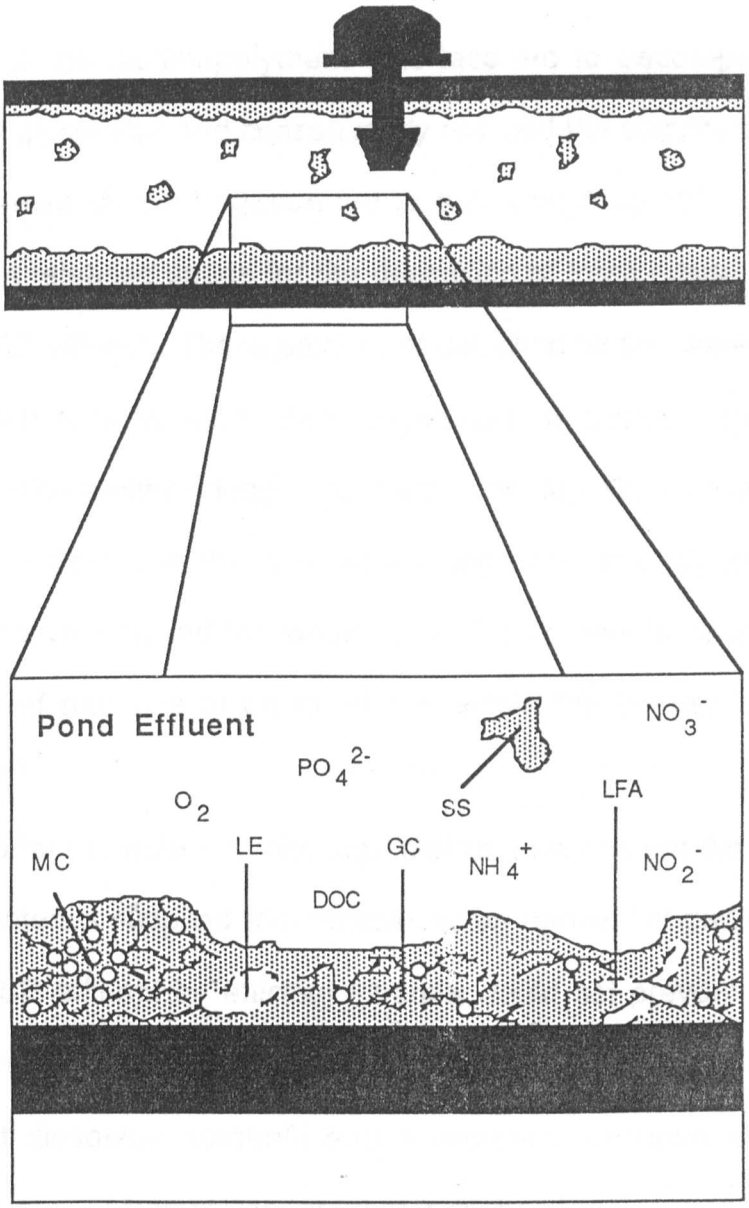


Figure 6.1 Schematic representation of the biofilm within irrigation laterals in a WSP reuse system. MC, bacterial microcolony; LE, lysing *Euglena*; GC, glycocalyx; SS, suspended solid.

It can be concluded from the field observations that the depth of the biofilm was controlled by a dynamic equilibrium. As the depth increased, organisms at the base of the biofilm became less able to obtain nutrients. Cell death at the biofilm/polythene interface led to decomposition of the extracellular glycocalyx and consequently reduced the stability of the biofilm. Hydraulic forces during irrigation led to the "sloughing-off" of patches of biofilm which released space for the deposition of fresh suspended material from the WSP effluent. These patches of detached biofilm were probably the major contributors to secondary deposition of organic matter on the inorganic particles within clogged emitters. The deposition of organic matter within the emitters and the subsequent regrowth of a glycocalyx at this location effectively sealed the water-path. This model is supported by the observation of particles of up to 10 mm within the laterals supplied with filtered WSP.

It is important to note that although biofilm development did not occur on emitters or laterals supplied with potable water, removal of particulate matter from the WSP effluent by efficient filtration would not prevent the eventual development of a biofilm because biofouling is dependent only on the provision of dissolved nutrients and a microbial inoculum able to utilize those nutrients. Attempts to prevent emitter clogging should therefore concentrate on a combination of measures including filtration, emitter design and field practices.

Filtration. Results of the reuse field trials suggest that removal of the phytoplankton in WSP effluents is not required in order to prevent emitter clogging. The conclusion that the development of cyanobacterial mats on

the surface of emitters was a consequence of the invasion of a nutrient-rich, wet and illuminated environment by organisms present in the soil, contradicted a prevailing view that such films are the result of WSP microalgae accumulating on the emitter surface. Media filtration would increase capital and operational costs and by removing a significant proportion of algal cells would decrease the fertilizing capacity of the effluent. Screen filters should therefore be installed and properly maintained so as to prevent the entry of gross solids including sand particles into the irrigation system.

Emitter design. The mechanisms which are used in many emitter designs to reduce and control the flow of water are usually those which also accentuate the emitter clogging problem. However, recent innovations in emitter design including the development of bubbler emitters and self-flushing designs may reduce emitter clogging problems.

Field practice. Care must be taken when designing and setting up any drip irrigation system to prevent intrusion of particulate matter into the irrigation laterals. The inclusion of soil particles, when joining sections of mainline and lateral tubing, will negate the effect of filtration and lead to clogging problems that will prove costly to resolve. It is also important that *all* sources of water entering the irrigation network undergo basic screen filtration to prevent accidental contamination of the entire system. Flushing out all laterals before each irrigation cycle is a simple procedure that would remove the aggregates formed by the sloughing-off of any biofilm within the laterals.

APPENDIX

Meteorological Data

Évora 1986

	Temp. (°C) Min.	Max.	Mean	Ppt. (mm) Total	Hrs. Sun. Mean Daily	Evap. (mm) Total
June	13.6	27.3	20.5	2.5	11.44	240.3
July	17.0	32.2	24.6	0.0	11.57	334.9
Aug.	14.8	28.5	21.7	0.8	10.77	254.1
Sep.	16.5	26.0	21.3	68.6	6.60	160.8
Oct.	13.7	23.0	18.4	39.7	6.77	107.3
Nov.	9.2	17.6	13.4	44.5	6.14	83.6

Data from the Instituto Nacional de Meteorologia e Geofísica, Évora Station

Santo André 1987

	Temp. (°C) Min.	Max.	Ppt. (mm) Total	Hrs. Sun. Mean Daily
June	10.7	27.6	0.4	10.22
July	14.5	32.0	2.4	NA
Aug.	13.0	33.5	16.0	8.88
Sep.	14.5	35.5	27.0	8.37
Oct.	9.0	22.5	164.6	4.02

Data from the Instituto Nacional de Meteorologia e Geofísica, Monte Chãos Station

Santo André 1988

	Temp. (°C) Min.	Max.	Mean	Ppt. (mm) Total	Hrs. Sun. Mean Daily
June	12.0	25.1	18.4	26.4	7.83
July	13.4	28.7	19.1	29.0	10.91
Aug.	11.0	29.4	18.7	0.0	10.54
Sep.	NA	NA	19.7	0.0	NA

Data from the Instituto Nacional de Meteorologia e Geofísica, Monte Chãos Station
NA Data not available

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