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Some effects of land treatment/disposal of New Zealand meat processing plant effluent on soil properties

A thesis

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Abstract

Meat processing plant effluent is a high-strength effluent comprising mainly organic materials including blood and fat. It is highly variable and often has high levels of suspended solids, biological oxygen demand, chemical oxygen demand, N and P. There is an increasing trend towards irrigation onto land for treatment and disposal of meat processing plant effluent.

Perpetuation of a meat processing plant effluent irrigation scheme is dependent on maintaining adequate soil permeability on the land treatment area. A decline in soil permeability has been observed at a number of New Zealand meat processing plant effluent irrigation sites. If surface ponding of effluent and anaerobic conditions become widespread then odour and trafficability problems may become severe and it may become impossible to dispose of effluent without runoff. The main objectives of this thesis were to describe the occurrence and determine the mechanisms that lead to a decline in soil permeability at meat processing plant effluent irrigation sites.

A reconnaissance survey of nine New Zealand meat processing plant effluent irrigation sites, from the King Country to Southland, was undertaken. At most sites, areas of soil surface crust development and effluent surface ponding were observed in topographic hollows and/or at the top ends of borders (where border dyke irrigation was practised). Surface crusting was associated with a build up in organic material, a decrease in soil bulk density and a decrease in infiltration rates. However, the survey demonstrated that land application of meat processing plant effluent was generally an effective means of dealing with large volumes of effluent. No long-term detrimental effects were identified, with surface crust development being regarded as a short-term problem that could be remedied, although sometimes at considerable cost to an effluent irrigation scheme operation.

Laboratory and field experiments were designed to investigate the cause of soil permeability decline. A factorial laboratory experiment examined the effect of effluent type, volume of effluent added, soil type, time between effluent applications, temperature and rainfall on a range of soil and leachate properties. All of the factors tested had some impact on the soil or leachate properties that were monitored. However, effluent type and volume, and temperature, were the most important factors. High volumes of primary and untreated effluent caused the largest decline in soil permeability and were also associated with surface coat development. Soil permeability decreased more at 10 °C than at 25 °C and recovered more quickly at the warmer temperature. At 25°C soil drying and cracking led to increased macropore flow and a decrease in the effectiveness of effluent treatment.

A field experiment was undertaken to compare the infiltration rates of untreated, primary treated, and anaerobically treated meat processing plant effluent with that of water. The infiltration rates of primary and untreated effluents declined faster than the infiltration rates of water or anaerobically treated effluent. The decrease in infiltration rate of primary and untreated effluents was attributed to physical pore

blockage by the suspended solids in the effluent. A significant linear relationship ($r = 0.97$) was determined between infiltration rate and total cumulative suspended solids added. The linear relationship fits the model of Berend (1967), the coefficients of which were determined for primary and untreated meat processing plant effluent. Berend's model was shown to have potential for use as a predictive tool to determine decline in infiltration rate as a function of effluent suspended solids content.

To determine the magnitude of soil permeability loss and the rate of recovery, following effluent application, a laboratory experiment was carried out at 25 °C and 13 °C, using repacked soil cores. At 25 °C soil core permeability dropped by a mean of 70 % four days after effluent application, but recovered back to the initial level after 23 days. At 13 °C soil core permeability dropped by a mean of 50 % four days after effluent application, and took over 50 days to recover. It was concluded that the time taken for soil permeability to recover following application of large doses (200 mm) of primary treated meat processing plant effluent will be considerably longer in winter (approximately six weeks) than in summer (less than three weeks).

Samples from effluent and water treated cores stored at 13 °C and at 25 °C, along with samples from field sites where meat processing plant effluent was regularly irrigated, were examined using a scanning electron microscope. There was a strong microbial response to addition of primary treated meat processing plant effluent to soils which resulted in formation of a semi-continuous coat on the soil surface. The surface coat developed under both field and laboratory conditions and formed and decomposed more quickly under warm moist conditions, taking 2 to 3 times longer to develop at 13 °C than at 25 °C. When allowed to dry out the coat did not decompose readily. A strongly developed continuous soil surface coat was present in areas where effluent had ponded in paddocks and was also present in areas where water ponding occurred, such as adjacent to water troughs.

It was concluded that the decline in soil permeability observed as a result of application of New Zealand meat processing plant effluents, at the sites investigated, was caused by development of a soil surface coat which was formed from both, the suspended solids from the effluent, and, the microbial materials that develop in response to effluent application. The implications for management of soils receiving meat processing plant effluent are discussed.

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Dedication

*I would like to dedicate this thesis to my grandmother,
Joan Bavenwood.*

*She is a lady of intelligence and generosity who has
supported us through all the years of our education. She
provides an example of unselfishness and non-materialism
that we all benefit from.*

M.B.B. April 1995

Inspiration

*"The source and final resting place of everything that grows,
soil thus inspires reverence not only in the peasant who derives
his daily bread from it, but also in the scientist who
contemplates its meaning as the place where life and death meet
and exchange vital energies."*

D.J. Hillel

Table of contents

Abstract	iii
Acknowledgements	v
Dedication	vi
Table of Contents	vii
List of Tables	xi
List of Figures	xiii
List of Abbreviations	xvi
 Chapter 1 Introduction	 1
1.1 Effluent disposal and the New Zealand meat industry	1
1.2 Objectives of this study	3
 Chapter 2 Literature Review	 5
2.1 Introduction	5
2.2 Meat processing plant effluent	5
2.2.1 Effluent sources	5
2.2.2 Effluent Treatment	6
2.3 Soil properties and processes that are important for effluent treatment and disposal	9
2.3.1 Introduction	9
2.3.2 Soil water movement	10
2.3.3 Soil chemical properties	13
2.3.4 Soil biological activity	16
2.4 Methods of land treatment/disposal of effluent and their effectiveness	20
2.4.1 Introduction	20
2.4.2 Overland flow	24
2.4.3 Irrigation	26
2.4.4 Rapid infiltration	29
2.4.5 Disease control	31
2.5 The effects of effluent on soil physical properties	32
2.5.1 Soil permeability	32
2.5.1.1 Introduction	32
2.5.1.2 Physical blockage of soil pores	36

2.5.1.3 Biological blockage of soil pores	40
2.5.1.4 Chemical blockage of soil pores	42
2.5.2 Aggregate stability	43
2.5.3 Bulk density	44
2.5.4 Other soil physical properties	45
2.6 The effects of effluent on soil chemical properties	45
2.7 Response of plants to effluent application	47
2.8 Design and management of land waste treatment systems	48
2.8.1 Introduction	48
2.8.2 Effluent loading rates	48
2.8.3 Effluent application rates	49
2.8.4 Rest periods	51
2.8.5 Site management and monitoring requirements	52
2.9 Conclusions	53
Chapter 3 Methods	55
3.1 Introduction	55
3.2 Soil profile descriptions	55
3.3 Soil physical properties	55
3.3.1 Soil hydraulic conductivity	55
3.3.1.1 Laboratory method	55
3.3.1.2 Field methods	56
3.3.2 Bulk density	60
3.3.3 Aggregate stability	60
3.3.4 Particle size distribution	61
3.3.5 Moisture retention	61
3.4 Soil chemical properties	61
3.5 Effluent total and suspended solids	62
3.6 Core preparation	63
3.7 Statistical analysis	63
Chapter 4 Survey of land effluent-treatment sites at meat processing plants in New Zealand	65
4.1 Introduction	65

4.2	Survey methodology	66
4.3	Brief history of effluent disposal at sites visited	67
4.4	Effluent treatment and irrigation scheme management practices	69
4.4.1	Effluent sources, pretreatment and volumes	69
4.4.2	Effluent properties at sites visited	70
4.4.3	Management of effluent irrigation schemes	71
4.5	Effects of effluent on soils	73
4.5.1	Pedological observations	73
4.5.2	Earthworm populations	73
4.5.3	Soil hydraulic conductivity	75
4.5.4	Soil bulk density	77
4.5.5	Surface crusting and ponding	78
4.5.6	Soil chemical properties	82
4.5.7	Other observations	82
4.6	Discussion	84
4.7	Conclusion	86
Chapter 5 Factorial trial to investigate the impact of effluent, soil and climate variables on selected soil properties		87
5.1	Introduction	87
5.2	Experimental design and methodology	89
5.2.1	Experiment design and variable selection	89
5.2.2	Experiment methodology and data analysis	91
5.2.3	Properties of added effluent	92
5.3	Results	93
5.3.1	Core hydraulic conductivity	93
5.3.2	Soil analysis	96
5.3.2.1	Soil bulk density	96
5.3.2.2	Soil pH	96
5.3.2.3	Soil electrical conductivity	97
5.3.2.4	Soil carbon	98
5.3.2.5	Soil aggregate stability	99
5.3.2.6	Soil surface coatings	99
5.3.3	Effluent treatment	104
5.4	Discussion	108

5.5	Conclusions	112
Chapter 6 Comparison between water and effluent infiltration rates		
	- a field trial	113
6.1	Introduction	113
6.2	Experimental design and methodology	116
6.3	Results	118
6.4	Model application	120
6.5	Discussion	124
6.6	Conclusion	125
Chapter 7 Recovery of soil permeability following effluent application		
	7.1 Introduction	127
	7.2 Experimental design and methodology	127
	7.2.1 Trial conducted at 25 °C	127
	7.2.2 Trial conducted at 13 °C	128
	7.2.3 Effluent properties	128
	7.3 Results	129
	7.3.1 Rate of recovery for soils stored at 25 °C	129
	7.3.2 Rate of recovery for soils stored at 13 °C	130
	7.4 Discussion	131
	7.5 Conclusion	132
Chapter 8 Investigation of the biological response to effluent addition using a scanning electron microscope		
	8.1 Introduction	133
	8.2 Sample selection and preparation	133
	8.3 Results	135
	8.3.1 Soil cores stored at 13 °C	135
	8.3.2 Soil cores stored at 25 °C	147

8.3.3 Samples from existing meat processing plant effluent irrigation sites	153
8.4 Discussion	162
8.5 Conclusion	164
Chapter 9 Discussion, recommendations and conclusions	165
9.1 Overview and synthesis of results	165
9.1.1 Introduction	165
9.1.2 Effects of irrigation of meat processing plant effluent at existing New Zealand sites	165
9.1.3 Causes of soil permeability decline	167
9.1.4 Predicting permeability decline as a function of addition of suspended solids	169
9.1.5 Recovery of permeability	171
9.2 Recommendations for effluent irrigation scheme design and management	172
9.3 Conclusions	174
9.4 Recommendations for future research	175
 List of Appendices	
1. Data for Chapter 4	177
2. Data for Chapter 5	201
3. Data for Chapter 6	219
4. Data for Chapter 7	223
 References	227
 List of Tables	
2.1 Characteristics of primary treated meat processing plant effluent	8
2.2 Characteristics of anaerobically and aerobically treated meat processing plant effluent	9
2.3 Site and soil characteristics and suitability for irrigation treatment of effluent	10
2.4 Summary of commonly used land treatment/disposal systems	22
2.5 Effectiveness of different application methods in removing components of effluent	23

2.6	Estimated maximum hydraulic application rates for land application of effluent	51
3.1	Soil permeability classes	57
4.1	Meat processing plants included in this survey	65
4.2	Effluent irrigation scheme duration and irrigation method for sites visited	68
4.3	Effluent sources, treatment, volumes and land area under effluent irrigation	70
4.4	Effluent properties for sites visited	71
4.5	Land use, stock with-holding times and irrigation return period for sites visited	72
4.6	Saturated hydraulic conductivities for effluent irrigated areas and areas that do not receive effluent	75
4.7	Soil bulk densities for sites that are effluent irrigated and sites that do not receive effluent	78
4.8	Change in selected effluent properties with distance along border	83
5.1	Factors that may influence soil permeability decline following effluent addition	89
5.2	Depth of effluent applied to cores at each irrigation (mm)	91
5.3	Selected properties of effluents used in factorial trial	93
5.4	Table of means for percent change in K_{sat} for cores, measured two days after effluent application ceased	94
5.5	Table of means for percent change in K_{sat} for cores measured thirteen days after effluent application ceased	95
5.6	Table of means for soil $pH_{(H_2O)}$ measured at the conclusion of the experiment	97
5.7	Table of means for soil electrical conductivity measured at the conclusion of the experiment	98
5.8	Table of means for soil carbon (%) measured at the conclusion of the experiment	99
5.9	Table of means for soil surface coat ratings two days after effluent application ceased	101
5.10	Table of means for soil surface coat ratings thirteen days after effluent application ceased	102
5.11	Table of means for soil surface coat ratings thirty-five days after effluent application ceased	102
5.12	Mean values of properties of core leachates compared to applied effluent	104
5.13	Table of means for core leachate pH	106
5.14	Table of means for core leachate electrical conductivity	107
5.15	Table of means for core leachate total solids content	108
5.16	Summary of impacts of experiment factors on variables tested . . .	109
6.1	Particle size distribution of primary treated effluents	114
6.2	Properties of water and effluent used in effluent infiltration trial . .	116
6.3	Summary of regression analysis of infiltration rate, i , versus	

	cumulative water added and cumulative suspended solids added .	123
7.1	Selected properties of the primary treated meat processing plant effluents used in permeability recovery experiments	128
9.1	Total cumulative solids, and depth of water required to halve effluent infiltration rates for a range of initial infiltration rates and suspended solids contents	170
A1.1	Soil permeability estimates and K_{40} measurements, Fairton	178
A1.2	Soil chemical data, Fairton	179
A1.3	Soil permeability estimates and K_{40} measurements, - Kaiapoi . . .	184
A1.4	Soil permeability estimates - Lorneville	187
A1.5	Soil chemical data - Lorneville	187
A1.6	Soil permeability estimates and K_{40} measurements - Makerewa . .	191
A1.7	Soil chemical data - Makerewa	191
A1.8	Soil permeability estimates - Taumarunui	197
A1.9	Soil chemical data - Taumarunui	197
A1.10	Soil permeability estimates and K_{40} measurements - Wakanui . .	199
A1.11	Soil chemical data - Wakanui	199
A2.1	Factorial trial design	201
A2.2	Core permeability data	202
A2.3	Core soil properties at conclusion of experiment	203
A2.4	Effluent leachate data	204
A2.5	Statistical analysis of soil permeability measurements	205
A2.6	Statistical analysis of soil properties measured at the conclusion of the experiment	207
A2.7	Statistical analysis of core leachate	216
A3.1	Moisture retention data for soil cores	220
A3.2	Infiltration data for effluent infiltration trial (Chapter 6)	221
A4.1	Data for core recovery trial, 25 degree C	223
A4.2	Normalised data for core recovery trial, 25 degree C	224
A4.3	Data for core recovery trial, 13 degrees C	225
A4.4	Normalised data for core recovery trial, 13 degrees C	226

List of Figures

2.1	Relationship between hydraulic conductivity and suction for a clay soil and a sandy loam	13
2.2	Equilibrium between exchangeable and solution cations	14
2.3	Overland flow of sewage effluent at an experimental site at Levin, New Zealand	24
2.4	Irrigation of a vegetable processing plant effluent using a travelling irrigator, Canterbury, New Zealand	27
2.5	Border dyke irrigation of meat processing plant effluent, Hawkes Bay, New Zealand	27
2.6	Rapid infiltration beds for sewage effluent treatment, Pauanui, New Zealand	30

2.7	Changes in permeability of soil under continuous inundation	35
3.1	Constant head method for measuring permeability	56
3.2	Disk permeameter for measuring saturated hydraulic conductivity .	58
4.1	Location of meat processing plant effluent disposal sites included in this survey	66
4.2	Surface crusting and ponding in a topographic hollow	79
4.3	Surface crusting and ponding at the top end of a border	79
4.4	Surface crust material at the Kaiapoi site, six months after effluent irrigation had ceased	80
4.5	Surface crusting as a result of irrigation of effluent with a high suspended solids concentration	81
4.6	Algae on the margin of an effluent ponded area	81
5.1	Effects of effluent on soil physical properties	87
5.2	Changes in core coatings with time	103
5.3	Photographs of effluent before and after flow through cores	105
6.1	Soil pore size distribution of a range of soils	114
6.2	Field equipment for comparison of water and effluent infiltration rates	117
6.3	Comparison between water and effluent infiltration rates	118
6.4	Ratio of effluent infiltration rate/water infiltration rate versus time	119
6.5	Regression analysis for i vs cumulative water infiltration	121
6.6	Regression analysis for i vs cumulative suspended solids infiltration	122
7.1	Percent change in permeability of cores treated with effluent or water, stored at 25 °C	129
7.2	Percent change in permeability of cores treated with effluent or water, stored at 13 °C	130
8.1	SEM photographs of the soil surface of water-treated soils stored at 13°C. Day 0 (a and b), 11 (c and d) and 63 (e and f) and a testate amoeba (g)	137
8.2	SEM photographs of the soil surface of water-treated soils stored at 13°C. Day 135 (a,b,c and d), and 155 (e,f and g)	138
8.3	SEM photographs of the soil surface of effluent-treated soils stored at 13°C. Day 4 (a and b), 7 (c and d) and 11 (e, f and g)	139
8.4	SEM photographs of the soil surface of effluent-treated soils stored at 13°C. Day 21 (a,b,c,d,e and f), and fat from core edge, day 63	140
8.5	SEM photographs of the soil surface of effluent-treated soils stored at 13°C. Day 28 (a, b and c), and 35 (d, e, f and g)	141
8.6	SEM photographs of the soil surface of effluent-treated soils stored at 13°C. Day 63	142
8.7	SEM photographs of the soil surface of effluent-treated soils stored at 13°C. Day 80	144
8.8	SEM photographs of the soil surface of effluent-treated soils stored at 13°C. Days; 98 (a, b and c), 135 (d and e) and 155 (f and g) .	145
8.9	SEM photographs of effluent-treated soils, 1 - 5 mm below the soil surface, stored at 13°C. Days; 0 (a and b), 11 (c, d and e) and	

	63 (f and g)	146
8.10	SEM photographs of the soil surface of effluent-treated soils stored at 25°C. Day; 1 (a, b and c), 8 (d, e and f) and 10 (g)	148
8.11	SEM photographs of the soil surface of effluent-treated soils stored at 25°C. Day; 16 (a, b and c), and 23 (d, e, f and g)	149
8.12	SEM photographs of the soil surface of effluent-treated soils stored at 25°C. Day; 30 (a and b), 44 (c and d) and 44 with water added at day 37 (e, f and g)	150
8.13	SEM photographs of the soil sub-surface of effluent-treated soils stored at 25°C. Day; 1 (a and b), 8 (c and d), 16 (e and f) and 38 (g)	151
8.14	SEM photographs of the soil surface of water-treated soils stored at 25°C. Day; 10 (a and b), and 8 (c and d)	152
8.15	SEM photographs water-irrigated soils from Wakanui soil surface (a, b and f), and subsurface (c), and non-irrigated soil surface from Taumarunui (d, e, and g)	155
8.16	SEM photographs of the soil surface (a, b, c, d and e), and subsurface (f and g) of low ridges in effluent irrigated paddocks at Wakanui	156
8.17	SEM photographs of a ponded area of an effluent-irrigated paddock at Wakanui. Pond surface (a, b, c and d), and 1 mm (e), 2 mm (f) and 4 mm (g) below the pond surface	157
8.18	SEM photographs of the soil surface (a, b, c, d, and e), and 1 cm depth (f and g) from Taumarunui. The site was being irrigated with effluent during sampling	158
8.19	SEM photographs of the soil surface of effluent-irrigated Taumarunui soils 2.5 weeks (a, b and c), and 4 weeks (d and e) after effluent application and soil sub-surface 2.5 weeks after irrigation (f and g)	159
8.20	SEM photographs of an effluent ponded soil surface (a, b, c, d and e), and 1 cm below the surface (f and g) from Taumarunui	160
8.21	SEM photographs of non-effluent-irrigated ponded soil adjacent to a water trough, Taumarunui. Soil surface (a, b, c, d and e), and 1 cm depth (f and g)	161

List of abbreviations, with some definitions, of selected terms used in this thesis

A	anaerobically treated effluent
%BS	base saturation expressed as a percentage
ρ_d	soil dry bulk density
ρ_w	density of water
BOD	biological oxygen demand. The quantity of dissolved oxygen required for the stabilisation of decomposable organic matter by aerobic biochemical action (usually measured over 5 days at 20°C)
cm	centimetre
CEC	cation exchange capacity
COD	chemical oxygen demand. A measure of the quantity of oxidisable compounds present in H ₂ O.
d	day
EC	electrical conductivity
ESP	exchangeable sodium percent = $100 \times \text{exchangeable Na} / \text{CEC}$
F	primary treated plus fellmongery effluent
h	hour
ha	hectare
i	infiltration rate
I	cumulative infiltration
K_{40}	hydraulic conductivity at 40 mm suction
K_{sat}	saturated hydraulic conductivity
ΔK_{sat}	percent change in core permeability
l	litres
m	metre
MBE	mean in core permeabilities measured before effluent application
mg	milligram
nd	not determined
NH ₃ -N	ammonia nitrogen
NO ₂ -N	nitrite nitrogen
NO ₃ -N	nitrate nitrogen
NZ	New Zealand
P	primary treated effluent
RMA	Resource Management Act 1991
S	sorptivity
SAR	sodium adsorption ratio: = $[\text{Na}^+] / [\text{Ca}^{2+} + \text{Mg}^{2+}]^{0.5}$ where concentrations are expressed in millimoles per litre
SD	standard deviation
SEM	scanning electron microscope
SS	total suspended solids
TEB	total exchangeable bases
TkN	total kjedahl extractable nitrogen
TOC	total organic carbon
TS	total solids

TS total solids
USEPA United States Environmental Protection Agency
USDA United States Department of Agriculture
VS volatile solids
W water
 μm micro metre
 μS micro sieman
 θ volumetric water content

Chapter 1: Introduction

1.1 Effluent disposal and the New Zealand meat industry

The New Zealand meat industry produces over a million tonnes of meat every year. For the year ended September 1993; 29.7 million sheep and lambs, 2.2 million adult cattle and 1.6 million calves and pigs were processed in New Zealand meat processing plants (New Zealand Official Yearbook, 1994). The meat industry is New Zealand's largest export industry, bringing an income to New Zealand of \$ 3 057.5 million in the year ended June 1993 (New Zealand Official Yearbook, 1994).

Meat processing generates large volumes of effluent concentrated at a relatively small number of sites. Each of the major meat processing plants in New Zealand contributes a pollution load equivalent to a city of 60 000 - 100 000 population (Cooper *et al.* 1979). Therefore the combined effluent from the New Zealand meat industry has, after primary treatment, a pollution load equivalent to that produced by the (human) population of New Zealand (Cooper *et al.* 1979, Cooper and Russell 1982). Hence the pollution potential of the meat industry is greater than that of the New Zealand domestic sector.

When New Zealand first established meat processing plants, untreated effluents were usually discharged directly to the nearest waterway - either a river or the sea. An exception was the Fairton plant in Canterbury which has been disposing of effluent by flood irrigation to pasture since 1899 (Keeley and Quin 1979). As public awareness of water pollution has increased, and laws controlling effluent discharge have become established, there has been a corresponding increase in the level of effluent treatment prior to discharge.

Land disposal of effluent represents an important option for the New Zealand meat industry. Suitable land areas are often available and wastewater irrigation avoids discharge of treated effluent directly to waterways. Construction and operating costs are often similar to other treatment options and there is an economic return in the form of livestock or crops from the treatment site (Russell and Cooper 1987).

Since implementation of the Resource Management Act, 1991 (RMA), it has become necessary to avoid, remedy or mitigate adverse effects on the environment (RMA, Section 5(2)(c)) and also to consider obligations under the Treaty of Waitangi (RMA Section 8). All forms of pollution entering natural water, irrespective of degree of treatment, are perceived as being offensive to Maori cultural and spiritual values (O'Regan 1984) whereas returning wastes to the earth is seen to protect the life-force of waterways and the mana of those who use them. Land disposal of effluent is, therefore, a means of effluent treatment that is acceptable in terms of tikanga Maori. Recognition of Maori concerns, along with increased environmental awareness, has led to increasing support for land disposal of effluents.

Application of wastes at rates which supply sufficient nutrients to replenish crop nutrient uptake has been advocated (Giffney 1984, Vanderholm 1984, O'Connor *et al.* 1991). For typical agricultural wastes, the nutrient load usually requires a sufficiently large area that the hydraulic load becomes a minor problem, as long as the application rate is kept lower than the soil's saturated infiltration rate (Giffney 1984). However, at many meat processing plant sites, effluents are applied at a rate that is much greater than that required to replenish crop nutrients, with disposal of effluent being the primary objective. At many sites, the cost of effluent application dictates that the effluent should be applied over the smallest area possible.

It is generally accepted that management of effluent loading rates and irrigation return periods are often based mainly on trial and error, as there is a lack of information available to accurately plan site-specific systems. At a number of New Zealand meat processing plant effluent irrigation sites, initial estimates of effluent loading rates have proved to be inadequate, resulting in surface ponding, anaerobic conditions and unpleasant odours. For example, effluent irrigation at the Kaiapoi meat processing plant, in Canterbury, had to be stopped after only 8 months in operation (in June 1989), due to excessive effluent ponding on the soil surface. The Kaiapoi effluent irrigation scheme was designed using some of the best available expertise and implemented using modern irrigation equipment. Problems such as those experienced at Kaiapoi can be very costly for the meat processing plant involved, potentially causing plant shut-down or damage to nearby surface waters if surface runoff or direct discharge of effluent occurs. The research in this thesis seeks to improve

understanding of some of the problems that have occurred and thus, contribute to their prevention in the future.

1.2 Objectives of this study

The objectives of this study are to:

1. determine changes in selected soil properties that have occurred, as a result of effluent irrigation, on existing New Zealand meat processing plant effluent irrigation sites;
2. identify the factors that contribute to a decline in soil permeability on New Zealand meat processing plant effluent irrigation sites; and
3. interpret the results to provide recommendations for design and management of meat processing plant effluent irrigation sites so that adverse effects of effluent irrigation on soil permeability can be prevented.

Chapter 2: Literature review

2.1 Introduction

This chapter reviews the information available on the properties, and methods of treatment and disposal, of meat processing plant effluent. The commonly recognised methods of land waste treatment and disposal are described and the interactions between soil and effluent are discussed. The effects of effluent on soil physical properties are reviewed in detail, especially in relation to soil permeability. Site management, particularly with regard to application rates, loading rates, and rest periods, is also reviewed.

2.2 Meat processing plant effluent

2.2.1 Effluent sources

The processes that are undertaken within a meat processing plant include stock holding, killing, bleeding, cutting, rendering, dressing, processing and packaging. Large volumes of water are used in these processes, resulting in an effluent with relatively high concentrations of organic materials. Water use varies widely between plants but typically is between 200 and 500 litres per sheep or lamb and between 1000 and 2000 litres per cattle beast (Russell and Cooper 1992).

The most notable characteristics which contrast meat processing plant effluent from domestic wastewater are its high grease content, high nitrogen concentrations and extreme variability over short time intervals for all commonly measured effluent properties (Tarquin 1974, Tarquin and Bautista 1976, Cooper and Russell 1991). Effluent volume and composition vary both throughout the day, as a plant conducts different operations, and also from day to day depending on the numbers and type of stock being processed (Cooper *et al.* 1979). Tarquin and Bautista (1974) estimated that 50% of a reasonably typical meat processing plant's effluent was generated on the killing floor. They reported that the strength of the effluent was greatest during

the killing hours but residual grease and blood kept the strength of the effluent fairly high for several hours after the daily clean-up operations began. The multiplicity and diversity of operations performed in plants, and the variety of chemicals and additives used in the preparation of the marketed products, account for the large variations that can occur between the chemical characteristics, strength and volume of waste discharged by different plants (Crandall *et al.* 1971).

The organic constituents of effluent from a meat processing plant (excluding fellmongery processing) come from four major sources; paunch contents, faecal materials, fat, and blood (Cooper *et al.* 1979). Fat and grease, and protein (mainly from blood) are the main contributors to the high concentrations of organic nitrogen (Crandall *et al.* 1971) and the high overall oxygen demand (Cooper *et al.* 1979) of meat processing plant effluents. A potential source of the high quantities of phosphorus contained in meat processing plant effluents is the use of phosphorus based chemicals for curing, water treatment, descaling of stainless steel surfaces and other cleaning operations (Crandall *et al.* 1971).

2.2.2 Effluent treatment

Effluent treatment methods employed in New Zealand meat processing plants include: screening for gross solids, primary treatment by sedimentation and fat floatation, anaerobic lagoons, anaerobic and aerobic lagoons in series, aerobic biological trickling filters (plastic media tower), physicochemical protein recovery, and irrigation (Cooper *et al.* 1979, Cooper and Russell 1991). All New Zealand meat processing plants employ some form of primary effluent treatment. At some sites all effluents are combined and treated in one common sedimentation/floatation tank. Separate treatment of fat-bearing effluents by screening and floatation is sometimes used. Some effluents, notably those from stockyards, are treated separately by screening and sedimentation and are combined with the other effluents only after primary treatment (Cooper and Russell 1982).

Anaerobic and aerobic biological secondary and tertiary treatment systems are widely used in the New Zealand meat industry. This is because most plants are situated in rural environments where discharge to a city sewage treatment plant is not an option,

and because these treatment systems are cheap to operate, requiring only a low energy input (Cooper and Russell 1982).

Discharge of treated effluent to waterways is still common but there is increasing interest in land based discharge/further treatment options. In 1984 nine New Zealand export meat processing plants were irrigating effluent (Russell *et al.* 1984); in 1992 this had increased to 13 plants (Russell and Cooper 1992), despite closure of some of the plants recorded in 1984.

Primary treated meat processing plant effluents have very high levels of biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (SS) and nitrogen (Table 2.1). The range of values given (Table 2.1) illustrate the variability in effluent properties, both with time and between treatment plants. For instance, the value of COD for the Fairton plant (Table 2.1) is outside the range identified as typical by Cooper and Russell (1992). The very high concentrations for some parameters in US effluents (Table 2.1) may be a result of minimal dilution (by water addition) in some effluent streams.

Table 2.1 **Characteristics of primary treated meat processing plant effluent.**
(All values are g m⁻³, except pH.)

Property ¹	Typical N.Z. range ²	Fairton Plant, NZ ³	U.S.A. Meat Plant ⁴
BOD	300-1 800	N.A.	200-15 000
COD	600-3 000	4 100	350-39 000
TkN	50-400	100	19-680
NH ₃ -N	5-50	N.A.	N.A.
NO ₃ -N + NO ₂ -N	0	N.A.	N.A.
TS	N.A.	3 400	540-14 000
VS	N.A.	N.A.	N.A.
SS	150-2 000	1 900	15-10 000
Fat and grease	100-1 200	N.A.	110-8 000
Total P	5-30	7	3-35
S	N.A.	50	N.A.
pH	N.A.	10.2	6.6-8.1
Organic C	300-1000	N.A.	N.A.
Cl	N.A.	280	N.A.
Na	50-250	230	N.A.
K	20-150	90	N.A.
Ca	3-250	140	N.A.
Mg	3-10	7	N.A.

- Notes**
- ¹ BOD = Biological oxygen demand, COD = chemical oxygen demand, SS = suspended solids, TS = total solids, VS = volatile solids, TkN = total kjedahl nitrogen.
 - ² Typical range for New Zealand meat processing plant effluent after Russell and Cooper (1992), and Cooper and Russell (1992).
 - ³ Data are for a composite sample made up of subsamples collected at 10 minute intervals over a whole day from Fairton Meat Processing Plant, Canterbury, New Zealand from Keeley and Quin (1979).
 - ⁴ Data are for a United States meat processing plant after primary treatment of skimming and sedimentation with a detention time of half an hour during peak flow from Tarquin and Bautista (1976).
 - ⁵ N.A. = not available in the source reference.

Following anaerobic and aerobic treatment, meat processing plant effluents may still be highly variable (Table 2.2). Comparison of data in Table 2.2 with that of Table 2.1 (primary treated effluent) shows that anaerobic treatment of meat processing plant effluent causes a large decrease in BOD, COD, SS and fat and grease but has little

effect on phosphorus or dissolved cations. Aerobic treatment gives a further decrease in COD, BOD and SS and may lead to a decrease in total Kjeldahl nitrogen (Tk-N) but with formation of some oxidised nitrogen (NO_2 and/or NO_3). Aerobic treatment has no effect on phosphorus or cation levels.

Table 2.2 Characteristics of anaerobically and aerobically treated meat processing plant effluent. (All values are in g m^{-3} except pH which is standard pH units.)

Property ¹	Anaerobic-aerobic lagoons ²	Anaerobic-aerated aerobic lagoons ³	Trickling filter ⁴	Anaerobic lagoon ⁵	Aerobic Lagoon ⁵
BOD	17-400	30-90	25-181	70-300	20-100
COD				180-750	80-400
Total N	179			50-200	40-180
NH_3	51-120	59-95	24-46	40-180	40-180
$\text{NO}_3 + \text{NO}_2$				0	0-100
Fat/grease	4-39	15-61	7-15	10-50	0-50
SS	12-144	110-308	32-92	40-200	20-100
Total P	8-20	7-15	8	5-30	5-30
Na				50-250	50-250
K				20-150	20-150
Ca				3-250	3-250
Mg				3-10	3-10

Notes ¹ BOD = biological oxygen demand, COD = chemical oxygen demand, SS = suspended solids.

² Data for four United States Plants from Crandall *et al.* (1971).

³ Data for two United States Plants from Crandall *et al.* (1971).

⁴ Data for two United States Plants from Crandall *et al.* (1971).

⁵ Typical values for New Zealand meat processing Plants from Russell and Cooper (1992).

2.3 Soil properties and processes that are important for effluent treatment and disposal

2.3.1 Introduction

The application of effluent onto soil can be limited by site factors such as drainage, slope, climate, and vegetation. Effluent movement within the profile is influenced by soil properties such as; structure, texture, consistence, porosity, presence of pans, gleying, and organic matter (Wells 1973, Stevenson 1976). Other factors that determine the effectiveness of effluent treatment include; clay mineralogy, soil pH, distance to stream or open water, depth of soil, and type of bedrock or regolith

material (Spyridakis and Welch 1976). A summary of the suitability of site and soil properties for irrigation treatment of effluent, as identified by Stevenson (1976), is given in Table 2.3.

Table 2.3 Site and soil characteristics and suitability for irrigation treatment of effluent (adapted from Stevenson 1976)

Property	Well suited to effluent disposal	Not suited to effluent disposal
Drainage	moderate, well drained, somewhat excessively drained	very poor, imperfect, excessive
Slope	flat to undulating, rolling, moderately steep.	steep
Moisture	subxerous, subhygrous, hygrous	hydrous
Climate	temperate, subtropic	sub-antarctic, alpine, sub-alpine
Soil structure	polyhedral, plate, apedal earthy	prism, column, block
Soil texture	sandy loam, silt loam, loam	silty clay/loam, clay loam, clay
Soil pores	many, abundant	few
Soil pans	none	carbonate pan, fragipan, iron pan, silica pan, humus pan
Soil gleying	none	weak to strong

2.3.2 Soil water movement

Knowledge of the rate that water, or effluent, moves into and through the soil is important for successful effluent irrigation scheme design and management. Soil structure, texture, pores and pans are all included in Table 2.3 because of their influence on soil pore size and distribution, and hence on soil water movement.

Soil hydraulic conductivity refers to the rate that a liquid moves into and through the soil. Maintenance of soil hydraulic conductivity is vital to an effluent land waste treatment or disposal system. The rate of water flow through soil can be described by Darcy's Law which states that the flux of water, q , is proportional to the hydraulic gradient multiplied by the conductivity of the soil:

$$q = Q/A = -K \Delta H/L \quad (2.1)$$

where Q is the rate of discharge through a cross-sectional area A , $\Delta H/L$ is the hydraulic gradient and K is the hydraulic conductivity of the soil. The negative sign is there, by convention, to indicate that the direction of water flow is from regions of higher to lower potential (McLaren and Cameron 1990).

For one dimensional vertical flow, expressed in differential form equation 2.1 becomes (Klute and Dirksen 1986):

$$q = -K(\theta) \delta H/\delta z \quad (2.2)$$

Where $\delta H/\delta z$ is the gradient of the hydraulic head, H , and $K(\theta)$ is the hydraulic conductivity at a given moisture content.

When soil is saturated (i.e. when all the pores are full of water) the soil hydraulic conductivity is at a maximum and this is denoted using the term K_{sat} .

A soil's infiltration rate is the volume flux of water flowing into the profile per unit of soil surface area (Hillel 1980). Infiltration is an important parameter for determining effluent irrigation application rates if all the applied effluent is to infiltrate into the soil, rather than run-off the surface. Cumulative infiltration may be described by the Phillips equation (Hillel 1980):

$$I = St^{1/2} + K_i t \quad (2.3)$$

where I is the cumulative quantity of water infiltrating a unit cross-sectional area of soil, S is the sorptivity of the soil (which indicates the capacity of the soil to absorb water), and K_i is the hydraulic conductivity at the moisture content related to I .

The infiltration rate, i , is the volume infiltrated per unit area per unit time (Hillel 1980). Therefore:

$$i = dI/dt = 0.5St^{-1/2} + K_i \quad (2.4)$$

Initially, infiltration is influenced by sorptivity. The sorptivity is dependent on the moisture content of the soil. A dry soil has a much larger matric suction and can, therefore, absorb water at a faster rate than a moist soil. For uniform soil, under ponding, the soil eventually approaches saturation and K_i approaches K_{sat} , the sorptivity term becomes insignificant and therefore i approaches K_{sat} .

The rate of flow of water through a soil pore (Q) is proportional to the fourth power of the radius of the pore (McLaren and Cameron 1990):

$$Q = (\pi r^4 / 8\eta)(\rho_w g \Delta H / L) \quad (2.5)$$

Where r = pore radius
 η = viscosity
 ρ_w = density of water
 g = acceleration due to gravity
 $\Delta H / L$ = the hydraulic gradient along the length (L) of the pore.

Soils in the field are usually unsaturated, i.e. not all soil pores are filled with water. In unsaturated soils, as the coarser pores drain, there is a large decrease in the rate that water moves through the soil (as indicated by equation 2.5). When soil pores are not water-filled, water movement may still occur, in water films around soil particles, or in the vapour phase (McLaren and Cameron 1990). The relationship between soil hydraulic conductivity and suction for two soils is illustrated in Figure 2.1.

The presence, size, distribution and continuity of soil pores have a large impact on the rate that effluent moves into and through a soil (as illustrated by Equation 2.5 and Figure 2.1). Under effluent irrigation systems which saturate the soil surface, effluent will flow rapidly through soil macropores. If continuous macropores pass through the depth of the soil profile then effluent may be conducted directly to the groundwater with minimal treatment occurring. However, if soil pores become blocked then the rate of water or effluent movement through the soil may decrease greatly, thus reducing a soil's ability to accept and treat effluent.

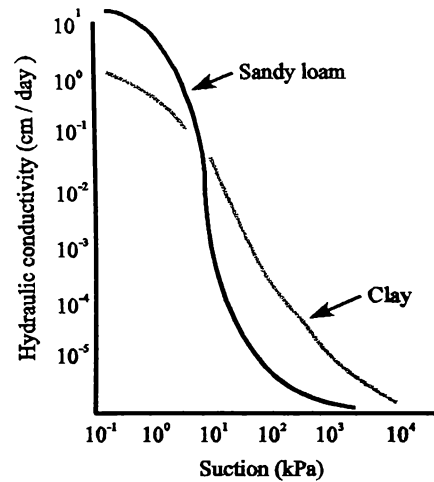


Figure 2.1 Relationship between hydraulic conductivity and suction for a clay soil and a sandy loam (after McLaren and Cameron 1990).

In this thesis the term "permeability" is used as a synonym for hydraulic conductivity. "Infiltration" is used specifically to refer to the permeability or hydraulic conductivity at the soil surface.

2.3.3 Soil chemical properties

Soil chemical properties have an important role in removing contaminants from an effluent. The solid phase of most soils usually carries a net negative charge. This charge is neutralised by positively charged cations which are attracted to, and accumulate near, soil particle surfaces. Cations associated with soil particle surfaces are in equilibrium, and exchangeable, with the cations in the soil solution (Figure 2.2).

Permanent charge in soils is the result of isomorphous substitution of cations within the structure of clay minerals. Variable, or pH dependent, charge arises from the dissociation of H^+ ions from the functional groups associated with soil organic matter, and through the addition or removal of H^+ ions from OH groups on mineral surfaces (McLaren and Cameron 1990). Variable charge is affected by soil

mineralogy and properties of the soil solution (including pH, ionic strength, and speciation).

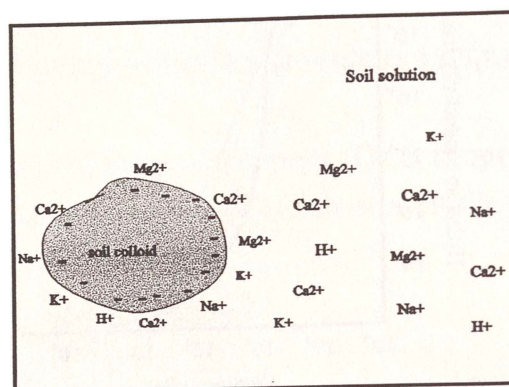


Figure 2.2 Equilibrium between exchangeable and solution cations (after McLaren and Cameron 1990).

A soil's cation exchange capacity is a measure of the soil's ability to hold and exchange cations. The proportion of the exchange capacity that is occupied by cations is referred to as the percentage base saturation (%BS):

$$\%BS = \text{TEB} \times 100 / \text{CEC} \quad (2.6)$$

Where TEB = total exchangeable bases (me%)
 CEC = cation exchange capacity (me%) (McLaren and Cameron 1990).

The total CEC and the %BS are important as they determine a soil's capacity to remove dissolved cations and other positively charged particles from an effluent. Soils effectively remove most cations from effluent by adsorption onto the exchange complex, or by precipitation, as the effluent moves through the soil (Loehr *et al.* 1979). Cations, including heavy metals, therefore accumulate in soil until the soil cation exchange complex becomes saturated. The ionic composition of the leachate would be expected to eventually approach that of the applied effluent as equilibrium between the cation exchange complex and the soil solution is reached (Bouwer and

Chaney 1974).

On most soil colloid surfaces there will also be some positively charged sites, especially in soils which contain Fe and Al oxides and short range order aluminosilicates such as allophane (McLaren and Cameron 1990). These sites attract anions from the soil solution and can therefore remove negatively charged species from applied effluents.

Phosphorus is a common contaminant in effluents and can be removed from effluent, that is applied to soil, by precipitation or adsorption by soil colloids. The removal of phosphorus, from an effluent, is, therefore, dependent on factors such as soil texture, soil pH, presence of calcium, and the amount of iron and aluminium oxides or aluminosilicates (e.g. allophane) present. Phosphorus may be removed from the site by plant uptake and subsequent removal with a crop. Although there is a large capacity for phosphorus removal from the effluent in most soils, phosphorus sorption capacity is finite and over a long time period, or with heavy loadings, the soils ability to remove phosphorus from the applied effluent may be exceeded (USEPA 1976, 1981). The time-period over which a soil will continue to intercept phosphorus without it leaching to groundwater is generally unknown. At the Fairton meat processing plant effluent irrigation site, in Canterbury, Keeley and Quin (1979) found no phosphorus in the groundwater after 90 years of irrigation of meat processing plant effluent. Phosphorus removal capacity is most likely to be exceeded in coarse textured soils with little calcium, aluminium, or iron (USEPA 1976).

Nitrogen removal from applied effluent occurs through crop uptake, growth of microbial cells, volatilisation of ammonia, assimilation into the soil organic matter and denitrification (Spyridakis and Welch 1976, USEPA 1976, 1981). Crop uptake and denitrification are the only two reliable long-term mechanisms for removal of nitrogen, and therefore affect the total amount of nitrogen leaching to the groundwater (Bouwer and Chaney 1974, USEPA 1976). To remove N effectively the crop should be harvested (USEPA 1981). In meat processing plant effluent much of the N is present in the form of protein. Studies have shown that the top 10 cm of soil could retain in excess of 980 kg protein N ha⁻¹, in a single application, provided soil pH was in the range of 6 to 9. The protein is, therefore, available for microbial

decomposition and eventual removal by the plant cover (Russell 1982). Gaseous losses of nitrogen at effluent treatment sites are usually less than 30% (Loehr *et al.* 1979) and, therefore, the main method for nitrogen removal is considered to be plant uptake and crop removal.

2.3.4 Soil biological activity

In most soils the micro-organism and earthworm populations make up the bulk of the soil biomass (McLaren and Cameron 1990). Both of these groups are of importance with regard to land treatment and disposal of effluent. Biological processes centre around soil microorganisms which alter waste constituents through decomposition, inorganic transformations and nutrient assimilation. Biological processes are generally restricted to approximately the upper metre of soil (Loehr *et al.* 1979) and mainly occur in the topsoil where the highest organic matter contents are found.

The soil microbial population is a mixture of bacteria, actinomycetes, fungi, algae and protozoa. Bacteria, with their very high surface area:volume ratio, and their prokaryotic cellular organisation are generally considered to have metabolic rates which are 5-10 times higher than fungi, when growing under similar conditions. Therefore, bacteria generally have the fastest response to additions of organic material. It has been suggested, that the rate of degradation of many organic waste constituents is controlled by soil bacterial populations (Overcash and Pal 1979). Many bacteria are heterotrophic and release CO₂ through the breakdown of plant and animal residues. Bacteria are essentially aquatic organisms, living in the films of moisture surrounding soil particles. Bacteria are dependant on soil conditions, particularly temperature, moisture, pH, redox potential, and food supply and there are rapid fluctuations in the size of soil bacterial populations in response to changing conditions (McLaren and Cameron 1990). Soil bacteria, rather than the organisms in the effluents, are mainly responsible for decomposition of effluent organic material. Therefore, soil is more effective in decreasing BOD than, for example, oxidation ponds (Vela and Eubanks 1973, Bouwer and Chaney 1974).

Actinomycetes have a true branching growth habit resembling fungal mycelia. Under neutral to slightly alkaline (pH < 8) conditions they may be the dominant soil

organism degrading organic waste. Under hot dry conditions, it is considered that degradation of organic wastes in soils is dependent on actinomycete activity (Overcash and Pal 1979).

Fungi are also principal agents in the decay of organic materials in soil, particularly the more resistant organic compounds like cellulose and lignin. They are able to attack materials at moisture contents that are too low for bacteria to operate (McLaren and Cameron 1990). Fungi tend to concentrate in the top few centimetres of soil (Overcash and Pal 1979). They have a branched, ramifying mycelial habit and spread rapidly and extensively even though the biomass might be quite small. Fungi are, in general, favoured by low pH (less than about 5.5) although individual species have quite narrow optimum pH tolerances and may be found in environments ranging from pH 4 to 10.

Effluent addition may provide soil moisture and nutrient conditions favourable to algal growth at the soil surface. Soil protozoa depend on utilising organic compounds or other microorganisms for their growth and energy (Overcash and Pal 1979), and therefore benefit indirectly from additions of effluent.

The amount of biodegradation depends on the nature of the organic components, the amount of solids in the effluent, the amount and frequency of effluent applications (Loehr *et al.* 1979, Fuller and Warrick 1985), and the microbial activity. When organic material is added to soil, decomposition can be described in three steps (Loehr *et al.* 1979):

1. Organisms digest the more easily decomposed material, consuming oxygen and releasing carbon dioxide in the process. This pulse of activity can result in a rapid increase in organism numbers. In cases of extreme overloading, temporary clogging of the soil can result. (Effluent BOD measures the amount of oxygen consumed during this stage).
2. Organism numbers decline as the easily decomposed organic fraction is exhausted. The resulting mass of dead microbial tissue, along with other intermediate decay products and the more resistant compounds from the

original addition, are partially degraded to a relatively stable end product, humus.

3. Organism numbers decline to about the same level as before the effluent addition.

In natural systems that receive localised or periodic additions of organic matter, these three stages may overlap with several processes occurring simultaneously (Loehr *et al.* 1979). There is usually a rapid increase in soil respiration rates following effluent application (step 1). For example simulated whey effluent application to soil induced a marked increase in the respiration rate within a few hours of application (M^cAuliffe 1978). De Vries (1972) found that maximum biological activity occurred 1 to 9 hours after primary treated sewage effluent application to a fine sand and 1.5 to 5 hours after application to a coarse sand. De Vries also observed that O₂ and CO₂ production base levels were reached after about 24 hours and concluded that effluent applications need to be at least 22 hours apart to prevent permeability decline due to incomplete satisfaction of the BOD. However, a slower response was recorded by Jewell and Loehr (1975) who showed that the oxygen uptake following application of food processing effluent to soil peaked within two days, but did not return to initial levels after 5 days. They also showed that the oxygen uptake increased with the rate of effluent application.

The soil microbial community changes in response to effluent application. Soils that have previously received effluent (acclimated soils) have been observed to have a quicker increase in respiration rate following whey addition (M^cAuliffe 1978) and a greater total oxygen uptake following food processor effluent application (Jewell and Loehr 1975) than non-acclimated soils. Increases in microbial populations and changes in species composition have been reported in soils as a result of: cannery effluent irrigation (Vela and Eubanks 1973), cattle slurry application (Opperman *et al.* 1989), and sewage effluent irrigation (Safir *et al.* 1990). Different micro-organisms respond to effluent application at different rates. For example, application of cattle slurry to a sandy free-draining soil led to an immediate increase in the numbers of viable bacteria and presumptive coliforms followed by increases in the numbers of protozoa and nematodes (Opperman *et al.* 1989). The maximum

responses for bacteria occurred after 10 days, and after 100 days for nematodes.

Meat processing plant effluents often contain particularly high levels of animal fats compared with sewage and other effluents. Animal fats are hydrolysed by lipases to produce free fatty acids and glycerol. Glycerol can be metabolised by microorganisms and the fatty acids may be broken down by oxidation. The rate at which fats decompose may be a limiting factor for minimising intervals between effluent application. Animal fats should be relatively rapidly metabolised by soil microorganisms (compared with petroleum hydrocarbons) although at temperatures of less than 15 °C biodegradation can be very slow (Overcash and Pal 1979). Tarquin (1974) observed that complete degradation of fats by soil microorganisms may take several months. A decomposition rate of 0.2 to 0.4% oil of soil weight (in the top 15 cm) per month is possible if the temperature remains above 10 - 15 °C (Overcash and Pal 1979). Fat residues remaining after oxidation become integrated into the soil matrix (USEPA 1981).

Although most studies report an increase in soil microbial activity following effluent addition, this is not always the case. In a study where soil cores were irrigated with treated sewage effluent or tap water, differences between soils were found to be greater than differences between treatments for protozoan fauna (Stout 1978), actinomycetes (Orchard 1978), and total microbial populations and respiratory activity (Cairns *et al.* 1978). The respiratory and enzyme activities were similar to, or slightly lower than, those recorded for fresh samples of the topsoils (Ross *et al.* 1978).

Some studies have been undertaken which examine microbial responses to meat processing plant effluent. Tarquin (1974) applied 50, 100 and 200 mm per week of primary treated meat processing plant effluent to a sandy clay loam soil, over seven months, and found that there was a large increase in both anaerobic and aerobic bacteria near the soil surface (0-15 cm) for all treatments. An increase below the topsoil occurred only where 200 mm per week of effluent was added. Tate (1973) reported that soils which received meat processing plant effluent had a higher soil respiratory activity and carbon mineralisation coefficient than neighbouring soils, both unirrigated and water irrigated. In a similar study, Ross *et al.* (1982) reported that

meat processing plant effluent irrigation resulted in increased soil microbial biomass, enzyme activities, and rates of CO₂ and net mineral N production from soil organic matter.

Temperature helps determine both the composition and activity of soil microflora (Lynch and Hobbie 1988). In the range of temperatures experienced in New Zealand biological degradation of added material could be relatively slow, especially in winter. Most species are active in the mesothermic range (20-35 °C) and degradation becomes very slow below about 20 °C (Overcash and Pal 1979). However microbial degradation of oils has been observed at temperatures ranging from -2 °C to about 70 °C. An increase of 10 °C is generally accepted to cause a doubling of reaction rates. Hsieh *et al.* (1981) reported that between 8 °C and 22 °C the mineralisation rate of sewage sludges in soil increased about 1.9 times for every 10 °C increase in temperature. The degradation rate of milk applied to four different soil types was significantly affected by temperature (Cooper and Morgan 1982). At 17 °C, BOD exertion took 6 days and lipid degradation 12 days, whereas, at 12 °C at least 24 days were required for lipid breakdown.

Earthworms feed on organic materials, including components of an applied effluent. They make an important contribution to the breakdown of organic material and its incorporation into the mineral soil. Earthworms also have a considerable effect on soil physical properties due to their burrowing activities. They promote aeration and drainage of the soil and contribute to soil structural development (McLaren and Cameron 1990). Earthworms cannot survive extended periods of soil saturation so if effluent application is allowed to cause soil saturation it may be detrimental to earthworm populations.

2.4 Methods of land treatment/disposal of effluent, and their effectiveness

2.4.1 Introduction

Land treatment of effluent is defined as the controlled application of effluent onto the land surface to achieve a designed degree of treatment through natural physical, chemical and biological processes within the soil-plant-water matrix (USEPA 1981,

Reed and Crites 1984).

Application of effluent to land has a number of advantages. It keeps effluent out of surface water and provides recycling where "pollutants" become nutrients for plant growth (Bouwer and Chaney 1974). Effluent comprises mostly water that contains essential plant nutrients such as N, P, K, and trace elements (De Vries 1972, Bouwer and Chaney 1974, Russell and Cooper 1987). Land waste treatment provides water reuse through groundwater recharge and increased plant growth (Tarquin and Bautista 1976) and it often has a low energy requirement compared with other waste treatment methods (Bouwer and Chaney 1974). Therefore land treatment can be an economical alternative to conventional treatment (Bendixen *et al.* 1969, Tarquin and Bautista 1976, Overcash and Pal 1979). Several factors make land treatment/disposal of effluent appealing to the food processing industry (Bendixen *et al.* 1969):

1. Food wastes have a high organic content and are difficult to treat by conventional methods.
2. Plant operation is often seasonal (land disposal avoids the problems associated with start-up and shut-down of conventional biological treatment plants, and periods of maximum effluent production often co-incide with summer soil moisture deficits).
3. Plants are often located in small towns or rural areas where municipal treatment facilities are not adequate or where extreme seasonal loads are impractical to handle.
4. Land disposal offers a high degree of flexibility.

The processes that have been used conventionally for land-based treatment of effluents are; overland flow, irrigation (including both high-rate irrigation and low-rate irrigation) and rapid infiltration (Bouwer and Chaney 1974, USEPA 1981, Fuller and Warrick 1985). A summary of these methods is given in Table 2.4.

Table 2.4 Summary of commonly used land treatment/disposal systems
(adapted from USEPA 1976, USEPA 1981, and Reed and Crites 1984).

	Irrigation	Rapid Infiltration	Overland flow
Objective	Low-rate: Irrigate at rates to match plant water/nutrient needs. Maximises plant production, may be considered a re-use option giving advanced effluent treatment. High-rate: Irrigate in excess of plant needs to maximise effluent treatment by supplying nutrients and water to crops - effluent treatment is the priority.	Maximise water filtration and percolation to ground- water. The primary aim is disposal with some treatment. Groundwater recharge may be an objective. Crop production is not a benefit.	Effluent is allowed to flow over the ground surface. May be used as secondary treatment of raw effluent or advanced treatment of secondary treated effluent. Crop harvest is incidental.
Dispersal of applied water	Low rate: Most water to evapotranspiration. Some water to percolation and leaching of salts. Runoff should be avoided or controlled. High rate: Most water to percolation and evapotranspiration. Runoff should be avoided or controlled. May result in buildup of groundwater mound.	Most water percolates to groundwater. Some water to evapo-transpiration. No runoff. May result in buildup of a large groundwater mound.	Most water to surface runoff. Some to evapo-transpiration and very little to percolation.
Impact on quality of applied water	BOD and SS almost completely eliminated. Nutrients removed by crop and soil. Heavy metals adsorbed or precipitated. Increase in hardness of percolate. Low rate: Total dissolved ionic solids concentration greatly increased by evapo-transpiration. Little change in total salts (applied = leached). High rate: Additional salts leached out of soil by excess applied water.	BOD and SS decreased. Some nutrient removal by soil and crop. Additional salts leached out of soil by excess applied water. Increase in hardness of percolate.	BOD and SS greatly decreased. High N and some P removal. Decrease in some heavy metals. Little change in total dissolved ionic solids.
Soil Permeability	> 1.5 mm hr ⁻¹ .	> 40 mm hr ⁻¹ .	< 5 mm hr ⁻¹ .
Texture	Clay loams to sand.	Sands to sandy loams.	Clays to clay loams
Water table	At least 1 m. For high loads, 3 m.	1 m during loading, 3 m during drying.	Below ground surface.
Vegetation	agricultural or forest	not required	agricultural (usually grass)
Slope	Pasture 0-7 high 8-20 low-moderate 21-35 very low > 35 unsuitable Forest high, high moderate very low	high low unsuitable unsuitable	high unsuitable unsuitable unsuitable
Area Required	up to or over 1 000 Ha	1-20 Ha	1-20 Ha
Minimum pre-application treatment	primary	primary	grit removal and comminution.
Application Method	spray or surface. 4-12 hr/application. 1 application/7-20 days	usually surface 8 hr/application 1 application/5-15 days	spray or surface 8-12 hr/ application 5-7 applic./week
Loading rate	15-100 mm week ⁻¹ , 0.5-6 m/yr.	100-2400 mm/week 6-125 m/yr.	60-400 mm/week 3-20 m/yr.

Effluent treatment mechanisms include a combination of physical, chemical, and biological processes within the soil profile (Loehr *et al.* 1979, Carlson *et al.* 1982). A summary of the estimated effluent treatment effectiveness of the three land treatment methods, (that were described in Table 2.4) are given in Table 2.5. Each treatment system is discussed in more detail in the following sections.

Table 2.5 Effectiveness of different application methods in removing components of effluent (% decrease, from Spyridakis and Welch 1976)

Parameter	Irrigation ¹	Overland flow ¹	Rapid Infiltration
BOD ²	99	80	99
SS ³	99+	80	99
N	70-90	60-90	30-80
P	95-99	60-80	50-90
Trace metals	95-99	60-80	50-90
Organic toxicants	99	60-80	90
Viruses/bacteria	99+	90	99+
Cations	50-75	30-50	30-75
Anions	0-50	0-10	0-50

¹ Includes nutrient removal via crop harvesting. ² BOD = Biological oxygen demand. ³ SS = suspended solids.

Land treatment of effluent is effective at removing effluent BOD and SS, regardless of the method used (Table 2.5). It can also be effective at removing N, P, trace metals, organics, and pathogens but is less effective at removing dissolved solids (cations and anions). Stevenson (1976) noted that the level of treatment of effluents achieved by land disposal may be highly variable, depending on factors such as previous treatment, effluent type, the application system and rates, soil type, vegetation cover, climate, and site management. Stevenson (1976) also suggested that if macropore flow occurs, minimal effluent treatment may occur. Therefore Table 2.5 should be regarded only as a general guide.

2.4.2 Overland flow

Overland flow is the controlled application of effluent to relatively impermeable soils on grass covered gentle slopes (Figure 2.3). Hydraulic loading rates are usually in the range of 5 - 30 cm per week (Reed and Crites 1984). Overcash and Pal (1979) recommended that overland flow should be viewed as a pretreatment process, and not as a method of terminal land application, because more than half of the applied effluent may end up as runoff. Overland flow systems are used where either the soil is too impermeable, the water table is too close to the surface or the suspended solids content of the effluent is too high to allow significant infiltration rates (Bouwer and Chaney 1974, USEPA 1976). An effective overland flow system should have a uniform slope of 2 to 8% enabling the effluent to move downslope and spread, uniformly, over the soil surface. A cover crop, usually grass, is grown to protect the soil from erosion and to maximise effluent treatment by providing a large surface area for biological activity (USEPA 1976).



Figure 2.3 Overland flow of sewage effluent at an experimental site at Levin, New Zealand.

As the effluent flows down the slope biological oxidation, sedimentation, and filtration (by the vegetation) are the primary mechanisms for organics and suspended solids removal from the effluent. Nitrogen removal occurs as a result of plant uptake, denitrification and volatilisation of ammonia-N. Phosphorus is removed by adsorption and precipitation. Phosphorus removal can be enhanced by adding aluminium sulphate or ferric chloride to the effluent just prior to application to the slope (USEPA 1981). Overland flow can effectively remove suspended solids and biological oxygen demand from effluent (Table 2.5) provided the loading rate is sufficiently small and the land has been graded to a sufficiently even slope to avoid channelling of the effluent flow (some channelling of effluent flow is visible in Figure 2.3) (Bouwer and Chaney 1974, USEPA 1976). Overland flow provides only limited removal of phosphorus and heavy metals (USEPA 1976) and, therefore, further treatment may be required. In essence the overland flow slope is similar in concept to any other attached growth or fixed film biological process, such as trickle filters, that are used in conventional sewage treatment plants (Reed and Crites 1984).

Overland flow has been reported to effectively remove meat processing plant effluent suspended solids and oxygen demand (Witherow 1973, Tarquin and Bautista 1976).

It is, however, still necessary to collect and dispose of the runoff and further treatment, to remove N, P and other cations, may be necessary prior to disposal. Tarquin and Bautista (1976) reported that over a 62 m long grassed slope 87% of suspended solids but only very small amounts of dissolved solids were removed from a primary treated meat processing plant effluent. Tarquin and Bautista (1976) recorded an 84% COD removal and recommended that for maximum COD removal a length greater than 62 m could be used. However, they also reported that where channelling occurred, on the slope, COD removal was less than 50%. Total N removal was recorded as 44% with most of the N removal attributed to removal with the suspended solids of the effluent. In an experiment where anaerobically treated meat processing plant effluent was applied to plots planted in bermuda grass, Witherow (1973) recorded the following effluent component removals: BOD 83%, COD 70%, total organic carbon 85%, $\text{NH}_3\text{-N}$ 84%, and P 64%.

Accumulation of organic solids materials at the top end of slopes in overland flow systems has been observed (Tarquin and Bautista 1976, Reed and Crites 1984).

Tarquin and Bautista (1976) described build-ups of "greasy-looking" solids at the top end of the slope which turned black and dried during the resting periods. They concluded that utilisation of a "proper" operating and drying schedule eliminated problems which might be caused by solids build-up. Reed and Crites (1984) suggested that high-pressure sprinklers should be used for high solids industrial effluents to ensure a more uniform distribution of the solids material, thus preventing build-up in one part of the irrigated area.

2.4.3 Irrigation

The objective of irrigation is to infiltrate all applied water, whether it occurs as precipitation or effluent (Nutter 1979, Bouwer and Chaney 1974, Fuller and Warrick 1985). Typically, 2-10 cm of effluent per week are applied in one, or several, applications. Effluent may be applied using sprinklers (Figure 2.4), furrows, borders (Figure 2.5) or basins (Bouwer and Chaney 1974, USEPA 1981). Irrigation is capable of producing the highest degree of effluent treatment of all the land treatment systems (Table 2.5, USEPA 1981).

Effluent irrigation may be at either a "low" or "high" rate. The objective of **low-rate** irrigation is to maximise crop production by applying effluent at a rate that meets crop water or nutrient requirements. As a consequence most of the water applied is either evaporated or transpired. Effluent treatment and disposal are secondary benefits. Low-rate irrigation is a suitable treatment alternative in low rainfall areas, where irrigation is required for optimum crop production, and it has the highest potential for removal of effluent pollutants. Because of the lower loading rates low-rate irrigation involves the largest land area and the widest dispersal of pollutants and therefore minimises adverse effects on soil and vegetation (USEPA 1976).



Figure 2.4 Irrigation of a vegetable processing plant effluent using a travelling irrigator, Canterbury, New Zealand.



Figure 2.5 Border dyke irrigation of meat processing plant effluent, Hawkes Bay, New Zealand

It has been suggested that if meat processing plant effluents were irrigated at rates designed to utilise the nutrients at fertiliser rates (low-rate irrigation) in New Zealand a large meat processing plant would require a land area of approximately 800 ha if the pasture was harvested (Russell and Cooper 1987). If stock grazed the irrigated area (thereby returning nitrogen to the soil in excreta), an even larger area would be required. Reticulation and management of a large area is expensive, and effluent is therefore commonly applied at a rate in excess of herbage requirements (i.e. high-rate irrigation).

High-rate irrigation (effluent applied in excess of crop water or nutrient requirements) is primarily a method of effluent treatment but it has the additional agricultural benefit of producing high-yield crops. Because of the high loading rates used much of the water percolates through the root zone to the groundwater. High-rate irrigation is a feasible treatment method in almost all climates and has the second highest potential (next to low-rate irrigation) for removal of effluent pollutants (USEPA 1976). Although this approach is wasteful of the available nutrients, advantages include a smaller requirement for suitable land, and lower capital and maintenance costs (Cooper and Russell 1982).

Irrigation of effluent provides effective effluent treatment (Table 2.5) (Bouwer and Chaney 1974, USEPA 1981, Reed and Crites 1984). Suspended solids are removed physically through filtration by the soil. Effluent BOD and COD are effectively removed in soil. Once the soil-microorganism community is adapted to effluent irrigation, it can oxidise $9\,000\text{ kg ha}^{-1}\text{ d}^{-1}$ (or up to $10\,000\text{ g m}^{-3}$) provided that surface clogging is avoided, macropore space is sufficient, optimum moisture levels are maintained and soil aeration is adequate (Loehr *et al.* 1979).

In sewage effluent, the BOD is often associated with the suspended solids whereas COD is more often associated with dissolved organic solids. The BOD load will not normally extend more than a few centimetres into the soil because the suspended material is filtered out or adsorbed near the surface (USEPA 1981). In untreated meat processing plant effluent, the majority of the BOD and COD (about 70%) is in a soluble form. However it is generally in charged chain-molecules which are readily adsorbed by the soil, therefore, the BOD and COD load is unlikely to penetrate far

into the soil (J.M. Russell *personal communication*). At shallow soil depths, oxygen diffusion rates are high, and biological oxidation provides the ultimate treatment and removal mechanism. A decrease in BOD before effluent reaches the groundwater should therefore be achievable (Bouwer and Chaney 1974, USEPA 1981). However, if soils become anaerobic, only about 10% of the BOD may be oxidised and presumably the remainder moves to the groundwater (Wallace 1976, Loehr *et al.* 1979).

A specific example of the effectiveness of soil for treating primary-treated meat processing plant effluent is given by Tarquin (1974). Tarquin reported that irrigation onto 45 cm of sandy clay loam over fine sand (100 mm per week) resulted in COD removals of greater than 90% in the top 15 cm and greater than 99% after flow through 1.2 m of soil. Nitrogen removal varied from 30% at an effluent addition rate of 200 mm per week to 95% for 100 mm per week and virtually all the fats present in the effluent were removed in the top 15 cm of the soil (Tarquin 1974).

Some New Zealand meat processing plants use border dyke irrigation systems. These combine the benefits of overland flow with irrigation. Where low infiltration rates result in requirements for large land areas it has been suggested that a combination of irrigation and overland flow, where some of the effluent is collected and disposed of elsewhere, can be used (Bendixen *et al.* 1969).

2.4.4 Rapid infiltration

Rapid infiltration is the application of effluent at rates of 50 cm to several metres per week (Bouwer and Chaney 1974, Reed and Crites 1984). Effluent is applied to specially prepared infiltration beds (Figure 2.6) for several days or weeks. Under continuous inundation the infiltration rate gradually decreases, therefore, a period of infiltration must be followed by a drying period to allow infiltration beds to recover their permeability. Rapid infiltration provides groundwater recharge and some effluent treatment (Bouwer and Chaney 1974, USEPA 1976). The method requires soil and geological materials with rapid permeabilities and generally the infiltration beds are kept free of plant growth. Rapid infiltration has the lowest potential for removal of pollutants of any of the land waste treatment systems (USEPA 1976).

Rapid infiltration effectively removes SS, BOD and pathogens, but is less effective than irrigation at removing N, P, trace metals, and organic toxicants (Table 2.5). Treatment is accomplished by biological, chemical, and physical interactions in the soil matrix with the near surface layer being the most active (Reed and Crites 1984). The suspended solids, BOD and faecal coliforms are removed by the filtering action of the soil.



Figure 2.6 Rapid infiltration beds for sewage effluent treatment, Pauanui, New Zealand.

Nitrogen removal, of up to 80%, has been achieved by carefully controlling hydraulic loading cycles, recycling portions of the treated effluent that are high in N, decreasing the infiltration rate and supplying an additional carbon source (USEPA 1981). The main mechanism of P removal is adsorption with some chemical precipitation. Therefore the long-term P removal capacity is limited (USEPA 1981). The destination of the treated water may be either groundwater recharge or recovery for reuse by direct plant uptake, extraction for irrigation, or recharge of surface streams (Reed and Crites 1984).

Despite rapid infiltration being commonly used for disposal of sewage effluent (e.g. Lance *et al.* 1980, Tare and Bokil 1982, Darby *et al.* 1991), no reports of meat processing plant effluent being treated by rapid infiltration were found in the literature.

2.4.5 Disease control

Bacteria and viruses have been found to be low or absent after one to several metres of infiltration in all but very coarse-textured soils (Bouwer and Chaney 1974, Loehr *et al.* 1979). Although one or more metres of soil appear necessary for complete removal of bacteria, most organisms are removed in the top 1 cm of soil (Spyridakis and Welch 1976). Filtration by the soil, and in some cases, by an additional organic mat in the top 1 mm of soil, is the primary means of retaining bacteria in the soil. Adsorption to soil particles is the basic mechanism for the retention of viruses (Loehr *et al.* 1979, USEPA 1981). Desiccation, radiation, and exposure to adverse conditions may also contribute to removal of micro-organisms in land waste treatment (USEPA 1981, Reed and Crites 1984).

Pathogenic organisms can spread from a land treatment site through the air, particularly if the effluent is applied by sprinklers (Bouwer and Chaney 1974). Bacterial survival in aerosols from spray irrigation depends on the ultra-violet radiation intensity, humidity, and wind velocity. Fuller and Warrick (1985) demonstrated that the spray-mist zone in an 8-16 km/hr wind extends for about 46 m downwind from a 9 m spray radius. They concluded that no health hazard existed beyond the spray-mist zone. Reed and Crites (1984) noted that the concentrations of virus and bacteria in aerosols from land treatment are equal to, or less than, the concentrations from activated sludge plants. They suggested that because there were no adverse health effects associated with sludge plants, then there shouldn't be any for land treatment.

In overland flow systems, bacteria and viruses are removed primarily by settling and entrapment of suspended solids harbouring the micro-organisms. However, retention times in overland flow systems are normally too short to cause a substantial decrease in bacteria and virus numbers (Bouwer and Chaney 1974).

In New Zealand, where effluent irrigation systems are often part of an animal grazing regime, there has been concern about animal health. In a study of faecal coliform numbers on pasture, following application of meat processing plant effluent, Donnison and Cooper (1989) recorded a 99% decrease within 14 days after irrigation in all seasons of the year. This indicates that a 14 day stock withholding time should be adequate to prevent disease transmission from effluent. Bell and Bole (1978) found that it took 50 hours of bright sunshine to kill faecal coliforms on reed canary grass in Canada, and suggested a one week rest period prior to grazing. There is, however, some evidence that organisms may survive for longer periods in the soil. *Escheria coli* and *Streptococis bovis* were found to survive for periods of up to three months and one month, respectively, when added to sterilised soil stored at 10 °C (Guy and Visser 1979). Survival periods were shorter in high clay and low pH soils.

From a communicable disease standpoint, land treatment is considered to be less hazardous than disposal of sewage effluent and other wastes into rivers and streams (Bouwer and Chaney, 1974 after Bernarde 1973).

2.5 The effects of effluent on soil physical properties

2.5.1 Soil permeability

2.5.1.1 Introduction

Maintaining soil permeability is essential for the continued viability of an effluent irrigation scheme. Addition of organic matter to soils is generally expected to increase soil permeability as it contributes to increased porosity and structural stability (Khaleel *et al.* 1981, Reed and Crites 1984). Increases in soil permeability have been reported following additions of solid wastes (Khaleel *et al.* 1981), and for effluent additions (e.g. Mathan 1994). However, in some instances decreases in permeability have been shown to occur as a result of effluent addition (e.g. Lance *et al.* 1980, Clanton and Slack 1987). The main cause of decreasing soil permeability is the blockage of soil pores. Factors that result in soil pore blockage may be classified as physical, biological, and chemical (Berend 1967, Rice 1974). Each of these

mechanisms is discussed in the following sections. The remainder of this section provides an overview of the changes in permeability that have been reported.

Effluent may move into, and through, soil more slowly than water. For instance, Bouwer *et al.* (1974) reported a permeability for secondary-treated sewage effluent of about half that for water at the same site. Permeabilities for effluent as low as 10 percent of the water value have been reported (USEPA 1976). Therefore effluent should be used for field measurements of permeability if at all possible.

The decrease in soil permeability and the resulting slower rate of infiltration of effluent (compared to water) can lead to effluent surface ponding and increased runoff. Surface ponding may lead to rapid leaching of waste constituents due to flow through large macro-pores which would not conduct effluent, except in saturated conditions. Surface ponding will cause a decrease in biological activity associated with decreased gaseous exchange and development of anaerobic conditions (Overcash and Pal 1979). If anaerobic conditions occur they will decrease the rate of decomposition of the solids and odour and insect problems may develop (Bouwer and Chaney 1974). Increased runoff may lead to soil erosion and contamination of surface waters (Overcash and Pal 1979, Vinten *et al.* 1983).

Applications of oil, or fat-rich effluents such as meat processing plant effluent, may induce soil water repellency which also affects soil permeability. This is due to the hydrophobic nature of oils, and to the initial accumulation of hydrophobic mucilaginous substances associated with increased microbial activity. However, these effects are usually short-term (2-8 weeks) and it is generally considered that the long term effect of oil addition to soil is beneficial to soil physical properties as a result of increased biological activity (Overcash and Pal 1979). Gupta *et al.* (1977) observed a higher water repellency on soil samples treated with sewage sludge than those with low or no sludge added.

The processes of decline and recovery of soil permeability have been described for a variety of conditions. Thomas *et al.* (1966) reported that the infiltration rate decline under **intermittent** daily sewage spreading on a sand exhibited three phases:

1. a slow decline in infiltration rates under aerobic conditions with a drop from 500 to 100 mm hr⁻¹ over 200 days;
2. a rapid decrease under anaerobic conditions to about 1 mm hr⁻¹ in the next 50 days; and
3. a further gradual decline under anaerobic conditions.

Upon resting, the soil recovered back to an infiltration rate of about 50 mm hr⁻¹ in 25 days and to about 70 mm hr⁻¹ after 100 days (Thomas *et al.* 1966).

Thomas *et al.* (1966) found that the primary site of clogging was in the top 1 cm of the soil. They observed that iron, phosphate, total organic matter, polysaccharide and polyuronide all accumulated in the clogged layer and may have all contributed to the clogging. Thomas *et al.* (1966) also reported accumulation of sulphide but suggested that this was an indicator of anaerobic conditions, and not a cause of primary clogging. The mass of total organic matter present appeared to contribute significantly to clogging, since the recovery of the infiltration rate was accompanied by a decrease in the concentration of total organic matter in the soil.

Under **continuous inundation** a shorter-term pattern (Figure 2.7) has been reported for a range of effluents (Allison 1947, Okubo and Matsumoto 1979, Fuller and Warwick 1985, Miyazaki 1993).

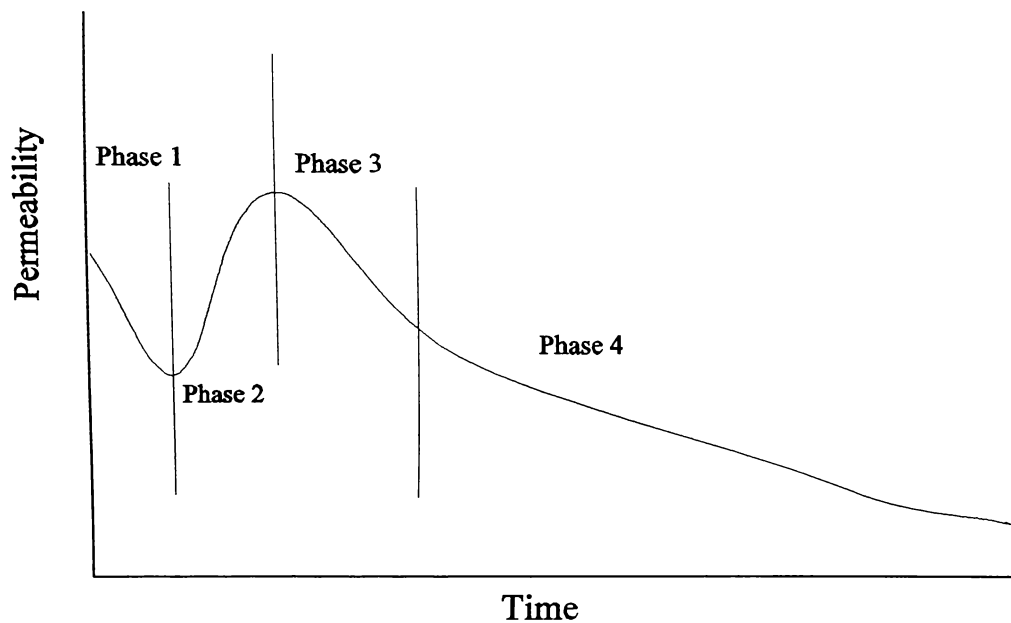


Figure 2.7 Changes in permeability of soil under continuous inundation (after Allison 1947, see text for definition of phases).

The phases shown in Figure 2.7 are explained as follows:

- Phase 1. a rapid decrease in the first 10 days or so. This has been attributed to aerobic microbial growth (Okubo and Matsumoto 1979), physical disintegration of aggregates (Allison 1947), and suspension of soil particles (Fuller and Warrick 1985).
- Phase 2. constant or increased infiltration rates between about 10 and 20 days, attributed to the dissolution of entrapped gasses (Allison 1947, Fuller and Warwick 1985).
- Phase 3. a rapid decrease in infiltration rates between about days 20 and 30. This was attributed to development of biological clogging under anaerobic conditions (Allison 1947, Okubo and Matsumoto 1979 and Fuller and Warrick 1985). This phase appears to equate to stage 2 of Thomas *et al.* (1966) with the development of anaerobic conditions

occurring more rapidly under continuous inundation than under intermittent irrigation.

- Phase 4. a continued slow decrease in infiltration rate. Allison (1947) suggested that biological clogging, aggregate disintegration as a result of prolonged submergence, and dispersion due to attack of microorganisms on organic materials that bind soil aggregates, may all contribute to this decrease. This phase probably equates to stage 3 of Thomas *et al.* (1966), described above.

A decline in soil permeability has been reported at dairy factory effluent disposal sites in New Zealand (Phillips 1971, Parkin and Marshall 1976, McAuliffe 1978) and in the United States (USEPA 1971), and at sewage disposal sites (Wilcock 1984, Cook *et al.* 1994).

In laboratory studies using undisturbed soil cores McAuliffe *et al.* (1982) found that a single application of simulated whey effluent resulted in approximately a 50% decrease in soil permeability within two days. Repetitive doses of effluent led to a decrease in soil permeability of over 99% in some cores. The decline was suggested to be a combination of both physical and biological blockage processes. Recovery of soil permeability following blockage was also observed. Cores which received a single application of simulated whey effluent, followed by water every second day, exhibited virtually complete recovery within two weeks. The high suspended solids effluent appeared to induce a longer-lasting blockage, as a period of up to 26 days was needed before the initial permeability was restored. Some cores receiving repetitive applications of simulated effluent showed no sign of recovery within 28 days of the final application. Soil permeability increases in the soil cores appeared to be the result of both, pore blockage removal and creation of new macropores. Of the mechanisms likely to form new macropores, earthworm activity appeared to be the most important (McAuliffe 1978).

2.5.1.2 Physical blockage of soil pores

As effluent moves into and through soil pores, suspended solids are removed and can,

at times, clog soil pores and thereby cause a decrease in the infiltration rate (Bouwer and Chaney 1974, Rice 1974, Loehr *et al.* 1979, USEPA 1976, Reed and Crites 1984, Vandevivere and Baveye 1992).

Three mechanisms that can limit particle movement into a soil were identified by McDowell-Boyer *et al.* (1986).

1. Surface crust formation. Larger particles accumulate on the surface, leading to a decrease in permeability.
2. Filtering. Particles small enough to enter the soil pore are mechanically removed by straining in small pores, with little decrease in permeability expected. Filtering near the surface may further restrict openings, leading to surface mat formation.
3. Physico-chemical forces. Very small particles, relative to soil pore size, can be removed by physical and chemical forces between particles and the soil aggregate surfaces.

Generally, in all but coarse sands and gravel, the suspended solids are filtered out at or very close to the soil surface where they tend to form a thin layer with low permeability. Fine suspended materials such as colloidal clay and algal cell particles may move deeper into the soil (Berend 1967, Bouwer and Chaney 1974). Vinten *et al.* (1983) observed that in a silt loam soil the coarse solids from a sewage effluent were filtered out in the top 10 mm of soil, while below this level finer solids were deposited by adsorption. There is a self-defence mechanism which prevents sub-surface clogging because surface clogging gradually decreases the rate and depth of penetration of particles (Berend 1967).

The soil can usually recover from clogging by organic materials, through natural decomposition processes during non-application or resting periods (Loehr *et al.* 1979, USEPA 1981, Vandevivere and Baveye 1992). If mineral solids are applied, periodic tilling of the soil may be necessary to break up the material and prevent clogging (USEPA 1976). Berend (1967) showed that thorough drying of the soil surface

effectively restored the seepage capacity of sand surfaces clogged with mineral material, provided the thickness of the surface layer did not exceed a few millimeters. Allowing a surface layer of organic materials to dry and crack has also been shown to restore soil permeability following inundation with sewage effluent (Rice 1974).

It has been observed that rapid infiltration basins experience less clogging following application of primary-treated effluent than when secondary-treated effluent has been applied (Rice 1974, Carlson *et al.* 1982). It was suggested that this was because the primary-treated effluent solids, which are larger than those in secondary-treated effluent, were retained at the biologically active soil surface where they became desiccated and decomposed relatively rapidly. The finer size of the suspended solids in the secondary treated effluent more easily penetrated the top soil layers, forming subsoil blockages, and did not degrade as rapidly (Rice 1974, Carlson *et al.* 1982), presumably due to less microbial activity at depth.

Physical pore blockage can be avoided by pretreatment to remove suspended solids (Bouwer and Chaney 1974, Loehr *et al.* 1979, McAuliffe *et al.* 1982). However, Berend (1967) reported that even a concentration of less than 100 g m^{-3} usually had a greater influence than other clogging factors (e.g. biological and chemo-physical).

Several experiments have shown that physical blockage of pores can be caused by sewage effluent, but the impact varies for different substrates and effluents. For example, in a silt loam soil, infiltration of 400 mm of sewage effluent, containing 39 g m^{-3} SS, caused the flow rate to decline to 20% of its initial value, with over 90% of the effluent SS filtered out. By contrast an effluent with 98 g m^{-3} SS, irrigated onto a coarse sand, had only 43% of the applied SS filtered out and the flow rate declined to only 75% of the initial infiltration rate (Vinten *et al.* 1983). Accumulation of suspended solids at the soil surface was shown, (using a scanning electron microscope (SEM) and ^{14}C labelled SS), to be responsible for the decline in infiltration rates. In another experiment, severe soil clogging occurred under domestic septic tank water effluent (SS of 75 g m^{-3}) application and in high volume greywater treatments (SS of 39 g m^{-3}), with negligible decline in permeability for tapwater and low-volume greywater treatments (Siegrist 1987, Siegrist and Boyle 1987). It was found that clogging was highly correlated with the cumulative loadings

of BOD and SS. Clogged surfaces exhibited accumulation of organic materials at the surface and in the top few millimetres of the soil. Soil clogging development was accelerated at higher loading rates and with more concentrated effluents. Siegrist (1987) suggested that soil clogging, as a result of application of domestic septic tank effluent, could be retarded by decreasing mass loading rates. This could be achieved by lowering hydraulic loading rates, or, by decreasing effluent suspended solid concentrations.

To maintain a rapid infiltration system, a suspended solids concentration of less than 10 g m^{-3} has been recommended (Rice 1974, Bouwer and Chaney 1974, Loehr *et al.* 1979). If effluent contains suspended solids in excess of 10 g m^{-3} , periodic removal of the sludge layer is required to avoid build-up of solids, and hence, a decrease in the infiltration rate (Bouwer and Chaney 1974).

Berend (1967) developed a model that relates changes in infiltration rates, as a result of physical pore blockage, to the suspended solids of the applied effluent. Berend observed that infiltration rates decrease linearly, if plotted against the cumulative height of the infiltrated water column. Similarly, Rice (1974) reported that the hydraulic impedance of the clogged layer was directly proportional to the total solids load. This is discussed further in Chapter 6.

Development of a surface layer of organic material does not always cause a decline in infiltration rates. For example, in an experiment where anaerobic swine lagoon effluent was applied to pasture, the cover crop was mowed but not removed. The cover-crop residue, along with the organic material in the applied effluent, created a thin organic mat on the soil surface. The mat did not appear to lead to physical pore blockage and may have been beneficial in dissipating the energy of the water from the sprinklers (Vanderholm and Beer 1970).

Physical pore blockage may also be caused by entrapped air bubbles (Vandevivere and Baveye 1992). For instance, Rice (1974) found that clogging developed below the surface, during long periods of intermittent inundation, and attributed it to entrapped, insoluble, gas bubbles. It was speculated that the gas may have been nitrogen which accumulated as a result of denitrification.

2.5.1.3 Biological blockage of soil pores

Microbial activity in soils receiving organic substances involves two processes - biodegradation of the added material, and, synthesis of organic matter, cells, tissues, gums and slimes (Fuller and Warrick 1985). Biological clogging occurs when bacterial growth or its by-products (polysaccharides, polyuronides and other organic compounds) decrease pore diameter. It usually occurs at the soil surface although it can be at any depth (Rice 1974, Bouwer and Chaney 1974, Thomas *et al.* 1966, Spyridakis and Welch 1976) and is a function of the waste organic material added and the soil pore space (Loehr *et al.* 1979). Biological clogging reaches a maximum when biological material fills all soil pores, giving a corresponding minimum permeability. In an Andosol this minimum permeability was about $2 \times 10^{-7} \text{ m s}^{-1}$ (Kawanishi *et al.* 1990). Biological activity may also lead to pore blockage as a result of production of gasses or due to the microbial destruction of materials that bind soil aggregates, therefore leading to disaggregation (Miyazaki 1993).

Increasing temperature may either cause an increase or a decrease in the development of soil pore blockage. Higher temperatures increase biological activity and, therefore, may increase soil pore clogging due to an increase in the amount of microbial material present. However, higher temperatures can also increase the rate of decomposition of organic material, and therefore decrease the amount of pore clogging. Polysaccharides are a major component in biological blockage of soil pores. Nevo and Mitchell (1967) reported that below temperatures of 20°C, decomposition of polysaccharides was inhibited but their synthesis continued slowly. Between 20 °C and 30°C, production and degradation rates of polysaccharides were approximately equal, and both rates increased with temperature. At 37°C, little polysaccharide was produced but the decomposition rate continued to increase. The findings indicated that soil clogging by polysaccharides may be of greater concern in cool, rather than warm climates (Nevo and Mitchell 1967). This suggestion was supported in an experiment where primary treated sewage effluent was applied to sand filters, at a rate of 20 cm day⁻¹, 5 days a week, with a daily application period of 2 hours. The physical condition of the filters did not deteriorate after 240 days at room temperature but when the experiment was repeated at 4 °C it resulted in failure in 10 days because of pore clogging (De Vries 1972). The clogging was found to

occur at the soil surface and was caused by a deposit of "sludge" sealing off the surface pores. The "sludge" may have been microbial polysaccharide or an accumulation of suspended solids material.

At temperatures below about 10 °C the microbial response has not always caused clogging. For example, soil clogging was found to increase with rising temperature under sewage effluent application (Gupta and Swartzendruber 1962) and following application of septic tank effluent to sand trenches (Kristiansen 1981). At 12 °C - 15 °C Kristiansen (1981) reported a clogged layer, of bacterial cells and slime, formed in the top 1 cm of the sand, whereas, no clear clogged layer was identified at temperatures that varied to as low as 4 °C.

Biological clogging is frequently associated with anaerobic soil conditions. Anaerobic conditions result in a lower rate of biological activity and therefore a tendency for sludge accumulation, and/or accumulation of polysaccharides. Anaerobic conditions, which give rise to soil biological clogging can result from hydraulic overloading, regardless of the BOD or organisms added (Spyridakis and Welch 1976). However, an excessive BOD load may also cause anaerobic conditions. Polysaccharides and polyuronides break down rapidly if aerobic conditions are restored (Nevo and Mitchell 1967, Spyridakis and Welch 1976).

There have been a number of investigations of biological pore blockage under anaerobic conditions, most using inundation of sand columns (Laak 1970, Kristiansen 1981, Taylor and Jaffe 1990). These studies have shown that clogging occurs mainly due to blockage by bacterial cells, and may cause a reduction in permeability of up to three orders of magnitude. A very small amount of bacterially produced slimy material may contribute to clogging by cementing together other particles such as bacterial cells and it has been suggested that that this may explain the reported correlations between clogging rate and polysaccharide content (Kristiansen 1981).

Bacterial soil pore blockage is not always limited to anaerobic conditions. Vandevivere and Baveye (1992) found that an obligately aerobic strain of bacteria (*Arthrobacter* AK19) was able to decrease permeability in sand columns by three to four orders of magnitude, in about one week, due to the formation of a thick, highly

porous, bacterial mat at the inlet end of the sand column. They found that clogging was mainly due to the bacterial cells, which tended to form large aggregates that impeded water flow, rather than uniform biofilms. They also reported that extracellular polymers were not necessary to induce severe bacterial clogging. Extracellular polymers were produced and appeared to cause additional clogging when the C/N ratio was high (77) but at lower C/N ratios (< 39) they seemed absent from the clogged layers. A 78% decline in infiltration rates under aerobic conditions over a three year period as a result of irrigation of secondary treated sewage effluent was reported by Cook *et al.* (1994) at the Rotorua (New Zealand) sewage irrigation site. They attributed the decline to biological clogging.

Algal growth on the soil surface may, in some instances, lead to increased infiltration rates during inundation because the algal mat becomes buoyant, thereby freeing the soil surface from clogged materials (Rice 1974). However, pore blockage from algal cells has been observed, for instance, at a rapid infiltration site in Arizona (Reed and Crites 1984).

2.5.1.4 Chemical blockage of soil pores

Chemical phenomena that affect soil permeability involve changes in the swelling properties of soils, and the dispersion of colloidal particles, brought about by variations in the composition of the liquid phase (Vandevivere and Baveye 1992). Effluent with a high sodium adsorption ratio (SAR) can cause deflocculation of clay minerals leading to a decrease in soil permeability, poor soil aeration and difficulty in seedling emergence (USEPA 1981, Reed and Crites 1984). This may be a problem with effluents from some fellmongery plants (Tarquin 1974).

As a general rule, an effluent SAR > 15 is considered unacceptable. However there is a difference depending on the dominant clay type; in kaolinitic soils the SAR can be as high as 20 before serious swelling problems occur, but SARs of 8 - 10 will cause swelling problems in soils where montmorillonite is dominant (Ferguson 1976). A soil exchangeable sodium percentage (ESP) > 10 may cause difficulty in fine-textured soils whereas coarse-textured soils may not show a decline in permeability as long as the ESP is not greater than 20 (USEPA 1981, Reed and Crites 1984).

2.5.2 Aggregate Stability

The main agents of soil aggregate stabilisation are organic materials, including the products of decomposition of plant and animal remains, the microorganisms themselves, and the products of microbial synthesis. Organic binding agents of aggregate stability can be classified into three groups (Tisdall and Oades 1982):

1. Transient, mainly polysaccharides.
2. Temporary, roots and fungal hyphae.
3. Persistent, resistant aromatic components associated with polyvalent metal cations, and strongly sorbed polymers.

Inorganic cementing agents such as iron and aluminium oxides and clays also provide aggregate stabilisation (Lynch and Bragg, 1985).

Soil aggregate stability has been shown to increase as a result of addition of organic materials such as animal manures, compost and sewage sludge (Klute and Jacob 1949, Pagalai *et al.* 1981, Lynch and Bragg 1985, Kinsbursky *et al.* 1989). Improved soil aggregate stability leads to increased macropore space, aeration, and root growth. This may help stabilise soils against erosion (Loehr *et al.* 1979, Khaleel *et al.* 1981) and some investigators have reported decreased runoff volumes from waste-incorporated plots (Khaleel *et al.* 1981).

It is difficult to relate changes in aggregate stability to the activities of specific microorganisms. For instance, in a study of the effects of organic amendments on aggregate stability and microbial activity, Griffiths and Jones (1965) found that different treatments produced their own characteristic microbial populations. Following addition of sewage sludge to a structureless, loess soil, Metzger *et al.* (1987) suggested that fungal carbohydrates and physical entanglement by mycelium may act as binding mechanisms involved in the formation of water-stable aggregates. In a later study, Kinsbursky *et al.* (1989) reported that, in sludge amended soils, cementing by fungal carbohydrates is a relatively more important binding mechanism

than physical entanglement by mycelium.

It has been suggested that humic substances are the predominant binding agent in soil microaggregates. This was substantiated by Piccolo and Mbagwu (1990) in a study of aggregate stability of microaggregates from soils treated with a variety of organic waste amendments. They showed a significant positive correlation between microaggregate stability and humic acids, and with humic plus fulvic acids, but no significant relationship with total organic matter.

A comparison of the effects of meat processing plant effluent and water, on aggregate stability, on a Lismore soil, in the South Island of New Zealand, was undertaken by Churchman and Tate (1986). They reported that effluent addition did not affect macroaggregate stabilities as measured by wet sieving, but it increased the stability of clay aggregation as measured after selective disaggregation treatments. They recorded highly humified organic matter associated with the soil clays as a result of meat processing plant effluent treatment. Churchman and Tate (1986) observed (using a scanning electron microscope) that a "web" (suggested to be polysaccharide) formed over the soil particles which became firmly bound after drying. The web was more continuous on the effluent treated soil than the irrigated or control soils.

2.5.3 Bulk density

Addition of organic wastes, to soil, generally causes an increase in soil organic matter and therefore a decrease in soil bulk density. Khaleel *et al.* (1981) derived a linear regression equation ($r^2 = 0.69$) between increases in soil organic carbon and reported decreases in soil bulk density as a result of solid organic waste application. They attributed the decrease in bulk density to the dilution effect resulting from the mixing of the added organic matter. However an increase in aggregation and, therefore, an increase in porosity would also be expected to have contributed to the decrease in soil bulk density.

In New Zealand M^cAuliffe (1978) found that bulk density decreased at some whey disposal sites and not others. Marris (1992) found no difference in soil bulk density for two soils to which whey had been applied.

2.5.4 Other soil physical effects

Sewage sludge, compost, meat processing plant effluent, and manure additions to soil have all been reported to increase soil water retention (Gupta *et al.* 1977, Kladienko and Nelson 1979, Khaleel *et al.* 1981, Ross *et al.* 1982) which was attributed to increased aggregation and therefore increased total pore space by Khaleel *et al.* (1981).

Accumulation of soil organic matter and an increase in soil moisture retention, may also lead to a decrease in soil penetration resistance. Stevens *et al.* (1988) found that applications of pig slurry, at rates greater than 250 m³ ha⁻¹ year⁻¹ for a total of eight years, caused a significant decrease in soil penetration resistance at a depth of 10 to 15 cm.

Effluent application can lead to a deterioration in soil properties. For example, increased pasture growth sometimes encourages higher stocking rates, which was observed to cause increased problems of pugging in soils with "weak" structures (such as Gley Soils and soils with high clay contents) at dairy factory effluent disposal sites (Wells and Whitton 1966).

Soil temperature changes have been observed as a result of solid organic waste addition. Gupta *et al.* 1977 showed that temperature fluctuations were greater on plots receiving sewage sludge, than on a control treatment. This was attributed to an increase in the specific heat capacity and a decrease in the thermal conductivity of the soil which received the sludge.

2.6 The effects of effluent addition on soil chemical properties

There is a large body of literature on the effects of effluent on soil chemical properties. This section briefly summarises some of these effects, particularly those reported in New Zealand.

In an investigation of three New Zealand meat processing plant sites, Wells and

Whitton (1970) reported that effluent irrigation raised soil nitrogen levels and increased the base saturation (by increasing Na and K) of topsoils. At the Fairton meat processing plant (in the South Island of New Zealand) where effluent irrigation nutrient loadings have been in excess of plant requirements, Keeley and Quin (1979) found that soil C, N, Ca, K and P levels had risen, but, that there was no change in soil pH, despite 90 years of application of pH 10 effluent. Similar effects have been reported for soils irrigated with dairy factory effluent (Wells and Whitton 1966), and for irrigation of whey (M^cAuliffe 1978).

The groundwater at the Fairton meat processing plant had a similar chemical composition to the effluent, except that nitrate-N was higher (at the expense of NH₃) and some N was not accounted for (Keeley and Quin 1979). It was suggested that considerable nitrification, and some denitrification occurred (Keeley and Quin 1979). In a trial where meat processing plant effluent was applied to an Allophanic Soil in the Waikato, Russell *et al.* (1984) found that losses of nitrate to the groundwater increased as the amount of N applied was increased. They suggested that total N losses to groundwater, following effluent applications of up to 1500 kg N ha⁻¹ yr⁻¹, were no greater than those expected from intensively grazed pasture.

A New Zealand example of the effects of sewage irrigation on soil chemical properties is provided by studies of the Templeton sewage irrigation scheme in Canterbury, where soils have been irrigated with treated domestic sewage effluent since 1958. In 1968 the site received 840 mm of effluent and 760 mm of rain, resulting in drainage of 900 mm (Quin and Forsythe 1978). This caused an increase in soil nutrient status, and an increase in pasture production, compared to a non-irrigated control (Quin and Woods 1978). Irrigation at Templeton has had little effect on the heavy metal composition of the soil or pasture (Quin and Sayers 1978). Losses of P in the drainage were low, but percentage losses of all other nutrients were high. Na displaced Ca and Mg from the soil, and nitrate losses were estimated at 180 kg ha⁻¹ yr⁻¹ of which 100 kg ha⁻¹ yr⁻¹ were attributed to urine patches (Quin and Forsythe 1978).

2.7 Plant responses to effluent application

Irrigation of effluent often results in increased dry matter yield. Increased pasture production has been reported for sites under dairy factory effluent irrigation and attributed to the high levels of nitrogen and potassium added in the effluent (Wells and Whitton 1966). Increases in pasture production of from 81 to 174 per cent, have been recorded at New Zealand sites receiving regular applications of meat processing plant effluent, throughout the growing season (Russell and Cooper 1987).

Application of meat processing plant effluent, with high N concentrations, can cause increased concentrations of nitrate in plants which may endanger stock health. Russell (1986) found that herbage from anaerobically treated effluent contained higher concentrations of nitrate-N than herbage irrigated with primary treated effluent. Based on "safe" nitrate levels in herbage the upper loading limit would be about 500 kg N ha⁻¹ yr⁻¹ for anaerobically treated effluent and about 1000 kg N ha⁻¹ yr⁻¹ for primary treated effluent (Russell 1986). Addition of primary treated meat processing plant effluent at rates of 50, 100 and 200 mm per week was found to inhibit grass seedling establishment (Tarquin 1974).

Pasture "burning" (i.e. dieback as a direct result of effluent contact with the foliage), as a result of whey application, was observed at all sites investigated by M^cAuliffe (1978) and has been reported elsewhere by Parkin and Marshall (1976). This has been attributed to various factors such as; insufficient dilution, effluent that has a high pH, effluent that had been allowed to go "septic" as a result of sitting in lines or holding tanks, effluent that was too hot, and spraying onto pasture that was "too long".

Pasture "pulling" (where grazing animals uproot plants) at whey application sites, was reported by M^cAuliffe (1978). He suggested that this was probably the result of loss of soil strength due to high moisture content and a tendency for plants to only develop shallow root systems under effluent irrigation.

2.8 Design and management of land waste treatment systems

2.8.1 Introduction

There are a number of guidelines available for design and management of land waste treatment systems (e.g. Overcash and Pal 1979, Loehr *et al.* 1979, USEPA 1981, Reed and Crites 1984, Vanderholm 1984). None are written specifically for meat processing plant effluent, and only the report of Vanderholm (1984) relates specifically to New Zealand conditions.

Proper design of land application facilities must relate the fate of pollutants to the properties of the soil with which they may interact and minimise the fraction of contaminants leaching into the groundwater (Loehr *et al.* 1979). The capacity of various land areas to accept, conduct and purify wastes varies widely, and good methods for determining these capacities are of crucial importance when evaluating land suitability for liquid-waste application (Bouma *et al.* 1983). Many workers have recommended that aerobic soil conditions should be maintained, surface ponding avoided and rest periods provided to allow the soil to dry and recover (e.g. Nevo and Mitchell 1967, De Vries 1972, Loehr *et al.* 1979, McAuliffe *et al.* 1982).

2.8.2 Effluent loading rates

The effluent loading rate (i.e. the total volume of effluent applied over a given time period) on a soil is usually limited by either the hydraulic capacity of the soil or the N-removal capacity of the soil-vegetation matrix (USEPA 1981, Reed and Crites 1984). A method for calculating the loading rate, based on hydraulic or N limitations, is given in USEPA (1981), and Reed and Crites (1984). In New Zealand, nitrogen is generally considered to be the limiting factor for meat processing plant effluent application (Russell *et al.* 1988, Russell and Cooper 1992). Design criteria for N application are given in Russell *et al.* (1988).

In systems with minimal pretreatment, the level of suspended solids may be the limiting design parameter, especially if the solids are slowly degradable and accumulate and clog the soil surface (Reed and Crites 1984). This may be the case

at some New Zealand meat processing plant effluent irrigation sites where effluent receives only contra-shear sieving prior to land application. Infiltration rate loss has caused problems at a number of New Zealand meat processing plant sites. For example, the Kaiapoi meat processing plant, in Canterbury, was forced to stop irrigating effluent to allow infiltration rates at the site to recover. Declining infiltration rates are more likely to be a problem in winter than summer, due to the lower temperatures. USEPA (1976) suggest that loading rates in winter should probably be decreased to about half those in summer to allow for slower drying rates and decreased biological activity.

The BOD of an effluent could also potentially limit the effluent loading rate in a soil system. As organic matter addition increases, soil respiration also increases until a maximum rate of oxidation is reached. Although the rate of organic carbon oxidation in soils is known to be high, limitations for effluent and sludge applications are not well established. However it is likely that factors such as soil permeability and nitrogen control will limit waste application rates long before maximum organic loading capacities are reached (Loehr *et al.* 1979). Phillips (1971) suggests that, for New Zealand dairy factory effluent, the daily average BOD application should not exceed 170 kg ha⁻¹ and should preferably be kept below 110 kg ha⁻¹.

2.8.3 Effluent application rates

Application rate refers to the rate at which effluent is irrigated onto the soil. The ideal rate depends largely on soil hydraulic properties. Many methods are available for measuring soil hydraulic characteristics and for calculating soil moisture regimes. However, there is as yet no generally accepted procedure for defining the capacity of a soil to accept, conduct, and purify liquid wastes (Bouma *et al.* 1983). This may be due to a number of factors (Bouma *et al.* 1983):

1. Estimates of soil permeability have poorly defined physical interpretation.
2. Permeability measurements are cumbersome and costly.
3. The dynamic character of the processes involved has sometimes been ignored,

as research has focused on obtaining one characteristic value for a given soil, such as one percolation or hydraulic conductivity rate. These values are inadequate for analysing transient processes that occur during intermittent applications of waste.

4. Simulation methods usually assume non-swelling soils without continuous macropores.
5. Emphasis has been placed on disposal rather than purification aspects of liquid movement. Excellent disposal may be associated with poor purification, therefore, both aspects need to be considered together when defining optimal application regimes.

The effluent application rate should be less than the soil infiltration rate. Theoretically this will prevent surface runoff when applying effluent to saturated soils (Vanderholm 1984). It has been suggested that the short term change in infiltration rate should be measured, when effluent is applied, and design sprinkler application rates should then be selected on the basis of the infiltration rate expected at the end of the application period (USEPA 1981). Spatial and seasonal variability should also be considered when undertaking infiltration rate measurements (Phillips 1971).

Recommendations for the effluent application rate (relative to the infiltration rate of water) vary widely. Vanderholm and Beer (1970) suggested that effluent irrigation rates should be 50 - 70% of the clean water infiltration rate. However application rates as low as 5% of the clean water infiltration rate have been suggested for septic tank effluent (Loehr *et al.* 1979). Vanderholm (1984) gave a recommended maximum effluent application rate, based on soil texture and slope (Table 2.6). Vanderholm derived the values given in Table 2.6 by reducing the recommended water irrigation rate (New Zealand Standard 5103, 1974), by 30% to allow for the "effects" of effluent.

For sloping soils Phillips (1971) suggested that the design application rate should be adjusted by a factor of 0.75 for 5-8% slope, 0.6 for 8-12% slope and on slopes greater than 12% irrigation should be avoided.

Table 2.6 Estimated maximum hydraulic application rates (mm hr⁻¹) for land application of effluent (after Vanderholm 1984).

Soil texture	slopes	slopes	slopes
	0-8°	9-12.5°	> 12.5°
Sands, light sandy loam, uniform in texture to 1.82 m, pumice.	22	18	14
Sandy loams to 0.6 m over-laying a heavier subsoil	14	12	9
Medium loams to sandy clays over a heavier subsoil	12	9	7
Clay loams over a clay subsoil	9	7	5
Silt loams and silt clays	7	6	4
Clays	5	4	3
Peat	12	-	-

2.8.4 Rest periods

A period of non-application is considered necessary to allow the soil to dry and re-aerate following effluent application. Drying restores the infiltration rate (Rice 1974, Bouwer *et al.* 1974, USEPA 1976) allowing any surface clogging layer to dry, crack, decompose or dissipate (Loehr *et al.* 1979, Bouwer and Chaney 1974, Fuller and Warrick 1985). The length of the rest period depends on the soil properties, land application process, waste characteristics, climatic condition, crop, and time of year. It may range from a day or less to several weeks. Fuller and Warrick (1985) suggested that there seems to be no single rest period that is suitable for all sites or even for a given effluent quality. As a preliminary estimate the removal, between effluent applications, of 30% of the available water storage of the 1.2 m profile should be adequate for the high-rate irrigation process (USEPA 1976).

The length of time the water remains in the soil affects the amount of waste constituents that can be removed from the effluent. This should be considered in determining application rates and rest periods (Loehr *et al.* 1979). Installation of tile

drains may hasten recovery to aerobic conditions and thus help prevent clogging of soil pores (Vanderholm and Beer 1970) but it will minimise the interaction between the solution and the soil solid phase, thereby increasing the likelihood of leaching.

In making recommendations for irrigation of dairy factory effluent, in New Zealand, Phillips (1971) suggested that the preferable irrigation interval is about three weeks (although it could be shortened in the summer when higher evapotranspiration rates dry the soil more quickly). This allows livestock to effectively graze the paddocks between irrigation events. The combination of small frequent applications of effluent may give slightly better overall treatment efficiency as reported, for instance, for irrigation of anaerobic swine lagoon effluent (Vanderholm and Beer 1970).

2.8.5 Site management and monitoring requirements

Very little information pertaining to crop and animal management that is recorded in the literature has direct relevance to New Zealand because New Zealand soils, climate and pastoral farming systems are different from those of other countries. Most New Zealand meat processing plants manage their irrigation sites based on local experience, gained by trial and error (Chapter 4).

It has been suggested that in order to avoid severe soil compaction and decreased infiltration rates, cattle or sheep should not be allowed onto saturated soils and rotations should be managed so that effluent can be applied immediately after stock are removed (USEPA 1981, Reed and Crites 1984). Ideally grass should be 5 - 8 cm long at the time of spraying to allow penetration of sunlight which maximises drying and, therefore, speeds up site recovery (Phillips 1971).

After installation of an effluent irrigation system, good management and monitoring of the system is essential so that undesirable performance can be corrected before serious damage occurs (Bouwer and Chaney 1974). The broad objectives of monitoring are to determine if the effluent quality requirements are being met, if any corrective action is needed to protect the environment or maintain the effluent treatment capacity of the system and to aid in system operation (USEPA 1981, Bouwer and Chaney 1974). The soil, vegetation and groundwater should be included

in a monitoring programme (USEPA 1981) and compared with the effects of alternative land uses in the area (Russell and Cooper 1987).

2.9 Conclusions

Land treatment and disposal of effluent have the advantages of utilising and recycling some of the nutrients in the effluent and avoiding discharge directly to waterways. The land waste treatment methods, that have been used, are overland flow, irrigation and rapid infiltration. Irrigation, at rates exceeding plant nutrient requirements, is the method of land disposal most commonly employed by the New Zealand meat industry. Irrigation provides the most effective effluent treatment and, providing direct macro-pore flow is avoided, is capable of removing virtually all the applied suspended solids from effluent. It has been shown to be effective in removing BOD, P, trace metals, virus, and bacteria, and can be effective in removing N and cations, depending on application rates and load.

Soil properties determine the effectiveness of soil for effluent disposal, both with regard to the soil's ability to accept and transmit effluent and its ability to remove or decompose suspended solids, nutrients and other contaminants from the effluent. Soil micro-organisms are responsible for removing BOD and decomposing added organic materials. There is often a significant increase in soil microorganism numbers and activity following effluent application. This is usually confined to the top few centimetres of soil. The rate of degradation of added material is considerably lower at temperatures below 15-20 °C. At cooler temperatures (less than about 15 °C) microbial production of polysaccharide continues while degradation is inhibited, which may contribute to soil pore blockage.

Maintaining the soil's effluent infiltration capacity is vital for an effluent irrigation scheme's viability. Effluent irrigation may increase soil hydraulic conductivity due to an increase in aggregate stability and porosity. Effluent addition may, however, cause a decrease in soil hydraulic conductivity due to blockage of soil pores by suspended solids from the effluent, blockage of soil pores by microbial material that develops in response to effluent addition, or dispersion of clay minerals causing loss of soil structure and porosity as a result of addition of effluent containing high

concentrations of sodium.

Physical pore blockage usually occurs at, or very close to, the soil surface where the suspended solids are filtered out as the effluent moves into the soil. It has been reported at a number of sites, worldwide, and is of particular concern for rapid infiltration systems. A number of models have been developed to describe the occurrence of physical pore blockage. Infiltration rates that have declined due to physical pore blockage will often recover if soils are given "rest periods" and allowed to dry. Organic matter will decompose and inorganic matter shrinks and cracks, during the rest periods, allowing infiltration rates to recover.

Biological blockage of soil pores may be the result of the physical presence of microorganisms or it may be due to the accumulation of by-products of bacterial growth such as bacterial slimes, including polysaccharides and polyuronides. Anaerobic conditions lead to very rapid decreases in hydraulic conductivity due mainly to polysaccharide accumulation and a decline in the biological breakdown of added materials. Hydraulic overloading by itself can produce anaerobic conditions and clogging within the soil regardless of the BOD or organisms added. Biological blockage has been shown to also occur under aerobic conditions.

Land waste treatment systems are complex, with many interactions occurring which are influenced by a large number of variables including effluent, soil, site, and climate properties. The occurrence of both physical and microbial pore blockage as a result of effluent application is well documented. However there is little information available on the specific factors that influence the development of pore blockage or on the relationship between the physical and biological processes that are involved. Little of the information that is available relates directly to meat processing plant effluent, either internationally or within New Zealand, or to the conditions encountered at New Zealand effluent irrigation sites.

Chapter 3: Methods

3.1 Introduction

The methods described in this chapter are the general methods that were used in more than one experiment. Methods specific to only one chapter are described within that chapter as are details such as the number of replications used.

3.2 Soil profile descriptions

Soil profile descriptions were carried out following the methods of Taylor and Pohlen (1979). Soil colours were determined by comparison with standard soil colour charts. Soil Horizon nomenclature is that of Clayden and Hewitt (1989).

Soil classifications are given for the current New Zealand system after Hewitt (1992). New Zealand genetic soil classifications follow Taylor and Pohlen (1979) and USDA Soil Taxonomy classifications were determined using the procedures of Soil Survey Staff (1990).

3.3 Soil physical properties

3.3.1 Soil hydraulic conductivity

Over the course of this study, different methods were used for measuring or estimating soil hydraulic conductivity, depending on the experimental design and the availability of equipment. Each of the methods used is described below and the advantages and disadvantages of each method are discussed.

3.3.1.1 Laboratory method

Hydraulic conductivities were measured following an adaptation of the method of Klute and Dirksen (1986). Soil cores were set up with containers of water supported over them (Figure 3.1) supplying a constant head.

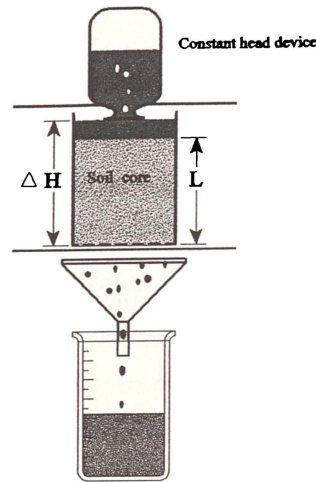


Figure 3.1 Constant head method for measuring permeability.

The volume of water flowing from the core with time is measured. This method is a direct application of Darcy's law where hydraulic conductivity is calculated (after Klute and Dirksen 1986) as:

$$K_{\text{sat}} = (Q/A)(L/\Delta H) \quad (3.1)$$

Where Q = volume of water collected/time taken (L^3T^{-1}),

A = x-sectional area of the core (L^2),

L = length of soil core (L), as illustrated,

ΔH = change in hydraulic head (H), as illustrated.

This method is easy to use and reasonable numbers of replications are possible. However conditions in the laboratory cannot reproduce field conditions.

3.3.1.2 Field methods

a. Permeability estimation

Permeability class estimates were made using the method of Griffiths (1985). The method utilises field moisture, texture, structure, penetration resistance, semi-confined

shear vane (degree of packing), biopore and coating observations to give an estimate of soil "permeability classes" (Table 3.1). The advantages of the method are that it provides a fairly replicable method of estimating permeability classes in the field without the need for time-consuming measurements. It also avoids the requirement for large volumes of water in the field. Estimates of the permeability class can be made for each horizon within the soil, which is usually beyond the scope of all but the most detailed measurement programmes. It is, however, only an estimate, but given the temporal and spatial variability in soil permeability measurements, it provides a reliable guide to the permeability status of a soil, as demonstrated, for example, in New Zealand Soil Bureau (1986).

Table 3.1 Soil permeability classes (after Griffiths 1985).

Permeability Class	Description	Infiltration rate	
		mm hr ⁻¹	m s ⁻¹
1	very slow	< 1	< 3 x 10 ⁻⁷
2	slow	1-4	3 x 10 ⁻⁷ - 1 x 10 ⁻⁶
3	moderately slow	5-19	1 x 10 ⁻⁶ - 5 x 10 ⁻⁶
4	moderate	20-64	5 x 10 ⁻⁶ - 2 x 10 ⁻⁵
5	moderately rapid	65-129	2 x 10 ⁻⁵ - 4 x 10 ⁻⁵
6	rapid	130-250	4 x 10 ⁻⁵ - 8 x 10 ⁻⁵
7	very rapid	>250	>8 x 10 ⁻⁵

b. Disk permeameter

A disk permeameter (Perroux and White 1988) was used to measure both soil surface saturated hydraulic conductivity (K_{sat} , Figure 3.2) and unsaturated hydraulic conductivity at a tension of 40 mm (K_{40}).

To measure K_{sat} the surface vegetation was clipped and the steel ring was pushed about 4 mm into the soil. To prevent leakage the outside of the ring was sealed with bentonite. The permeameter was then placed on the steel ring. Water flow was started and the change in water reservoir level was measured with time. As many readings as possible were made in the first few minutes (from which sorptivity can be calculated) and then groups of 10 or so readings were made periodically until steady state was reached. It usually took several hours to reach steady state and the

water reservoir was refilled as necessary.

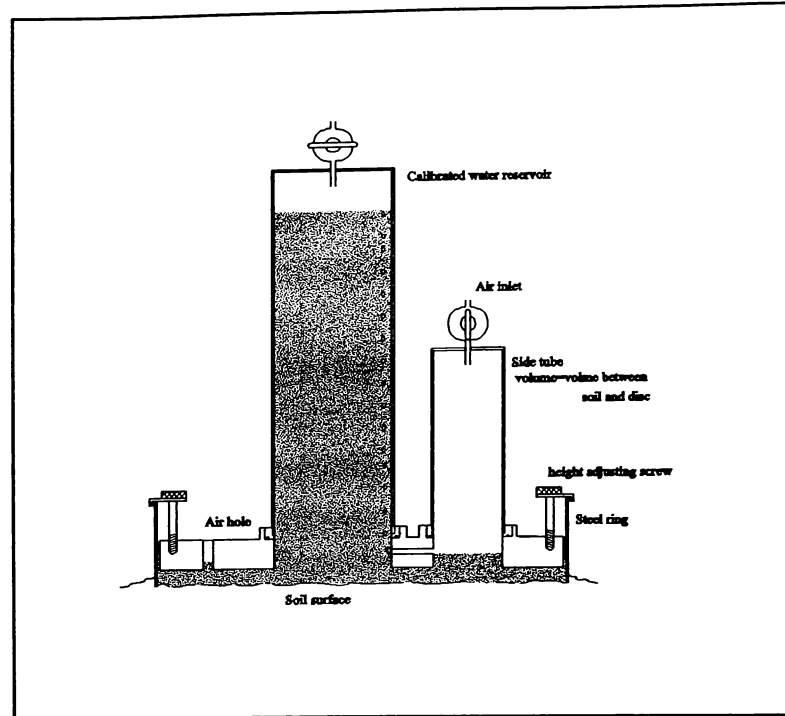


Figure 3.2 Disk permeameter for measuring saturated hydraulic conductivity (after CSIRO 1988).

Calculation of S and K is based on Equation 2.3 (Section 2.3.2). For a short time after water application commences, commonly the first minute or two, the sorptivity is the predominant component of flow and cumulative infiltration, I , can be assumed to be equal to $St^{1/2}$. To determine the sorptivity (S_o) a graph of I versus $t^{1/2}$ was drawn, for the first few minutes of water flow, and the sorptivity was determined as the slope of the straight-line part of the graph. At longer times, K was calculated as (CSIRO 1988):

$$K_o = i - 4bS_o^2/\pi r_o(\theta_o - \theta_n) \quad (3.2)$$

where

- i is the infiltration rate
- b is a constant determined as 0.55,
- S_o is the sorptivity
- r_o is the radius of the ponded area,
- θ_o is the volumetric moisture content at the measurement potential,
- θ_n is the initial volumetric moisture content.

The disk permeameter for unsaturated hydraulic conductivity measurements utilises

a bubbling tower with an adjustable water level to supply a negative head to the water reservoir. Measurements were made in the same way as described above for saturated conditions, except that a bed of sand was used to provide contact between the base of the permeameter and the soil surface.

The advantages of the disk permeameter are that it provides a method to measure unsaturated hydraulic conductivities at a range of tensions, it requires less water than alternative field measurement techniques and it provides a convenient means of measuring water volumes. However, with only one instrument available, and several hours required per measurement, the number of replications that can be undertaken is limited. Field infiltration rates are variable, therefore, a large number of replications are preferable. A further disadvantage is the sensitivity to the volumetric moisture content near the soil surface (recommended top 5 mm) soil. Many New Zealand soils under pasture have a thin organic debris layer at the soil surface which can have a porosity and bulk density that is different from underlying soil, and accurate determination of soil properties in the thin surface layer can be difficult.

c. Twin Rings

The twin ring method (Scotter *et al.* 1982), for measuring saturated hydraulic conductivity utilises two rings of different diameters. The steady state infiltration rate of ponded water is measured in each ring. In smaller rings sorptivity tends to be the dominant component of the infiltration rate, whereas in larger rings the K_{sat} component predominates. Therefore by using rings of different sizes a simultaneous equation can be solved to give both S and K . The hydraulic conductivity was calculated as follows (Scotter *et al.* 1982):

$$K = (q_1 r_1 - q_2 r_2) / (r_1 - r_2) \quad (3.3)$$

Where q_1 and q_2 are the steady state flux densities and r_1 and r_2 are the radii of the rings used. A number of replicates were used to measure q and the mean used in the calculations.

Providing the frequency distribution is approximately normal, an estimate of the standard error of K (SE) is (Scotter *et al.* 1982):

$$SE = [(r_1 s_1)^2/n_1 + (r_2 s_2)^2/n_2]^{1/2} \quad (3.4)$$

where s_1 and s_2 are the standard deviations of q_1 and q_2 respectively, and n_1 and n_2 are the number of replicate measurements.

Rings of 11, and 35 cm diameter were carefully pushed, up to 1 - 2 cm, into the soil surface and ponded to a depth of about 1 cm. Any leaks around the edges were sealed using bentonite on the outside of the rings. The water level was maintained in the rings for an hour or two and then the volume of water infiltrating was measured for a unit time, using a precise water level marker, a measuring cylinder and stopwatch, usually with about 10 replicates for each ring. Measurements were repeated periodically until steady state was achieved.

An advantage of this method over the disk permeameter is that it allows many replicates to be made at the same time, as construction of rings is not difficult or expensive. It is also suited to making measurements using effluent as well as water, whereas the disk permeameter's mesh would be blocked by effluent suspended solids.

3.3.2 Bulk density

Soil dry bulk density (ρ_b) is the ratio of the mass of dry soil to the total volume of soil. Soil dry bulk densities were measured following the methods of Burke *et al.* (1986) using cores (5 cm deep and 5 cm in diameter), where possible, and sand replacement on stony soils.

3.3.3 Aggregate stability

The aggregate stability in water, of soil from cores (Chapter 5), was measured by moistening 2 - 4 mm sized air-dry aggregates by placing them onto moist filter paper. The moistened aggregates were then placed on a sieve set and immersed in water and raised and lowered 4 cm, 30 times per minute, for 30 minutes.

The mass of aggregates retained as a percentage of the total weight of soil added was calculated as:

$$\text{Water stable aggregate \%} = \sum [100(a_i - b_i)/(c/mf-s)] \quad (3.5)$$

where a_i = mass of soil on sieve i , b_i = mass of sand on sieve i , c = mass of air dry soil added, mf = moisture factor, s = total mass of sand in the sample.

3.3.4 Particle size distribution

Particle size distribution refers to the relative proportions of sand, silt and clay in a soil. These were estimated in the field, by hand texture, and measured in the laboratory using the hydrometer method (Gee and Bauder 1986).

3.3.5 Moisture retention

Moisture retention describes the relationship between matric potential and soil water content. The moisture contents at matric potentials of less than -100 cm were determined following the "tension method" (Haines apparatus) of Burke *et al.* (1986). Higher matric potentials were determined using pressure plates, following the "gas pressure method" of Burke *et al.* (1986). Samples were approximately 5 cm in diameter and 1 cm in depth.

3.4 Soil chemical properties

Total nitrogen was determined following the Kjeldahl method. Approximately 0.5 g of finely ground, air dried, soil was weighed into a 50 ml Kjeldahl flask. A small amount of distilled water was added to moisten the soil, then one kjeldahl catalyst tablet and a speck of selenium were added. Five ml of concentrated H_2SO_4 was added and the sample was digested on the digestion stand until the mixture decolourised. It was then heated for a further 30 minutes. The sample was cooled then a further 20 ml of distilled water was added, the contents transferred to a 50 ml volumetric flask and made up to the mark. This was shaken vigorously then left to stand overnight. A 10 ml aliquot was pipetted into a Markham steam distillation

apparatus and approximately 20 ml of 40% NaOH was added. Ten ml of 1% boric acid and 5-6 drops of bromocresol green-methyl red mixed indicator were added to a conical flask which was placed under the delivery tube of the Markham steam distillation apparatus. Steam distillation was carried out until 20-25 ml of distillate had been collected. The distillate was then titrated against 0.01 M HCl to a neutral grey colour and corrected for reagent blank.

Organic carbon was determined following the method of Schollenberger as described by Allison 1965. Approximately 0.5 g of finely ground soil was weighed into a 500 ml flask. Potassium dichromate (0.785 g) was added and about 10 ml of distilled water was used to wash any soil or dichromate from the sides to the bottom of the flask. A blank with no soil was also prepared. Concentrated sulphuric acid (20 ml) was added to all flasks and they were warmed, without boiling, for half an hour. The mixture was allowed to cool, then 100 ml of distilled water was added and it was again left to cool. Five ml of phosphoric acid was added and the mixture was titrated with 0.5 M ferrous ammonium sulphate solution, using barium diphenylamine sulphonate indicator.

Soil pH and electrical conductivities were measured following the methods of Blakemore *et al.* (1987). Soil pH was determined on air-dry (< 2 mm) soil in a soil: distilled water ratio of 1:2.5. Samples were stirred for 10 minutes and allowed to stand overnight. Measurements were made using a glass/reference electrode. Measurements of pH in CaCl₂ were made as described above except that 0.01 M CaCl₂ was substituted for the distilled water. To determine electrical conductivity, air-dry (< 2 mm) soil in a 1:5 soil: distilled water ratio was shaken for 30 minutes then centrifuged. The supernatant was then poured directly into the measurement cell.

All ratings of chemical properties were made according to the classification of Blakemore *et al.* (1987).

3.5 Effluent total and suspended solids

Total solids is the mass of residue following evaporation to dryness at 105°C (Russell

1984). Suspended solids are defined as the nonfilterable residue retained by a Whatman GF/C 9 or 11 cm diameter glass fibre filter paper (Russell 1984). Both total and suspended solids were measured following the methods of Russell (1984). Dissolved solids were determined by difference between total and suspended solids.

3.6 Core preparation

The soil cores, used in experiments described in chapters 5, 7, and 8, were packed with soil, to a depth of 15 cm, using an adaptation of the method of Fireman (1944). Soil was packed, at field soil moisture content, into PVC pipe with an internal diameter of 10 cm and a brass gauze taped to the base of the core to support the soil. Large stones and earthworms were removed and the soil was broken down to aggregates of less than about 3 cm diameter. Soil was added to a core and then the core was repeatedly dropped from a height of 2.5 cm to facilitate packing.

3.7 Statistical analysis

The statistical analysis of the core factorial trial (Chapter 5) were undertaken using "genstat V". Other statistical analysis were conducted using MYSTAT, Lotus123, or Microsoft Excel computer software.

Chapter 4: Survey of land effluent-treatment sites at meat processing plants in New Zealand

4.1 Introduction

In 1989/90 a reconnaissance survey was undertaken of nine meat processing plants that dispose of their effluent on land (Table 4.1). The sites were located throughout New Zealand (Figure 4.1) and represent a range of soils and climates. The objectives of the survey were:

1. To document the current practise of land disposal of effluent at New Zealand meat processing plants.
2. To determine the long-term effects of disposal of effluent from meat processing plants on selected soil properties and identify any problems that may have been occurring.

Table 4.1 Meat processing plants included in this survey

Plant	Location	Meat Company ¹
Fairton	Canterbury, 6 km northeast of Ashburton, adjacent to SH1.	Canterbury Frozen Meat Co. Ltd.
Feilding	Manawatu, 2 km from Feilding, east of the Oroua River, Feilding-Bunnythorpe Rd.	AFFCO.
Kaiapoi	Canterbury, 2 km east of Kaiapoi, 15 km north of Christchurch.	Alliance Freezing Company Ltd.
Lorneville	Southland, 10 km north of Invercargill, off SH6.	Alliance Freezing Company Ltd.
Makarewa	Southland, 12 km north of Invercargill, off SH6.	Waitaki International Ltd.
Oringi	Hawkes Bay, 10 km south of Dannevirke, adjacent to SH2.	Richmond Meats Ltd.
Takapau	Hawkes Bay, 5 km north of Takapau township, Fraser Rd.	Richmond Meats Ltd.
Taumarunui	King Country, Effluent disposal site is 10 km southeast of Taumarunui, Burnands Rd.	AFFCO
Wakanui	Canterbury, 10 km east of Ashburton, Seafield Rd.	Fortex Group Ltd.

¹ The meat company name listed is the company at the time of site visit - there have been some changes since then.

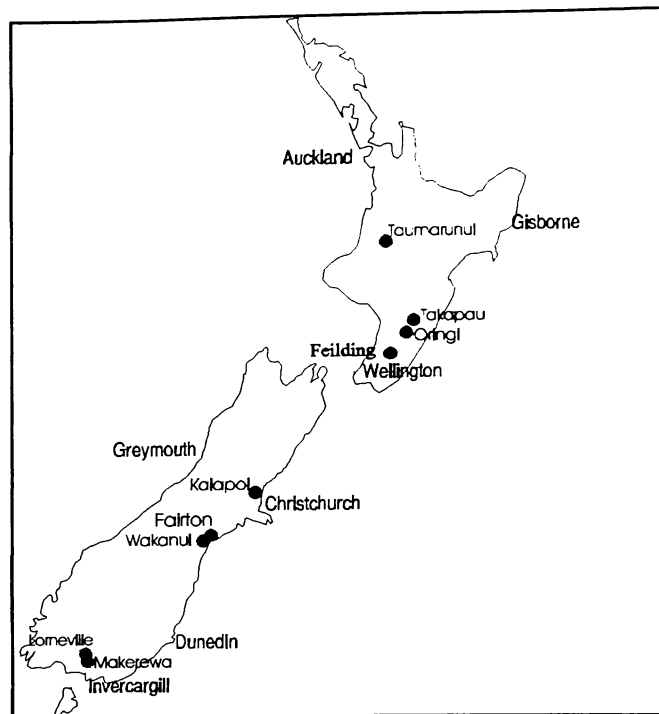


Figure 4.1 Location of meat processing plant effluent disposal sites (coloured dots) included in this survey.

Since this survey was undertaken there have been changes in effluent volumes, sources, treatment and management at a number of the sites that were visited. No attempt has been made to record subsequent changes in this report.

4.2 Survey methodology

The Fairton, Lorneville, Kaiapoi, Makerewa, Taumarunui and Wakanui sites were visited in November/December 1989 in fulfilment of a contract for Ministry for the Environment. Information for these sites was included in a contract report (Balks 1990). The remaining sites (Feilding, Takapau and Oringi) were visited in August 1990.

At each location (except Kaiapoi) a site which had not received effluent and a comparable "typical" site of effluent disposal were investigated. At most sites a full soil profile description was undertaken and permeability class estimates were made. Saturated and unsaturated hydraulic conductivity measurements were carried out and

samples were taken for determination of soil bulk density and chemical analysis. Methodology details were given in Chapter 3.

At each meat processing plant staff members involved in the effluent disposal operation were interviewed, and general observations were made, regarding the history and management of the operation.

The main findings of the survey are discussed in the following sections and more detailed data are included in Appendix 1.

4.3 Brief history of effluent disposal at sites visited

Effluent irrigation scheme duration and irrigation methods are summarised in Table 4.2. The longest-running effluent irrigation scheme is that of the Fairton meat processing plant which has been irrigating effluent since 1899 (Table 4.2). Initially Fairton used "wild flood" irrigation (i.e. allowing effluent to flow out across a paddock surface following the natural topography) but later border dykes were established. The area under irrigation at Fairton was expanded in the 1970s and 1980s and some of the original blocks have been reworked with new borders installed.

The shortest-lived irrigation scheme (Table 4.2) was at Kaiapoi. After only eight months in operation the decline in soil infiltration rates led to surface ponding, development of anaerobic conditions, and a consequent severe odour problem. Difficulties with vehicle access, formation of large wheel ruts and bogging of the irrigator also occurred. Following cessation of irrigation, the area was allowed to dry out and recover. In November-December 1989 land restoration work was carried out. This included disking severely ponded areas, on which vegetation had been killed, and recontouring rutted areas. Irrigation of effluent, treated using a 24-hour balancing pond and a trickling tower, recommenced in December 1989, on a small scale, to prevent drought damage to the grass.

Table 4.2 Effluent irrigation scheme duration and irrigation method for sites visited.

Plant	Scheme duration	Irrigation method employed
Fairton	1899 - present	Border dyke irrigation. 200 and 300 m long borders.
Feilding	1985 - present	Discharge to Oroua River, irrigation by travelling spray-irrigator during low river flow, usually December to April.
Kaiapoi	Oct. 1988 - June 1989	Travelling spray-irrigator. Stopped due to severe decline in soil infiltration rates.
Lorneville	1962 - present	Discharge to Makerewa River, irrigation by ponding or, since 1972, by spray irrigation during river low-flow or plant malfunction.
Makarewa	1960 - present	Discharge to Makerewa River, spray irrigation during summer low river flow, usually 2 - 4 months per year.
Oringi	1981 - present	Border dyke irrigated. The original area was enlarged following problems of infiltration rate decline.
Takapau	1981 - present	Border dyke irrigated, borders 70 m long.
Taumarunui	1979 - present	Spray irrigated. Changed from travelling irrigator to "big guns" in 1989.
Wakanui	1985 - present	Travelling spray-irrigator. A small gun was used to irrigate deer-chain effluent over a 5 ha area from 1981 - 1989.

At the time of visit the Wakanui meat processing plant was irrigating effluent at "water irrigation rates" (i.e. at rates that meet plant moisture requirements) over 150 ha. The remainder of the farm was irrigated with water.

Border dyke irrigation was utilised for effluent disposal at sites in the Canterbury and Hawkes Bay regions, where border dykes are widely used for water-irrigation. In other regions, travelling irrigators were the most popular choice although at the time of my visit Taumarunui was changing from travelling irrigators to "big guns".

Problems of travelling irrigators becoming "bogged" have been experienced at a number of sites. Makerewa had a cumbersome, hand-moved, pipe and sprinkler system.

4.4 Effluent treatment and irrigation scheme management practices

4.4.1 Effluent sources, pre-treatment, and volumes

Effluent sources, pretreatment, volumes, and land areas used for disposal are summarised in Table 4.3. The two main differences in effluent sources, between plants, are the inclusion (or otherwise) of stock-holding yard wastes, and the presence or absence of a fellmongery. The fellmongery plants encountered in this survey were all using a $\text{Ca}(\text{OH})_2$ based process which results in a high pH, low SAR, effluent.

The Lorneville meat processing plant accepted effluent trucked from a wool scouring plant in Invercargill and the Makerewa meat processing plant received effluent from a neighbouring tannery.

Three plants, Feilding, Lorneville, and Makerewa, discharge to adjacent rivers, except during periods of river low-flow which occur in the summer, and had tertiary effluent treatment systems (detailed in Appendix 1). All other plants had screening with only Taumarunui providing primary, dissolved air flotation treatment, prior to irrigation onto land.

The volumes of effluent given (Table 4.3) are only a general guide as effluent volume fluctuates throughout the season, depending on the numbers of stock being handled.

The volumes and land areas included in Table 4.3 indicate that a wide range of effluent loading rates were being employed. For Kaiapoi the volume that was being irrigated prior to June 1989 is given. Upon problems with their irrigation scheme a water conservation programme was introduced into the Kaipoi plant which resulted in a 40% decrease in effluent volume, giving a maximum daily output of 4 000 m³ (Carl Temm, *personal communication*).

Table 4.3 Effluent sources, treatment, volumes and land area under effluent irrigation¹

Plant	Effluent sources	Effluent pretreatment	Effluent volume (m ³ day ⁻¹)	Area irrigated (ha)
Fairton	Killing chain, fellmongery and pelthouse	Floatables skimmed off	Up to 11 000	400
Feilding	Killing chain, fellmongery, rendering plant, stock holding yards, stormwater	Tertiary	3 000	50
Kaipoi	Killing chain, fellmongery	Screening and flotation	6 000	110
Lorneville	Killing chain, fellmongery, further processing plant, wool scour.	Tertiary	1 000 - 3 000	-
Makarewa	Killing chain, rendering plant, casings factory, fellmongery, tannery	Tertiary	10 000 - 13 000. Max. of 4 500 irrigated	350
Oringi	Killing chain, casings plant	Contra-shear screen	4 000	85
Takapau	Killing chain, stock holding yards	Contra-shear screen	up to 2 000	180
Taumarunui	Killing chain, stock holding yards	Primary, dissolved air floatation	18 000-20 000	70
Wakanui	Killing chain, rendering, stock holding yards	Contra-shear screen	1 000	150

¹ These data pertains to the time of the survey - changes have been made at many of these sites since then. This information was derived from observation and discussion with meat processing plant staff.

4.4.2 Effluent properties at sites visited

The data on effluent properties, that were available (Table 4.4) reflect the variability of meat processing plant effluents and the level of effluent treatment being carried out. At plants where effluent was screened and irrigated, generally, very few

measurements of effluent properties were undertaken by the companies. Feilding, Makerewa and Lorneville provide tertiary treatment and discharge to rivers and, therefore, had detailed information available as a result of the requirements of their discharge rights. It is likely that the effluent from the other meat processing plants would be similar to that described for New Zealand meat processing plants in Table 2.1. The high pHs at the Feilding and Kaiapoi sites are the result of the fellmongeries at those sites. The relatively low BODs and suspended solids at Feilding, Lorneville and Makerewa are the result of the tertiary effluent treatment carried out at these plants.

Table 4.4 Effluent properties for sites visited¹

Plant	Total solids (g m ⁻³)	Suspended solids (g m ⁻³)	pH	BOD (g m ⁻³)	Fat (g m ⁻³)	TkN (g m ⁻³)	NH ₃ -N (g m ⁻³)
Feilding	1000	45 - 270	8	23 - 93	-	-	-
Kaiapoi	-	250 - 700	7.5-9	570 - 1 500	50 - 400	120-190	-
Lorneville	-	50 - 100	-	20 - 100	-	-	10 - 180
Makarewa	-	8 - 254	-	23 - 257	-	-	87 - 240
Oringi	1000 - 2000	-	6.5	-	-	-	-

¹ These data were provided as personal communications from plant staff. They pertain to the time of the plant visit and may not be indicative of current data. Sites not listed did not provide any data.

4.4.3 Management of effluent irrigation schemes

All the sites visited, except Kaiapoi, were in clover-ryegrass pasture and used for stock-holding or sheep, deer or cattle grazing (Table 4.5). Kaiapoi was in fescue grass intended for hay or silage production. An increase in pasture or crop production was reported at most sites, as a result of effluent irrigation. Cropping was undertaken occasionally at most sites. For example, at Fairton crops of oats, peas, maize, barley and wheat had been grown. Maize was particularly successful when grown under effluent irrigation at Fairton (R. McCormack *personal communication*) and was also regularly grown at the Wakanui effluent irrigation site.

The Oringi and Kaiapoi sites were managed primarily for effluent disposal, whereas at other sites effluent application tended to be more incidental to the management of the land for production. At the Oringi site, grass is kept fairly long as this has been

found to improve effluent distribution over borders. Oringi graze only sheep as they have found cattle to cause pugging damage to the borders.

Table 4.5 Land use, stock with-holding times and irrigation return period for sites visited¹

Plant	Predominant land use	Other land uses	Stock with-holding time	Irrigation return period
Fairton	stock holding, animal grazing	some cropping	3 weeks	1 week to several months
Feilding	dairy farm	some cropping	-	irregular
Kaipoi	pasture for silage/hay	none	not grazed	-
Lorneville	stock holding	beef and lamb fattening	-	irregular
Makarewa	dairy farms	-	1-2 weeks, sometimes less	irregular
Oringi	sheep/lambs	firewood gums	-	about 20 days
Takapau	cattle/sheep	lucerne cropping	no stock withholding	1 week, sometimes less
Taumarunui	sheep/cattle	some hay and fodder crops	3-4 weeks	6 - 10 weeks
Wakanui	deer/sheep	some cropping	2 weeks	2 - 3 weeks

¹ This data pertains to the time of the survey - changes have been made at many sites since then.

Many of the newer borders at Fairton are 200 m long, following recommendations for irrigation of Lismore Soils (Taylor, 1981). Operators find the shorter borders less desirable because they have to switch the effluent flow between borders more frequently. The older (300 m long) borders tend to receive a larger portion of the effluent as they can be left unsupervised for longer periods.

During wet winter conditions effluent moves along borders very rapidly, presumably as a result of lower soil infiltration rates. Therefore, larger land areas are required for effluent irrigation. For example, at Fairton in dry summer conditions 4 - 6 ha day⁻¹ are irrigated while during a wet winter period, when the meat processing plant is operating to capacity, up to 60 ha may be irrigated in one day (Canterbury Frozen Meat Company staff, *personal communication*).

Stock with-holding times were very variable (Table 4.5) with a minimum of three weeks cited at two sites, but two other sites reported that they sometimes left stock in a paddock during effluent irrigation. A number of farm managers commented that stock, particularly lambs, tended to "scour" if put on paddocks too soon (less than one to two weeks) after effluent application. Stock do not like the effluent irrigated pasture and will always graze the non-irrigated areas of a paddock first. Where tertiary treated effluent is irrigated reported stock aversion to effluent irrigated pasture was less. At Makerewa (which irrigates tertiary treated effluent) dairy cows have been observed to drink from irrigation ditches with no apparent adverse effects (Mr A. Gray *personal communication*).

Effluent irrigation required direct field supervision by at least 1 staff member at Makarewa (24 hrs/day), Fairton (12 hrs/day), Oringi (8-12 hrs/day), and Takapau (up to 4 hours/day) with intermittent staff attention required at Fielding, Lorneville, Kaiapoi, Wakanui, and Taumarunui.

4.5 Effects of effluent on soils

4.5.1 Pedological observations

Soil profile descriptions, classification and site factors, including parent materials, depth to water table, and climate are given in Appendix One. The soil profile descriptions confirm the similarity of selected effluent treated and non-treated comparison sites. Wakanui was the only site where marked differences in pedological properties were observed that could be related to the effects of effluent. At Wakanui the topsoil under effluent irrigation was more porous and less compacted than that under water irrigation.

4.5.2 Earthworm populations

Earthworms are potentially beneficial at an effluent disposal site as they may contribute to the breakdown of the effluent as well as assisting in maintaining (or even increasing) soil permeability, aeration, and soil structure development.

There was an increase in the earthworm population on the effluent irrigated areas, compared with non-irrigated areas at some sites, but not others. At both Wakanui and Takapau marked increases in earthworm numbers were observed. For example, an effluent irrigated area at Wakanui had more than 30 earthworms per 3 000 cm³ of topsoil whereas at an adjacent water-irrigated site only one earthworm was seen.

At Lorneville a few small introduced earthworms were found at the effluent irrigated site. At a neighbouring non-irrigated site large native earthworms were present. The native earthworms were found in the subsoil but large (5 mm diam) worm channels were evident throughout the soil. It is possible that the large doses of effluent are responsible for the absence of native earthworms at the effluent treated site, but their survival in the modified environment of pastoral farming is probably not common.

At Oringi earthworms were found in all areas, except those where prolonged surface ponding of effluent occurred. However they were more common in areas of the paddock that did not receive effluent. At Kaiapoi a few earthworms were observed in areas that had not been severely damaged by effluent irrigation, but none were seen in areas where effluent had ponded.

The lack of an observed increase in earthworm numbers at some sites may have been because of the high pH of effluents which contain fellmongery effluent. High pHs may have a detrimental effect on earthworms. For example, the range of pH tolerance of *Aporrectodea trapezoides* lies between pH 5.8 and 8.3 (Kühnelt 1976). The pH of Kaiapoi effluent ranged between 7.5 and 9 in December 1989 (C. Temm *personal communication*) and Keeley and Quin (1979) report a pH of 10.2 as a typical value for composite effluent samples at Fairton. These pHs would have had potentially damaging effects on earthworm populations. Wakanui and Takapau did not have fellmongeries and therefore their earthworm populations would not have been subjected to high pH effluents.

4.5.3 Soil hydraulic conductivity

Application of effluent was found to cause an increase in saturated hydraulic conductivity (K_{sat}) at some sites while decreases were recorded at other sites (Table 4.6). There were no differences ($P < 0.05$) in saturated hydraulic conductivity measurements, between sites that received effluent and those that did not, at Fairton, Lorneville, Makerewa, and Taumarunui (Table 4.6). However, at Fairton there appeared to be a decline in K_{sat} in small areas at the top, and in some instances the bottom, ends of borders where water was observed to pond on the surface of the ground.

Table 4.6 Saturated hydraulic conductivities (K_{sat})¹ for effluent irrigated areas and areas that do not receive effluent

Plant	K_{sat} , No effluent (mm hr^{-1})			K_{sat} , effluent irrigated (mm hr^{-1})		
	mean	std. dev.	no.	mean	std. dev.	no.
Fairton	180	120	5	95	50	5
Kaiapoi						
<i>ponded</i>	n.a. ²	-	-	40	28	3
<i>disked</i>	n.a.	-	-	> 400 ³	-	-
<i>vegetated</i>	n.a.	-	-	200	80	3
Lorneville	380	470	3	420	140	3
Makerewa	140	50	4	135	62	3
Taumarunui	69	25	5	40	25	5
Wakanui	60	20	2	> 400 ³	-	-
Oringi, pasture ⁴						
<i>15 m along border</i>	n.a.	-	-	23	7	3
<i>50 m along border</i>	n.a.	-	-	49	14	4
<i>150 m along border</i>	n.a.	-	-	101	2	2
Oringi - gum trees						
<i>5 m along border</i>	n.a.	-	-	1	1.6	5
<i>60 m along border</i>	n.a.	-	-	19	0.9	5
<i>120 m along border</i>	n.a.	-	-	80	16	5
<i>spray irrigation</i>	n.a.	-	-	14	16	5

¹ All measurements were made using a disk permeameter, except the Oringi gum trees which were measured using twin rings.

² Not Applicable

³ Infiltration rate so rapid ($> > 400 \text{ mm hr}^{-1}$) it could not be accurately measured with the disk permeameter.

⁴ Oringi meat processing plant, paddock 13.

Changes in K_{sat} with distance along borders was investigated at the Oringi site. Measurements were made 15, 50 and 150 m from the top end of a border under

pasture, and 5, 60 and 120 m along a border under gum trees (Table 4.6). Measurements were also made in an area of gum trees under spray irrigation. There was a marked increase ($P < 0.005$) in K_{sat} with increasing distance from the top end of borders. The lower K_{sat} at the top end of the border is attributed to the greater amount of effluent that is received at that end. The decline in K_{sat} was greater under the trees than on pasture, with a decrease to as low as 1 mm hr^{-1} (Table 4.6). Canopy closure, causing shading from the trees, may have contributed to the decrease in K_{sat} by slowing the rate of soil drying and effluent decomposition. The litter of wet leaves on the ground may have also been contributing to soil pore blockage. A lot of suspended solids material from the effluent was left clinging to the trees in spray irrigated tree areas and this may have helped prevent the K_{sat} in the spray irrigated trees from declining as much as it did at the top end of the borders under trees.

At the Wakanui site there was a large *increase* in K_{sat} at the effluent irrigated site compared to the non-irrigated site ($P < 0.005$, Table 4.6) which was attributed to the presence of large numbers of earthworms in the effluent irrigated soil (section 4.5.2).

At Kaiapoi a comparison was made between the K_{sat} of a previously ponded site (an area that had been severely impacted by effluent ponding, and on which very little vegetation remained), a disked site (a ponded site that had been subsequently disked), and a vegetated site (an effluent irrigated site that was less severely damaged, and on which vegetation had survived) (Table 4.6). The vegetated site had a rapid K_{sat} . However, at the previously ponded site the K_{sat} was lower ($P < 0.005$), despite a period of six months since effluent irrigation had ceased. Disking the soil was effective in restoring the soil's K_{sat} , presumably by creating large continuous macropores. The K_{sat} of the disked area was so rapid that accurate measurements could not be made with the disk permeameter.

Unsaturated hydraulic conductivity measurements showed no clear trends as a result of effluent application. Data are included in appendix 1.

4.5.4 Soil bulk density

A significant decrease in soil bulk density was found to occur towards the top ends of borders at Fairton, Takapau, and Oringi, and at the effluent irrigated site at Wakanui ($P < 0.005$, Table 4.7). The lower bulk densities at the top ends of borders are attributed to the large volumes of effluent received at these sites and the decrease at Wakanui is attributed to the effects of the large earthworm population (Section 4.5.2). In contrast, the ponded site at Kaiapoi had a higher bulk density than the other Kaiapoi sites that were measured. Compaction, as a result of disruption of the weak soil structure, may have contributed to the increased bulk density and to the ponding at Kaiapoi.

At Taumarunui there was no difference in bulk density between the sites (Table 4.7) and at Lorneville, although statistically significant, the difference between 0.81 and 0.76 Mg m⁻³ was fairly small. At Makerewa the higher surface soil bulk density at the effluent irrigated site probably reflects the compaction resulting from trampling by dairy cows whereas the non effluent-irrigated area was under sheep grazing.

Table 4.7 Soil bulk densities for sites that are effluent irrigated and sites that do not receive effluent.

Plant	Bulk density, No effluent, (Mg m ⁻³)			Bulk density, effluent irrigated, (Mg m ⁻³)		
	mean	std. dev.	no.	mean	std. dev.	no.
Fairton	1.10	0.05	12	-	-	-
<i>6 m along border</i>	n.a. ¹	-	-	0.69	0.06	4
<i>155 m along border</i>	n.a.	-	-	1.03	0.08	4
<i>280 m along border</i>	n.a.	-	-	1.16	0.1	4
Kaiapoi						
<i>ponded</i>	n.a.	-	-	1.24	0.07	3
<i>disked</i>	n.a.	-	-	1.12	0.03	2
<i>vegetated</i>	n.a.	-	-	1.02	0.05	3
Lorneville	0.81	0.03	6	0.76	0.01	5
Makerewa	0.87	0.01	6	1.09	0.03	6
Takapau	1.15	0.05	3	-	-	-
<i>5 m along border</i>	n.a.	-	-	0.98	0.08	3
<i>30 m along border</i>	n.a.	-	-	1.11	0.02	3
<i>60 m along border</i>	n.a.	-	-	1.17	0.03	3
Taumarunui	0.68	0.02	9	0.68	0.03	10
Wakanui	1.34	0.05	5	1.10	0.04	5
Oringi, pasture ²						
<i>15 m along border</i>	n.a.	-	-	0.59	0.04	8
<i>50 m along border</i>	n.a.	-	-	0.77	0.05	5
<i>150 m along border</i>	n.a.	-	-	0.93	0.005	3
Oringi - gum trees						
<i>5 m along border</i>	n.a.	-	-	0.71	0.04	5
<i>60 m along border</i>	n.a.	-	-	0.95	0.1	4
<i>120 m along border</i>	n.a.	-	-	0.97	0.04	3
<i>spray irrigation</i>	n.a.	-	-	0.91	0.08	6

¹ Not applicable² Oringi site, paddock 13.

4.5.5 Surface crusting and ponding

Some surface crusting and ponding, of effluent or rainfall, was observed at most of the meat processing plant effluent disposal sites visited. Surface crusts formed either in hollows, where effluent accumulates due to surface runoff (Figure 4.2), or at the top ends of borders where the effluent impact is the greatest (Figure 4.3).

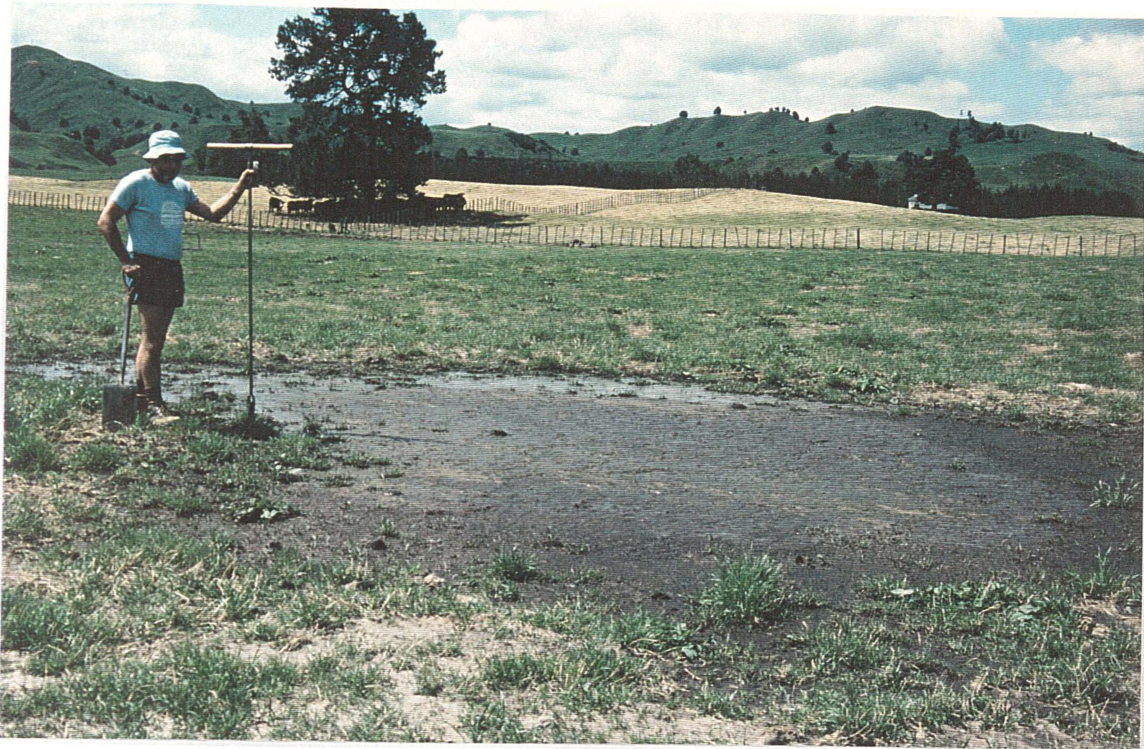


Figure 4.2 Surface crusting and ponding in a topographic hollow



Figure 4.3 Surface crusting and ponding at the top end of a border

The most serious case of surface ponding encountered in this survey was that reported for the Kaiapoi meat processing plant (section 4.3). At the time of the visit to this site, six months after effluent irrigation had ceased, a surface crust of organic material was still evident in many areas (Figure 4.4).



Figure 4.4 Surface crust material at the Kaiapoi site, six months after effluent irrigation had ceased.

High suspended solids effluents may cause immediate development of surface crusting. For example at the time of visiting the Taumarunui site an effluent "holding pond" had recently been cleaned out and the high suspended solids concentration effluent from this had been irrigated onto pasture causing surface accumulation of the suspended solid material (Figure 4.5). The contribution of micro-organisms to surface crust development was also evident at some sites, with algae clearly visible in some ponded areas (Figure 4.6).



Figure 4.5 Surface crusting as a result of irrigation of effluent with a high suspended solids concentration



Figure 4.6 Algae on the margin of an effluent ponded area

4.5.6 Soil chemical properties

Results of soil chemical analysis are included in Appendix One. At Lorneville, Makerewa, Taumarunui and Wakanui there were no marked differences in soil C, N or pH between sites that received effluent and neighbouring, non-irrigated sites. The soil electrical conductivity on effluent treated sites was similar to non treated soil at Lorneville, Makerewa, and Taumarunui but at Wakanui it was higher ($130 \mu\text{S cm}^{-1}$) at the effluent irrigated site than at a water irrigated site ($55 \mu\text{S cm}^{-1}$).

At the Fairton site soil pH, electrical conductivity, and carbon and nitrogen contents, were all highest at the top end of the border, apparently as a result of the higher effluent inputs in these areas. There was a rise in electrical conductivity from $55 \mu\text{S cm}^{-1}$ at non-irrigated sites to $750 \mu\text{S cm}^{-1}$ at the top end of the border in paddock D1.

An electrical conductivity of $750 \mu\text{S}$ equates to a total soluble salt percentage of 0.25 % (after Taylor and Pohlen 1979) which is likely to adversely affect plant growth. Poor plant growth was evident at the top end of the border in this paddock.

While most of the impacts of effluent application are concentrated in the topsoil, there is evidence that changes may occur in the subsoil. For instance, at Fairton the electrical conductivity and carbon values in the Bw horizon were higher at the effluent treated site than at the control.

4.5.7 Other observations

Changes in the composition of effluent as it moved along a border were recorded at Oringi (Table 4.8). The most important difference was a decline in the solids content of the effluent as the distance travelled along the border increased, indicating that some of the solids had settled out of suspension in the upper regions of the border.

Table 4.8 Change in selected effluent properties with distance along border¹

Date of sampling	Distance to drain m	pH	Electrical conductivity μS	total solids g m^{-3}	suspended solids g m^{-3}
28/8/90	0	6.7	730	1800	-
	10	6.8	600	1700	-
	70	6.8	760	1700	-
	150	6.8	770	1500	-
30/8/90	0	6.4	360	1100	600
	10	6.4	310	1000	400
	50	6.5	310	800	400
	80	6.5	340	800	400

¹ All data are means of three replications

Hydrophobicity was observed to have increased in areas that had received effluent at the Kaiapoi site. It is suggested that fat from the effluent may be contributing to this effect.

At Makerewa estimated permeability classes were very rapid in the topsoil but moderately slow in the subsoil resulting in water perching on the subsoil and surface ponding during prolonged periods of effluent irrigation.

A trend of increasing soil moisture contents, towards the top ends of borders, was observed at Takapau. Measurements of soil moisture content, made more than a month after effluent irrigation and a few days after heavy rain, gave gravimetric water contents ranging from 0.41 at the bottom end of a border to 0.59 at the top end with a non-irrigated site having a gravimetric moisture content of 0.31. The increased moisture content corresponds to the lower bulk densities reported (section 4.5.4) and suggests that effluent application led to an increase in soil water holding capacity at this site. An increased water holding capacity may result from an accumulation of organic material or a change in soil porosity as a result of the increased earthworm activity at the site.

4.6 Discussion

The survey presented in this chapter demonstrates that land disposal of effluent, often with minimal effluent pretreatment, is successfully employed by New Zealand meat processing plants on a variety of soils under a range of climatic conditions. Both border dyke and sprinkler irrigation systems were widely used, however, a greater input of staff supervision was usually required for the border dyke irrigation systems.

Effluent irrigation had the lowest impact on the soil system at sites where tertiary treated effluents were irrigated only during summer periods of low river flow (Feilding, Lorneville, and Makerewa). Of the sites which employed only screening, prior to irrigation in all seasons, the most apparently successful were Wakanui and Takapau. At the time of site-visits, neither Wakanui nor Takapau had a fellmongery operation, so both had relatively low pH effluents. Effluent was spread rapidly and evenly over the soil surface at both sites and large increases in earthworm numbers were evident, resulting in decreased bulk density and increased soil hydraulic conductivity on effluent irrigated sites.

The remaining sites (Fairton, Taumarunui, Kaiapoi, and Oringi) all had some evidence of soil surface crust development and effluent ponding, either at the top ends of borders or in topographic hollows. Surface crusting can lead to a decrease in surface soil permeability, effluent ponding on the soil surface, the development of anaerobic conditions, unpleasant odours and the death of vegetation. If surface crusting becomes widespread, as it did at Kaiapoi, the effluent irrigation scheme may have to be discontinued. Crusted areas can take a long time to recover. Areas at Taumarunui had not recovered three months after effluent irrigation had stopped and at Kaiapoi crusting was still evident six months after effluent irrigation ceased.

A number of ameliorative techniques have been used to counteract soil crusting, including deep ripping (at Taumarunui), mole drainage (at Makerewa), and ploughing (at Kaiapoi). Ripping appeared to be the simplest treatment, and was effective in allowing ponded areas to drain and dry out without requiring pasture resowing. It may not take very long, however, for the ripped surface to reseal, necessitating repeated treatment. A disadvantage of ripping is the potential for relatively untreated

effluent to flow through macropores, directly to the groundwater. Therefore, preventing surface crusting from occurring, by changing the pattern of irrigation and rest periods, is ultimately more effective than being forced to continually utilise ameliorative action. The meat processing plants visited in this survey had developed workable systems, largely by trial and error.

Changes along the lengths of borders in border dyke irrigation systems provide a useful illustration of the effects of increasing amounts of effluent application. The top ends of borders are flooded for several hours during effluent application, however, effluent flow is switched to a new border as soon as effluent nears the bottom end of a border. The surface crust at the top ends of borders was associated with decreases in soil dry bulk density and hydraulic conductivity and increases in soil carbon, nitrogen, pH and electrical conductivity. There was a tendency for the effluent suspended solids to settle out at the top ends of borders thus contributing to surface crust development. Algae was visible in some ponded areas, indicating that microbial materials were also present. The surface crusting observed at the top ends of borders was similar to that described by Tarquin and Bautista (1976) and Reed and Crites (1984) for the top ends of overland flow effluent treatment systems.

Churchman and Tate (1986) reported that an increase in the amount of fellmongery effluent at the Fairton site led to a weakening of the soil structure but they found no changes in measured microaggregate stabilities. However, no damage to soil structural development was observed in this study, suggesting that dispersion was not a problem at any of the locations visited. On sites with fellmongery effluent the high levels of Ca^{2+} relative to Na^{+} probably help prevent dispersion from occurring. Losses in soil permeability, associated with surface crust development, become evident relatively quickly and so force action to be taken to relieve the problem. Therefore, surface crusting is unlikely to cause long-term impacts on the sustainability of an effluent irrigation scheme.

Ideally surface saturation (and therefore macropore flow) should be avoided under sprinkler irrigation, however, effluent surface ponding during irrigation was observed at every site visited. Many of the soils studied had higher surface saturated hydraulic conductivities, as a result of the presence of biopores, with lower saturated hydraulic

conductivities in subsurface horizons, where biopores were absent. If irrigation is to be carried out at rates faster than the subsoil can sustain (and most meat processing plants appeared to do this), it may be better to irrigate in short, repeated bursts to take advantage of the high surface hydraulic conductivity, but allowing time for the liquid to move down through the soil. This should prevent water perching on subsurface horizons and saturating the upper horizons of the soil, causing runoff, ponding, and damage to soil structure by vehicle traffic.

4.7 Conclusion

Irrigation of meat processing plant effluent in New Zealand is generally a successful means of disposing of large volumes of effluent without causing serious detrimental long-term effects to the soil properties investigated.

At most of the effluent irrigation sites visited, areas of surface crusting and effluent accumulation, in small surface depressions and/or at the top end of borders was observed. Surface crusting tended to lead to a build up of organic matter and a decrease in soil hydraulic conductivity in affected areas. Where surface crust development become widespread it led to development of surface ponding, anaerobic conditions and odour problems. At one site irrigation had to be stopped altogether to allow the soil to recover.

Surface crusting and a decline in infiltration rates was attributed to both, the accumulation of suspended solids material from the effluent and the accumulation of micro-biological materials which grow in response to effluent addition. Soil crusting effects were confined to the soil surface and there was no evidence of dispersion of clay materials or damage to soil structure.

Surface crusting can be ameliorated using techniques such as ripping or ploughing, but it is better to prevent it from occurring by decreasing the effluent load to a site and increasing the time between irrigation events.

Chapter 5: Factorial trial to investigate the impacts of effluent, soil and climate variables on selected soil properties

5.1 Introduction

The effects of effluent on soil physical properties, as discussed in Chapter 2, are summarised in Figure 5.1.

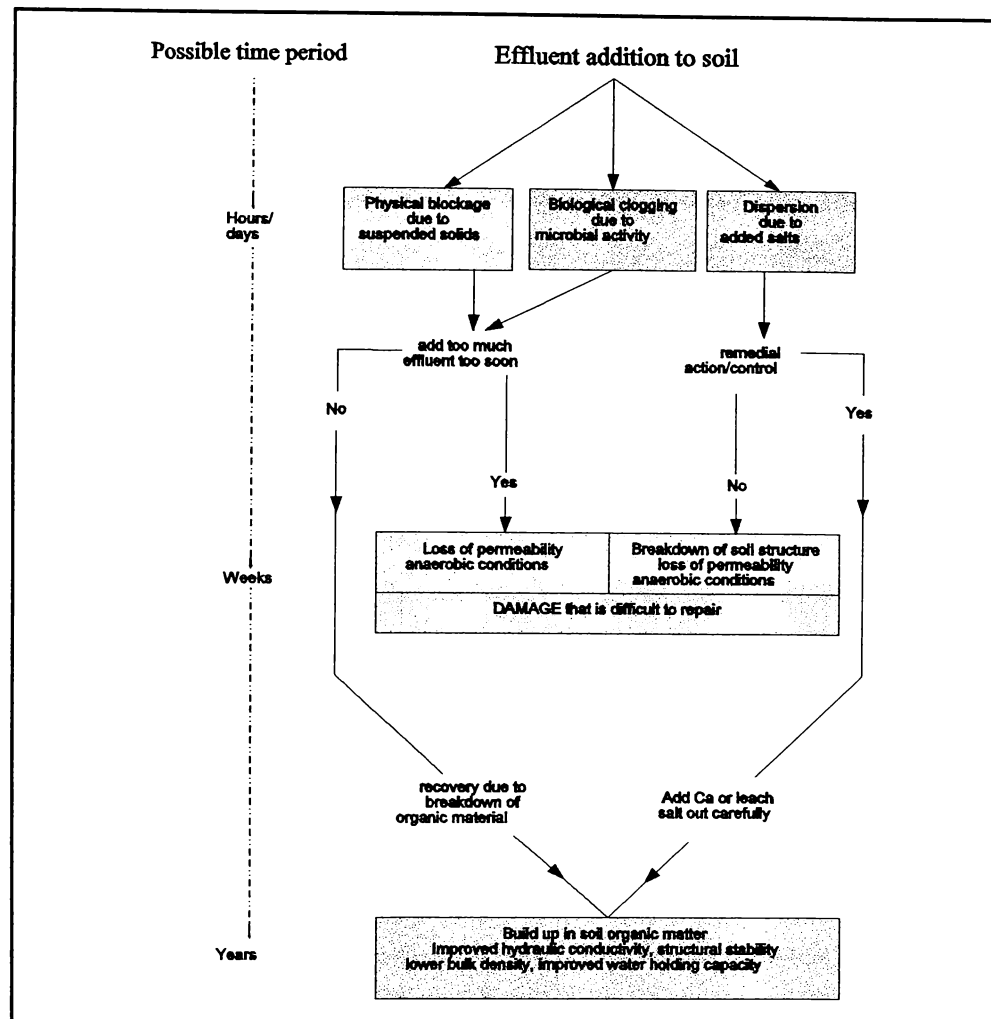


Figure 5.1 Effects of effluent on soil physical properties

Physical blockage of soil pores by suspended solids may occur as an immediate result of effluent addition. Most suspended solids are retained near the soil surface and,

given sufficient time between effluent applications, they degrade and dry which allows the soil permeability to recover. The factors influencing physical soil pore blockage include effluent suspended solids content, volume of effluent applied, the pore size distribution of the soil, and the particle size distribution of the solids in the effluent. Factors affecting the rate of recovery include the time between irrigations and climatic factors that control soil moisture content and temperature (and therefore the rate of microbial degradation).

Biological blockage of soil pores results from the enhanced growth of microbial organisms in response to effluent addition. The factors which affect the development of this form of blockage include effluent properties (such as N, P and other nutrient content, pH, and volume added), temperature, soil moisture content, time between irrigations, and the microbial species inherent in the soil or added in the effluent.

Dispersion of soil colloids occurs as a result of the addition of ions, particularly Na^+ and other monovalent cations. Factors affecting dispersion are the soil clay content and mineralogy, the sodium adsorption ratio of the applied effluent, the volume and frequency of effluent applications and the volume and frequency of rainfall that will leach excess salts from the soil.

The factors which may influence soil permeability as a result of effluent addition are summarised in Table 5.1. Many of the factors are interrelated. While factors that may affect soil infiltration rates are readily identified, there is very little quantitative information available that relates to the severity of impacts or the relative influence of these factors. This chapter describes a laboratory experiment designed to investigate the relative importance of some of the factors affecting soil permeability as a result of application of meat processing plant effluent. The experiment also provided an opportunity to monitor the effect of effluent application on a range of other soil properties and to measure selected properties of core leachates to investigate the effectiveness of soil at treating effluent.

Table 5.1 Factors that may influence soil permeability decline following effluent addition

	Possible influencing factors
Effluent factors	suspended solids content particle size distribution nutrient content pH microorganism population sodium adsorption ratio
Soil factors	pore size distribution microbial species present permeability aggregate stability particle size distribution clay mineralogy
Climate factors	temperature rainfall evapotranspiration
Management factors	effluent volume applied/land area time between effluent applications site vegetation stock management irrigation method and application rate.

5.2 Experimental design and methodology

5.2.1 Experiment design and variable selection

A 2nd factorial trial design (Box *et al.* 1978) was used which allows a relatively large number of variables to be tested. It utilises a high and low level for each variable, with each variable tested against every other variable but with no replicates of any one set of treatments. Using 64 repacked soil cores (which was the maximum number logistically reasonable) a trial was designed with two half-replications of a 4 x 2⁴ factorial design, testing two soil types, two volumes of effluent, two lengths of time between irrigation, two rainfall depths and four effluent treatments. Each half-replicate set was stored at a different temperature. The core treatments that were applied are listed in Appendix 2 (Table A2.1). Repacked soil cores (as opposed to

undisturbed soil cores) were used to minimise between-core variability in K_{sat} so that the effects of the chosen treatments, on K_{sat} , could be observed.

The effluents included in the study were; Hamilton tap water (W), primary treated meat processing plant effluent (P), primary treated effluent with an imitation fellmongery effluent (comprising sodium sulphide (160 g m^{-3}), sodium thiosulphate (15 g m^{-3}) and calcium hydroxide (180 g m^{-3})) added (F), and anaerobically treated effluent (A). The effluents were obtained from a local meat processing plant. Primary treated effluent was used as it is the effluent most commonly disposed of on land. Primary treated effluent with an added imitation fellmongery effluent was included because many meat processing plants have a fellmongery and the problems associated with the high salt content require further investigation. Anaerobically treated effluent was included because increased treatment of effluent prior to irrigation is becoming more common. Tap water was used as a control because a large component of the other effluents comprises tap water.

The soils selected were A horizon samples of Bruntwood sandy loam (Allophanic Soil, Hewitt 1992, described in Appendix 3) and Kopua stony silt loam (Brown Soil, Hewitt 1992, described in Appendix 1). The Bruntwood soil is formed in alluvium derived predominantly from tephra. Yellow brown loams, which generally equate to Allophanic Soils, were described as "ideal" for effluent disposal (Wells 1973). The Kopua soil is typical of that occurring on alluvial terraces in the Hawkes Bay, Wairarapa, Manawatu, and Canterbury areas. It is derived from greywacke alluvium with some loess. A number of New Zealand meat processing plants are situated on similar soils.

The periods between irrigations that were selected were nine and three days. Nine days represents an interval similar to that in common use and three days was chosen to investigate the ability of the soil to recover between effluent applications over a shorter time period.

Volumes of effluent equivalent to 1825 mm yr^{-1} and 5475 mm yr^{-1} were applied. The lower volume is within the range recommended by Russell (1986), based on acceptable N levels in pasture. The 5475 mm yr^{-1} level would be considered high, but is comparable with that used by McAuliffe (1978) in studies of dairy factory effluent.

The depth of effluent applied to each core at each application is summarised in Table 5.2. The lower volume every nine days gave the same depth of effluent per application as the higher volume every three days (Table 5.2).

Table 5.2 Depth of effluent applied to cores at each irrigation (mm)

Time between applications	High volume	Low volume
9 days	135	45
3 days	45	15

The two depths of rainfall applied to soil cores were selected to approximate a mean Hamilton winter rainfall (209 mm/month) and a mean Hastings summer rainfall (33 mm/month) (New Zealand Meteorological Service 1983). The rainfalls selected are representative of the regions from which the soils used in the experiment came and also of the range of rainfalls experienced at New Zealand meat processing plant effluent irrigation sites.

Cores were stored in constant temperature rooms, at either 10 °C or 25 °C. A cover of tinfoil was kept on cores (except when effluent was being added or measurements taken) to ensure that environmental conditions were uniform for all cores, regardless of position in rooms.

5.2.2 Experiment methodology and data analysis

Prior to application of effluent, seven measurements of core saturated hydraulic conductivity (K_{sat}) were made on each core, over a period of several weeks (following the method described in section 3.2.1.1). The mean of the seven measurements was considered to represent the initial K_{sat} for each core prior to effluent addition.

Effluent was applied to the cores, according to the experimental design, by ponding on the core surface to a depth of 1 cm. After one month, the permeability of some cores had decreased to the point where one effluent application had not completely drained before the next application was due. The trial was then stopped and core K_{sat} was measured, 2, 13 and 35 days after the final effluent application, to monitor core recovery. After 35 days cores were fairly dry and macro-pore flow (as a result of soil

shrinkage) was common. After day 35, a further treatment of effluent was applied to cores to re-moisten them. Three days later, 500 ml of effluent was applied to each core and the leachate was collected for analysis.

Following completion of the experiment the soil cores were dismantled and the soil bulk density, aggregate stability, pH, electrical conductivity, and organic carbon content was measured for each core (using methods given in Chapter 3).

Because of the large variability in K_{sat} between cores the data were standardised for initial difference between cores, with the percentage change in core K_{sat} calculated as:

$$\Delta K_{sat} = 100 \times K_{sat} / MBE$$

Where MBE is the mean of the K_{sat} measurements made on a core prior to effluent addition.

ΔK_{sat} values were used in the subsequent statistical analysis.

5.2.3 Properties of added effluents

The pH, electrical conductivity, total solids, and suspended solids of the effluents applied to cores during the experiment are given in Table 5.3. Effluent was collected, and applied to cores, on the dates indicated (Table 5.3). Some of the effluent was stored in a refrigerator (4°C) for use on the intervening days, as required.

The anaerobic effluent collected on 24 May had an unusually high suspended solids content (Table 5.3). It had a thick oily appearance and was the result of an equipment failure at the effluent treatment plant. There was an immediate decrease in core permeability and a visible soil surface-crust formed on cores that received the high suspended solids anaerobically treated effluent, on May 24. In cores that received a high volume, and especially those that also received high rainfall or were stored at 10 °C, the permeability did not recover. In cores receiving lower volumes of effluent and rain, or stored at 25 °C, the coat dried and cracked and core permeability recovered. Prior to addition of the anaerobic effluent on 24 May the cores receiving anaerobic effluent had shown no sign of decreases in effluent infiltration rates. Because the anaerobic effluent of May 24 was anomalous, and adversely affected the permeability

of some cores, the data for cores that received anaerobically treated effluent were excluded from the statistical analysis of ΔK_{sat} .

Table 5.3 Selected properties of effluents used in factorial trial¹

Effluent	Date	pH	Electrical conductivity ($\mu\text{S cm}^{-1}$)	Total solids (g m^{-3})	Suspended solids (g m^{-3})
Primary (P)	15 May	6.9	2000	2100	750
	24 May	7.2	1250	1000	600
	5 June	6.5	1000	900	260
	10 June	6.3	900	1100	380
Primary + fellmongery (F)	15 May	11.1	2600	2750	850
	24 May	10.8	1850	1600	670
	5 June	11.1	1500	1900	380
	10 June	11.1	1500	1800	380
Anaerobic (A)	15 May	7.5	1500	390	60
	24 May	7.4	1600	7800	6800
	5 June	7.1	1300	400	30
	10 June	7.0	1200	400	50
Tap water (W)	10 June	7.9	200	nd ²	nd
	28 July	7.8	180	nd	nd

¹Data are means of two replicates. ² nd = not determined

5.3 Results

The results in this Chapter are presented mainly as Tables of means. The full data and statistical analysis are included in Appendix 2.

5.3.1 Core hydraulic conductivity

Two days after effluent application ceased the K_{sat} of the cores had decreased for nearly all treatments, with an overall mean of 61% of the original K_{sat} (Table 5.4). The K_{sat} slowed to less than 1 mm hr^{-1} in a few cores which had received high volumes of P or F effluents.

Table 5.4 Table of means for percent change in K_{sat} (ΔK_{sat}) for cores, measured 2 days after effluent application ceased.

	Temperature (°C)		Volume		Soil		Effluent			Rain		Time (days)	
	10	25	high	low	K	B	W	P	F	low	high	3	9
Temperature													
10	50												
25	-	73											
Volume													
high	38	43	41										
low	62	102	-	82									
Soil													
K	35	64	36	63	50								
B	64	81	45	100	-	73							
Effluent													
W	63	89	72	79	61	91	76						
P	42	75	34	83	57	60	-	58					
F	45	54	16	83	32	67	-	-	49				
Rain													
low	41	76	36	80	48	69	74	59	42	58			
high	59	70	45	84	52	76	78	58	57	-	64		
Time													
3	57	74	34	97	53	77	76	61	59	64	67	65	-
9	43	72	47	67	46	68	76	55	40	53	61	-	57

Note: Groups within which significant differences ($P < 0.05$) occurred are shown in colour. Single factor interactions (i.e. the effects of just one of the variables included in the experiment) are shown on these tables as the diagonal line across the top edge, the remainder of the table illustrates two-factor interactions.

Two days after effluent application ceased the volume of effluent added was the largest single-factor influence on core permeability ($P < 0.001$) with a mean ΔK_{sat} of 41 % for cores receiving high volumes of effluent and 82 % for cores receiving low volumes of effluent (Table 5.4). The effects of temperature, soil and effluent were also significant. The K_{sat} of cores stored at 10 °C slowed more ($\Delta K_{sat} = 50\%$) than those stored at 25 °C ($\Delta K_{sat} = 73\%$) and Kopua soil cores slowed more ($\Delta K_{sat} = 50\%$) than Bruntwood soil cores ($\Delta K_{sat} = 73\%$). Cores receiving primary treated effluent or fellmongery effluent had greater decreases in permeability than those that received water (Table 5.4). Rain and time did not show up as significant single factors.

Significant two-factor effluent-volume, time-volume, and temperature-volume interactions occurred (Table 5.4). Mean ΔK_{sat} was lowest for cores receiving high volumes of primary-treated or fellmongery effluents (34% and 16% respectively, Table 5.4). Low volumes of effluent applied every three days did not cause a

significant decline in core permeability ($\Delta K_{\text{sat}} = 97\%$) but high volumes every three days caused a large decline ($\Delta K_{\text{sat}} = 34\%$, Table 5.4). For low temperature - high volume treatments the mean ΔK_{sat} was 38% whereas for high temperature - low volume treatments the mean ΔK_{sat} was 102% (Table 5.4).

Following drying of cores for 13 days, the mean ΔK_{sat} was 102% (Table 5.5) indicating that, on average, all cores returned to pre-effluent permeability rates. There were, however, some cores with permeabilities greater than at the start of the trial and others that still exhibited substantial decrease in core permeability.

Table 5.5 Table of means for percent change in K_{sat} (ΔK_{sat}) for cores measured 13 days after effluent application ceased.

	Temperature °C		Volume		Soil		Effluent			Rain		Time, days	
	10	25	high	low	K	B	W	P	F	low	high	3	9
Temperature °C													
10	86												
25	-	118											
Volume													
high	73	116	94										
low	99	120	-	109									
Soil													
K	85	111	92	103	98								
B	87	125	97	115	-	106							
Effluent													
W	100	126	132	94	103	123	113						
P	64	131	76	119	103	92	-	98					
F	94	96	75	115	87	103	-	-	95				
Rain													
low	74	135	105	105	102	107	112	108	94	105			
high	97	100	84	114	93	105	114	87	96	-	99		
Time days													
3	100	118	86	132	116	102	118	100	109	110	108	109	
9	72	117	103	87	79	110	108	95	81	100	90	-	95

Note: Groups within which significant differences ($P < 0.05$) occurred are shown in colour. Single factor interactions (i.e. the effects of just one of the variables included in the experiment) are shown on these tables as the diagonal line across the top edge, the remainder of the table illustrates two-factor interactions.

Thirteen days after effluent application ceased, temperature was the only significant single-factor interaction ($P = 0.01$, Table 5.5) affecting K_{sat} with cores stored at 10 °C having a lower K_{sat} than cores stored at 25 °C. The cores stored at warmer temperatures were visibly drier and shrinkage cracks (and hence macropore flow) were more common. Among the two-factor interactions temperature-rain, effluent-volume, and time-volume, were significant (Table 5.5).

Rain-temperature interactions (Table 5.5) show that cores receiving low rainfall at 25 °C had an increased permeability ($\Delta K_{\text{sat}} = 135\%$), probably due to excessive drying, and hence macropore flow. Effluent-volume data show that high volume P and F treatments (with mean ΔK_{sat} of 76% and 75% respectively) had not fully recovered, whereas permeability in low volume and water-only cores had either recovered or increased.

The three day - low volume treatments had a higher mean ΔK_{sat} (132%) than other time-volume treatment combinations (Table 5.5). The high volume P and F treated cores were slower to recover than other effluent-volume combinations.

5.3.2 Soil analysis

5.3.2.1 Soil Bulk density

The dry bulk density of Bruntwood soil cores was $0.67 \pm 0.02 \text{ g cm}^{-3}$ whereas the dry bulk density of Kopua soil cores was $1.1 \pm 0.1 \text{ g cm}^{-3}$. The bulk density of repacked Bruntwood soils was less than that of the same soil in the field (mean bulk density of 0.72, range 0.63-0.8), and less variable. The mean bulk density of the Kopua soil cores was greater than that measured in the field (0.88 g cm^{-3}). Soil type was the only significant single-factor affecting soil bulk density ($P < 0.001$). There was a soil-temperature interaction ($P = 0.002$). The mean bulk density for Kopua soil at 10 °C was 1.07 g cm^{-3} and at 25 °C 1.19 g cm^{-3} . For the Bruntwood soil at 10 °C mean bulk density was 0.70 and at 25 °C it was similar (0.67 g cm^{-3}).

5.3.2.2 Soil pH

Soil pH (measured in water) was affected by both temperature and effluent type (Table 5.6). Mean soil pH at 25 °C was about half a pH unit higher than for the same effluent at 10 °C (Table 5.6). Cores that received W, P and F effluents all had a pH in the range 5.0 - 5.3, while the pH in A-effluent treated cores had dropped to 4.7 (Table 5.6). Soil and volume also had a significant ($P < 0.05$) effect on soil pH but these differences were less than 0.1 pH units and are not considered to be of practical importance. Two-factor volume-effluent and temperature-effluent interactions

($P < 0.001$) were also evident (Table 5.6). Higher volumes of P and A effluents gave small decreases in soil pH, relative to W and F, at 25 °C with a greater apparent decrease at 10 °C.

Table 5.6 Table of means for soil $\text{pH}_{(\text{H}_2\text{O})}$ measured at the conclusion of the experiment.

	Temperature		Soil		Effluent				Rain		Time		Volume	
	10 °C	25 °C	K	B	W	P	F	A	low	high	3 (days)	9 (days)	high	low
Temperature °C														
10	4.9													
25	-	5.3												
Soil														
K	4.9	5.4	5.14											
B	4.8	5.3	-	5.06										
Effluent														
W	5.2	5.5	5.4	5.3	5.3									
P	4.7	5.3	5.1	4.9	-	5.0								
F	5.1	5.5	5.3	5.3	-	-	5.3							
A	4.4	5.1	4.8	4.7	-	-	-	4.7						
Rain														
low	4.9	5.4	5.1	5.1	5.4	5.0	5.3	4.8	5.1					
high	4.8	5.3	5.1	5.0	5.3	5.0	5.3	4.7	-	5.1				
Time (days)														
3	4.9	5.4	5.2	5.1	5.4	5.1	5.3	4.8	5.2	5.1	5.1			
9	4.8	5.3	5.1	5.0	5.3	5.0	5.3	4.7	5.1	5.0	-	5.1		
Volume														
high	4.8	5.3	5.1	5.1	5.4	4.9	5.4	4.6	5.1	5.0	5.2	5.1	5.06	
low	4.9	5.4	5.2	5.1	5.3	5.2	5.3	4.8	5.1	5.1	5.1	5.0	-	5.1

Note: groups within which significant differences ($P < 0.05$) occur are shown in colour. Single factor interactions (i.e. the effects of just one of the variables included in the experiment) are shown on these tables as the diagonal line across the top edge, the remainder of the table illustrates two-factor interactions.

The pH in CaCl_2 was lower than that for H_2O and there was less difference between the different effluents (data are included in Appendix 2). Effluent and temperature showed up as significant ($P < 0.001$) for pH in CaCl_2 , as was recorded for pH in water.

5.3.2.3 Soil electrical conductivity

Effluent type, soil type and volume all affected the soil electrical conductivity ($P < 0.001$, Table 5.7). The electrical conductivity of the water-only treated soils was lower than that for any of the soil cores which received effluent. Bruntwood soils had a higher mean electrical conductivity ($210 \mu\text{S cm}^{-1}$) than Kopua soils ($170 \mu\text{S cm}^{-1}$). Higher volumes gave higher mean values ($220 \mu\text{S cm}^{-1}$ compared to $160 \mu\text{S cm}^{-1}$).

cm⁻¹). Significant soil-volume and effluent-volume interactions occurred (Table 5.7).

The electrical conductivities of the effluent being applied (Table 5.3) ranged from 200 $\mu\text{S cm}^{-1}$ for tap water to 2800 $\mu\text{S cm}^{-1}$ for F effluent. In spite of the relatively high electrical conductivities of some of the applied effluents, and the rise in electrical conductivity of non-water treated cores, all soils recorded low (150-400 $\mu\text{S cm}^{-1}$) electrical conductivities at the completion of the experiment (Table 5.7).

Table 5.7 Table of means for soil electrical conductivity ($\mu\text{S cm}^{-1}$) measured at the conclusion of the experiment.

	Temperature °C		Soil		Effluent				Rain		Time days		Volume	
	10	25	K	B	W	P	F	A	low	high	3	9	low	high
Temperature °C														
10	190													
25	-	190												
Soil														
K	160	170	170											
B	210	210	-	210										
Effluent														
W	60	80	50	80	70									
P	190	180	150	220	-	180								
F	230	270	220	280	-	-	250							
A	270	240	240	270	-	-	-	250						
Rain														
low	200	190	170	210	70	200	250	260	190					
high	180	190	160	210	70	170	250	250	-	190				
Time														
3	190	190	170	210	70	190	260	240	190	190	190			
9	180	200	160	220	70	180	240	270	190	180	-	190		
Volume														
low	160	160	120	200	70	160	210	200	170	150	150	170	160	
high	220	220	210	230	70	210	290	310	220	220	230	210	-	220

Note: Groups within which significant differences ($P < 0.05$) occur are shown in colour. Single factor interactions (i.e. the effects of just one of the variables included in the experiment) are shown on these tables as the diagonal line across the top edge, the remainder of the table illustrates two-factor interactions.

5.3.2.4 Soil Carbon

The carbon content of the Bruntwood soil (7.3%) was higher ($P < 0.001$) than the Kopua soil (6.7%, Table 5.8). There was a significant ($P < 0.001$) interaction between soil and volume of effluent added with larger volumes associated with an apparent increase from 6.7% C to 7% C in the Kopua soil and a decrease from 7.4 % to 7.2 % in the Bruntwood. The mean carbon percentage was lower at 25 °C than

at 10 °C. This may have been a result of increased carbon mineralisation at the higher temperature. The lowest C % was recorded for cores that received only water and were stored at 25 °C (Table 5.8).

Table 5.8 Table of means for soil carbon (%) measured at the conclusion of the experiment.

	Temperature °C		Soil		Effluent				Rain		Time days		Volume	
	10	25	K	B	W	P	F	A	low	high	3	9	low	high
Temperature °C														
10	7.1													
25	-	6.9												
Soil														
K	6.9	7.3	6.7											
B	6.4	7.3	-	7.3										
Effluent														
W	7.0	6.5	6.4	7.1	6.8									
P	7.4	6.7	6.7	7.4	-	7.1								
F	6.8	7.1	6.7	7.2	-	-	7.0							
A	7.2	7.1	6.8	7.5	-	-	-	7.1						
Rain														
low	7.2	6.9	6.7	7.4	6.7	7.1	7.1	7.2	7.0					
high	7.0	6.9	6.6	7.2	6.8	7.0	6.8	7.1	-	6.9				
Time														
3	7.1	6.9	6.7	7.3	6.8	7.0	7.0	7.3	7.0	7.0	7.0			
9	7.1	6.8	6.6	7.3	6.7	7.1	6.9	7.0	7.0	6.8	-	6.9		
Volume														
low	7.0	6.8	6.4	7.4	6.8	6.8	6.8	7.2	7.0	6.8	6.8	6.9	6.9	
high	7.1	7.0	6.9	7.2	6.7	7.3	7.1	7.1	7.0	7.1	7.2	6.9	-	7.0

Note: Groups within which significant differences ($P < 0.05$) occurred are shown in colour. Single factor interactions (i.e. the effects of just one of the variables included in the experiment) are shown on these tables as the diagonal line across the top edge, the remainder of the table illustrates two-factor interactions.

5.3.2.5 Soil aggregate stability

Aggregate stabilities were uniformly high (80-90%) for all cores, but were higher ($P=0.002$) for the Kopua soil (87%) than the Bruntwood soil (84%). The high values obtained may be the result of the periodic inundation of the cores which has removed any unaggregated material.

5.3.2.6 Soil surface coatings

Surface coatings were observed on cores 12 days after initial effluent application. They were first identified on cores that were receiving high volumes of P or F effluent at 25 °C. When effluent application ceased, all high volume P and F cores had

relatively continuous coatings, low volume P and F cores had intermittent coatings, and W cores had no surface coating.

A black soil-surface coat (0.25-1 cm thick) composed of filtered suspended solid material formed on the surface of all the A cores as a result of application of the high suspended solids content effluent on 24 May. By 29 May the surface coat had cracked and the permeability was restored on the A cores which had an opportunity to dry. Where drying was slower (10 °C room, high volumes and three-day rotation) the permeability remained very low.

The surface coats for all cores were rated on a scale of 0 to 3 as follows:

- 0 = no visible surface coat
- 1 = some surface coat material visible (less than 20 % of surface affected)
- 2 = surface coat present on more than 20% of the core surface, but not continuous
- 3 = coat developed over the entire core surface.

Surface coats were rated 2, 13 and 35 days after effluent irrigation was stopped. Effluent type, the time between applications and the volume of water or effluent applied all affected crust formation recorded two days after effluent application ($P < 0.001$, Table 5.9). W treated cores had a coat rating of 0 (ie no coat formed) while A cores had a mean rating of 2.6, indicating that most cores had a continuous or semi-continuous coat (which was the result of the one batch of high suspended solids effluent). Cores with 9 days between irrigations had greater coat development than those irrigated at 3 day intervals (Table 5.9). High volume effluent treatments had more coat development (with a coat rating of 2.0) than cores that received low volumes of effluent (coat rating of 1.0). Significant volume-effluent ($P < 0.001$) and volume-time ($P = 0.005$) interactions for coat development occurred. Higher volumes of effluent gave increased soil surface coat formation on P, F, and A treated cores. There was little difference between the effect of high volumes added every nine days or every three days (mean of 1.9 compared to 2.1) but at low volumes there was a lot less coating on cores irrigated every three days than 9 days (mean of 0.4 compared to 1.5).

Table 5.9 Table of means for soil surface coat ratings 2 days after effluent application ceased.

	Temperature		Soil			Effluent			Rain		Time		Volume	
	10	25	K	B	W	P	F	A	low	high	3	9	low	high
Temperature °C														
10	1.5													
25	-	1.5												
Soil														
K	1.5	1.6	1.5											
B	1.6	1.4	-	1.5										
Effluent														
W	0.0	0.0	0.0	0.0	0.0									
P	2.0	1.7	2.0	1.7	-	1.9								
F	1.3	1.8	1.5	1.6	-	-	1.5							
A	2.8	2.4	2.6	2.5	-	-	-	2.6						
Rain														
low	1.5	1.4	1.5	1.5	0.0	1.9	1.5	2.6	1.5					
high	1.5	1.5	1.6	1.4	0.0	1.9	1.6	2.5	-	1.5				
Time														
3	1.2	1.2	1.3	1.1	0.0	1.5	1.1	2.1	1.2	1.2	1.2			
9	1.9	1.7	1.8	1.8	0.0	2.2	2.0	3.0	1.8	1.8	-	1.8		
Volume														
low	1.1	0.8	1.1	0.9	0.0	0.9	0.9	2.1	1.0	0.9	0.4	1.5	1.0	
high	1.9	2.1	2.0	2.1	0.0	2.9	2.2	3.0	2.0	2.1	1.9	2.1	-	2.0

Note: Groups within which significant differences ($P < 0.05$) occur are shown in one colour.

Thirteen days after effluent application ceased (Table 5.10) the overall mean surface coat rating was 1.2, compared to a rating of 1.5 recorded two days after effluent application was stopped.

Effluent type, volume of effluent and time continued to have significant ($P < 0.001$) effects on coat development 13 days after effluent application ceased (Table 5.10). A volume-time interaction ($P = 0.02$) was also still evident.

Soil surface coating assessment 35 days after the end of effluent application (Table 5.11) indicated very little change had occurred since day 13. The surface coats on the A cores were still evident - they had dried and did not appear to alter greatly with time. Volume and effluent effects were significant ($P < 0.001$). Time was no longer a significant factor and there were no significant two-factor interactions. Two of the water-treated cores stored at 10 °C had developed some surface coating, presumably a microbial response to the damp conditions.

Table 5.10 Table of means for soil surface coat ratings 13 days after effluent application ceased.

	Temperature		Soil			Effluent			Rain		Time		Volume	
	10	25	K	B	W	P	F	A	low	high	3	9	low	high
Temperature °C														
10	1.3													
25	-	1.1												
Soil														
K	1.3	1.3	1.3											
B	1.3	1.0	-	1.1										
Effluent														
W	0.0	0.0	0.0	0.0	0.0									
P	1.5	1.0	1.4	1.1	-	1.3								
F	0.9	1.1	1.0	1.0	-	-	1.0							
A	2.6	2.4	2.6	2.4	-	-	-	2.5						
Rain														
low	1.3	1.3	1.3	1.3	0.0	1.4	1.3	2.6	1.3					
high	1.2	0.9	1.2	0.9	0.0	1.1	0.8	2.4	-	1.1				
Time														
3	1.0	0.8	1.0	0.9	0.0	1.0	0.6	2.1	1.1	0.8	0.9			
9	1.5	1.4	1.5	1.4	0.0	1.5	1.4	2.9	1.6	1.3	-	1.4		
Volume														
low	1.0	0.6	0.9	0.7	0.0	0.8	0.5	2.0	0.9	0.7	0.4	1.3	0.8	
high	1.5	1.6	1.6	1.6	0.0	1.8	1.5	3.0	1.7	1.4	1.5	1.6	-	1.6

Note: Groups within which significant differences ($P < 0.05$) occurred are shown in one colour.

Table 5.11 Table of means for soil surface coat ratings 35 days after effluent application ceased.

	Temperature		Soil			Effluent			Rain		Time		Volume	
	10	25	K	B	W	P	F	A	low	high	3	9	low	high
Temperature °C														
10	1.2													
25	-	1.2												
Soil														
K	1.3	1.4	1.3											
B	1.1	1.1	-	1.1										
Effluent														
W	0.3	0.0	0.3	0.0	0.1									
P	1.3	1.5	1.3	1.5	-	1.4								
F	1.0	1.0	1.4	0.6	-	-	1.0							
A	2.4	2.4	2.5	2.3	-	-	-	2.4						
Rain														
low	1.1	1.4	1.3	1.3	0.1	1.5	1.1	2.4	1.3					
high	1.3	1.0	1.4	0.9	0.1	1.3	0.9	2.4	-	1.2				
Time														
3	1.1	1.0	1.3	0.8	0.1	1.3	0.9	2.0	1.1	1.0	1.1			
9	1.3	1.4	1.4	1.4	0.1	1.5	1.1	2.8	1.4	1.3	-	1.4		
Volume														
low	0.9	0.8	1.1	0.6	0.0	1.0	0.6	1.7	0.9	0.8	0.6	1.1	0.8	
high	1.6	1.6	1.6	1.6	0.3	1.8	1.4	3.0	1.7	1.5	1.6	1.6	-	1.6

Note: Groups within which significant differences ($P < 0.05$) occurred are shown in one colour.

The mean coat rating for P and F treated cores dropped between two and thirteen days after effluent application ceased, but there was very little change thereafter (Figure 5.2). The coat rating did not change greatly for either the A-treated or the W-treated cores, over the 35 days following the end of effluent application (Figure 5.2). A small amount of microbial surface coating developed on some of the water treated cores between days 13 and 35.

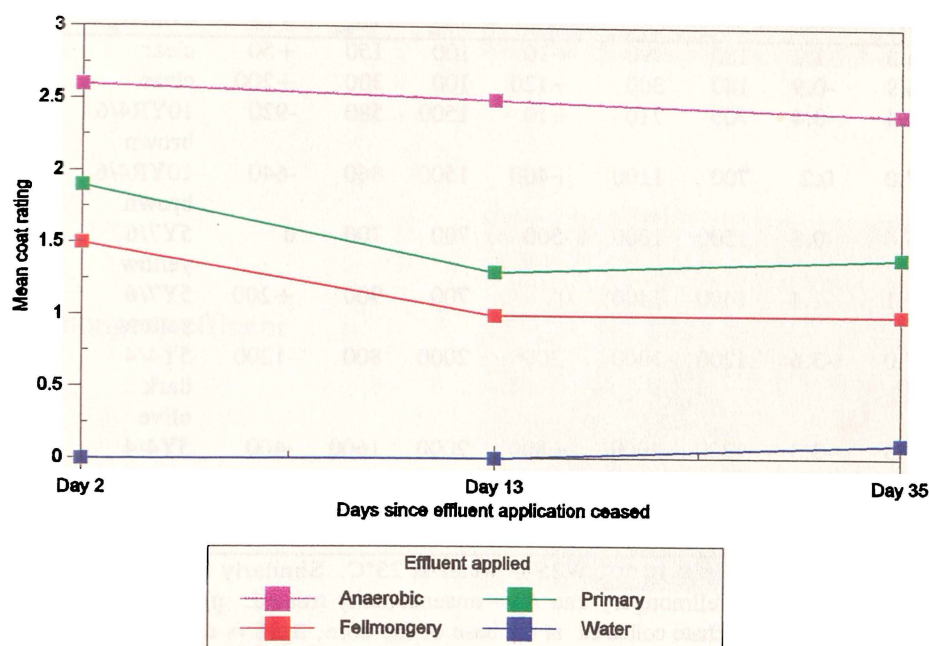


Figure 5.2 Changes in core coatings with time

Upon dismantling the cores it was found that all the coatings were superficial, about 1 mm in thickness, and there was no visible effect evident in the underlying soil. Surface coats appeared to be formed from a combination of suspended solids material from the effluent and biological material growing as a result of the nutrient/moisture additions.

Springtails (*Collembola sp.*) first appeared in cores that were irrigated with A effluent at 25 °C about two weeks after effluent irrigation commenced. Later they appeared on many effluent treated cores at both temperatures. It was observed that

the surface coat broke up more rapidly on cores with large springtail populations.

5.3.3 Effluent treatment

The changes in the effluent properties, as a result of the effluent passing through the soil (Table 5.12) give an indication of the effluent treatment achieved by the soil.

Table 5.12 Mean values of properties of core leachates compared to applied effluent¹.

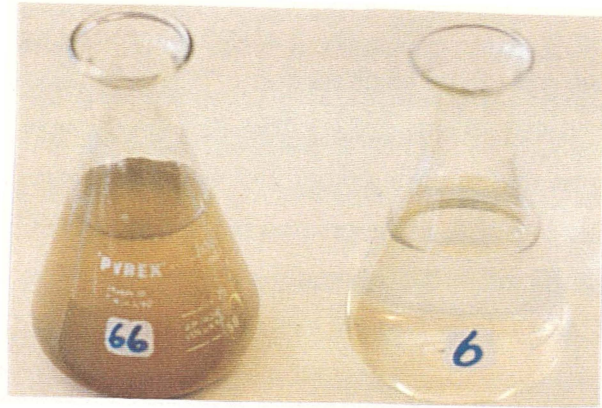
Eff.	pH _{in}	pH _{out}	ΔpH	EC _{in}	EC _{out}	ΔEC	TS _{in}	TS _{out}	ΔTS	Colour _{in}	Colour _{out}
W10	7.5	6.3	-1.2	180	190	+10	100	150	+50	clear	clear
W25	7.8	6.9	-0.9	180	300	+120	100	300	+200	clear	clear
P10	6.8	6.4	-0.4	700	710	+10	1500	580	-920	10YR4/6 brown	5Y8/1 light grey
P25	6.8	7.0	0.2	700	1100	+400	1500	860	-640	10YR4/6 brown	5Y8/1 light grey
A10	7.4	6.6	-0.8	1500	1000	-500	700	700	0	5Y7/6 yellow	5Y8/3 pale yellow
A25	8.5	7.1	-1.4	1400	1400	0	700	900	+200	5Y7/6 yellow	5Y8/3 pale yellow
F10	10.6	7.0	-3.6	1200	1000	-200 ²	2000	800	-1200	5Y4/4 dark olive	5Y8/2 - 5Y7/6 light grey-yellow
F25	10.6	7.3	-3.3	1200	2000	+800	2000	1600	-400	5Y4/4 dark olive	5Y8/4 - 5Y7/6 pale yellow- yellow

¹ Eff. = effluent; W10 = water at 10 °C, W25 = water at 25°C. Similarly for other effluents where P = primary treated, F = fellmongery and A = anaerobically treated. pH_{in} = pH of the applied effluent, pH_{out} = pH of the leachate collected at the base of the core, ΔpH = difference in pH between effluent inflow and out flow. Similarly for other measures where EC = electrical conductivity (μS cm⁻¹), and TS = total solids (g m⁻³).

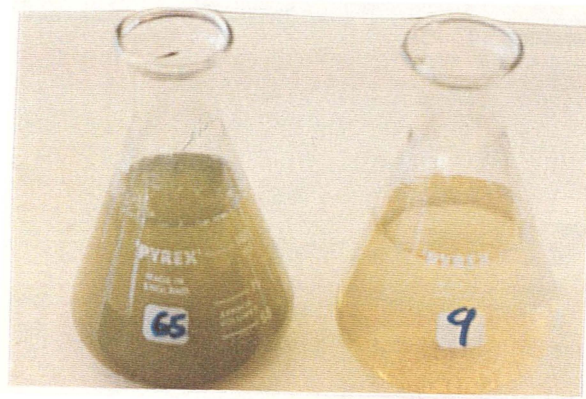
² Very variable, range -500 to +300.

There was a marked change in the colour of leachate when compared to inflow (Table 5.12, Figure 5.3), except in cores where macropore flow was evident. For W-treated cores, the leachate was clear except for one core that was slightly discoloured. The P effluent changed from brown to light grey with a few cores appearing pale yellow to yellow and one that was bright yellowish brown. The F effluents changed in colour from dark olive to pale yellow or yellow with one clear and one light grey. These were not as well amended as those with P effluents. Inflow of A effluent was yellow with leachates recorded as light grey, pale yellow or clear.

Primary treated effluent



Fellmongery effluent



Anaerobically
treated effluent

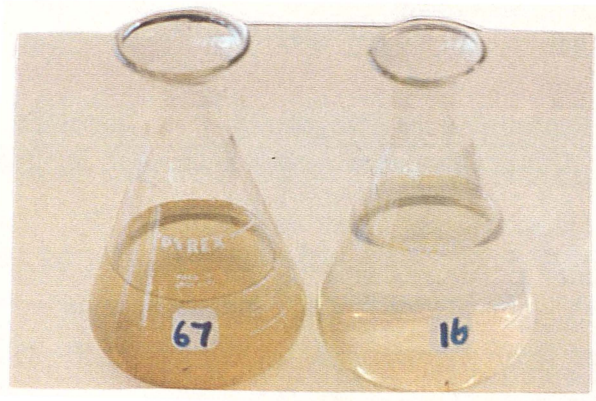


Figure 5.3 Photographs of effluent before (container on left hand side of each photograph) and after flow through cores

The pH of the leachate was lower than that of the applied effluent for most cores (Table 5.12).

The pH of the leachate was affected by the type of effluent, and by temperature ($P < 0.001$, Table 5.13). The higher pH associated with higher temperatures appears to be due to core drying and shrinkage, resulting in an increase in macropore flow. The F and A effluents had higher pH as did their core leachates. There was also a significant soil-temperature interaction ($P < 0.001$), with the Bruntwood soil at 25 °C giving the highest mean pH.

Table 5.13 Table of means for core leachate pH.

	Temperature °C		Soil			Effluent			Rain		Time (days)		Volume	
	10	25	K	B	W	P	F	A	low	high	3	9	low	high
Temperature °C														
10	6.5													
25	-	7.1												
Soil														
K	6.6	6.9	6.7											
B	6.5	7.2	-	6.8										
Effluent														
W	6.3	6.9	6.5	6.6	6.6									
P	6.4	7.0	6.7	6.7	-	6.7								
F	6.9	7.3	7.0	7.2	-	-	7.1							
A	6.5	7.1	6.7	6.9	-	-	-	6.8						
Rain														
low	6.5	7.1	6.7	6.8	6.6	6.7	7.1	6.8	6.8					
high	6.5	7.1	6.7	6.9	6.6	6.7	7.1	6.8	-	6.8				
Time														
3	6.5	7.1	6.7	6.8	6.5	6.7	7.2	6.7	6.8	6.8	6.8			
9	6.6	7.1	6.8	6.9	6.6	6.7	7.1	6.9	6.8	6.8	-	6.8		
Volume														
low	6.6	7.0	6.7	6.9	6.5	6.7	7.0	6.9	6.7	6.9	6.8	6.8	6.8	
high	6.4	7.1	6.8	6.8	6.6	6.7	7.2	6.6	6.8	6.7	6.7	6.8	-	6.8

Note: Groups within which significant differences ($P < 0.05$) occurred are shown in colour.

Effluent, temperature, and volume all affected leachate electrical conductivity (Table 5.14). The lowest leachate electrical conductivity ($250 \mu\text{S cm}^{-1}$) was recorded for water treated cores and the highest ($1510 \mu\text{S cm}^{-1}$) was for fellmongery effluent treated cores (Table 5.14). Mean leachate electrical conductivities were higher at 25 °C than at 10 °C.

The effluent-temperature interaction was significant (Table 5.14) as a result of the big differences in electrical conductivities between effluents combined with a tendency for them to be higher at higher temperatures. An increase in electrical conductivity in core leachate, compared to applied effluent, occurred at 25 °C for W, P and F effluents (Table 5.12). This may be due to the remobilisation of some salts that had accumulated in the soil as a result of the drying of soil cores following the cessation of effluent irrigation.

Table 5.14 Table of means for core leachate electrical conductivity ($\mu\text{S cm}^{-1}$).

	Temperature °C		Soil		Effluent				Rain		Time (days)		Volume	
	10	25	K	B	W	P	F	A	low	high	3	9	low	high
Temperature °C														
10	720													
25	-	1200												
Soil														
K	740	1170	950											
B	710	1220	-	970										
Effluent														
W	190	310	220	280	250									
P	710	1090	950	860	-	900								
F	1030	1990	1520	1500	-	-	1510							
A	970	1390	1140	1230	-	-	-	1180						
Rain														
Low	690	1300	980	1010	260	930	1600	1190	1000					
Hi	760	1090	920	920	240	870	1410	1170	-	920				
Time														
3	740	1210	950	1000	270	970	1460	1190	1030	910	970			
9	710	1180	960	940	230	830	1560	1170	960	940	-	950		
Volume														
low	640	1090	810	1090	280	820	1310	1050	940	790	850	880	870	
high	810	1290	920	1010	220	980	1710	1310	1050	1050	1090	1020	-	1050

Note: groups with significant differences ($P < 0.05$) within them are shown in one colour.

The total solids in the leachate were affected by temperature, effluent and volume ($P < 0.001$, Table 5.15). Higher total solids were recorded for F effluent than others as a result of the higher level of total solids applied, and the larger proportion of dissolved solids (which are less likely to be retained in the soil than suspended solids). Total solids in leachates were higher at higher temperature and higher volumes. Effluent-temperature ($P < 0.001$), effluent-volume ($P < 0.001$), temperature-soil ($P = 0.02$) and soil-volume ($P = 0.02$) interactions were all significant.

The high-temperature Bruntwood soil cores had higher total solid concentrations in leachates, probably as a result of macro-pore flow (Table 5.15). The total solids

content of core leachate for P treatments (Table 5.15) was 30-60% of that applied with the biggest decrease at 10 °C. The total solids leachate from A treated cores was unchanged, or showed an increase, particularly at 25 °C. In the anaerobic effluent most of the solids were usually dissolved and therefore pass through the soil. The increase in total solids out, over that applied for water-treated cores and other treatments at 25 °C (Table 5.12) was probably due to the loss of soil material from cores, which was more common where macropore flow was occurring.

Table 5.15 Table of means for core leachate total solids content.

	Temperature °C		Soil		Effluent				Rain		Time (days)		Volume	
	10	25	K	B	W	P	F	A	low	high	3	9	low	high
Temperature °C														
10	550													
25	-	910												
									Grand mean = 730					
Soil														
K	590	850	720											
B	510	980	-	740										
Effluent														
W	150	290	180	260	220									
P	580	860	740	700	-	720								
F	780	1610	1150	1240	-	-	1195							
A	700	890	810	780	-	-	-	790						
Rain														
low	530	960	750	740	210	700	1280	790	740					
high	580	860	690	750	230	740	1110	800	-	720				
Time														
3	580	940	760	770	250	810	1190	800	780	750	760			
9	520	880	680	720	190	630	1200	790	710	690	-	700		
Volume														
low	440	790	560	680	230	680	930	650	660	580	630	610	620	
high	660	1030	880	810	210	760	1460	940	830	860	890	790	-	840

Note: groups with significant differences ($P < 0.05$) within them are shown in one colour.

Table 5.16 Summary of impacts of experiment factors on variables tested¹

Variable ²	Experiment Factors					
	Effluent	Volume	Soil	Temp.	Rain	Time
K _{sat} - 2	x	x		x		x
K _{sat} - 13	x	x		x	x	x
Soil pH	x	x		x		
Soil EC	x	x				
Soil ρ_d			x	x		
Soil C	x	x	x	x		
Agg. stabil.	x			x		
Coat - 2	x	x				x
Coat - 13		x				x
Coat - 35						
Leachate pH		x	x	x		
Leachate EC			x	x	x	
Leachate TS	x	x	x	x		

¹ Coloured boxes indicate significant ($P < 0.05$) one-factor effects, x indicates significant ($P < 0.05$) two-factor interactions.

² K_{sat} - 2 = K_{sat} two days after effluent application ceased, K_{sat} - 13 = K_{sat} thirteen days after effluent application ceased, EC = electrical conductivity, ρ_d = bulk density, Agg. stabil. = soil aggregate stability, Coat - 2 = soil surface coat two days after effluent application ceased, similarly for coat - 13 and coat - 35, TS = total solids.

The type of effluent added had some impact on every variable tested except for soil bulk density. Volume affected every variable except soil bulk density and aggregate stability (Table 5.16). The interaction between effluent and volume was the strongest effect observed in this experiment with high volumes of P and F effluent leading to the largest decline in soil K_{sat}. Effluent and volume were also associated with the visible soil surface coat formation. The cores which had very large decreases in soil K_{sat} (to $< 5 \text{ mm hr}^{-1}$) all exhibited surface coating assessed as level "3" indicating that the coat may have been responsible for the decrease in soil K_{sat}. The K_{sat} recovered when cores were allowed to dry, and even if the soil surface coat was still present, the K_{sat} recovered as soon as the coat dried and cracked.

Similar responses to effluent application were generally observed for the two soil types, despite their different textures and mineralogies. There was no relationship between the soil-type and development of soil surface coating, indicating that both soils were equally susceptible to surface coat development. There were significant

differences in soil bulk density, carbon content, aggregate stability, and electrical conductivity between the two soil types (Table 5.16), which are attributed to the inherent differences between the two soils. Two days after effluent application ceased, the decrease in K_{sat} was greater in the Kopua soil than in the Bruntwood soil. The Kopua soil had a lower mean K_{sat} and may, therefore, have been more susceptible to pore blockage. However, 13 days after effluent application ceased there was no difference in ΔK_{sat} between the two soil types.

Temperature had an effect, particularly on ΔK_{sat} and leachate properties. At the higher temperature greater soil drying, and hence, increased soil shrinkage was observed, especially in the Bruntwood soil. The increased K_{sat} , and higher core leachate pH, electrical conductivity and total solids in cores stored at the higher temperature were taken to be an indication of the occurrence of macropore flow.

Time between effluent applications was significant as a single factor only in coat formation where nine days between effluent applications gave greater coat development than three day intervals, probably due to the higher dose per application at longer time intervals. The extra soil moisture added as rain showed up as only weakly significant in interactions with temperature for soil K_{sat} at 13 days, and with leachate electrical conductivity. The low rainfall treatments were apparently more prone to core macropore flow as a result of drying and consequent soil shrinkage.

The slowing of P or F effluent movement through cores could be observed in the course of addition of one dose of effluent and is attributed to physical blockage of soil pores by the suspended solids from the effluent. The soil surface coats appear to be formed, at least initially, from the suspended solids material from the effluent. However, some material which appeared to be microbiological became visible within some soil surface coats. The hazard of applying high suspended solids effluent was clearly illustrated by the anaerobic effluent of 24 May where a soil surface coat formed and led to an immediate decrease in core permeability.

The findings presented here indicate that atypical variations in effluent properties, such as the high suspended solids content of the A effluent of 24 May, can have large effects on soils and should be taken into account when designing a system. Effluent properties may vary beyond their usual range as a result of plant malfunctions,

variations in the activities within the factory and events such as clearing out holding ponds. If there is not sufficient flexibility to allow an area that receives a particularly high dose of material time to recover prior to further effluent application then surface ponding and runoff of effluent may result.

Effluent application had very little effect on soil bulk density or aggregate stability in the time-frame of this experiment. Aggregate stabilities remained very high for all treatments, indicating that dispersion of clay minerals was not occurring. Therefore physical and biological blockage were the only processes contributing to a decrease in core permeability in this experiment.

Significant differences in soil pH, carbon content and electrical conductivity were recorded in relation to a number of the experiment factors (Table 5.16), however the changes in soil pH were small. Both soils buffered the high pH F effluents (pH 11) with effluent leachate having a pH of about 7 and soil pH remaining relatively unaffected at about 5. As some changes in soil pH, carbon and electrical conductivity were recorded in this short-term experiment, the implication is that careful long-term monitoring of effluent addition should be undertaken at effluent irrigation sites as cumulative changes in these properties could become detrimental to the soil system.

The effectiveness of soil in treating effluent was illustrated by the leachate properties investigated in this experiment. Flow of effluent through a 15 cm deep soil generally provided a marked improvement in effluent colour, and solids content and led to a decrease in effluent pH when high pH effluents were applied. The effectiveness of the soil at effluent renovation was lower at 25 °C than at 10 °C, which is attributed to increased drying leading a higher incidence of soil shrinkage and macropore flow at the higher temperature.

The use of repacked soil in the cores destroyed the natural soil structure but was considered necessary to observe the effects of the treatments that were imposed, due to the large between-sample variability in K_{sat} that can occur in undisturbed soil. In the field situation there are many other factors that may also affect the decline in soil permeability that were not tested in this experiment, including direct solar radiation, diurnal temperature variation, and the effects of wind and grazing animals. However,

the surface crusts and associated decline in infiltration rates observed in this experiment were similar to those observed in the field survey (Chapter 4). Therefore it is considered that the results provide information on factors that influence decline in soil permeability following effluent application to soil.

5.5 Conclusion

All of the factors tested (effluent type, volume of effluent applied, soil type, temperature and rainfall) had some effect on the soil or leachate variables that were monitored, illustrating the complexities and inter-relationships that occur within the soil system. However, effluent type, the volume of effluent added, and the temperature had larger impacts with rainfall having relatively little effect.

High volume applications of P and F effluents (equivalent to 5475 mm yr⁻¹) were clearly not sustainable, causing K_{sat} to decrease substantially after only one month of application. The experiment indicates that high application rates should not be attempted. Effluent application at rates equivalent to 1825 mm yr⁻¹, led to a decline in K_{sat} similar to that observed in water-treated cores and was therefore considered more suitable. The development of a soil surface coat, formed from suspended solids from the effluent and microbial materials growing in response to the effluent, contributed to the decline in K_{sat} .

The effect of effluent application on soil hydraulic conductivity was influenced by the temperature, with a larger decrease in K_{sat} at 10 °C and faster recovery at 25 °C. There is, therefore, likely to be a seasonal difference in the way that a soil responds to, and recovers from effluent application.

The two soils used in this experiment responded to effluent application in a generally similar manner, even though they had markedly different inherent soil properties. Therefore, it is suggested that the processes of soil surface coat formation and associated permeability decline are more strongly controlled by effluent and climate variables than by soil properties.

Chapter 6: Comparison between water and effluent infiltration rates - a field trial

6.1 Introduction

It was apparent in Chapter 5 that the suspended solids concentration of the effluent, and the volume of effluent applied, contributed to the observed decline in infiltration rates. While a number of instances of decline in infiltration rates due to suspended solids in effluent have been previously reported (Section 2.4.1.2), no examples that related directly to meat processing plant effluent, or even to effluents with similarly high suspended solids concentrations, were found. Furthermore much of the literature relates to the conditions of rapid infiltration, rather than irrigation as practised by New Zealand meat processing plants. Both Rice (1974) and Bouwer *et al.* (1974) suggested that to prevent soil pore blockage the suspended solids concentration in effluent should be less than 10 g m^{-3} . However, many meat processing plant effluents currently irrigated onto New Zealand soils have higher concentrations. Primary treated meat processing plant effluents contain suspended solids in the range of $150 - 2000 \text{ g m}^{-3}$, and even following tertiary treatment, suspended solids concentrations remain above the recommended concentrations at $20 - 100 \text{ g m}^{-3}$ (Russell and Cooper 1992).

Recommended rates of effluent irrigation, which make some allowance for a reduction in effluent infiltration rates, compared to water, vary widely. For example the USEPA (1976) recommended rates between 10% and 50% of those for "clean" water but also state that determining rates of effluent application "is more of an art than a science". In comparison Vanderholm (1984) recommended an application rate of 70% of that for "clean" water.

The relationship between effluent particle size and soil pore size is important as it will determine the likelihood of effluent particles becoming trapped in soil pores. The particle size distribution of a primary treated meat processing plant effluent (Table 6.1) is within the same range of orders of magnitude as the soil pore size distribution for a range of soils (Figure 6.1). Most of the effluent suspended solids (i.e. material $> 1.2 \mu\text{m}$ in diameter) was in the $1.2 - 200 \mu\text{m}$ diameter size range. There were also some larger particles (Table 6.1). Many soil pores are also in the range $1.2 - 200 \mu\text{m}$ in

diameter (Figure 6.1). Therefore, the particles from a primary treated meat processing plant effluent are likely to become lodged in soil pores.

Table 6.1 Particle size distribution of primary treated effluents¹

Particle size range μm	Sample A			Sample B			Sample B through soil cores ³		
	Mean ² %	Mean ² g m^{-3}	S.D. %	Mean %	Mean g m^{-3}	S.D. %	Mean %	Mean g m^{-3}	S. D. %
< 1.2	61	963	-	47	719	-	88	264	-
1.2 - 63	24	379	3	43	658	5	12	36	5
63 - 200	9	142	1	8	122	4	0	0	0
200 - 600	4	63	1	1	15	1	0	0	0
>600	2	32	1	1	15	1	0	0	0
Total	100	1580		100	1530		100	300	

Notes ¹The particle size distributions of two samples of primary treated meat processing plant effluent (collected at different times to demonstrate the variability that occurs) were measured by passing the effluent through a nest of sieves with 600, 200, and 63 μm diameter openings and with GFC filter paper (1.2 μm). ² data for sample A are means of 4 samples; others are means of 3 samples. ³ This is effluent sample B following infiltration through a 15 cm deep core of Bruntwood A horizon.

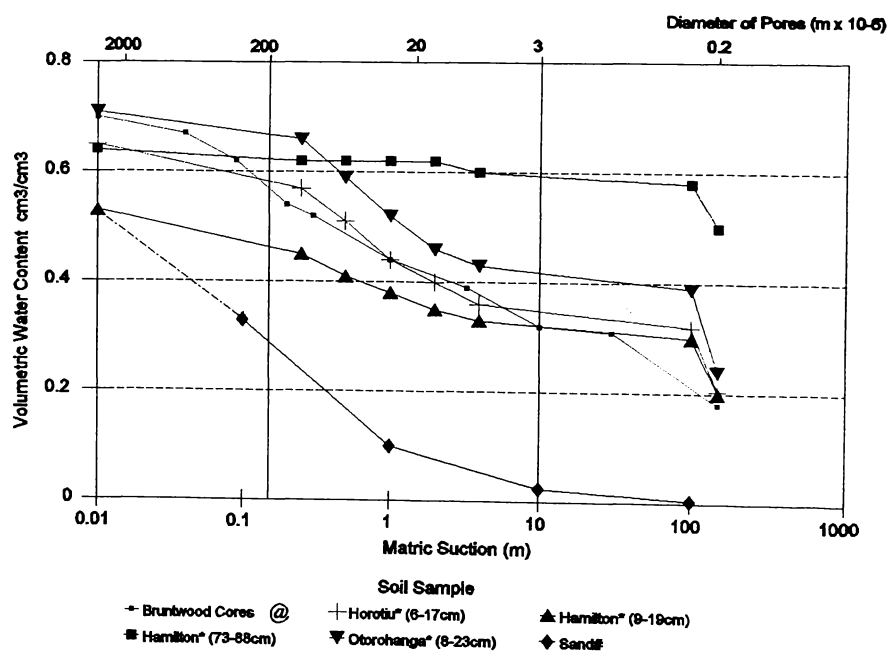


Figure 6.1 Soil pore size distribution of a range of soils (@ = data included in appendix 5, * = data from NZ Soil Bureau (1986), # = after Marshall and Holmes (1988).)

Most suspended solids are retained at or very close to the soil surface (Berend 1967, Bouwer and Chaney 1974). Suspended solids retention at the soil surface is probably due to a lack of continuous coarse pores in most soils, the effect of adsorption of solid particles to soil surfaces and the rapid decline in pore effectiveness as particles become trapped.

Berend (1967) suggested a model which could be used for predicting infiltration rate decline as a function of the suspended solids content of flood waters. Berend observed that seepage rates decrease linearly, if plotted against the cumulative height of the infiltrated water column, thus leading to the relation:

$$i = i_o - \alpha vgs \quad (6.1)$$

where: i = instantaneous infiltration rate (LT^{-1})

i_o = initial i

α = coefficient ($L^3T^{-1}M^{-1}$)

v = suspended solids concentration (ML^{-3})

g = fraction of suspended matter retained on or about the soil surface - dimensionless

s = cumulative height of the infiltrated water column (L).

The time (t) function of infiltration can be derived mathematically (Berend 1967) giving:

$$i = i_o e^{-\alpha vgs} \quad (6.2)$$

The first objective of this chapter was to determine the difference in infiltration rates between water and effluent from New Zealand meat processing plants which contain a range of suspended solids contents. The second objective was to determine whether the model of Berend (1967) is applicable to New Zealand meat processing plant effluents.

6.2 Experimental design and methodology

An experiment was carried out to compare the infiltration rates of untreated, primary treated and anaerobically treated meat processing plant effluents with the infiltration rate of water on a Bruntwood silt loam under pasture situated near Hamilton (described in Appendix 3). Five sets of twin rings were used to measure infiltration rates for up to seven hours following the method of Scotter *et al.* (1982) as described in Chapter 3. Water infiltration rates were measured one day, and on the following day the rings were shifted laterally, approximately 2 m, and the measurements were repeated using an effluent. The procedure was repeated on three occasions, for the different effluents.

Water was acquired from a nearby farm water supply and selected properties of the water and effluents used are summarised in Table 6.2. The experimental site and equipment are illustrated in Figure 6.2.

Table 6.2. Properties of water and effluent used in effluent infiltration trial¹.

Effluent	Electrical conductivity ($\mu\text{S cm}^{-1}$)	Total solids (g m^{-3})	Suspended solids (g m^{-3})
Water 1 ²	120	120	nd ³
Untreated	720	2250	1400
Water 2	110	nd	10
Primary- treated	970	1400	550
Water 3	110	135	15
Anaerobically- treated	1550	610	15

¹Water data are the mean of two samples, primary and raw effluent the mean of three, and anaerobic effluent the mean of four samples. ²Water 1,2, and 3 are used to distinguish the water samples for the three different times when the experiment was undertaken. ³nd = not determined.

Total and suspended solids were highest in the primary treated and untreated effluents and lowest in water (Table 6.1). The high electrical conductivity and high proportion of dissolved solids (595 g m^{-3}) of the anaerobic effluent reflects the inclusion of fellmongery effluent in the anaerobic effluent stream.

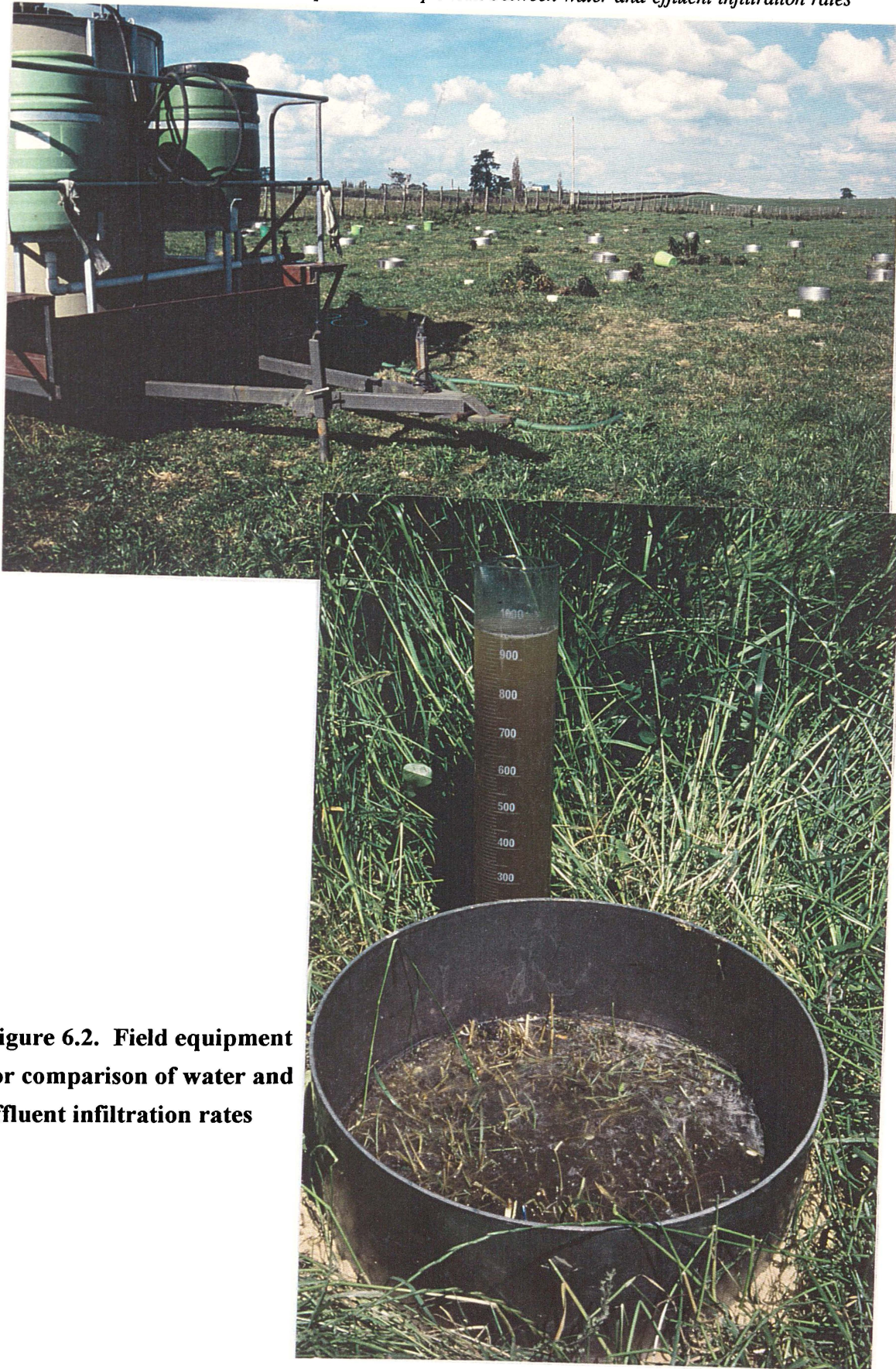


Figure 6.2. Field equipment for comparison of water and effluent infiltration rates

6.3 Results

Results of the experiment are summarised in Figure 6.3 and the data are included in Appendix 3.

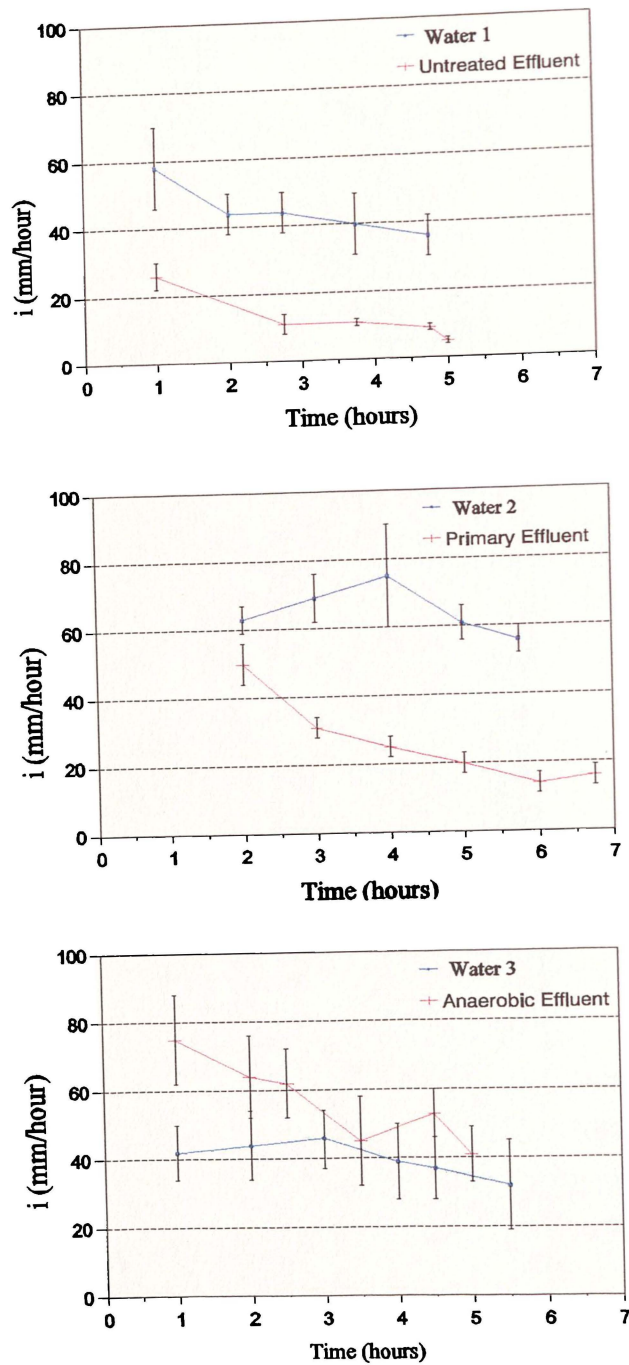


Figure 6.3 Comparison between water and effluent infiltration rates
(Error bars = 1 standard error of the mean)

The infiltration rate of primary and untreated effluents was lower than the infiltration rate of water (Figure 6.3). However the infiltration rate of the anaerobically treated effluent was not significantly different from the infiltration rate of water. The decline in infiltration rates for the primary treated effluent was slower, than the decline in infiltration rate of the untreated effluent (Figure 6.3).

To compare the infiltration rate of the three effluents with water, the ratio of the infiltration rate of effluent to the infiltration rate of water ($i(\text{effluent})/i(\text{water})$) was calculated for each effluent treatment (Figure 6.4). In generating the relationships shown in Figure 6.4, the initial effluent infiltration rate was assumed to be equal to the initial water infiltration rate.

A decline to 50% of water infiltration rate occurred after about one hour of application of untreated effluent and after about three hours of application of primary treated effluent (Figure 6.4) whereas there was no difference between the infiltration rate of water and anaerobic effluent. The infiltration rate of untreated effluent initially slowed more quickly than that for primary treated effluent, however, after about four hours the infiltration rates were about 1/3 of the water infiltration rate for both the primary and untreated effluents.

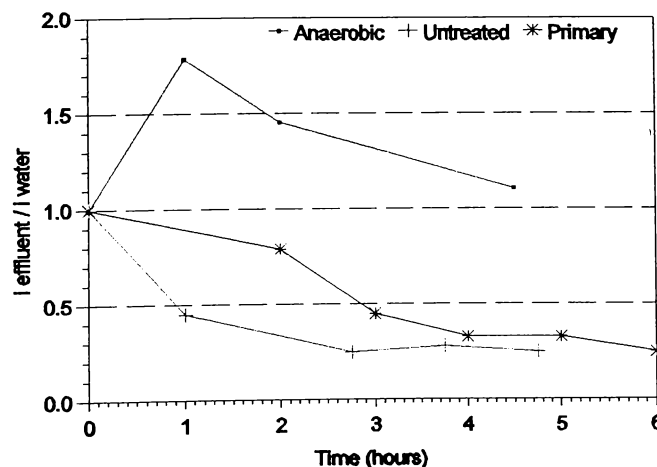


Figure 6.4 Ratio of effluent infiltration rate/water infiltration rate versus time

6.4 Model application

Regression analysis of the infiltration rate, i , against the total water infiltrated, I , and the total suspended solids added, for each effluent, for all treatments together, for primary and untreated together and, for water and anaerobic effluents together are illustrated in Figures 6.5 and 6.6, and summarised in Table 6.3.

In order to calculate cumulative infiltration and cumulative suspended solids application it was necessary to obtain a value for the initial infiltration rate. This was not measured. An initial infiltration rate of 70 mm hr^{-1} was adopted, by interpolation from the graphs in Figure 6.3. This value was used in the calculation of cumulative suspended solids and cumulative infiltration for all treatments. (To check the impact of adopting a value of 70 mm hr^{-1} for i_0 , the regression values were also calculated using an i_0 of 50 and 90 mm hr^{-1} . The regressions thus obtained were similar to those given in Table 6.3, indicating that the result is not strongly sensitive to i_0 , and, therefore, suggesting that adoption of a value of 70 mm hr^{-1} was reasonable.)

All individual treatments, except water 2 (Figure 6.5b), show good correlations between i and cumulative water and cumulative suspended solids. The poor correlation shown by water 2 is associated with larger measurement variability (Figure 6.3) than that of the other treatments. When all treatments are included, cumulative water infiltration (Figure 6.5i) does not give a good correlation but cumulative suspended solids (Figure 6.6i) does. This relationship is further improved if only the primary and untreated effluents are selected (Figure 6.6g).

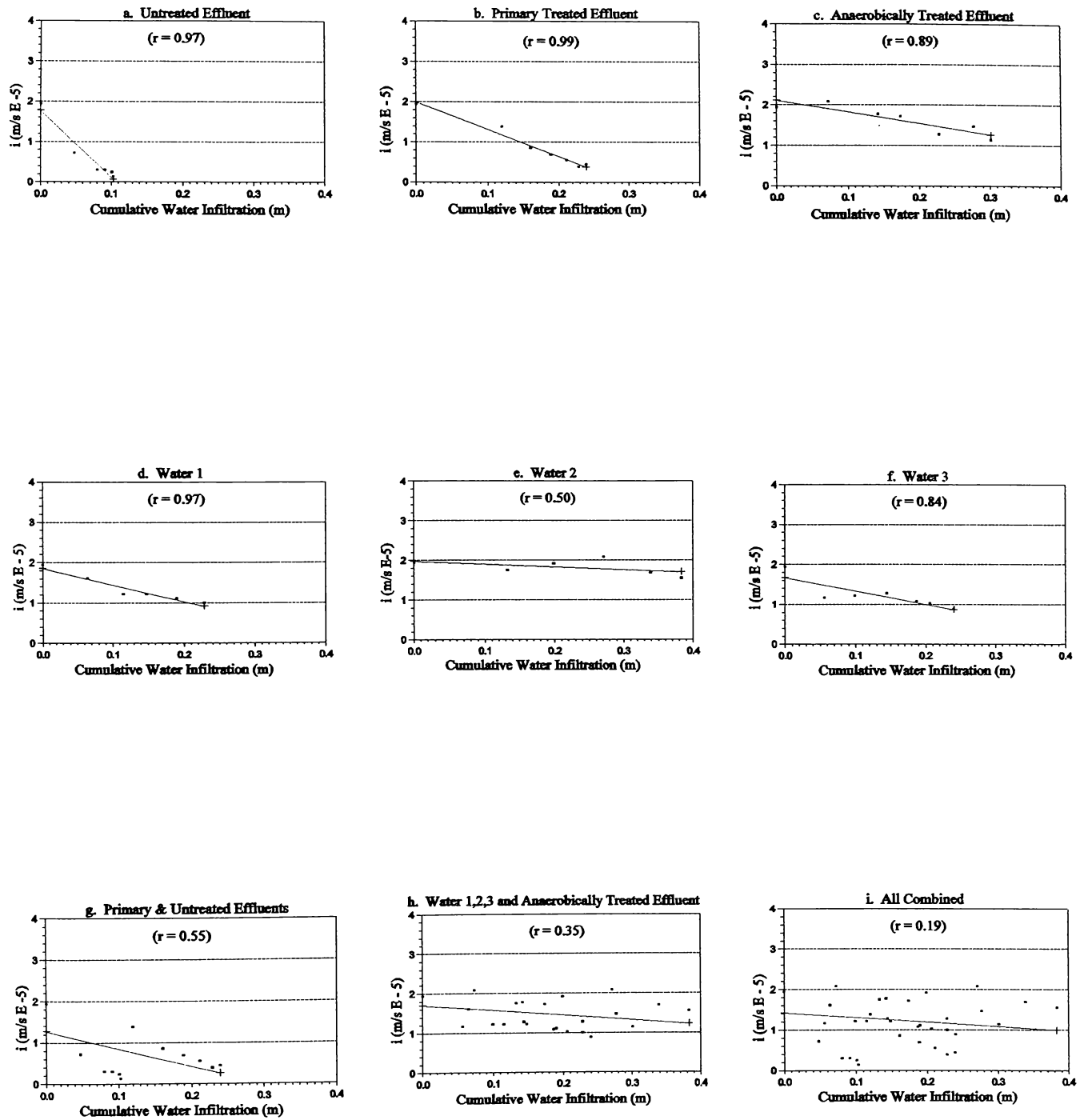


Figure 6.5 Regression analysis for i vs cumulative water infiltration

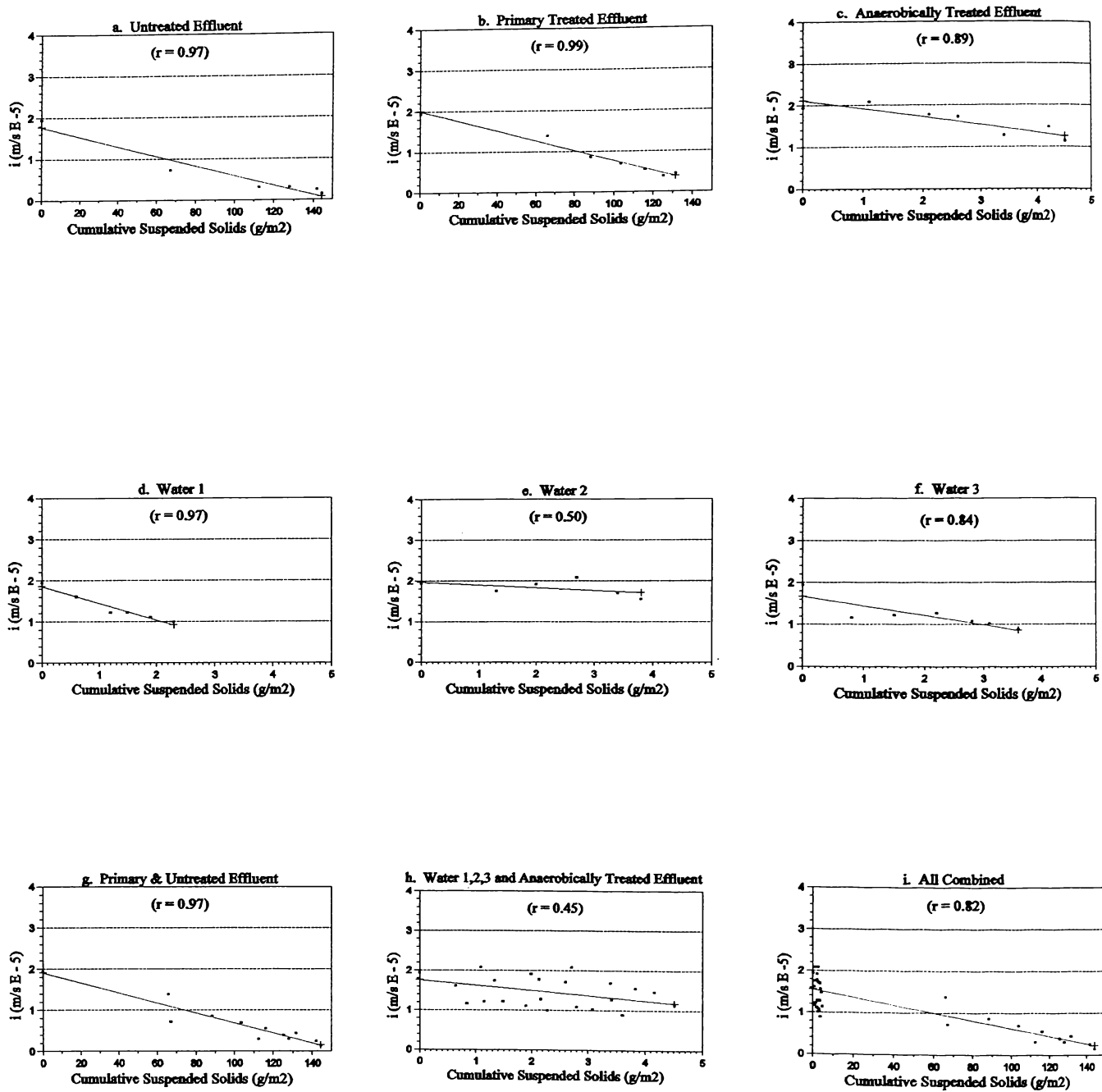


Figure 6.6 Regression analysis for i vs cumulative suspended solids infiltration

Table 6.3 Summary of regression analysis of infiltration rate, i , versus cumulative water added and cumulative suspended solids added.

	i vs cumulative water			i vs cumulative suspended solids		
	Intercept $\text{m s}^{-1} * 10^{-5}$	Slope $* 10^{-5}$	r	Intercept $\text{g m}^{-2} * 10^{-5}$	Slope $* 10^{-5}$	r
Water 1	1.9	-4.1	0.97	1.9	-0.41	0.97
Water 2	2.0	-0.7	0.50	2.0	-0.07	0.50
Water 3	1.7	-3.3	0.84	1.7	-0.22	0.84
Untreated	1.8	-16.5	0.97	1.8	-0.01	0.97
Primary	2.0	-6.8	0.99	2.0	-0.01	0.99
Anaerobic	2.1	-2.9	0.89	2.1	-0.19	0.89
All	1.4	-1.1	0.19	1.6	-0.01	0.82
Prim +	1.3	-4.2	0.55	1.9	-0.01	0.97
Untreated Rest	1.7	-1.2	0.35	1.8	-0.13	0.45

Notes: Water 1 = water measurements made in association with untreated effluent application, Water 2 = water measurements made in association with primary treated effluent, Water 3 = water measurements made in association with anaerobically treated effluent. All = regression analysis of all the water and effluent data together, Prim + Untreated = analysis of primary and untreated effluent data together, Rest = analysis of all water and anaerobic effluent data together.

Berend's model (equation 6.1) has the same form as the regression equations for cumulative suspended solids (Table 6.3), where vs = the cumulative suspended solids. For meat processing plant effluent g (the fraction of suspended matter retained on or about the soil surface) is about 0.95 (as derived from Table 6.1) and i_0 corresponds to the intercept values given in Table 6.3. Solving equation 6.1 for α gives an α value of $1 \times 10^{-7} \text{ m}^3 \text{ s}^{-1} \text{ g}^{-1}$ for primary and untreated effluents, both individually and together. The value of α depends on the kind of suspended matter, its concentration, the nature of the soil, and the initial infiltration rate (Berend 1967). The particularly high suspended solids concentrations in primary and untreated effluents suggest that suspended solids are more important in determining α than the influence of initial soil infiltration rates and related properties.

The good correlation ($r = 0.97$) between infiltration rate and cumulative suspended solids for primary and untreated effluents, when considered together, suggests that the model of Berend (1967) has potential wider application in predicting the decline in effluent infiltration rates as a result of application of high suspended solids meat

processing plant effluents.

Equation 6.2 can be solved for time for a given decline in infiltration rate, eg. for infiltration rate to halve:

$$i/i_0 = 0.5 = e^{-\alpha v g} \quad (6.3)$$

solving for t gives:

$$t = -\ln 0.5 / \alpha v g \quad (6.4)$$

Solving equation 6.4 (where for the effluents in this discussion $\alpha = 1 \times 10^{-7} \text{ m}^3 \text{ s}^{-1} \text{ g}^{-1}$, $g = 0.95$ and for primary treated effluent $v = 550 \text{ g m}^{-3}$ and for untreated effluent $v = 1400 \text{ g m}^{-3}$) predicts that the time to halve infiltration rate for primary treated effluent is 3 hours, 40 minutes and for untreated effluent it is 1 hour, 30 minutes. These times are in reasonable agreement with those indicated in Figure 6.3, suggesting that this relationship could be used to give an initial prediction of the likely decline in infiltration rates, due to effluent application, as a function of the suspended solids content of the effluent.

6.5 Discussion

The experiment described in this chapter demonstrated that the infiltration rates for primary and untreated effluents were significantly lower, and decreased more with time, than the infiltration rate of water. The decrease in infiltration rate was greatest for the highest suspended solids (untreated) effluent, as would be expected from the results of Chapter 5. Comparison between soil pore size distribution and primary treated effluent particle size distribution showed that the suspended solids in meat processing plant effluents are similar in size to many soil pores. Therefore, the suspended solids can be expected to become lodged in, or block soil pores. The decrease in infiltration rate for primary and untreated effluents, compared to water, was attributed to pore blockage by the suspended solids from the effluent.

Because the infiltration rate of effluent is not the same as that of water it is suggested

that when an effluent irrigation scheme is being designed then infiltration rate measurements should be undertaken using the effluent that is to be irrigated, rather than water. However, the model of Berend (1967) has potential for use as an alternative to extensive field measurements. Berend's model (Berend, 1967) has potential application in deciding the amount of treatment needed to remove suspended solids prior to effluent application, and in predicting the length of time that effluent can be irrigated before effluent infiltration rates decline significantly. While it has been demonstrated to work well for the Bruntwood soil further work needs to be undertaken on a range of other sites to confirm the wider applicability of this relationship for New Zealand conditions.

In this experiment effluent was ponded on the soil surface for several hours which represents the situation at the top end of borders in border-dyke irrigation systems. It is suggested that in border dyke irrigation schemes short borders, with frequent shifts of effluent application between borders will be best for prevention of physical pore blockage.

6.6 Conclusion

There was a significant decline, with time, in the infiltration rates of primary and untreated effluents compared with water or anaerobically treated effluents. This was attributed to physical pore blockage by the suspended solids in the effluent.

High suspended solids effluent (suspended solids greater than about 1000 g m^{-3}), such as the untreated effluent of this trial, can be applied for only very short periods (less than one hour) before an effluent infiltration rate decline to half of that for water occurs. Primary treated effluent (suspended solids of about 500 g m^{-3}) can only be applied for 2 - 3 hours before the effluent infiltration rate declines to about half of that for water.

A linear relationship ($r = 0.97$) existed between infiltration rate and total cumulative suspended solids added. This fits the model of Berend (1967) which could be used as a predictive tool to determine decline in infiltration rate as a function of effluent suspended solids content.

Conditions in this experiment were similar to those of border-dyke irrigation where effluent is ponded on the soil surface for several hours. To avoid a decline in infiltration rates under border dyke irrigation, when using primary treated or untreated effluents, it is suggested that short borders should be used and the border under irrigation should be changed frequently.

Physical pore blockage is likely to be the first step in the formation of a soil surface-coat. There is a need to investigate the rate at which permeability recovers because if more effluent is added prior to recovery then the decline in infiltration rates could be expected to compound.

The large differences between water and effluent infiltration rates imply that when an effluent irrigation scheme is being designed, soil infiltration rates should be measured with an effluent similar to that which is proposed to be disposed of, rather than with water.

Chapter 7

Recovery of soil permeability following effluent application

7.1 Introduction

It was demonstrated, in Chapters 5 and 6, that applications of effluent to soil can cause a decrease in soil permeability. It is, therefore, important to determine the rate of permeability recovery. If additional applications of effluent are made prior to recovery, further permeability decline may cause effluent surface ponding and lead to irrigation scheme failure. Soil temperature was shown earlier (Chapter 5) to influence the rate of recovery of soil permeability and is widely known to affect the rate of microbial activity. This chapter describes two laboratory experiments that were undertaken at different temperatures (13 °C and 25 °C) to determine the loss and recovery of K_{sat} following effluent application. In the next chapter (Chapter 8) the biological response to effluent application under similar experimental conditions, is described.

7.2 Experimental design and methodology

Both experiments used soil cores packed with soil from a Horotiu silt loam Ap horizon (using the method described in Section 3.6). The soil (a Typic Orthic Allophanic Soil), and the site from which the soil was obtained, are described in Parfitt *et al.* (1980). The A horizon of the Horotiu soil is similar to the A horizon of the Bruntwood soil used in the earlier experiments (Chapters 5 and 6) in this thesis. Repacked soil cores (rather than undisturbed) were used for the reasons explained in section 5.2.1. Measurements of K_{sat} were made using the method described in Section 3.2.1.1. Because of the large variability in K_{sat} between cores the percent change in K_{sat} (ΔK_{sat} , calculated as described in Section 5.2.2) was determined for each individual core.

7.2.1 Trial conducted at 25 °C

The K_{sat} of cores was measured six times to enable the initial K_{sat} of the soil to be calculated. Twenty cores were then selected for inclusion in the experiment, avoiding

cores that had particularly low, high or erratic K_{sat} results. Two litres of primary treated meat processing plant effluent (equivalent to a depth of 210 mm) was applied to each of 10 cores. The same amount of water (210 mm) was applied to each of the remaining 10 cores. Core K_{sat} was then measured 1, 4, 7, 10, 13, 17 and 23 days after effluent or water application.

7.2.2 Trial conducted at 13 °C

The K_{sat} of each core was measured four times before forty cores were selected for use in the experiment. Again, cores with exceptionally high, low or erratic K_{sat} results were avoided. Two litres of primary treated meat processing plant effluent (equivalent to a depth of 210 mm) was applied to each of 20 cores and two litres of tap water was applied to each of the remaining 20 cores. They were then stored in an unheated room which maintained a fairly constant temperature (13 ± 2 °C) throughout the duration of the experiment. Core K_{sat} was then measured 2, 4, 7, 11, 16, 21, 28, 34, 41, 49, 62, 70, 86 and 100 days after effluent or water application.

7.2.3 Effluent properties

Selected properties of the effluents used in each experiment are given in Table 7.1. The effluent used in the 13 °C trial had a higher pH and electrical conductivity, and lower suspended solids than the effluent used for the 25 °C trial. The differences between the effluents are a result of the variability of effluent, as the experiments were conducted at different times.

Table 7.1 Selected properties of the primary treated meat processing plant effluent used in permeability recovery experiments.

Property	13 °C	25 °C
pH	9.4	7.5
Electrical conductivity ($\mu\text{S cm}^{-1}$)	850	690
Total solids (g m^{-3})	1 800	1 800
Suspended solids (g m^{-3})	500	950

7.3 Results

A complete summary of the data presented in this chapter is included in Appendix 4.

7.3.1 Rate of recovery for soils stored at 25 °C

Application of effluent to the soil cores stored at 25 °C resulted in a substantial decrease in core K_{sat} (Figure 7.1). In contrast the K_{sat} of the water treated cores remained fairly constant over time (i.e. ΔK_{sat} remained at approximately 100%). On days 1, 4, 7, and 10 there was a significant ($P < 0.001$) difference between the ΔK_{sat} of effluent and water treated cores. There was a gradual recovery in the K_{sat} of the effluent treated cores over time and after 23 days there was no longer a significant difference between treatments (Figure 7.1).

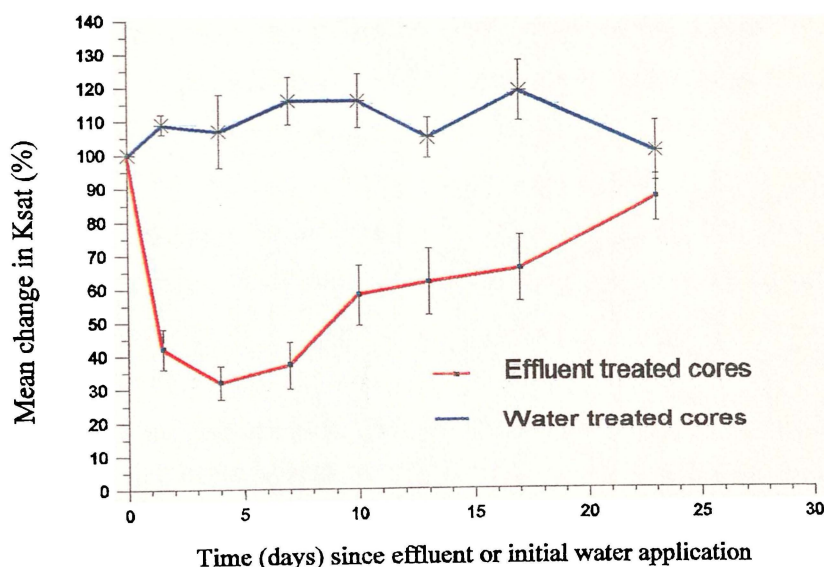


Figure 7.1 Percent change in permeability of cores treated with effluent or water, stored at 25 °C (Error bars are 1 standard error of the mean).

A surface crust was observed to develop immediately following effluent addition, formed from the solid components of the effluent. This appeared to develop into an algae/slime cemented material by day 3 but began to break up by day 7. By day 13 the surface crust had subsided to a discontinuous film on most cores and by day 23 surface crusting was no longer visible (this is further discussed in Chapter 8).

7.3.2 Rate of recovery for soils stored at 13 °C

The mean ΔK_{sat} of cores stored at 13 °C that were treated with water fluctuated between 80 and 100% (Figure 7.2) with a possible slight decrease over time. The ΔK_{sat} of effluent treated cores dropped to less than 50 % at day two and then recovered slowly so that by day 49 there was no significant difference between the two treatments ($P < 0.05$). The ΔK_{sat} of effluent treated cores had only recovered to about 75% by day 100.

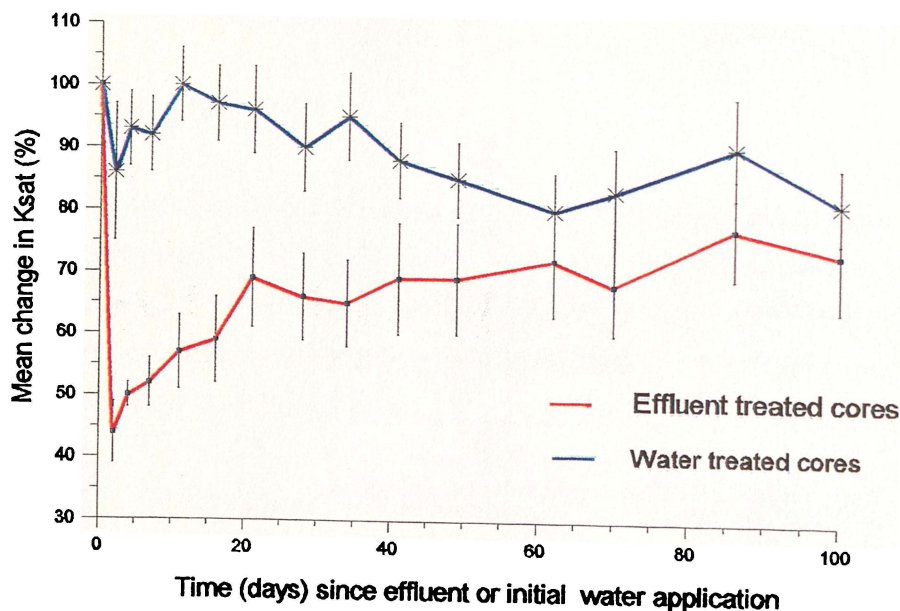


Figure 7.2 Percent change in permeability of cores treated with effluent or water, stored at 13 °C (Error bars are 1 standard error of the mean)

A surface crust, similar to that described in section 7.3.1, developed within a few days of effluent application. It was still visible, although no longer continuous, 49 days after effluent application, but only small remnants were still visible by day 100.

7.4 Discussion

There was a marked decline in core K_{sat} following application of primary treated meat processing plant effluent at both temperatures. The K_{sat} of cores stored at 25 °C recovered after about 23 days, however cores stored at 13 °C took twice as long (about 50 days) to recover to levels that were not significantly different from water treated cores. The slower rate of recovery of soil K_{sat} at 13 °C, than at 25 °C, may contribute to the lower infiltration rates observed at effluent irrigation sites in winter than in summer (Section 4.4.3).

The K_{sat} was observed to decrease during effluent application which, along with the low K_{sat} measured the following day, can be attributed to the suspended solids component of the effluent. The difference in the suspended solids content of the two effluent samples did not appear to greatly affect the ΔK_{sat} which dropped to about 45% on the day after effluent application in both the experiments. The continued decrease in K_{sat} recorded at day four on the cores stored at 25 °C was probably the result of the build up in biological material on the soil surface (see Chapter 8).

All effluent treated cores had some fat visible on the core surface following effluent addition. This became less evident after about 1 week in the cores stored at 25 °C but some fat was visible for up to 10 weeks on the cores stored at 13 °C indicating that the fat material was much slower to break down at the cooler temperature.

While conditions in these experiments are different from those prevailing in the field they do suggest that there is a marked difference in recovery rates at different temperatures. Under field conditions it would be expected that desiccation, caused by sun and wind, would make recovery more rapid than that recorded here. It could therefore be expected that under warm summer conditions it would take less than three weeks for soil permeability to recover following application of a large (200

mm) dose of primary treated meat processing plant effluent. However when the temperature is around 13 °C, it may take twice as long for soil permeabilities to recover and if the mean temperature dropped further it could take considerably longer, especially if combined with surface ponding from winter rainfall.

7.5 Conclusion

The time taken for soil permeability to recover following application of large doses (200 mm) of primary treated meat processing plant effluent will be considerably longer in winter than in summer. Soil permeabilities are likely to recover in less than three weeks in warm summer conditions, but may take over twice as long to recover in cold winter conditions.

Chapter 8

Investigation of the biological response to effluent addition using a scanning electron microscope

8.1 Introduction

The results described in previous chapters have shown that application of meat processing plant effluent may cause a decrease in soil permeability, and that recovery of permeability was influenced by temperature. While initial decline in permeability is affected by the suspended solids component of the effluent (Chapter 6) it was apparent that microbial activity may have contributed to some of the soil surface coating and permeability decline. This chapter describes a series of investigations in which a scanning electron microscope (SEM) was used to qualitatively determine the microbiological response to effluent application to soil.

8.2 Sample selection and preparation

Samples for SEM viewing were taken from both effluent and water treated soil cores which had been stored at 13 °C and at 25 °C. In order to relate the results of the laboratory experiments to the field situation, two field meat processing plant effluent irrigation sites (Wakanui and Taumarunui) were also sampled.

Soil cores stored at 13 °C

Eight soil cores that were stored at 13 °C, four of which had received effluent and four of which were water treated, were sampled. The cores were prepared at the same time, and treated in the same manner, as those described in Section 7.2. The cores were sampled prior to effluent or water application and 4, 7, 11, 21, 28, 63, 73, 80, 98, 114, 135, 149 and 155 days after effluent application.

Soil cores stored at 25 °C

Eight cores, six of which received effluent and two of which received water, were stored at 25 °C. The cores were prepared, as described in section 7.2 except that a different

batch of effluent was applied to them. The effluent that was applied to six of the cores consisted of 210 mm of contra-sieved meat processing plant effluent, with a pH of 7.1, a total solids content of $2\,900\text{ g m}^{-3}$ and a suspended solids of 610 g m^{-3} . An equivalent depth (210 mm) of water was applied to the remaining two soil cores which acted as a control. By 37 days after the initial effluent or water application the cores had become very dry and changes in soil microbial development were no longer evident. To test the effect of adding moisture, 50 mm of water was applied to half of the cores on day 37. Core surface and subsurface samples were taken prior to effluent application and then 1, 2, 4, 8, 10, 16, 23, 30, 38 and 44 days after the initial effluent or water application.

Field sample collection

Samples were collected from the Wakanui meat processing plant effluent irrigation site, near Ashburton, in October 1992 and from the AFFCO meat processing plant effluent irrigation site near Taumarunui in February 1993. The weather at Ashburton in the fortnight preceding sampling had been cool and wet. Prior to sampling at Taumarunui the weather had been hot and dry with all soils, except those that had been recently irrigated, in a very dry condition. Samples were sealed in plastic bags and transported to the laboratory. The following day SEM samples were prepared and freeze-dried.

Samples of soils that had been irrigated with effluent were taken from a range of sites at both Wakanui and Taumarunui. Control samples were taken from a water irrigated site at Wakanui and from a non-irrigated site at Taumarunui.

Sample preparation for SEM viewing

The following sample preparation method was developed. Thin (approximately 1 mm) slices of soil were cut from soil cores or larger field samples using a scalpel. These were fastened to microscope stubs using double-sided carbon tape. Samples were immersed in liquid propane for about 30 seconds then transferred to liquid nitrogen and dried in a freeze-drier overnight. This allowed biological material to be preserved in what appeared to be a reasonably whole state. Samples were then stored at room temperature in a dessicator. They were sputter-coated with gold/palladium and viewed using an Hitachi S4 100 SEM.

In the course of this work over 450 samples were prepared and viewed. When soil cores were sampled, generally, 2 surface and 2 subsurface samples were taken from each of four cores, two that had been effluent treated and two that had received only water. Multiple samples, at a range of depths were taken for all the field samples that are described.

8.3 Results

Results of the SEM investigations are presented as a series of photographs in Figures 8.1 to 8.21. The numbers on the base of the SEM photographs are (in order from left to right): the camera photo number, the electron acceleration voltage, the magnification to which the SEM was set when the photograph was taken (where k stands for thousand), and the length of the scale on the photograph (μm). The photographs included in this chapter were selected to show representative samples of the features discussed.

8.3.1 Soil cores stored at 13 °C

Typical photographs of the water-treated soil surface (Figure 8.1) show no visible micro-organisms in soils on day 0 (Figure 8.1 a and b), day 11 (Figure 8.1 c and d), or day 63 (Figure 8.1 e and f) and the soil matrix is clearly visible. A few testate amoebae (Figure 8.1 g) were occasionally observed. By day 135, although the general soil matrix was unchanged (Figure 8.2 a and b), a film of biological material developed on some soil surfaces (Figure 8.2 c and d). Note that Figure 8.2 d is a 15 000 times magnification of an area on the right-hand-side of Figure 8.2 b. The biological material remained localised and was not evident in samples taken on day 155 (Figure 8.2 e, f and g).

The addition of effluent to soil cores led to a marked biological response. Some suspended solids material from the effluent is visible in Figure 8.3 a, c, e, f and g. This material partially covered the soil surface, but by day four the remaining soil surface was masked by a fine net of biological material (Figure 8.3 b). By day seven this net had become virtually continuous over much of the soil surface with individual bacteria evident (Figure 8.3 c and d). On day 11 (Figure 8.3 e, f, and g) core surfaces appeared similar to those viewed on day seven. Plant material (probably from effluent paunch material, i.e. undigested material from the animals gut) is visible on the soil surface (Figure 8.3 e and f). The smooth area on the right hand side of Figure 8.3 g is possibly fatty material

and f). The smooth area on the right hand side of Figure 8.3 g is possibly fatty material from the effluent.

A low magnification view of the core surface sampled on day 21 (Figure 8.4a) showed suspended solid material and a coating of biological material on the soil surface. The surface coat was fairly continuous (Figure 8.4 b, d and e) although gaps were visible in some areas (Figure 8.4c). The extreme coating visible in Figure 8.4 e and f may be associated with fat from the effluent. Figure 8.4 g shows fat taken from the edge of a soil core (where it had adhered since effluent application 64 days prior to sampling) which is similar in appearance to the surface shown in Figure 8.4 e.

Samples from day 28 (Figure 8.5) showed that bacteria were present but the soil coating was no longer continuous (Figure 8.5 a and b), and in some areas was not visible at all (Figure 8.5 c). Figure 8.5 d, e, f, and g show a progression of magnification from 400 to 10 000 times, of the core surface on day 35. These show a large number of bacteria on the soil surface but the coating material between them is relatively discontinuous.

By day 63, a diversification of the soil micro-organism population was evident (Figure 8.6). Fungi were present in some cores (Figure 8.6 a and b). Some larger pieces of suspended solids material (Figure 8.6 c) were still visible although being attacked by bacteria (Figure 8.6 d). Small colonies of actinomycetes, as identified by the $0.5\ \mu\text{m}$ widths of the filamentous cells, (Figure 8.6 e and f) and a few testate amoebae (Figure 8.6 a and g) were also present.

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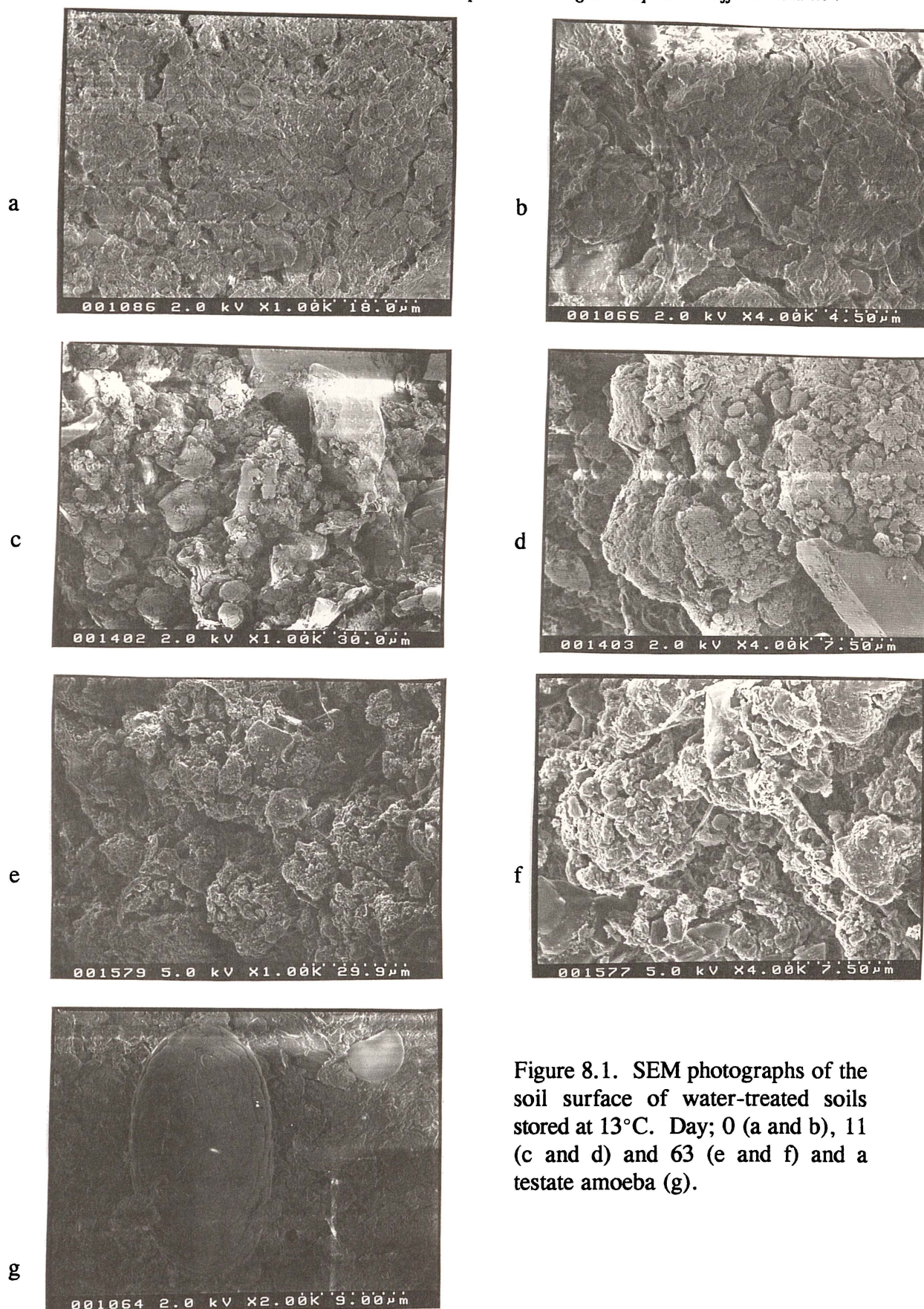


Figure 8.1. SEM photographs of the soil surface of water-treated soils stored at 13°C. Day; 0 (a and b), 11 (c and d) and 63 (e and f) and a testate amoeba (g).

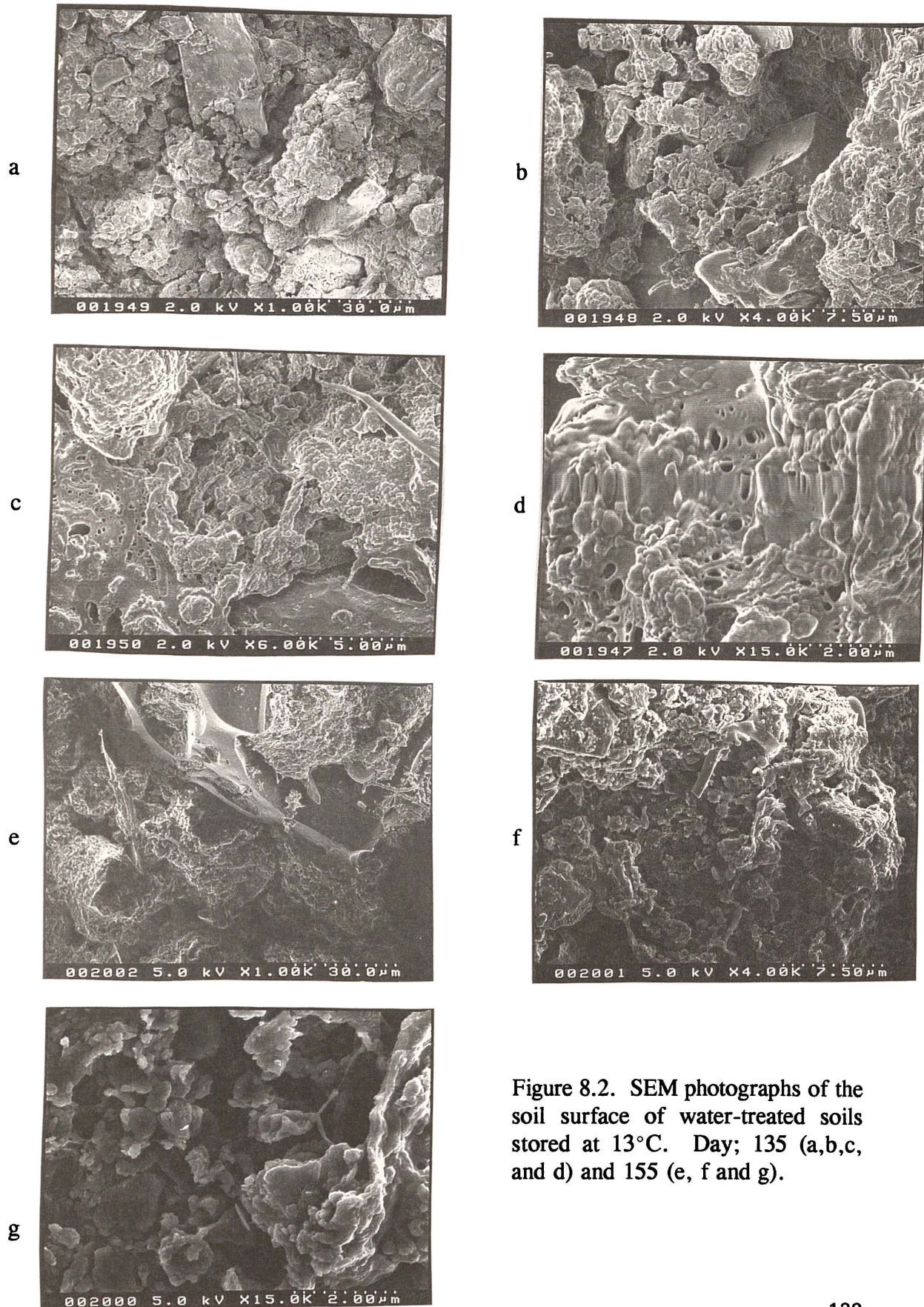


Figure 8.2. SEM photographs of the soil surface of water-treated soils stored at 13°C. Day; 135 (a,b,c, and d) and 155 (e, f and g).

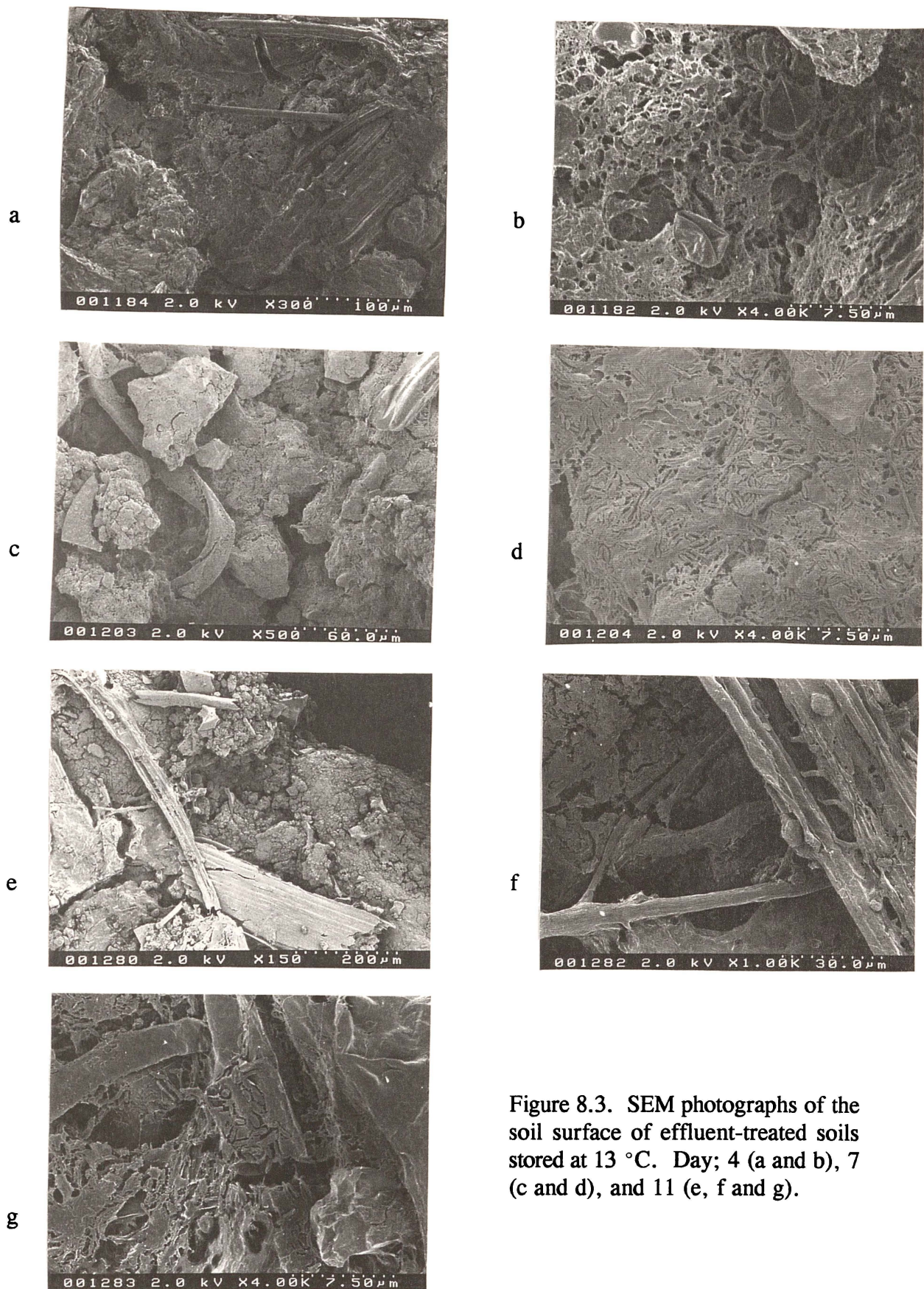


Figure 8.3. SEM photographs of the soil surface of effluent-treated soils stored at 13 °C. Day; 4 (a and b), 7 (c and d), and 11 (e, f and g).

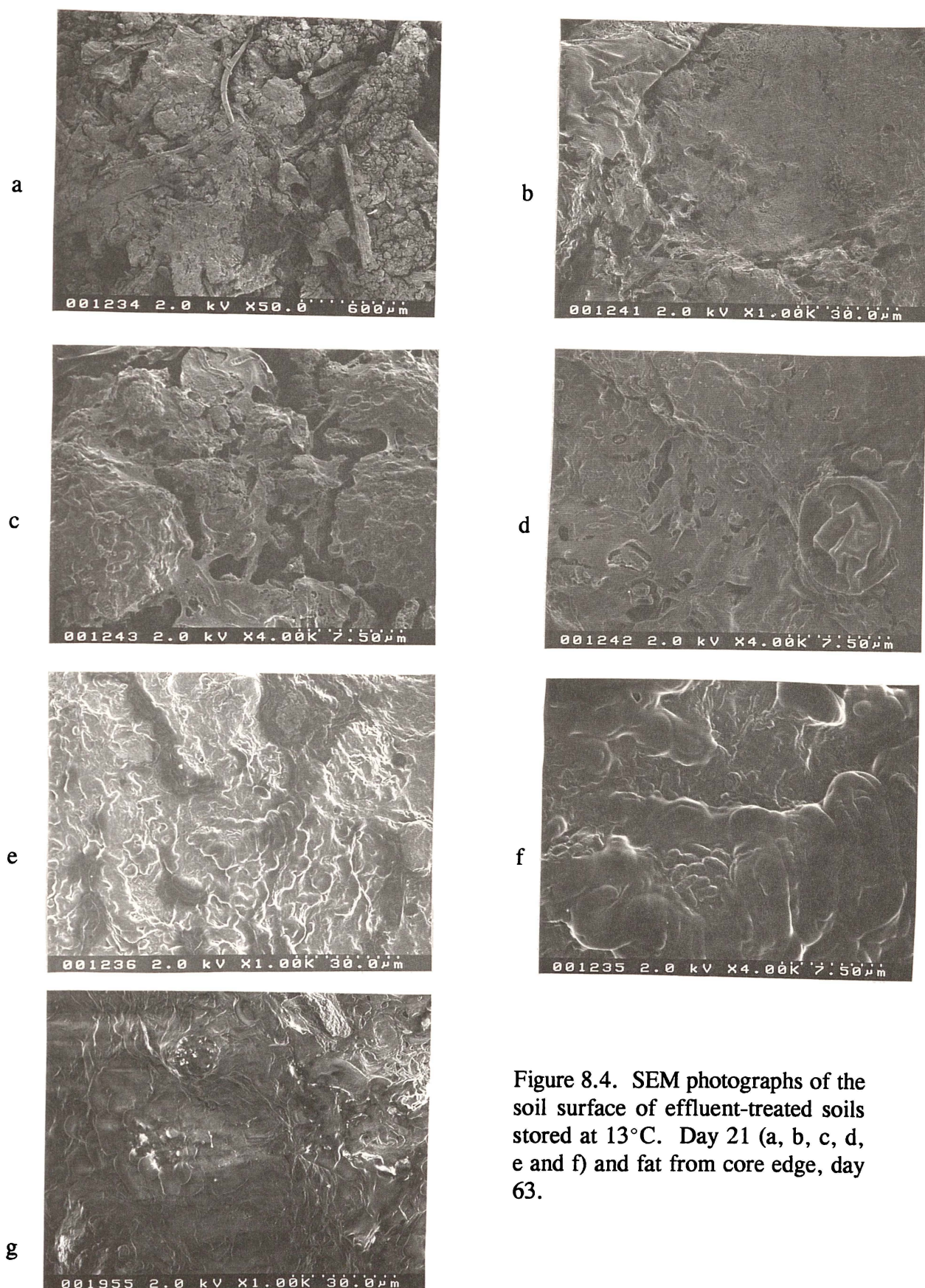


Figure 8.4. SEM photographs of the soil surface of effluent-treated soils stored at 13°C. Day 21 (a, b, c, d, e and f) and fat from core edge, day 63.

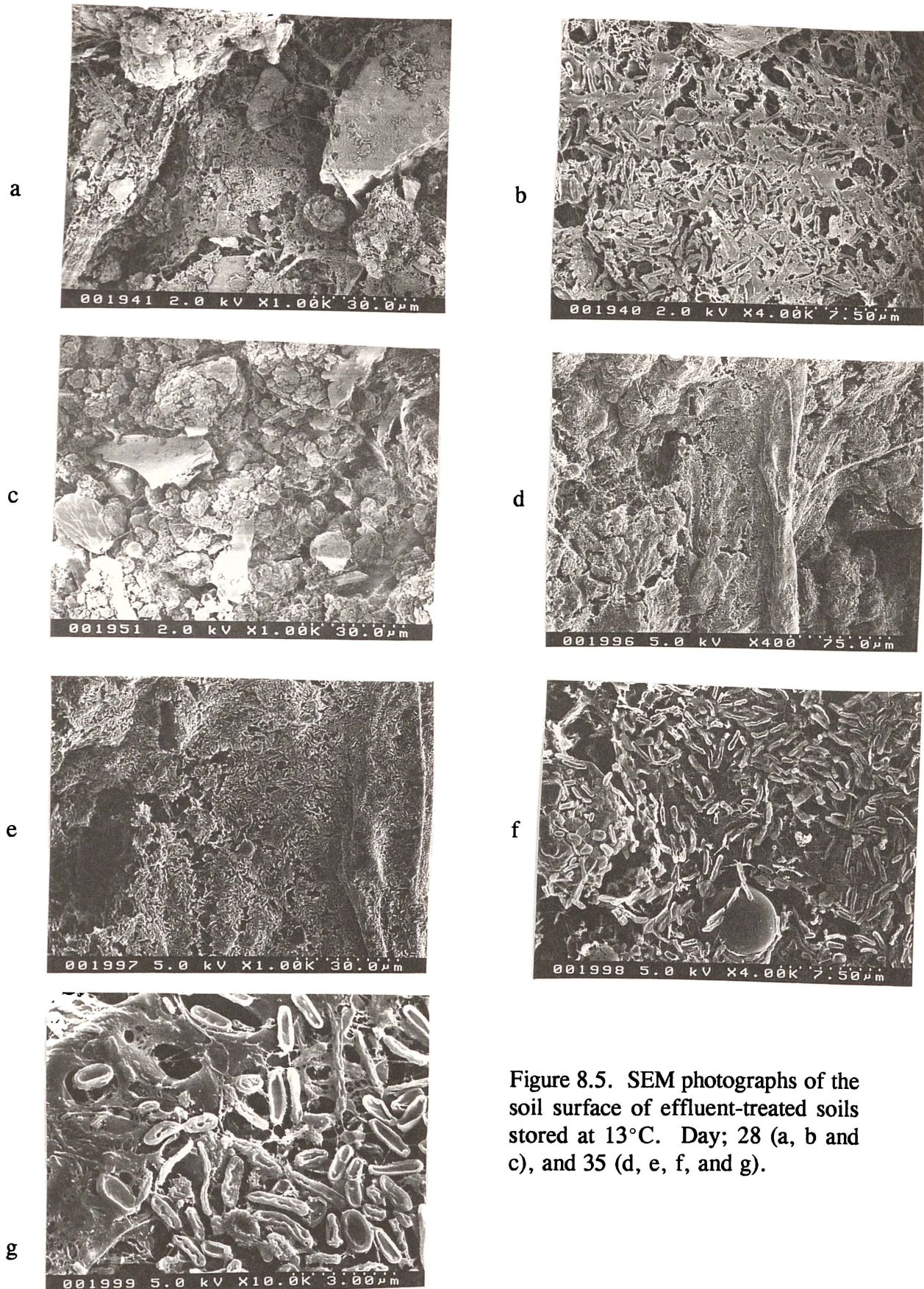


Figure 8.5. SEM photographs of the soil surface of effluent-treated soils stored at 13°C. Day; 28 (a, b and c), and 35 (d, e, f, and g).

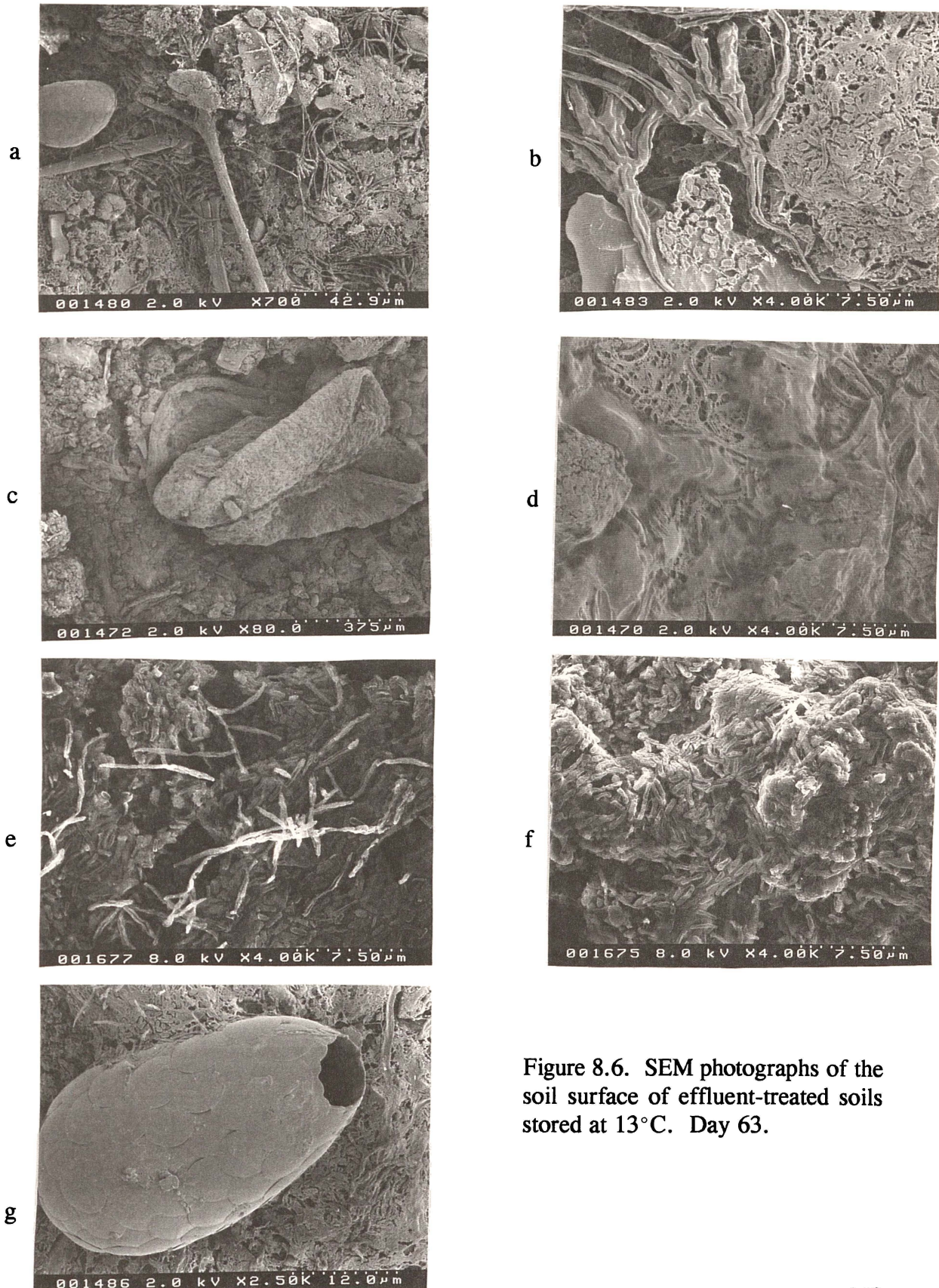


Figure 8.6. SEM photographs of the soil surface of effluent-treated soils stored at 13°C. Day 63.

Eighty days after effluent application, a coating of bacteria was still evident on most core surfaces (Figure 8.7). Some areas, which were possibly fat material, were largely unaffected by microbial attack (Figure 8.7 c and d) but larger areas were being colonised by actinomycetes (Figure 8.7 e, f and g).

Ninety eight days after effluent application, testate amoebae (Figure 8.8 a) and a variety of bacterial forms were evident (Figure 8.8a and b). Non branching actinomycetes (Figure 8.8c) which may be *Arthrobacter* or *Cellulomonas* were also visible. By day 135 (Figure 8.8 d and e) the continuous coating had retreated markedly and by day 155 (Figure 8.8 f and g), apart from a few testate amoebae, there was very little microbial material visible.

The considerable microbial response, described above, was confined to the soil surface. Samples from between 1 mm and 5 mm below the soil surface (Figure 8.9) were generally devoid of visible microorganisms, although a coating on some soil particles was occasionally observed in small areas under higher magnification e.g. Figure 8.9 e.

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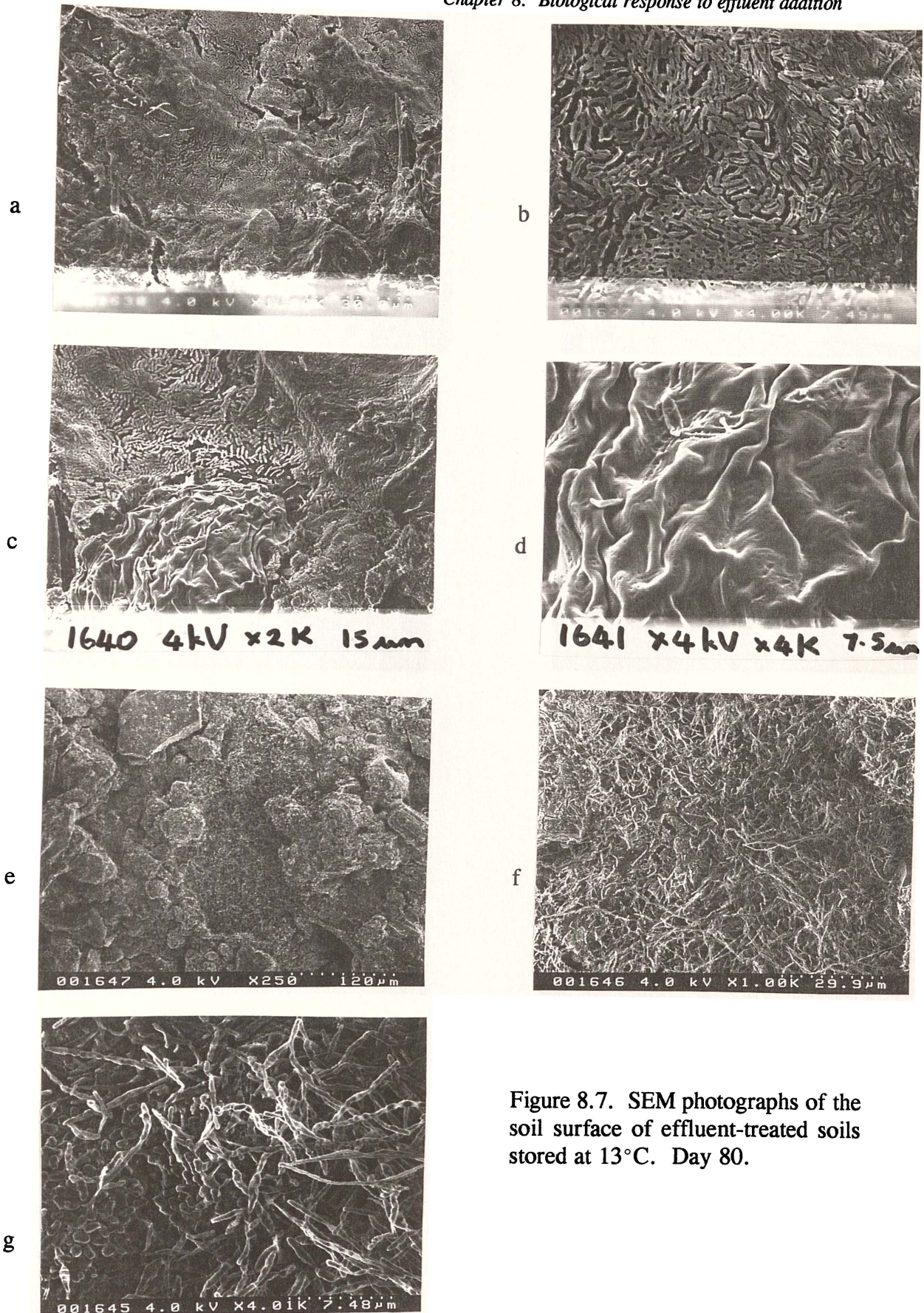


Figure 8.7. SEM photographs of the soil surface of effluent-treated soils stored at 13°C. Day 80.

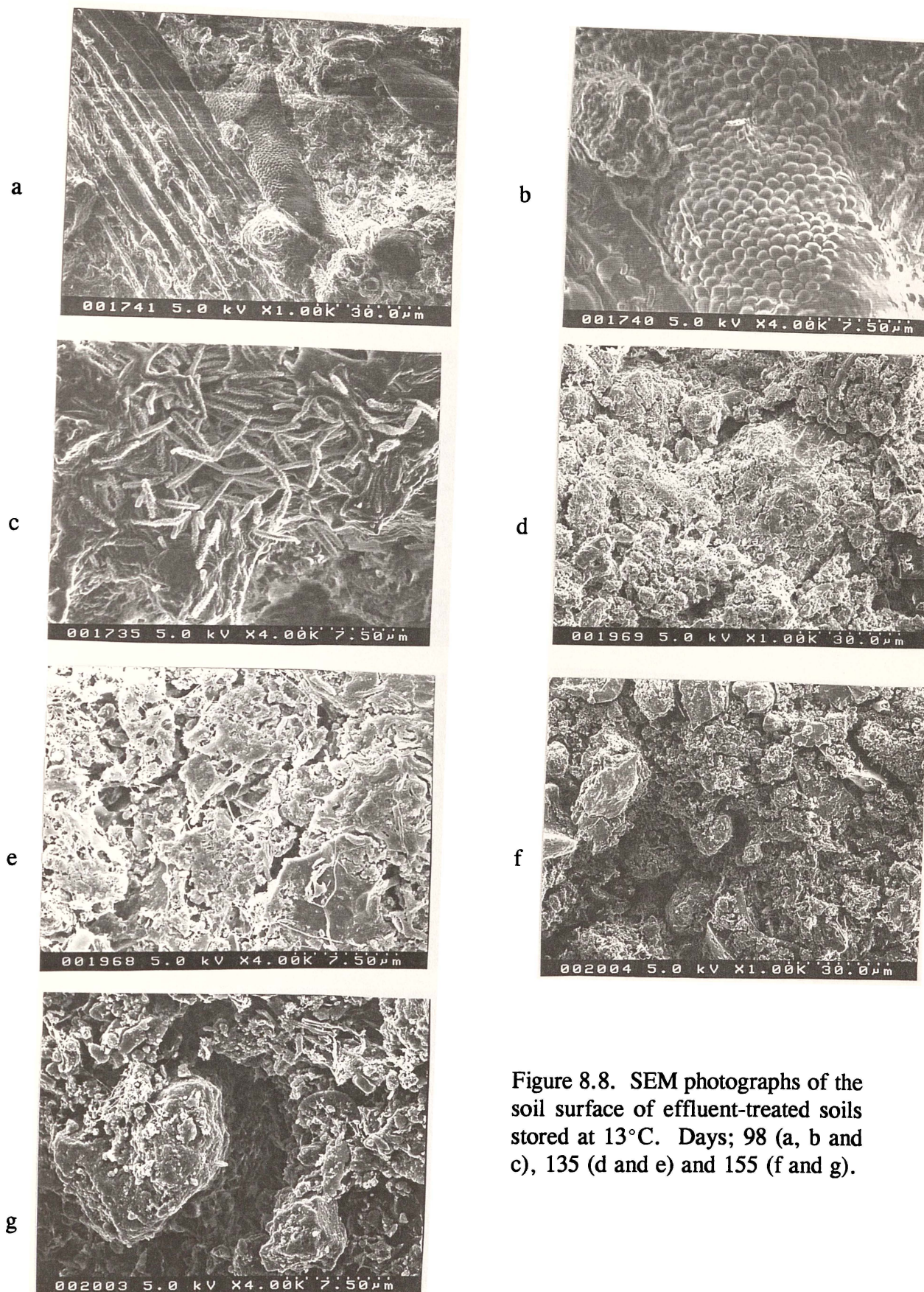


Figure 8.8. SEM photographs of the soil surface of effluent-treated soils stored at 13°C. Days; 98 (a, b and c), 135 (d and e) and 155 (f and g).

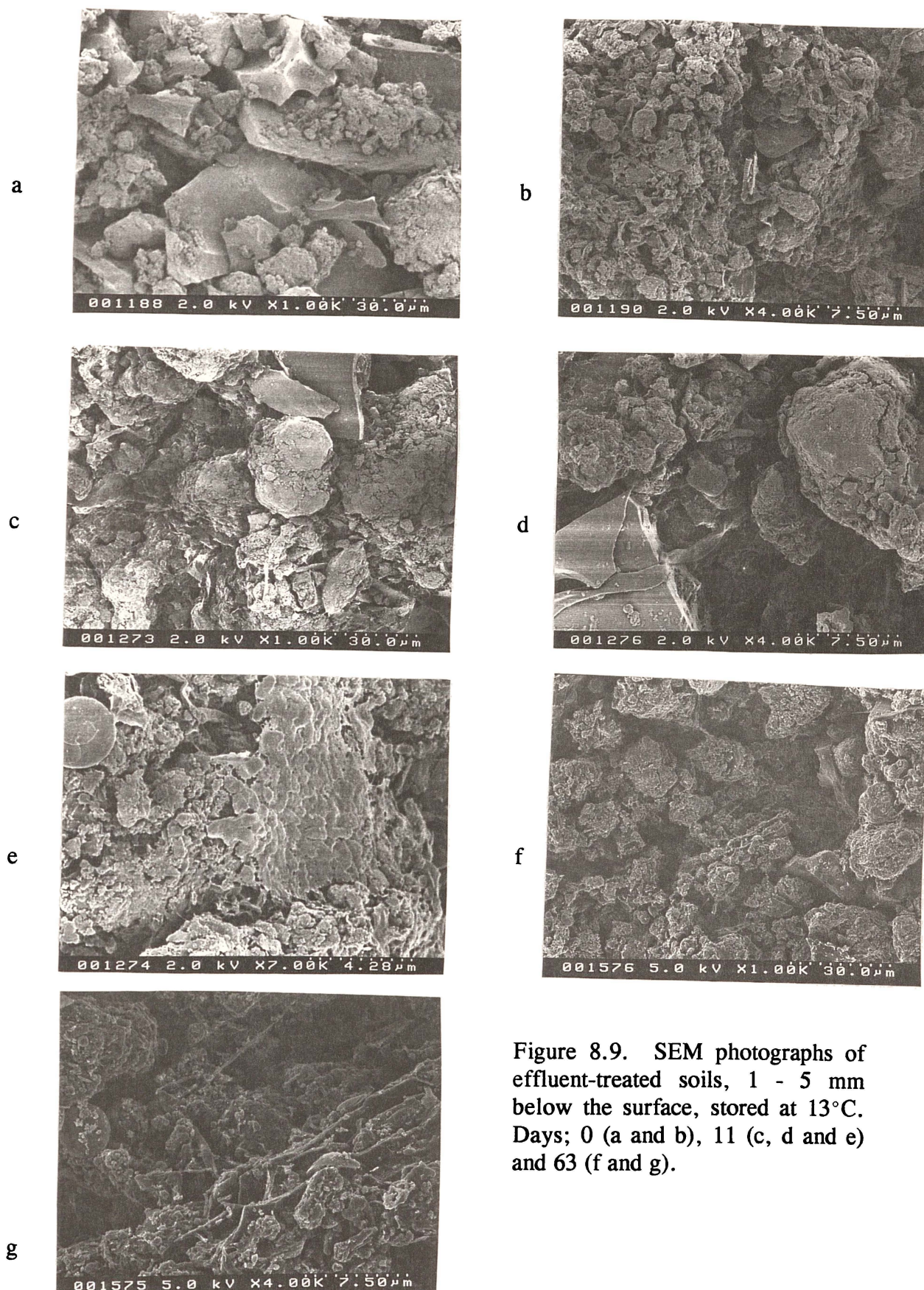


Figure 8.9. SEM photographs of effluent-treated soils, 1 - 5 mm below the surface, stored at 13°C. Days; 0 (a and b), 11 (c, d and e) and 63 (f and g).

8.3.2 Soil cores stored at 25 °C

In soil cores stored at 25 °C, biological coating was evident 1 day after effluent application (Figure 8.10 a, b, and c). By day 8, this had developed into a continuous film on the soil surface (Figure 8.10 d, e, f and g) with some indication of individual bacteria within the covering film (Figure 8.10g).

By day 16 (Figure 8.11 a and b) the cores were still uniformly coated but the presence of actinomycetes (Figure 8.11c) showed that some diversity was starting to occur. The diversity of micro-organisms continued to increase by day 23 with what appeared to be chains of spores of streptomycetes (Figure 8.11 d and f) and colonies of bacteria appearing (Figure 8.11 g) although more typical samples exhibited relatively featureless coatings such as that in Figure 8.11 e.

On day 30 (Figure 8.12 a and b) a uniformly coated soil surface was still evident. This surface coat was easily seen with the naked eye although it was less than 1 mm thick. It was fairly strong and coherent, requiring a scalpel to cut through it, and could be effectively peeled back to reveal the soil beneath. By this time the cores were very dry and it appeared that very little change in the soil crust was occurring. On day 37, 500 ml of water was added to some cores. This helped promote the degradation of the surface coat. Samples that did not receive water, viewed on day 44 (Figure 8.12 c and d), appeared to have a very similar coating to those from day 30, while water treated soils appeared to be relatively free of biological coating on day 44 (Figure 8.12 e and f). However some biological material was observed to be still present in some areas of cores that received water, on day 37 (Figure 8.12 g, which is a close-up of a coated patch in the upper right hand side of Figure 8.12e).

Samples from depths ranging from immediately below the crust to about 5 mm below the soil surface (Figure 8.13) generally showed no visible microbial material. However on day 1 samples, a slight net development over soil surfaces was evident in some areas (Figure 8.13 b). Cores treated only with water showed no significant biological development (Figure 8.14) with no changes evident during the course of the experiment.

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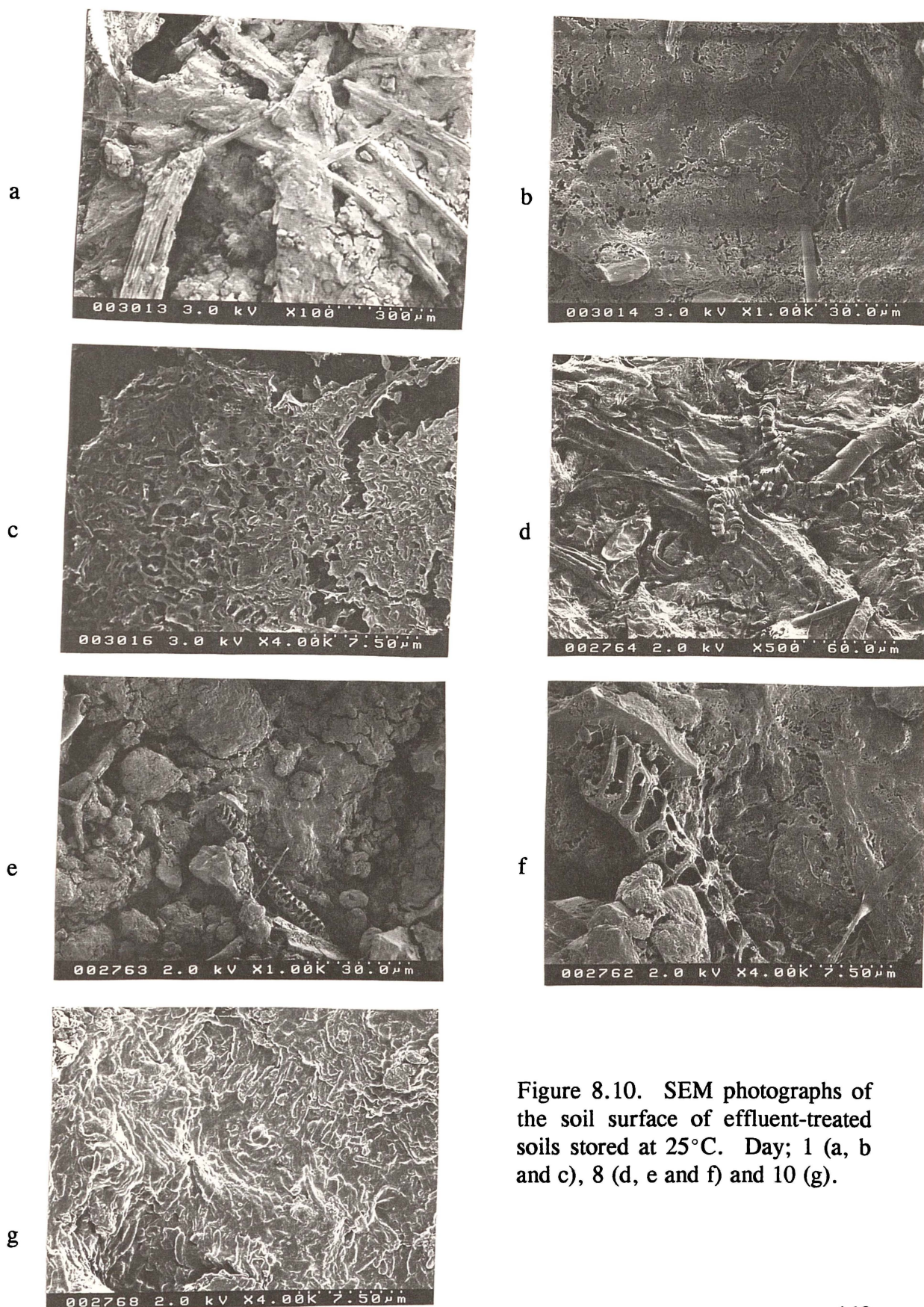


Figure 8.10. SEM photographs of the soil surface of effluent-treated soils stored at 25°C. Day; 1 (a, b and c), 8 (d, e and f) and 10 (g).

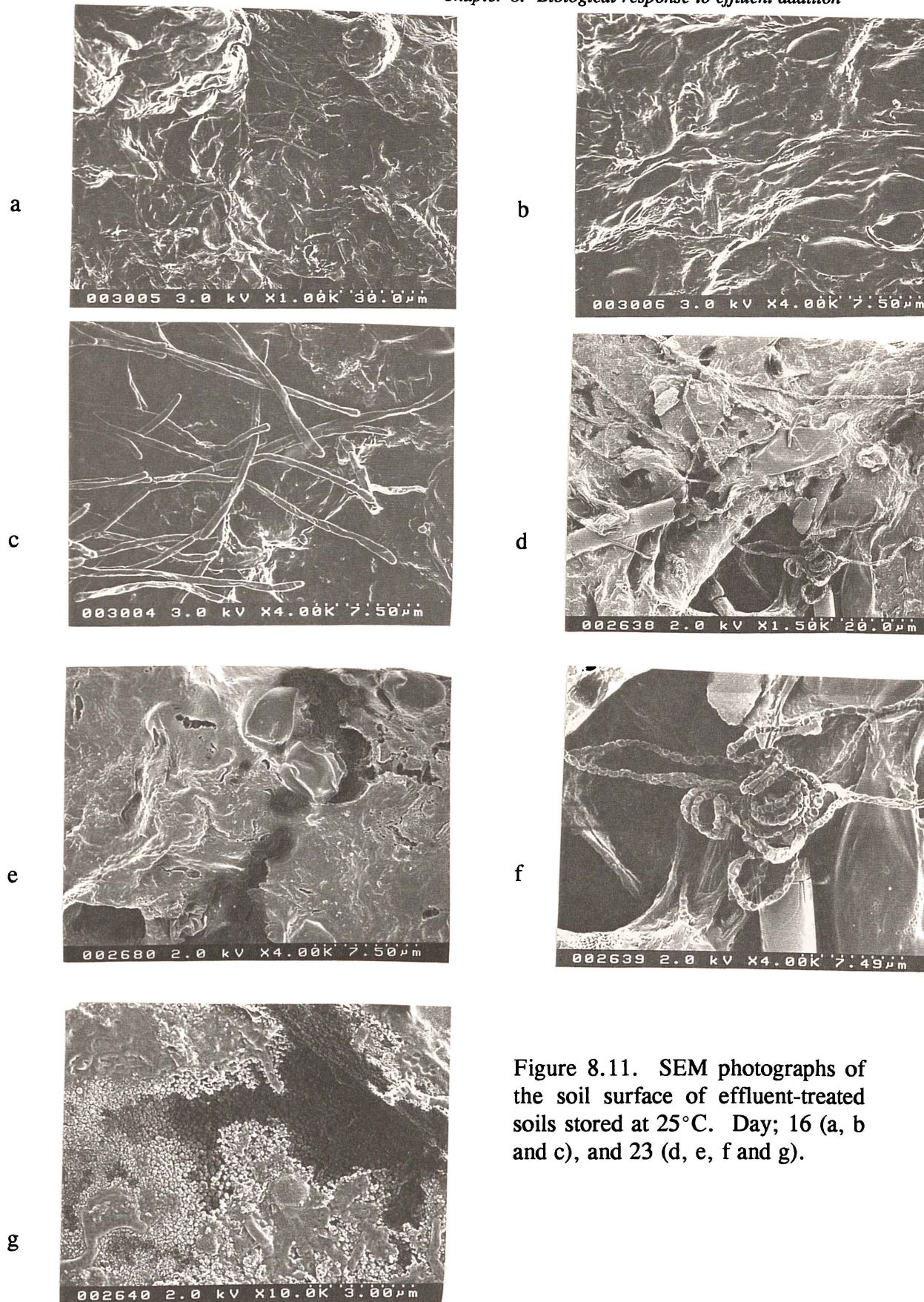


Figure 8.11. SEM photographs of the soil surface of effluent-treated soils stored at 25°C. Day; 16 (a, b and c), and 23 (d, e, f and g).

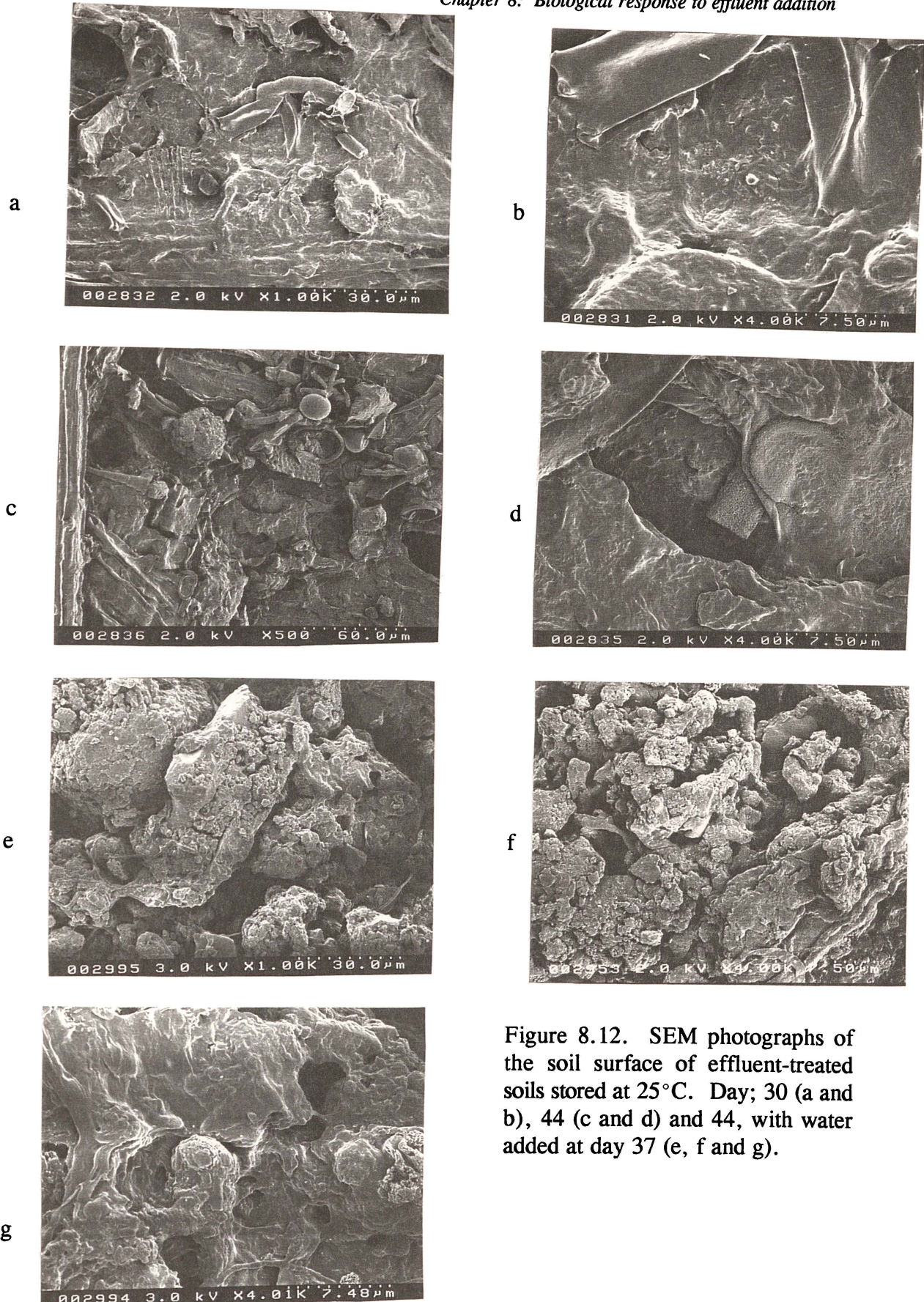


Figure 8.12. SEM photographs of the soil surface of effluent-treated soils stored at 25°C. Day; 30 (a and b), 44 (c and d) and 44, with water added at day 37 (e, f and g).

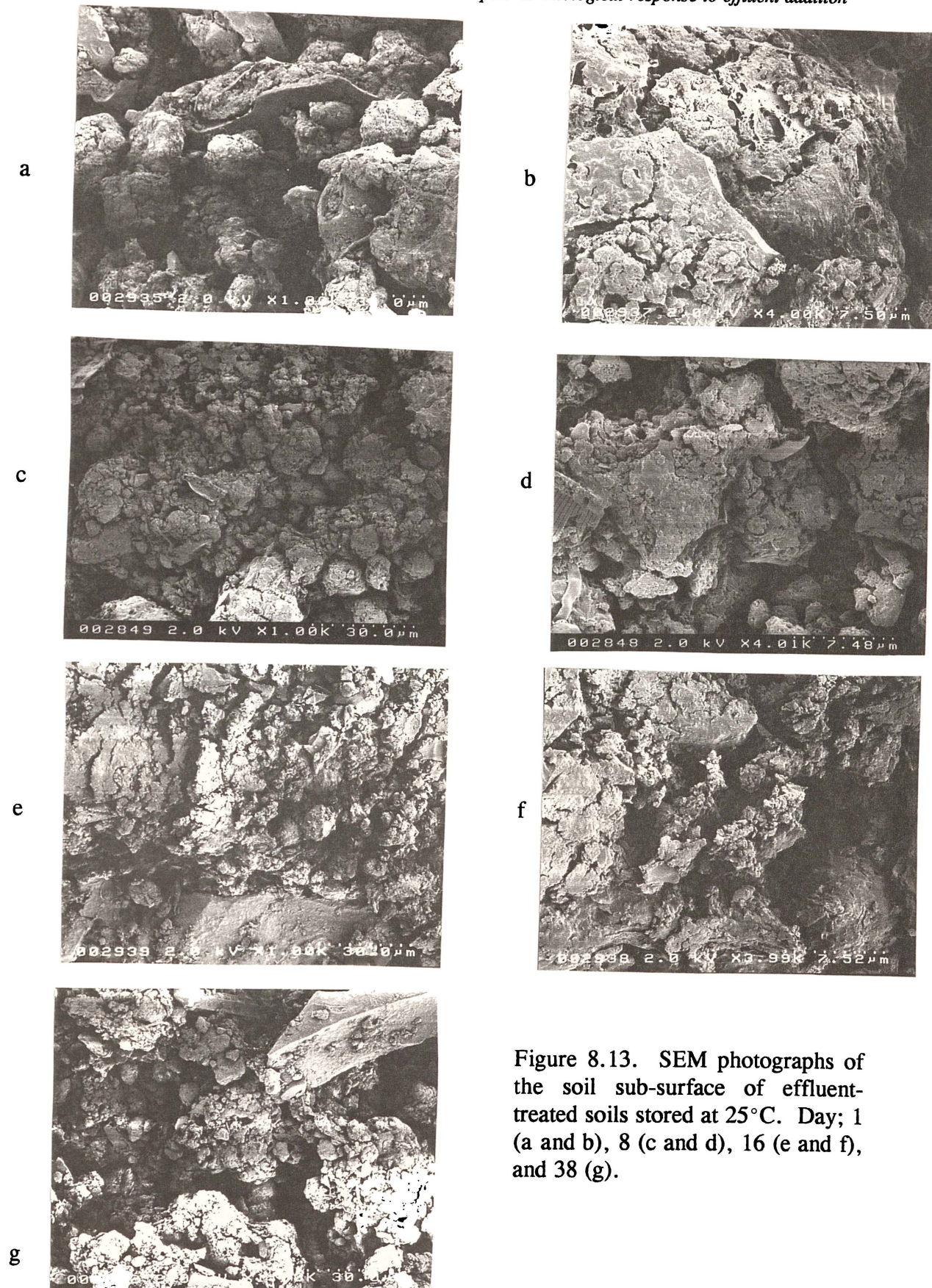


Figure 8.13. SEM photographs of the soil sub-surface of effluent-treated soils stored at 25°C. Day; 1 (a and b), 8 (c and d), 16 (e and f), and 38 (g).

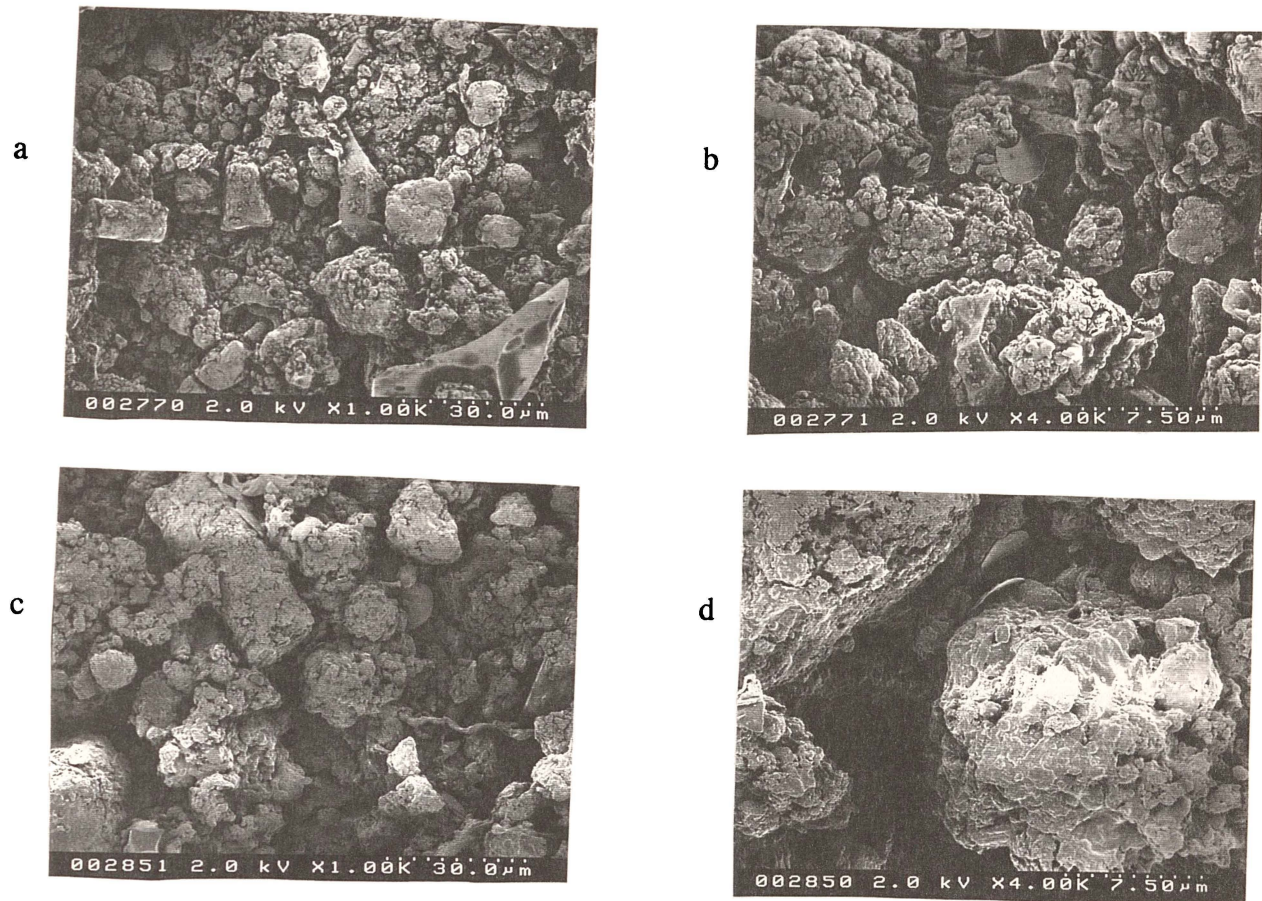


Figure 8.14. SEM photographs of the soil surface of water-treated soils stored at 25°C. Day; 10 (a and b), and 8 (c and d).

8.3.3 Samples from existing meat processing plant effluent irrigation sites

Water irrigated samples from Wakanui and non-irrigated samples from Taumarunui typically had no visible microbial material, either at the soil surface or beneath it (Figure 8.15 a, b, c, d, and e). However, at both sites small areas of surface coating (Figure 8.15 f and g) were seen and diatoms were evident at Taumarunui (Figure 8.15 g).

Samples from low ridges in effluent irrigated Wakanui paddocks (Figure 8.16 a, b, c and d) showed some biological coating of soil particles, but no micro-organisms were distinctly visible. A low power view (Figure 8.16 e) showed a lot of fibrous material covering the soil surface - this may be fungi, plant roots or suspended solids (probably paunch material) from the effluent. Subsurface samples (Figure 8.16 f and g) have a somewhat coated appearance, suggesting that some biological activity was extending beneath the soil surface.

Samples from a topographic hollow in which effluent was ponded on the soil surface at Wakanui showed spectacular biological coating (Figure 8.17) with a large amount of fungal material (Figure 8.17 a and b) and a film giving a continuous coating between the fungal strands (Figure 8.17 c and d). The coating and diatoms were present at depths of 1 mm (Figure 8.17e) and 2 mm (Figure 8.17 f) below the soil surface but at 4 mm depth (Figure 8.17 g) there was very little evidence of microbial activity.

Samples from the soil surface at Taumarunui, in a paddock that was being irrigated at the time of sampling (Figure 8.18) had a lot of fibrous material, probably derived from the suspended solids in the effluent, lying on the soil surface (Figure 8.18 a). A bacterial coat was also evident (Figure 8.18 b and c) but in some samples there was only a discontinuous net-coating (Figure 8.18 d and e). Very little biological material was evident in samples from 1 cm depth (Figure 8.18 f and g).

Samples from the soil surface, at Taumarunui, taken two and a half weeks (Figure 8.19 a, b and c) and four weeks (Figure 8.19 d and e) after effluent irrigation showed a large amount of fungal hyphae with a fairly continuous coating and diverse microflora including bacteria and diatoms. The "spiky" object in Figure 8.19e is probably a pollen grain. The samples illustrated in Figure 8.19 f and g were taken from the soil surface immediately beneath the surface crust of biological material. They indicate that there is no coating on

the soil particles although some microbial features (Figure 8.19g) are visible.

Samples from the soil surface at Taumarunui, taken from the edge of an area where effluent was ponded on the soil surface (Figure 8.20) show abundant soil micro-organisms and surface coating. The shiny surface (Figure 8.20 a and b) is probably algal cells embedded in their extracellular slime. Diatoms were also very common (Figure 8.20 a and c). Samples in Figure 8.20 d and e were from a dried pond surface and I interpret the pattern visible in these photographs as dried-out algae. The samples shown in Figure 8.20 f and g are from a depth of 1 cm below the pond surface, and some biological net material is evident.

Figure 8.21 shows samples from an area that was surface ponded with water, adjacent to a stock water trough. This site received no meat processing plant effluent, but was subjected to inputs of cattle dung and urine as the cattle tended to congregate around the trough. Diatoms, algae and bacteria were evident at the soil surface (Figure 8.21 a, b, c, d, and e) and a net-coating was visible 1 cm below the soil surface (Figure 8.21 f and g). The microbial growth visible in samples from the water ponded site (Figure 8.21), was similar to that from the effluent ponded site (Figure 8.20).

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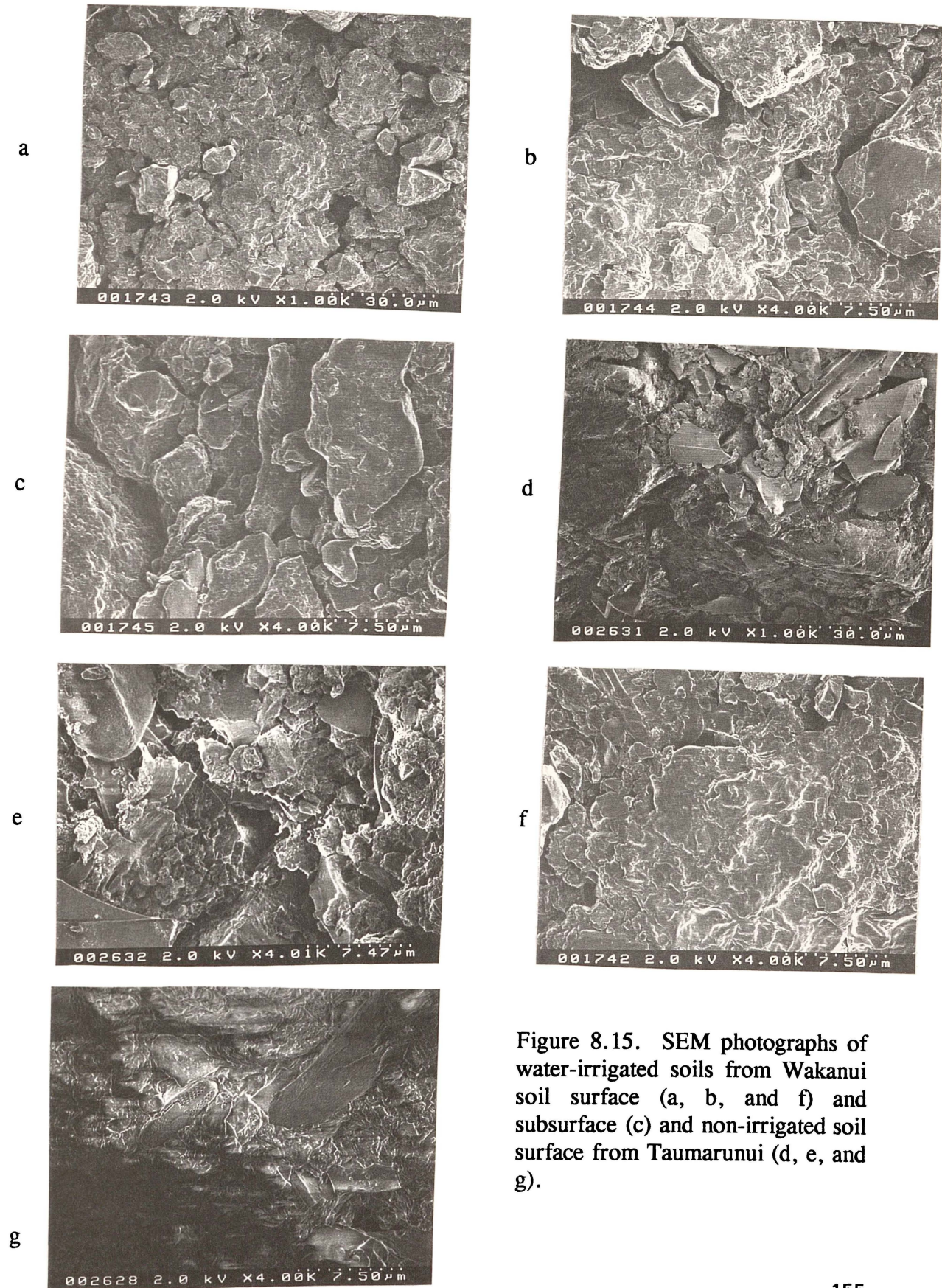


Figure 8.15. SEM photographs of water-irrigated soils from Wakanui soil surface (a, b, and f) and subsurface (c) and non-irrigated soil surface from Taumarunui (d, e, and g).

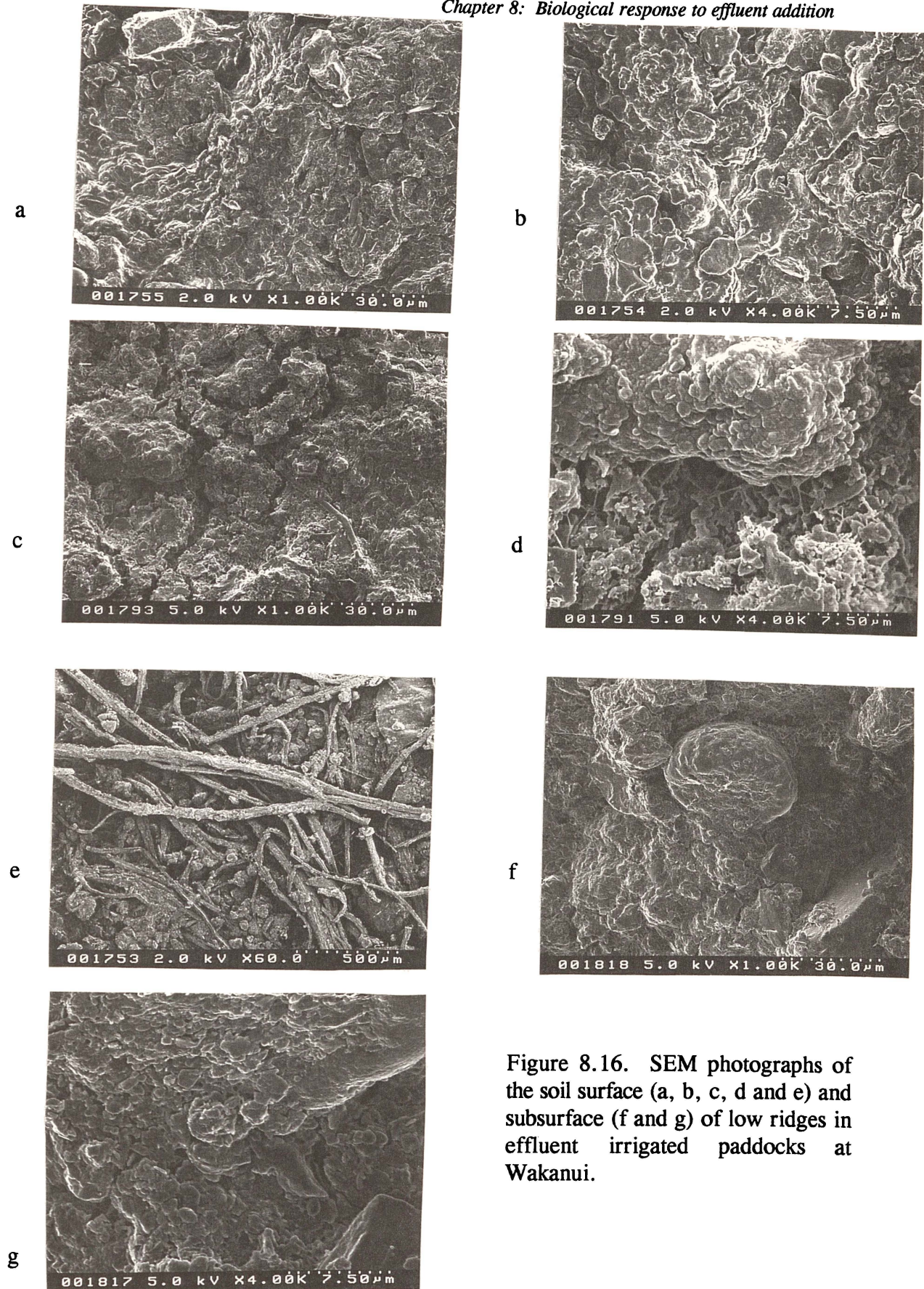


Figure 8.16. SEM photographs of the soil surface (a, b, c, d and e) and subsurface (f and g) of low ridges in effluent irrigated paddocks at Wakanui.

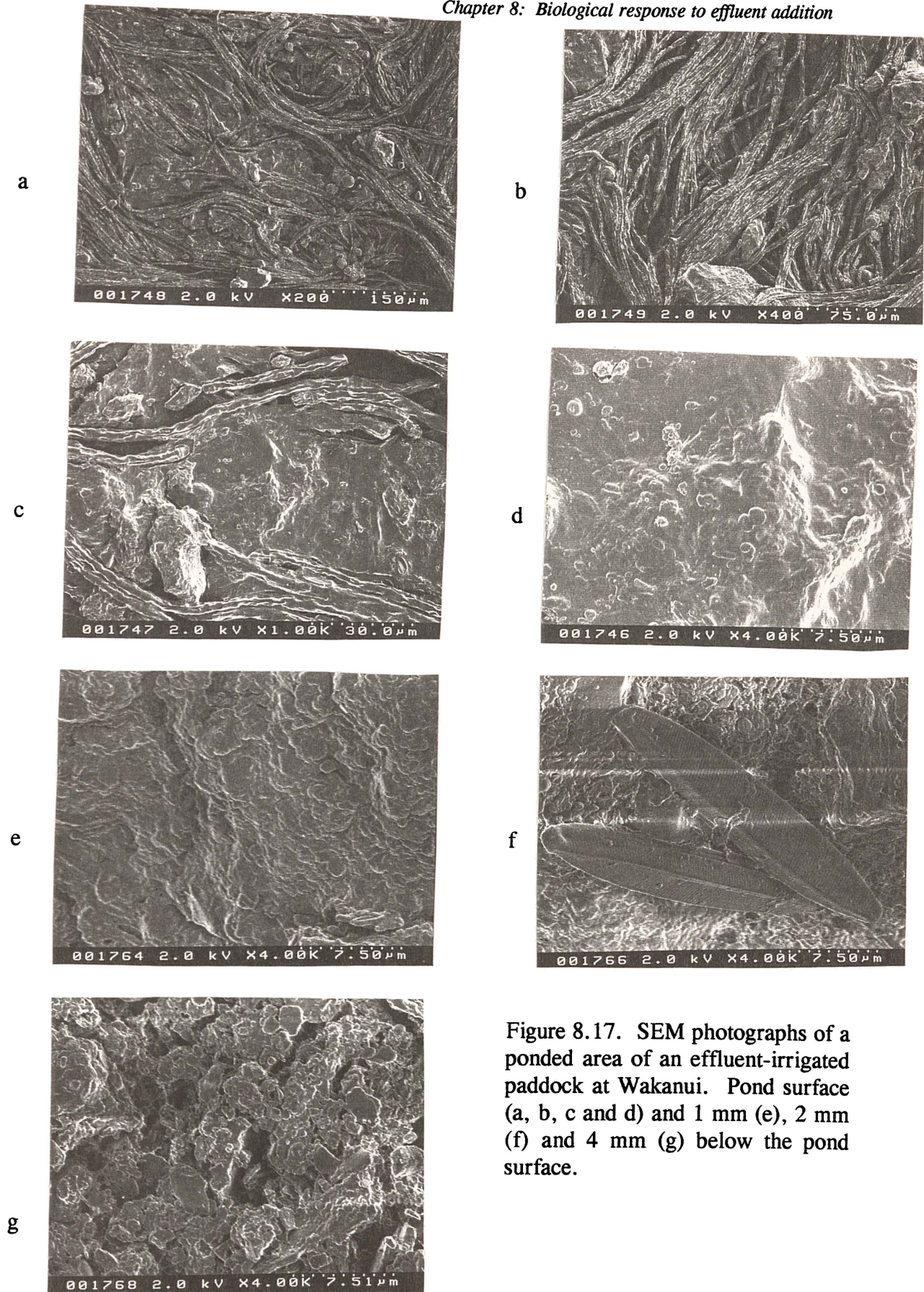


Figure 8.17. SEM photographs of a ponded area of an effluent-irrigated paddock at Wakanui. Pond surface (a, b, c and d) and 1 mm (e), 2 mm (f) and 4 mm (g) below the pond surface.

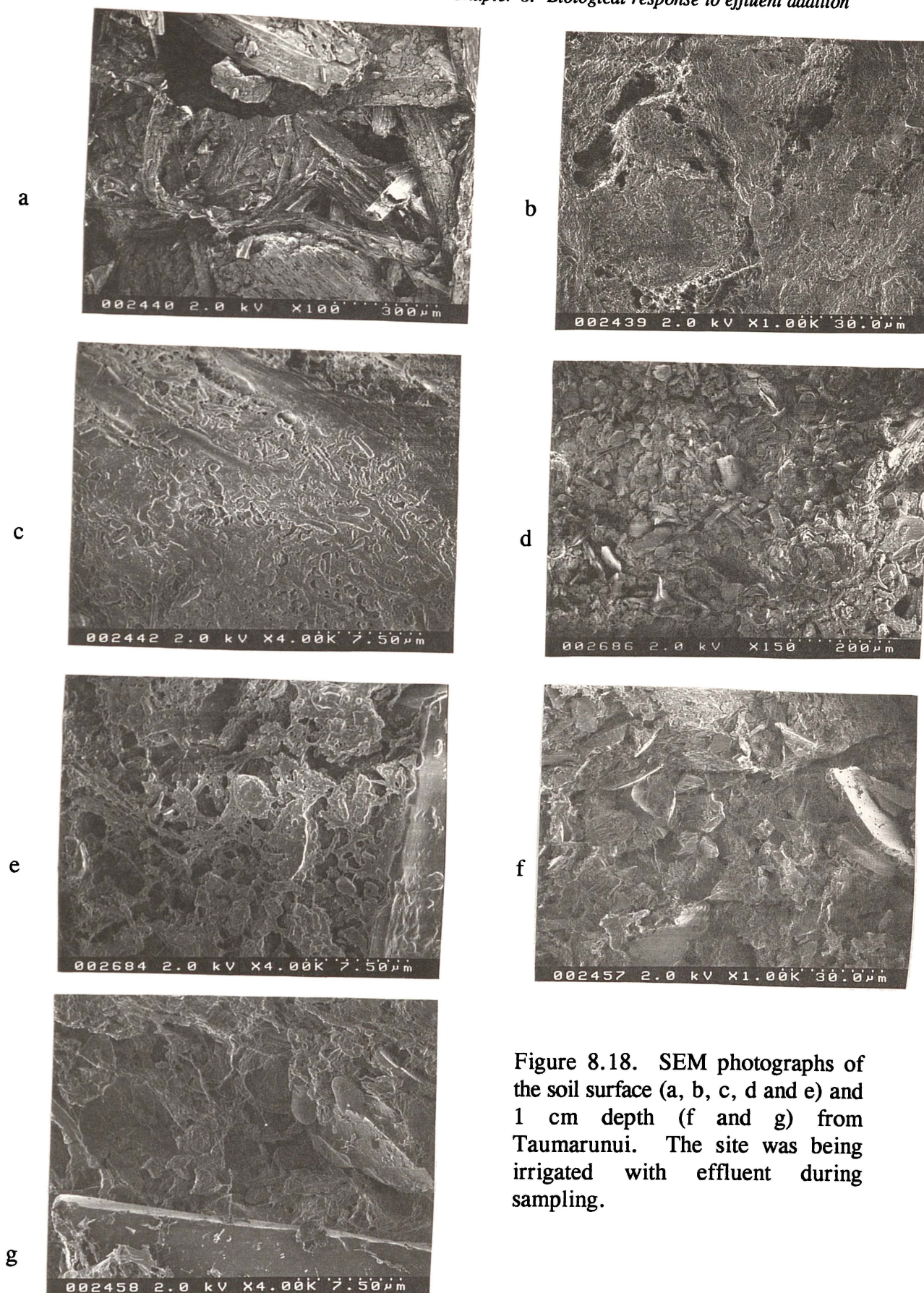


Figure 8.18. SEM photographs of the soil surface (a, b, c, d and e) and 1 cm depth (f and g) from Taumarunui. The site was being irrigated with effluent during sampling.

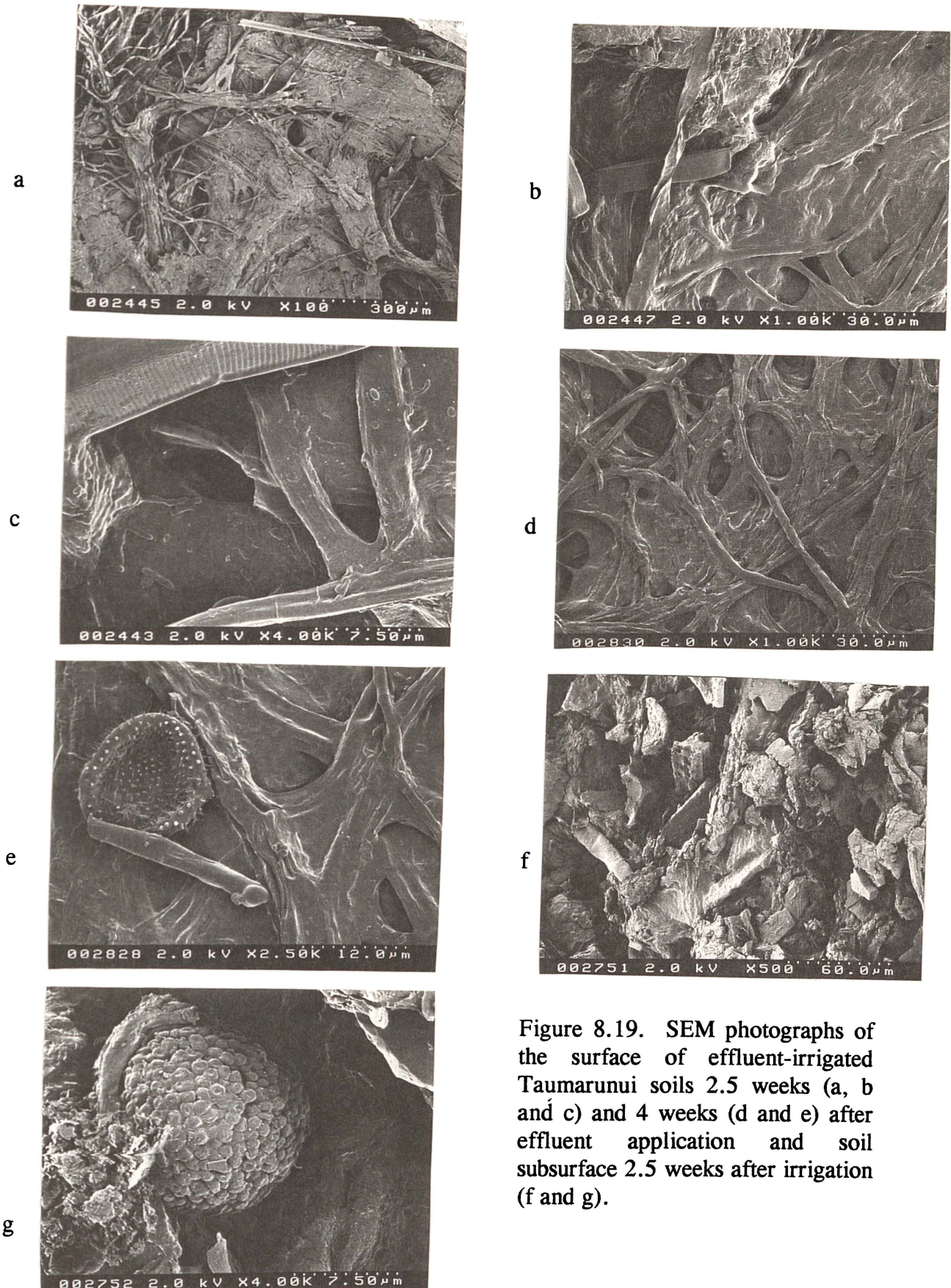


Figure 8.19. SEM photographs of the surface of effluent-irrigated Taumarunui soils 2.5 weeks (a, b and c) and 4 weeks (d and e) after effluent application and soil subsurface 2.5 weeks after irrigation (f and g).

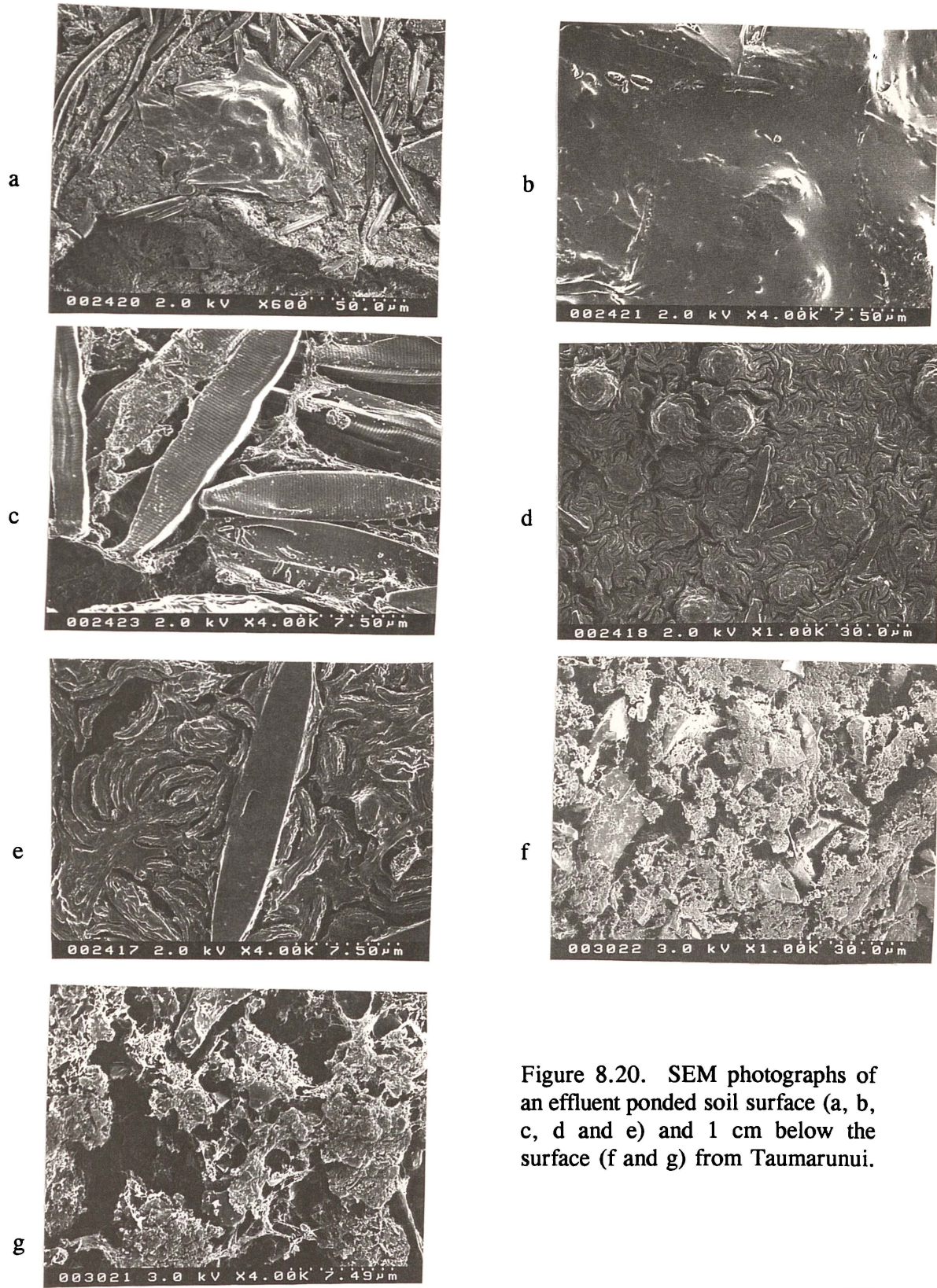


Figure 8.20. SEM photographs of an effluent ponded soil surface (a, b, c, d and e) and 1 cm below the surface (f and g) from Taumarunui.

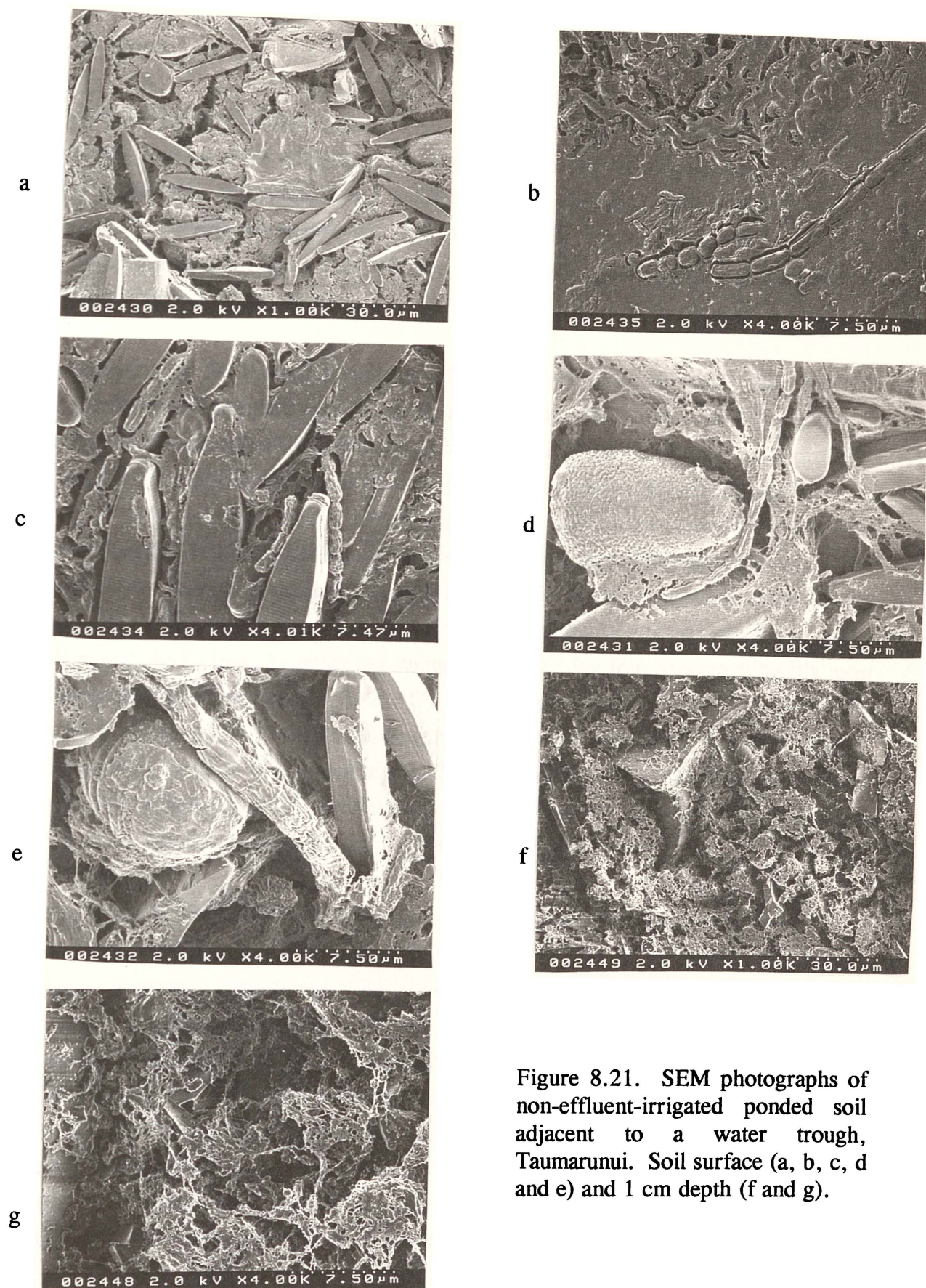


Figure 8.21. SEM photographs of non-effluent-irrigated ponded soil adjacent to a water trough, Taumarunui. Soil surface (a, b, c, d and e) and 1 cm depth (f and g).

8.4 Discussion

The SEM photographs clearly illustrate the response of micro-organisms to the addition of meat processing plant effluent. On soils that did not receive effluent there were generally no soil microorganisms visible (except for the water ponded area at Taumarunui). On effluent treated soils, microbial activity was concentrated in a thin film on the soil surface, although in both effluent and water ponded areas a discontinuous net was evident to about 1 cm depth.

A progression in the microbial response following effluent application was evident. Initially a discontinuous film formed on the soil surface. With time, the film developed into a continuous coating within which individual bacteria became visible. It is probable that the "film" consisted of a microbial polysaccharide slime produced by the bacteria. This stage was followed by a diversification of the soil micro-organisms with fungi becoming common and a variety of bacterial colonies also becoming evident. The bacterial coating tended to break down with time, becoming more porous, and gradually disappearing. In the soil cores stored at 13 °C, the whole process took place over about 155 days with the biological coating beginning to form by day four and reaching it's most continuous state by about day 21. At 25 °C a bacterial coating had formed on the surface 1 day after effluent application and had become continuous by about day 7. The very dry conditions that ensued in the cores stored at 25 °C appeared to inhibit break-down of the surface crust which remained relatively unaltered up until day 44. Addition of water to the dry cores promoted crust breakdown over a period of a week.

In cores stored at 13 °C there was a gradual recovery in core permeability, over about 50 days, following effluent addition (Figure 7.2, page 130). The microbial response to effluent application in cores stored at 13 °C developed over a similar period. Gaps in the core coat were first observed about day 20 and a diversification in the microbiological community developed between 35 and 63 days after effluent application while the initial coating declined. At the warmer temperature (25 °C), soil core permeability was slowest between 4 and 7 days after effluent application and it took about 23 days for soil cores to recover their permeability (Figure 7.1, page 129). The period of slowest permeability corresponds to the period of continuous soil core surface coat development with recovery coinciding with development of a more diverse range of micro-organisms. The cores in

the permeability recovery experiment received additions of water as a result of infiltration measurements being undertaken. The rapid breakdown of the surface coat following water application, on day 37 in the SEM core experiment at 25 °C, suggests that moisture was limiting decomposition of the microbial material. It is probable that if more moisture had been available the surface coat on the cores in the SEM experiment, stored at 25 °C, would have decomposed more rapidly.

Bacterial blockages have, in recent studies, been attributed to the organisms themselves rather than to extra-cellular slimes (for example, Vandevivere and Baveye, 1992). However, in this study the period of lowest K_{sat} corresponded to the period of maximum slime development and, once the slime-coating subsided the K_{sat} generally recovered despite the presence of large numbers of bacteria.

Photographs of samples from active meat processing plant effluent irrigation schemes had coatings that were very similar to those that formed under laboratory conditions, with similar assemblages of organisms appearing. At Taumarunui, where the weather was fine and hot, the soils were very dry at the time of sampling and the surface crust on soils that had been effluent irrigated 2.5 and 4 weeks prior to sampling had a surface coating very similar to that observed on the soil cores stored at 25 °C. Effluent irrigated soil samples from Wakanui, which had been subjected to cool wet weather, tended to have only a discontinuous film present. At both Wakanui and Taumarunui, effluent ponded areas had strongly developed surface coatings within which bacteria, algae, fungi, and diatoms were all evident. It is interesting to note that the water ponded area at Taumarunui also exhibited a similar surface coating. It is suggested that microbial soil surface coatings form in response to favourable moisture and nutrient conditions that are not necessarily effluent-dependent.

The net-like coating observed in some sub-surface samples appears very similar to that reported by Churchman and Tate (1986) at the Fairton meat processing plant effluent irrigation site. The development sequences shown here indicate that the net develops in association with the bacterial response to effluent and water addition to soils.

A strongly developed continuous soil surface coat was observed to form in areas where effluent or water ponds in paddocks. Once effluent ponds on the soil surface, growth of

micro-organisms is promoted and leads to formation of surface coatings. The coatings contribute to further decline in soil infiltration rates, which leads to further surface ponding, therefore creating a positive reinforcement cycle. It is suggested that the cycle of positive reinforcement is one of the key factors in observed declines in effluent infiltration at irrigation sites. To prevent declining soil infiltration rates, sufficient time between irrigations must be allowed for the microbial coat to degrade. This time will be considerably longer in winter than in summer.

8.5 Conclusion

There was a strong microbial response to addition of primary treated meat processing plant effluent to soils which resulted in formation of a semi-continuous coat of microbial material on the soil surface. The coat formed under both field and laboratory conditions. The microbial soil surface coat formed and decomposed more quickly under warm moist conditions, taking 2 to 3 times longer to develop and break down at 13 °C than at 25 °C. If allowed to dry out the coat may not decompose readily.

The development of a microbial soil surface coat following effluent irrigation follows a progression from the development of a thin film of material, within which bacterial forms become evident. Over time a diversity of microbial forms develops with fungi, actinomycetes and a range of colonial bacteria appearing. Eventually the film breaks down, leaving only the bacterial forms which then gradually breakup and disappear.

A coating of microbial materials on the soil surface is likely to contribute to a decrease in effluent infiltration rates, which may, in turn, cause conditions of surface ponding favourable to further microbial growth.

Chapter 9: Discussion, recommendations and conclusions

9.1 Overview and synthesis of results

9.1.1 Introduction

The New Zealand meat industry has been utilising irrigation as a means of disposing of large volumes of effluent which often has a high BOD and a suspended solids content in the range of 500 - 2000 g m⁻³. Irrigation is carried out on a wide range of soils at a growing number of sites distributed throughout New Zealand. Problems of a decline in soil permeability, sometimes resulting in serious problems of surface ponding, loss of trafficability, unpleasant odours, and the inability to continue to dispose of effluent have been known to occur at a number of New Zealand meat processing plant effluent irrigation sites.

The mechanisms leading to a decline in soil permeability at New Zealand meat processing plant effluent disposal sites have not been well understood and the problem has been dealt with mainly by trial and error. Most of the research that has previously been undertaken relating to declining infiltration rates following effluent application has been for low (< 100 g m⁻³) suspended solids sewage effluents under conditions of continuous inundation on sand beds (for example Vinten *et al.* 1983, Siegrist and Boyle 1987). The primary objectives of the research undertaken in this thesis were to determine the occurrence, and establish the causes, of soil permeability decline at meat processing plant effluent irrigation sites.

9.1.2 Effects of irrigation of meat processing plant effluent at existing New Zealand sites

The survey of existing meat processing plant effluent irrigation sites (Chapter 4) showed that a decline in soil permeability in topographic hollows and/or at the top ends of borders (at sites where border dyke irrigation was used) was common, leading to effluent and rainfall ponding on the soil surface. The only sites that did

not exhibit any surface crusting and ponding were sites that were irrigated for only two or three effluent applications per year (during periods of summer low river flow) with tertiary-treated effluent. The ponded areas had a crust, of apparently organic material, on the soil surface. The ponded areas had lower soil bulk densities than non-crusting areas, indicating that compaction was not the cause of the problem. The presence of water lying on the soil surface of ponded areas, for several days at a time, indicated that the infiltration rates in ponded areas were considerably lower than 1 mm hr^{-1} .

There was evidence that soil pore blockage and surface coat formation, as a result of both suspended solids from the effluent and the presence of microbial materials, contributed to the decline in infiltration rates at field sites. Suspended solids tended to accumulate at the top ends of borders where they settled out of the effluent as the velocity of effluent flow declined. Effluent was observed to saturate the soil surface, during application, at every site visited, even those using sprinkler irrigation. Surface saturation resulted in overland flow and accumulation of effluent in topographic hollows, hence providing an increased suspended solids load to the topographic hollows. Microbial material was visible on the ground surface in some ponded areas (e.g. Figure 4.6), indicating that microbial interactions may have also been contributing to permeability decline.

There is a lack of previously published field surveys of effluent irrigation impacts on soils at meat processing plant effluent irrigation sites. Wells and Whitton (1970) visited three New Zealand sites and undertook elemental analysis of the effluent, soil and plants. They did not investigate soil physical properties or wider management activities. Surveys of the effluent treatment methods employed at New Zealand meat processing plants (Cooper *et al.* 1979, Cooper and Russell 1982, and Cooper and Russell 1992) did not provide site specific information, nor did they include information related to impacts on soils. However there is some information available regarding the dairy industry. Problems including effluent application in excess of soil infiltration rates, surface ponding, runoff, unpleasant odours, and the death of the cover crop, have been reported at dairy factory effluent irrigation sites in New Zealand (Parkin and Marshall, 1976) and in the United States (USEPA 1971). Parkin and Marshall (1976) alluded to surface sealing and suggested that improved removal

of oil and grease from the effluent might help prevent surface sealing from occurring. The problems associated with a decline in infiltration rates at dairy factory effluent disposal sites are apparently similar to those identified at meat processing plant effluent irrigation sites.

9.1.3 Causes of soil permeability decline

The field survey (Chapter 4) indicated that both suspended solids and micro-organisms probably contributed to the development of surface crusting and permeability decline. A series of experiments were designed to further investigate the mechanisms, and identify the factors, that influence the decline and recovery of soil permeability when meat processing plant effluent is applied to land.

An association between development of soil surface coating and a decrease in soil permeability was apparent at both existing effluent irrigation sites (Chapter 4) and in the laboratory experiments (Chapters 5 and 7). It was apparent that all of the pore blockage was occurring at the soil surface, with minimal impact beyond about 2 mm below the soil surface. There was no evidence, in either the field survey, or in any of the experimental work, that dispersion of clay minerals was a major factor contributing to permeability decline.

The primary cause of declining infiltration rates identified in this study was the suspended solids in the effluent (Chapters 5 and 6). However, it was evident that microbial materials, developed in response to the effluent, also contributed to pore blockage, particularly in areas where surface ponding developed (Chapter 8). Most previous workers have concentrated on either biological pore blockage (e.g. Nevo and Mitchell 1967, Kawanishi *et al.* 1990, Vandevivere and Baveye 1992), or on physical pore blockage (e.g. Berend 1967, Vinten *et al.* 1983, McDowell-Boyer *et al.* 1986). The contention that both physical and microbial factors may have an influence on soil permeability at effluent irrigation sites has received little attention in the past, but has been suggested to be important in effluent holding ponds (Chang *et al.* 1974), rapid infiltration beds (Rice 1974) and in soils receiving whey application (McAuliffe 1978).

Physical blockage of pores by suspended solids from the effluent was demonstrated by the linear relationship between the cumulative suspended solids applied and the effluent infiltration rate (Chapters 6). The cumulative suspended solids load is controlled by the type and volume of effluent applied. The laboratory experiment in Chapter 5 indicated that the type and volume of effluent applied, and the temperature were the most important factors affecting the decline and recovery of soil permeability (out of those that were tested). The main influence of temperature was on the rate of the microbial response to effluent (Chapter 8). Temperature also influenced the rate of soil drying.

The decline and recovery of soil permeability as a result of addition of meat processing plant effluents to soils under New Zealand conditions, identified by the field and laboratory investigations, can be summarised as follows.

1. Rapid decline in the soil infiltration rate during effluent application, as a result of soil surface pore blockage by suspended solids material from the effluent. The infiltration rate was shown to decrease in direct proportion to the cumulative suspended solids applied.
2. The microbial response to effluent application, initially primarily bacterial, leads to production of extracellular slimes which coat the soil surface. The surface coating, along with the physical presence of the bacteria, may contribute to a further decline in soil permeability.
3. If no further effluent is added, the initial microbial slime breaks up, the microbial flora becomes more diversified and, along with the effluent suspended solids material, gradually decomposes and declines until the soil permeability recovers.
4. If further effluent application occurs prior to complete recovery of the soil permeability, then soil pore blockage may become exacerbated.

The two soils used in the factorial experiment (Chapter 5) both had similar responses to effluent application with respect to permeability decline and surface coat formation. Similar surface coats were also observed on the range of soils studied in the field. Therefore it is suggested that the results obtained in this thesis would be transferable to other New Zealand soils (of moderate permeability) that are likely to be considered for land treatment of meat processing plant effluent.

9.1.4 Predicting permeability decline as a function of addition of suspended solids

Previous attempts to predict permeability decline have been based upon relationships between effluent solids contents and infiltration rates (Berend 1967, De Tar 1979, Clanton and Slack 1987) or on the effects of accumulation of biological materials (Okubo and Matsumoto 1979, Taylor and Jaffe 1990, Taylor *et al.* 1990). The models that consider biological materials cannot be applied to the meat processing plant effluents studied in this thesis as they ignore the large impact of effluent suspended solids on infiltration rates. Of the models that relate to the effects of effluent solids contents, only the model of Berend (1967) was found to be useful. The model proposed by Berend (1967, Equation 6.1), is a linear relationship which determines infiltration rate as a function of cumulative suspended solids and can therefore, be used to predict initial infiltration rate decline.

The data obtained in Chapter six was used to determine a value for the coefficient in Berend's model (α) of $1 \times 10^{-7} \text{ m}^3 \text{ s}^{-1} \text{ g}^{-1}$ for both primary and untreated meat processing plant effluents. The fact that α was the same for two different effluents suggests that this value may be appropriate for wider application of the model for meat processing plant effluents in New Zealand. Berend (1967) suggests that the value of α depends on the kind and concentration of the suspended solids as well as on soil properties. It is suggested that the particularly high suspended solids contents of meat processing plant effluents may be the main factor influencing α and so the relationship may hold on a range of soils.

The equation of Berend (1967) has potential application for high suspended solids effluents for:

- predicting the decline in infiltration rates during effluent application;
- determining the duration or depth of effluent application that can be utilised without causing a serious decline in infiltration rates; and
- determining the amount of pre-treatment that may be necessary to remove suspended solids from an effluent prior to irrigation.

The following example demonstrates how Berend's model could be used. If, for example, it is decided that effluent application should only proceed until the effluent infiltration rate is halved (i.e. $i/i_0 = 0.5$), then equation 6.1 can be solved, as follows:

$$\begin{aligned}
 i &= i_0 - \alpha vgs \\
 \rightarrow i/i_0 &= 0.5 = 1 - \alpha vgs/i_0 \\
 \rightarrow \alpha vgs/i_0 &= 0.5 \\
 \rightarrow vs/i_0 &= 0.5/0.95 \times 1 \times 10^{-7} \\
 \rightarrow vs/i_0 &= 5.26 \times 10^6 \quad \text{g s m}^{-3} \quad (9.1)
 \end{aligned}$$

where all symbols and units are defined in Chapter 6.

Equation 9.1 can then be solved for a range of initial infiltration rates and effluent suspended solids contents to give the depth of effluent that can be irrigated before the infiltration rate could be expected to halve (Table 9.1).

Table 9.1 Total cumulative solids, and depth of water required to halve effluent infiltration rates for a range of initial infiltration rates (i_0) and suspended solids contents.

i_0 mm hr ⁻¹	i_0 m s ⁻¹	¹ vs to halve i_0	Depth of water (mm) to halve i_0 when:			
			² $v = 500$	$v = 1000$	$v = 1500$	$v = 2000$
100	2.8×10^{-5}	147	294	147	98	74
50	1.4×10^{-5}	74	148	74	49	37
25	6.9×10^{-6}	36	72	36	24	18
5	1.4×10^{-6}	7.4	15	7.4	5	4

¹ vs = cumulative suspended solids content g m⁻², ² v = suspended solids content g m⁻³

9.1.5 Recovery of permeability

Having established that a decline in soil permeability occurs as a result of meat processing plant effluent application, it is important to also determine the rate of permeability recovery. It was evident that if further effluent application occurred prior to recovery of soil permeability then further decline resulted.

Field and laboratory observations suggested that permeability recovery occurs when either the soil surface coat dries and cracks or when sufficient time has elapsed for soil micro-organisms to decompose the added suspended solids material and the microbial slime associated with microbial activity. Recovery of soil permeability was shown (Chapter 7) to be temperature dependant - being slower at 13 °C than at 25 °C. It was estimated, therefore, that recovery of permeability in effluent treated soils may occur in less than three weeks in summer, but may take twice as long in winter.

There was some indication, in both field and laboratory experiments, that soil macro-fauna (in particular, earthworms and springtails) also aided permeability recovery by physically breaking up the soil surface coat. Water infiltration rates have previously been reported to be up to ten times higher for soils in which earthworms are present, compared to similar soils that lack earthworms (Lee and Foster 1991). The impact of earthworms was evident at the Wakanui site in the field survey, where water infiltration rates were considerably higher for areas with large numbers of earthworms (under effluent irrigation) than in water irrigated areas with a moderate earthworm population. While earthworm numbers had increased at two effluent irrigation sites, it was possible that at many sites, prolonged surface ponding and high (> 8) pH effluents were detrimental to earthworm populations. This suggests that management of soil biological properties could be an integral factor in effluent irrigation scheme design.

The decrease in soil permeability observed at most field sites was not regarded as a long-term problem as it developed relatively quickly (for example, after eight months at Kaiapoi). Irrigation scheme operators are forced to take action to ameliorate the effects on the soil. Ploughing, ripping and prolonged rest periods were all successful in restoring soil permeability (Chapter 4). Therefore a decline in soil permeability

due to surface crust development is unlikely to cause permanent degradation of the soil resource if appropriate ameliorative action is taken.

9.2 Recommendations for effluent irrigation scheme design and management

The following recommendations regarding effluent irrigation scheme design and operation are made, based upon the research reported in this thesis and other observations that have been made in the course of undertaking the research.

Land disposal of effluent is an option that should be considered when designing any meat processing plant effluent disposal scheme, even if it is used only as an alternative to river discharge during periods of low river flow (as, for example, at Makarewa). It is during dry summer periods that effluent is of most benefit for irrigation purposes. In drought-prone areas, application of effluent at rates which meet plant moisture requirements should be encouraged as this provides water and nutrient benefits to receiving areas and minimises the detrimental impacts of disposing of excessive volumes of effluent on a small area.

It was observed that measured soil infiltration rates tend to be lower in wetter/cooler months. It is therefore recommended that if infiltration measurements are to be undertaken for design of an effluent irrigation project they should be made when soil is at its seasonally wettest (usually late winter). Infiltration measurements should be made using the effluent that is to be used rather than "clean" water as there is likely to be a marked difference between effluent and water infiltration rates (as demonstrated in Chapter 6).

In border dyke irrigation schemes, physical pore blockage can be minimised by use of short (100 - 200 m) borders with adequate grass cover (one site was successfully using 70 m long borders). The grass helps to sieve out the suspended solids from the effluent, thus preventing it from reaching the soil surface. When using shorter borders it is necessary to change the border under irrigation more frequently, thus minimising the duration of effluent application, and therefore minimising the accumulation of suspended solids at the top end of borders.

To prevent physical pore blockage by effluent, the cumulative suspended solids loading must be controlled. The model of Berend (1967) may be a suitable tool for predicting appropriate cumulative suspended solids loadings.

If soil surface coating problems occur, it is necessary to cease irrigation to allow the coat to dry off, break up, and decompose, thereby allowing soil permeability to recover. Irrigation should then recommence at a lower or less frequent rate. If the surface coat is not allowed to dry and dissipate then soil permeability is likely to continue to decrease, approaching zero.

In areas where permeability has declined, ripping of the soil surface will provide recovery without a requirement to resow pasture. However, unless there is a change in the irrigation regime, ripped areas will quickly reseal and surface ponding return. Ploughing will also provide recovery of soil permeability, however this requires re-establishment of pasture.

In summer, an irrigation return period of three weeks following large (> 100 mm) applications of high ($> 500 \text{ g m}^{-3}$) suspended solids effluent should be adequate to ensure full recovery of effluent infiltration rates. However, an irrigation return period of at least six weeks would be more appropriate in winter.

9.3 Conclusions

1. A decline in soil permeability is common at New Zealand meat processing plant effluent irrigation sites. At most sites it is confined to small areas where effluent accumulates in topographic hollows or at the top ends of borders (in border dyke irrigation schemes).
2. The decrease in soil permeability can develop relatively quickly (potentially in less than a month if repeated large effluent applications are made) and is more likely to develop in winter than summer.
3. The decrease in soil permeability as a result of effluent irrigation was shown to be a result of development of a coating of material on the soil surface. The coat comprised suspended solids material from the effluent (which alone can cause a large decline in effluent infiltration rates) and microbial material which develops following effluent application.
4. An inverse linear relationship was shown to occur between the cumulative suspended solids applied and the effluent infiltration rate.
5. The model of Berend (1967) describes the relationship between infiltration rate and the cumulative suspended solids applied. Berend's model has potential for application in effluent irrigation scheme design and planning.
6. The microbial response to effluent application was shown to comprise several phases. Initially a bacterial slime develops on the soil surface, within which the bacteria themselves became evident after a few days. Over time the slime material breaks down and decomposes, the micro-organisms became more diverse with fungi and actinomycetes appearing. Finally the microbial materials decompose and disappear.
7. Recovery of soil permeability occurred either when the soil surface coat was allowed to dry and crack, or when sufficient time had elapsed for the microbial slime to decline.

8. Recovery of soil permeability was considerably faster at warmer temperatures, taking less than three weeks at 25 °C and about six weeks at 13 °C.

9.4 Recommendations for future research

The survey of existing sites that was reported in this study provides a useful insight into the activities and state of meat processing plant effluent application. It would be useful to repeat this survey at periodic intervals, perhaps about every 10 years, to document the changes in effluent irrigation practice and to identify and monitor changes in the soils at effluent irrigation sites.

The model of Berend (1967) has been shown to have potential application as a tool for predicting infiltration rate decline as a result of effluent application. Berend's model needs to be tested and verified for the wide range of soils and effluents that are encountered in New Zealand.

The economic and the environmental cost/benefits of different levels of effluent treatment prior to irrigation should be studied.

A high earthworm population is potentially beneficial at an effluent disposal site, as was reported at the Wakanui site. Further research into the effects of inoculating sites with suitable earthworm species and the tolerance of different species to meat processing plant effluent should be undertaken.

The microbial response to effluent application needs to be further studied, under controlled conditions, to determine the effects of different effluent application rates, return periods, and effluent properties.

Appendix 1: Data for Chapter four

Fairton Meat Processing Plant - sampled 5-6 December 1989.

Climate: Data for Ashburton shows a mean annual rainfall of 750 mm, reasonably evenly distributed throughout the year. Mean temperature is 16.5 °C in January and 5.2 °C in July. The area has a summer water deficit and is prone to drought (data from New Zealand Meteorological Service 1983).

Parent material: Glacial outwash gravel of Otiran age (Suggate 1973) overlain by loess.

Watertable: 21 +/- 6 m (Keeley and Quin 1979). .

Soil series: Lismore stony sandy loam.

Soil classification: NZ - Typic Orthic Brown Soil; NZ Genetic - Shallow soil associated with Yellow Grey Earths; Soil Taxonomy - Udic Ustochrept.

Fairton Site I, no effluent

This site has not been ploughed for many years (probably > 30). It is used for stock holding and the pasture is very poor.

Location: Fairton control paddock approximately 300 m east of the works buildings. Site is in middle of paddock, 40 m northeast of lysimeter row (NZMS260 L37 145032).

Vegetation: Sparse ryegrass, clover, many flat weeds.

Topography: Flat terrace surface. Microtopographic hummocks up to 30 cm.

Profile description:

Horizon	Depth (cm)	Description
Ap	0-23	Brownish black (10YR 2/3) stony sandy loam; strongly developed medium block and nut breaking to weakly developed very fine crumb structure; slightly sticky; plastic; common very fine roots; common unweathered subrounded greywacke gravels and stones; thin 'organic' crust on surface; distinct irregular boundary,
BA	23-35	Brown (10YR 4/4) and brownish black (10YR 3/2) stony sandy loam; weakly developed fine block and crumb structure; sticky; plastic; common very fine roots; common unweathered subrounded greywacke stones; indistinct smooth boundary,
Bw	35-65	Yellowish brown (10YR 5/6) gravelly, stony, sandy loam; moderately developed fine and medium granular structure; sticky; few very fine roots in cracks around stones; profuse unweathered subrounded greywacke gravels and stones; indistinct smooth boundary,
C	65-90+	Gravelly stony sand; single grain; non sticky; non plastic; profuse unweathered subrounded greywacke gravel, sand and stones.

Fairton, site II, border dyke effluent irrigated

Site II is border dyke effluent irrigated. This border was also sampled for surface bulk density and soil chemical analysis at 6, 155 and 280 m from the top end. Sites I and II are in pasture and both are used as stock holding paddocks so are subjected to large numbers of stock. As a result of this, the pasture at both sites was in poor condition. Site II had last received effluent one month prior to sampling.

Location: Fairton meat processing plant farm, paddock D1, 80m from the outlet end of the eighth border across from the central race (NZMS260 L37 153013).

Vegetation: Sparse, but consisted of ryegrass, few small clovers, docks, other weed species.

Topography: Border dykes on originally generally flat alluvial terrace.

Profile description: Same as site I except, the surface 'organic' crust is absent, and the structure of the Ap horizon is moderately developed coarse block breaking to weakly developed fine and medium block and granular, and the structure of the BA is moderately developed coarse block breaking to strongly developed fine granular.

Fairton, site III, border dyke effluent irrigated

Samples were taken 6, 85 and 185 m from the top end of paddock D3 (site III). Site III was border dyked in January 1983. It has 200 m long borders and is effluent irrigated less frequently and with lower total volumes of effluent than site II. It had a much higher quality pasture, at the time of sampling, than site I or II and was being used for cattle fattening rather than stock holding.

Table A1.1 Soil permeability estimates and K_{40} measurements - Fairton

Site/sample	Permeability class estimate	mean	K ₄₀ SD	No.
Site I, no irrigation				
Ap	5	1.6	1	5
BA	4	ND	-	-
Bw	4	ND	-	-
C	7	ND	-	-
Site II, effluent irrigated				
Ap	4	13	4	4
BA	4	ND	-	-
Bw	4	ND	-	-
C	7	ND	-	-

Table A1.2 Soil chemical data - Fairton

Site/ sample	pH (H ₂ O)	pH (KCl)	Elec. cond. μS	C%	N%	C/N
Site I - no irrigation						
Ap	5.8	4.9	55	3.7	0.2	15.5
Bw	5.9	4.1	40	0.7	0.1	10.3
Site II - effluent irrigated						
6 m	6.2	6.3	750	9.6	1.0	10.0
85 m						
Ap	5.8	4.6	200	2.9	0.2	13.1
Bw	5.4	4.0	125	1.6	0.1	13.0
155 m	5.7	4.8	320	5.9	0.4	14.0
280 m	5.6	4.6	75	4.4	0.3	16.3
Site III - effluent irrigated						
6 m	6.5	5.4	140	3.1	0.2	12.9
85 m	6.0	4.8	110	3.4	0.3	13.6
185 m	5.8	4.8	90	3.9	0.3	15.0

* Data are means of two replications

Feilding meat processing plant - sampled 19 August 1990.

A brief auger survey was carried out to assess the soil at this site. The high water table and gleyed nature of these soils indicates that they would not be suitable for effluent irrigation all year round.

Effluent treatment: Fellingmongery waste goes to a balancing tank from which the solids go to a solids settling pond, the liquid to a manganese catalysed treatment, to remove sulphide, and thence to the aerobic pond. Yards waste goes to the solids settling pond and then to primary sedimentation along with the killing chain effluent. The effluent then goes through 3 anaerobic ponds then an aerobic pond (total residence time is about 10 days). The effluent is then discharged to the river, except during summer low flow when a portion of the effluent is irrigated.

Climate: Data for Palmerston North airport indicate a mean annual rainfall of 922 mm with a mean monthly temperature of 17.2 °C in February and 7.5 °C in July (New Zealand Meteorological Service 1982).

Topography: Degradational terrace surface about 5 m lower than the terrace of site II.

Parent material: Alluvial silts and sands.

Water table: Observed at between 80 and 130 cm depth in August, it is presumably somewhat lower in summer.

Soil type: Te Arakura silt loam (Cowie 1978).

Soil Classification: NZ - Mottled Orthic Brown Soil; NZ genetic - Gley soil from alluvium;
Soil Taxonomy - Typic Haplaquent

Feilding site I - no effluent

Location: Brian Guy's property, paddock 23, about 30 m east of terrace edge.
NZMS1 N149 085500

Vegetation: Clover-ryegrass pasture.

Soil profile description - auger sample only:

Horizon	Depth cm	Description
Ap	0-20	Dark brown (10YR3/4) heavy silt loam,
Bg	20-80	Silt loam with common medium distinct bright brown (7.5YR5/8) mottles,
Cg	80-100	Loamy sand with common medium distinct bright brown (7.5YR5/8) mottles,
Cr	100-130+	Sand; water table at 130 cm.

Appendix 1: Data for Chapter four

Feilding - site II, effluent irrigated

Location: NZMS1 N149 080498.

Vegetation: Clover-ryegrass pasture.

Profile description: (auger sample only)

Horizon	Depth cm	Description
Ap	0-20	Dark brown (10YR3/3) silt loam,
Bg	20-40	Fine sandy loam with common medium distinct bright brown (7.5YR5/8) (7.5YR5/8) mottles,
Cg	40-80	Loamy sand with common medium distinct bright brown mottles,
Cr	80+	Sand; water table at 80 cm.

Kaiapoi meat processing plant - sampled 21 and 22 December 1989.

Due to the short time of operation of this scheme, the variable nature of the soils, and the difficulty in identifying a control site because of the earthworks that had been carried out, no attempt was made to carry out a site comparison. Three sites were briefly investigated, all within 100 m of each other. Site I was on an area where effluent had ponded in the past, it was largely free of vegetation and no remedial work had been undertaken. Site II had also been a site of effluent ponding to the point where no vegetation remained; it had been recently disked in a bid to restore permeability to the soil. Site III was a vegetated site that had not been seriously affected. None of the sites had been irrigated with effluent since June 1989. All three sites were prepared in the spring of 1988 by paraploughing, possibly recontouring, and the establishment of fescue pasture for hay and/or silage production.

Effluent application: Originally $6000 \text{ m}^3 \text{ day}^{-1}$ was irrigated over 110 ha using a travelling irrigator. By December 1989 a 40% reduction in water use had been made giving a maximum plant output of $4000 \text{ m}^3 \text{ day}^{-1}$ of which only a portion was being irrigated.

Climate: Data for Christchurch airport indicate a mean annual rainfall of 650 mm with a larger portion falling in the autumn/winter. Mean temperatures are 17°C in January and 5.6°C in July. The area is prone to summer drought (data from NZ Meteorological Service 1983).

Parent material: Holocene sand and silt alluvium, derived from greywacke, of the Springston Formation, and sand dunes of the Christchurch Formation (Brown 1973).

Water table: 0.5 - 1.5 m below ground surface in December 1989.

Soil type: Soils were recorded as Waikuku, Waimakariri, Kaiapoi, and Taitapu series soils (T.H. Webb, pers. comm. 1989). The area has been recontoured, with sand dunes removed and used to infill depressions. The soils are variable but generally consist of over 1 m of silt loam to sandy loam material.

Soil Classification: New Zealand - Earthy Fill Anthropic Soils and Mottled Sandy Brown Soils; NZ Genetic - Recent soils and Yellow-brown sands; Soil Taxonomy - Typic Psammaquent.

Kaiapoi site I - ponded area, non-disked

Location: Approximately 150 m southeast of Courtenay stream and approximately 300 m northeast of effluent holding pond, 30 m from irrigation hydrant (NZMS260 M35 830573).

Vegetation: Limited cover, few docks and flatweeds

Topography: In slight hollow on generally flat river flood plain, protected by stopbanks.

Soil profile description:

Horizon	Depth	Description
	cm	
Ap	0-20	Dull yellowish brown (10YR 4/3) and brownish grey (10YR 4/1) fine sandy loam with common fine distinct brown (10YR 4/6) mottles; weakly developed fine blocky

Appendix 1: Data for Chapter four

		structure; slightly sticky; slightly plastic; firm; few very fine roots; sharp wavy boundary,
Br	20-30	Grey (5Y 4/1) fine sandy loam; common fine distinct brown (7.5YR 4/6) mottles; massive; slightly sticky; slightly plastic; friable; few very fine roots; distinct irregular boundary,
Bg	30-55	Dull yellowish brown (10YR 4/3) sand with grey (5Y 4/1) loamy sand in lenses; few distinct bright brown mottles on root channels in loamy sand, lenses; single grain; non sticky; non plastic; few very fine roots; distinct irregular boundary,
Cr	55-80+	Grey (5Y 4/1) sand; single grain; non sticky; non plastic; Water table at 80 cm.

Kaiapoi site II - ponded area, disked

Location: 15 m east of site I.

Vegetation: None (recently disked).

Topography: As for site I.

Soil profile description:

Horizon	Depth cm	Description
Ap	0 - 25	Dull yellowish brown (10YR 4/3) fine sandy loam; weakly developed coarse block breaking to weakly developed fine block and granular structure; slightly sticky; slightly plastic; friable; few very fine roots (none living); distinct smooth boundary,
Cu1	25-55	Yellowish brown (2.5Y 5/3) sand; single grain; non sticky; non plastic; few very fine roots; distinct smooth boundary,
Cu2	55-85+	Grey (5Y 4/1) sand; single grain; non sticky; non plastic; few very fine roots; water table at 1.0 m.

Kaiapoi - site III grassed area

Location: 20 m west of site I in area of best vegetation growth around.

Vegetation: Fescue grass.

Topography: On slight rise on generally flat river flood plain (protected by stopbanks).

Appendix 1: Data for Chapter four

Profile description:

Horizon	Depth cm	Description
Ap	0-25	Dull yellowish brown (10YR 4/3) fine sandy loam; weakly developed medium and coarse block breaking to weakly developed fine and medium nut structure; slightly sticky; slightly plastic; common very fine roots; indistinct smooth boundary,
Bw	25-50	Yellowish grey (2.5Y 4/1) fine sandy loam with common coarse distinct bright brown (7.5YR 5/8) mottles; weakly developed medium and coarse block breaking to single grain structure; non sticky; non plastic; few very fine roots; diffuse smooth boundary,
C	50-80+	Grey (5Y 4/1) sand; single grain; non sticky; non plastic; few very fine roots.

Table A1.3 Soil permeability estimates and K_{60} measurements - Kaiapoi

Site/sample	Permeability class estimate	K ₆₀ (mm hr ⁻¹)		
		mean	SD	No.
Site I - effluent ponded area				
Ap	7	5	3	2
Bw1	2	ND	-	-
Bw2	5	ND	-	-
C	6-5	ND	-	-
Site II - recently disked area				
Ap	7	12	3	2
Cu1	3	ND	-	-
Cu2	5	ND	-	-
Site III - less damaged area (still vegetated)				
Ap	7	40	18	2
Bw	3	ND	-	-
C	5	ND	-	-

Lorneville meat processing plant - sampled 14 and 15 December 1989

Effluent treatment: Incoming effluent is first passed through a contra-shear from which the solid material passes to a solids digestion tank and from there to anaerobic ponds. Liquids pass to a dissolved air floatation tank. One quarter of the outflow goes to a methane digester, the remainder to an anaerobic pond and thence to a series of aerobic ponds with a total area of 30 ha.

Effluent application: Effluent is normally discharged to the Makerewa River but is irrigated onto farmland during periods of low river flow or as an emergency measure during periods of plant breakdown. The volume spray irrigated is limited to 10 000 m³ per week by the pump facilities available. The flood irrigated volume is not measured. Flood irrigation is carried out by ponding effluent to about 0.5 m depth on a "flood banked" paddock, repeated at approximately monthly intervals.

Water table: probably near river level, between 2 and 5 m below the ground surface.

Climate: Data from Invercargill show a mean annual rainfall of 1100 mm distributed throughout the year but with a slightly lower rainfall expected in late winter. Mean air temperature in January is 14°C and in July is 5°C (New Zealand Meteorological service 1983).

Vegetation: Clover-ryegrass pasture.

Topography: Flat, river flood plain. Both sites are protected from river floods by stopbanks but, nevertheless, both are subject to periodic river flooding.

Parent material: Silt alluvium over alluvial gravels and sand derived from schist and greywacke.

Soil classification: New Zealand - Mottled Orthic Recent Soil; NZ Genetic - Recent soil from alluvium; Soil Taxonomy - Aquic Udorthent.

Lorneville site 1, no effluent

Location: In paddock directly south of effluent treatment plant. About 100 m south of anaerobic pond number six and 50 m southwest of access gate in corner of paddock (NZMS260 E46 479181).

Profile description:

Horizon	Depth cm	Description
Ap	0-30	Brown (10YR 4/4) silt loam; very strongly developed fine and medium nut breaking to weakly developed very fine crumb structure; slightly sticky; plastic; many very fine roots; diffuse smooth boundary,
Ag	30-50	Brown (10YR 4/4) silty clay loam; strongly developed fine and medium nut breaking to weakly developed fine granular structure; sticky; plastic; many very fine roots; distinct smooth boundary,
Bg	50-60	Light yellow (2.5Y 7/3) sandy clay loam; many coarse prominent bright brown (7.5YR 5/8) mottles; weakly developed coarse prismatic breaking to massive structure; contains many large worm channels; sticky; plastic; few

Appendix 1: Data for Chapter four

very fine roots; distinct irregular boundary,

Cg	60-80	Greyish yellow (2.5Y 6/2) loamy sand; few medium distinct bright brown (7.5YR 5/8) mottles; contains many large worm channels; single grain; non sticky; non plastic; large native earthworms present; diffuse smooth boundary,
C	80-110+	Gravelly coarse sand; single grain; common weakly weathered subrounded gravels.

Lorneville site II - effluent flooded

Site II has been intermittently flood irrigated. Site II is in a paddock which has a stopbank formed around its edge to prevent flow of effluent into adjacent waterways. This paddock was last flooded three times at monthly intervals between mid-February and April 1989.

Location: Lorneville meat processing plant farm on low terrace approximately 300 m southeast of effluent treatment plant and 40 m northeast of access gate in southern corner of paddock (NZMS260 E46 482186).

Vegetation: Ryegrass and other grasses, no docks or clover.

Topography: Flat river floodplain.

Parent Material: Gravelly sand alluvium overlain by 0.5 -1 m of finer alluvium derived from schist and greywacke.

Profile description:

Horizon	Depth cm	Description
Ap	0-33	Dark brown (10YR 3/4) silt loam; strongly developed fine and medium nut breaking to crumb structure; slightly sticky; plastic; friable; many very fine roots; diffuse smooth boundary,
Bg	33-45	Dull yellowish brown (10YR 5/4) sandy clay loam; many coarse prominent bright brown (7.5YR 5/8) mottles; moderately developed medium block breaking to granular structure; sticky; plastic; firm; few very fine roots; distinct smooth boundary,
Cul	45-60	Dull yellowish brown (10YR 5/3) sandy loam; few medium faint bright yellowish brown (10YR 6/8) mottles; massive; slightly sticky; slightly plastic; friable; few fine roots; distinct smooth boundary,
Cu2	60-80+	Gravelly coarse sand, single grain; profuse weakly weathered subrounded gravels;

Table A1.4 Soil permeability estimates - Lorneville

Site/sample	Permeability class estimate
Site I - no effluent	
Ap	7
Ag	7
Bg	7
Cg	4
C	6
Site II - effluent flooded	
Ap	6-7
Bg	3
Cu1	3
Cu2	4

Table A1.5 Soil chemical data - Lorneville

Site/sample	pH (H ₂ O)	pH (KCl)	Elec. cond. μS	C%	N%	C/N
Site I/Ap	5.2	4.2	80	12.0	0.45	26.7
Site II/Ap	5.6	4.6	80	12.6	0.46	27.4

* Data are means of two replicates

Makerewa meat processing plant - sampled 12, 13 and 16 December 1989

Effluent treatment: Where possible, wastes are screened prior to moving to the treatment system. Treatment consists of: a contra shear screen; fat saveall; four anaerobic ponds in series, with an estimated residence time of approximately three days; an effluent clarification stage using two circular clarifiers in parallel; and two further ponds in series, both of which are mixed aerobic/anaerobic. The theoretical total retention time based on an input of 12 000 m³ per day is 15 days.

This system has been in place since the early 1960s. Prior to that time treatment was achieved using only anaerobic ponds.

Effluent application: Effluent is spray irrigated using manually movable pipes with attached sprinklers. Effluent is pumped from pond six up to a higher level terrace where it is distributed in open ditches to pumping sites and then pumped through the pipe/sprinkler system. The system can operate 24 hours/day seven days/week if required. One person per shift is required to supervise the system when in operation. Additional labour is required to relocate mains and pipes. The irrigation system has a maximum capacity of 4500 m³/24 hours (intake to the effluent treatment plant is 10 000 - 13 000 m³ day⁻¹) applied over a total area of approximately 350 ha with a return period of two to three weeks.

Crop/animal management: The area irrigated consists of two dairy farms owned and operated by independent farmers and a works-owned farm that is used primarily for stock-holding purposes. Some cropping, silage and hay making are carried out on the dairy farms. Farmers attempt to have paddocks grazed prior to irrigation and generally keep cows off for 1-2 weeks afterwards. This is not always strictly adhered to and stock do not seem to have a strong aversion to recently irrigated pasture. Lambs, however, tend to scour if allowed to graze pasture within a week or so of irrigation (P. Soper, pers. comm. 1989).

Water table: Between 2 and 5 m below the ground surface, over nine boreholes between September 1984 and April 1985 (Carrier and Associates 1985).

Climate: As for Lorneville.

Parent Material: 1 - 5 m of loess, derived from greywacke and schist, on weathered outwash gravels and till of the penultimate and possibly older glaciations (Wood 1966).

Soil type: Waikiwi silt loam (sites I and II) and Waikiwi mottled silt loam (site III).

Soil Classification: New Zealand - Typic Firm Brown Soil; NZ Genetic - Southern Yellow-brown Earth;
Soil Taxonomy - Typic Haplumbrept.

Makerewa site I - no effluent

Location: Alistair Shirley's property, road paddock near crest of rise about 50 m east of fence and 150 m from road (NZMS260 E46 476220).

Vegetation: High quality pasture including rye grass, cocksfoot, and white clover.

Topography: Gently rolling - site located on the crest of a small rise.

Landuse: Sheep grazing

Profile description:

Horizon	Depth cm	Description
Ap	0-25	Dark brown (10YR 3/3) silt loam; strongly developed fine, medium and coarse nut and granular structure; slightly sticky; plastic; friable; many very fine roots; indistinct smooth boundary,
AB	25-37	Brown (10YR 4/4) and yellowish brown (10YR 5/6) silt loam; strongly developed medium nut breaking to moderately developed fine and very fine crumb and granular structure; slightly sticky; slightly plastic; friable; common very fine roots; diffuse smooth boundary,
Bw1	37-60	Yellowish brown (10YR 5/8) heavy silt loam; moderately developed fine block breaking to moderately developed fine and very fine crumb and granular structure; sticky; plastic; friable; few faint yellowish brown (10YR 5/8) clay coatings; few very fine roots; diffuse smooth boundary,
Bw2	60-85	Yellowish brown (10YR 5/8) silty clay loam; few fine black Mn concretions; massive; sticky; plastic; friable; diffuse smooth boundary,
C	85-110+	Yellowish brown (10YR 5/8) silt loam; massive; sticky; plastic; friable.

Makerewa Site II - effluent irrigated

Site II was representative of the majority of the landscape and similar to site I. Sites II and III were in the same paddock which was last ploughed 6 years prior to sampling (Mr G. Gunther, pers. comm.). Neither site had received effluent irrigation since the summer of 1986-87. No irrigation was carried out in the 1987-88 and 1988/89 seasons because river flows allowed normal discharges to be made.

Location: G. Gunther's property, in hay shed paddock adjacent to boundary with the Makarewa meat processing plant farm. 100 m west of hay-shed on high part of an undulation (NZMS260 E46 487222).

Vegetation: Clover, ryegrass, cocksfoot pasture.

Topography: As for site I.

Profile description: as for site I except structure of the Ap horizon was strongly developed coarse block breaking to strongly developed coarse nut structure.

Makerewa - Site III - effluent irrigated in depression

Site III (a Waikiwi mottled silt loam) was on a topographically low-lying area where water ponds during periods of intense irrigation or prolonged rainfall. Site III had been mole drained in an attempt to relieve the ponding. Silage is sometimes fed out in the vicinity of site III.

Location: G. Gunther's property, 40 m west of hayshed, 60 m east of site II (NZMS260 E46 487222).

Vegetation: Rye grass; docks; very little clover "grass tends to grow rank and stock don't like it" G. Gunther (pers. comm.)

Topography: Gently rolling - this site situated in low part of a hollow.

Profile description:

Horizon	depth cm	Description
Ap	0-25	Dull yellowish brown (10YR 4/4) silt loam with a few fine distinct bright brown (7.5YR 5/8) mottles and concretions; strongly developed very coarse block breaking to moderately developed fine block and granular structure; slightly sticky; slightly plastic; friable, many very fine roots, diffuse smooth boundary,
AB	25-40	Greyish yellow brown (10YR 4/2) and dull yellow orange (10YR 6/4) heavy silt loam with common medium distinct bright brown (7.5YR 5/8) mottles; strongly developed fine nut structure; slightly sticky; plastic; friable; very strong ped strength; common very fine roots; diffuse smooth boundary,
Bgl	40-60	Dull yellow orange (10YR 6/4) silty clay loam with many fine, medium and coarse distinct bright brown (7.5YR 5/8) mottles; moderately developed coarse block breaking to strongly developed fine block structure; sticky; plastic; friable; very strong ped strength; common faint clay coatings; few very fine roots; diffuse smooth boundary,
Bg2	60-80	Dull yellowish brown (10YR 6/3) clay loam with many fine medium and coarse bright brown (7.5YR 5/8) mottles; moderately developed coarse block breaking to moderately developed fine block; very sticky; common faint clay and iron/manganese coatings; diffuse smooth boundary,
C	80-200	(By auger.) Greyish yellow (2.5Y 7/2) sandy clay loam with profuse fine, medium and coarse bright brown (7.5YR 5/8) mottles; gravels encountered at 2 m.

Table A1.6 Soil permeability estimates and K_{40} measurements - Makarewa

Site/sample	Permeability class estimate	K ₄₀ (mm hr ⁻¹)		
		Mean	SD	No.
Site I, no irrigation				
Ap	7	27	18	5
AB	7	-		
Bw1	4	-		
Bw2	3	-		
Site II - effluent irrigated				
Ap	7	4	2	3
AB	7	-		
Bw1	5	-		
Bw2	3	-		
C	3	-		
Site III - effluent irrigated, hollow				
Ap	6	-		
AB	7	-		
Bg1	4	-		
Bg2	3	-		

Table A1.7 Soil chemical data, Makarewa.

Site/sample	pH (H ₂ O)	pH (KCl)	EC μS	C%	N%	C/N
Site I - no irrigation						
Ap	5.8	4.8	50	5.1	0.3	17.0
Bw	6.0	4.5	15	1.2	0.1	12.0
Site II - effluent irrigated						
Ap	6.2	4.9	40	4.6	0.3	15.3
Bw	5.9	4.3	70	1.6	0.1	16.0
Site III - effluent irrigated, hollow						
Ap	5.5	4.6	160	4.5	0.3	15.0
Bg	6.1	4.6	80	1.3	0.1	13.0

Oringi meat processing plant

Effluent properties: Effluent sampled at the top end of borders on two consecutive days in August 1990 had a pH of 6.4 and 6.7, an EC of 350 and 740 μS and a total solids content of 1000 and 1 900 g m^{-3} .

A spring flows from the terrace side adjacent to the effluent disposal site - it is thought that much of the added water escapes to the Manawatu River via springs such as this one.

There was no reaction to the NaF test for allophane in the A horizon of these soils but a moderate positive reaction was obtained in the B and C horizons.

Measurements were made in a border dyke irrigated block of coppicing gum trees (site III) and in a spray irrigated stand of coppicing gums (site IV). Effluent was sampled, and bulk density measurements made, along the length of a border in paddock 15 (site V).

Climate: Mean annual rainfall: 1093 mm with more in winter/spring than summer/autumn; mean air temperature is 17.3 °C in February and 7.3 °C in July (NZ Meteorological Service 1983).

Parent material: Alluvial gravels and sands from predominantly greywacke with some loess.

Soil type: Kopua sandy loam.

Soil Classification: New Zealand - Typic Orthic Brown Soil; NZ Genetic - moderately to very strongly leached intergrade between Yellow-brown loams and Yellow-brown earths (Pohlen, 1971); Soil Taxonomy - Udic Ustochrept.

Oringi site I - no effluent sampled 31 January 1989

Location: Oringi freezing works farm, 50 m north of pine/gum tree hedge, 30 m northeast of metal pit. NZMS260 T24 682001.

Vegetation: Clover-ryegrass pasture.

Topography: Flat terrace surface. This site has never been irrigated and so has not been border dyked.

Profile description:

Horizon	Depth cm	Description
Ap	0-28	Brownish black (10YR3/2) gravelly sandy loam; moderately developed very coarse block breaking to moderately developed very fine to medium block and granular structure; slightly sticky; slightly plastic; friable; many very fine roots; many weakly weathered subrounded greywacke gravels and stones; diffuse smooth boundary,
Bw	28-50	Dark brown (10YR3/4) gravelly sandy loam; moderately developed fine and very fine block plus fine granular structure; non-sticky; non-plastic; very friable; many very fine roots; many weakly weathered

Appendix 1: Data for Chapter four

subrounded greywacke gravels and stones;
diffuse smooth boundary,

C

50-80+

Gravelly sand; single grain; non-sticky; non-plastic; loose; few very fine roots; profuse unweathered to weakly weathered subrounded greywacke gravels, stones and a few boulders.

Oringi - site II, effluent irrigated sampled 21 August 1990

Site II (in paddock 13) is border dyke effluent irrigated. Records showed that it had been irrigated over 7-13 June 1990, and prior to that in July 1989, with effluent travelling 100-150 m down the border and not always being evenly distributed (Tai Hoera pers. comm. 1990).

Location: Oringi freezing works farm, paddock 13, third border east of gate to race. NZMS260 T24 683996.

Vegetation: Ryegrass pasture.

Topography: Flat terrace surface, border dyked

Profile description: as for site 1 except structure of Ap horizon is recorded as moderately developed fine and very fine nut structure breaking to moderately developed crumb structure. This difference could be the result of the generally moister state of this soil at the time of sampling.

Takapau meat processing plant

Site I has never been irrigated and has not been border dyked. Site II is border dyke effluent irrigated. Both sites are on the same terrace which is generally gently sloping northwest. The Takapau soil is reasonably uniform and consists of a brownish black (10YR2/2) silt loam topsoil overlying very friable fine sandy loam with gravelly sandy loam at about 50 cm. This overlies greywacke gravel and sand alluvium.

Effluent application: 2000 m³/day is applied, using border dyke irrigation, over a total area of 180 ha, 5 days/week, from October to May. Less effluent is applied during June-July and the plant closes down for 6-8 weeks in August/September. The effluent is pumped from the plant to a holding dam at the highest point in the irrigation area. It is then gravity fed through a series of races to the borders. The borders are generally no more than 70 m long and the holding dam gives a water supply of 8 cusecs which ensures that the water flows out readily across the borders, one of which is irrigated at a time. It takes approximately 10 minutes in summer and 17 seconds in winter for the water to flow along the length of the border (R. De Stackpole pers. comm. 1990). This system is effective in relatively evenly distributing the effluent across the land but requires full time attention from the irrigation scheme operator.

Crop/animal management: In 1990 young bulls were being grazed but the area was previously used for sheep and lambs. No special stock management is employed although it has been observed that stock scour if left grazing paddocks during or immediately after effluent application (R. De Stockpool pers. comm. 1990). Lucerne has been grown for hay. There has been a gradual increase in the amount of barley grass and goose grass invading the effluent irrigated pastures. Plant growth increases under effluent irrigation, particularly under the summer drought conditions which prevail in this area (R. de Stackpoole, pers. comm. 1990).

Soil/site: The soil is Takapau silt loam, a Typic Allophanic Brown Soil (after Hewitt 1992) formed primarily from greywacke-derived gravel and sand alluvium with some loess and tephra addition. The water table is at about 5 m. Neighbours depend on this for bore water and some problems of nitrate contamination of groundwater in these bores was occurring and being monitored. Deeper bores were not being affected in 1989.

Taumaruni meat processing plant - sampled 7 and 8 November 1989

Effluent application: 18 000 - 20 000 m³ of effluent/day, five days/week for eight months of the year (mid-November through to mid-August). Irrigation is generally conducted over an area for half to one day at a time with a six to ten week break between irrigations.

Crop/animal management: On one occasion when fat came through the system, due to a plant failure, stock would not eat the affected pasture for up to eight weeks afterwards (R. Bougen pers. comm. 1989).

Climate: Mean annual rainfall of 1440 mm with a mean temperature in January of 18°C and in July of 7.3°C (New Zealand Meteorological Service 1983).

Parent material: Pumice dominated alluvium. formed on a river terrace of cobble through to mud sized pumice alluvium though sand and gravel predominate (Kermode 1977). This alluvium is mainly derived from the Taupo Tephra eruption of 1850 yrs BP (Hay 1967).

Water table: is controlled ultimately by the level of the Wanganui River (about 40m below and to the west of the effluent disposal site). The terrace alluvium is free draining with no impediments likely to cause perching. The eastern side of the site is marked by the Waiwherowhero Stream towards the north and a swampy, semi abandoned, stream channel towards the south. Both these streams lie approximately 10 m below the terrace surface. It is therefore reasonable to assume that the watertable lies between 10 and 40 metres below the terrace surface and is unlikely to rise significantly or cause any limitations to effluent irrigation.

Soil type: Manunui fine sandy loam

Soil classification: New Zealand - Allophanic Orthic Pumice Soil; NZ Genetic - Yellow-brown pumice soil (Wilde 1977); Soil Taxonomy - Typic Udivitrand.

Taumarunui - Site I no effluent

Location: Stock holding paddock south of managers house and west of holding pond. In middle of paddock 30m east of Totara tree, 50 m west of holding pond and 50 m south of manager's house (NZMS1 N101 854106).

Topography: Broad flat area of terrace - terrace does however have a generally hummocky meso-topography.

Vegetation: Clover/ryegrass pasture with plantain, occasional docks and common pasture weeds

Appendix 1: Data for Chapter four

Profile description:

Horizon	depth cm	Description
Ap	0-18	Brownish black (10YR 2/3) fine sandy loam; weakly developed coarse block breaking to moderately developed fine nut and crumb structure; non sticky; slightly plastic; many very fine roots; distinct irregular boundary.
Bw	18-30	Yellowish brown (10YR 5/6) gravelly coarse sandy loam; weakly developed medium block breaking to weakly developed medium crumb structure; non sticky; non plastic; common very fine roots; common weakly weathered sub-rounded pumice gravels; diffuse smooth boundary.
C	30-95+	Dull yellow (2.5Y 6/3) loamy sand; few fine distinct bright brown (7.5YR 5/8) mottles; strongly developed medium crumb structure; non sticky, non plastic.

Taumarunui - site II - effluent irrigated.

Last irrigated about 4 months prior to sampling. Samples were also taken, for chemical analysis, from one of the low-lying hollows, where water ponds following effluent irrigation.

Location: Southern paddock on higher part of terrace 50m west of pine trees and creek, 30 m northeast of new sprinkler head, 150 m south of gate (NZMS1 N101 858101).

Vegetation: Clover-ryegrass pasture.

Topography: Smooth, flat part of terrace.

Profile description:

Horizon	depth cm	Description
Ap	0-15	Brownish black (10YR 2/3) gravelly fine sandy loam; weakly developed coarse block breaking to moderately developed medium crumb structure; non sticky; slightly plastic; many very fine roots; common weakly to moderately weathered sub-rounded pumice gravels; distinct irregular boundary,
Bw	15-25	Yellowish brown (10YR 5/6) gravelly loamy sand; weakly developed coarse block breaking to moderately developed medium crumb-structure; non sticky; non plastic; common very fine roots; common weakly weathered sub-rounded pumice gravels; diffuse smooth boundary,
C	25-95+	Orange (7.5YR 7/6) gravelly loamy sand; strongly developed medium and coarse crumb structure; non sticky; non plastic; common unweathered sub-rounded pumice gravels and few pumice stones.

Table A1.8 Soil permeability estimates - Taumarunui

Site/sample	Permeability class estimate
Site I (no effluent)	
Ap	4
Bw	4
C	5
Site II (effluent irrigated)	
Ap	4
Bw	4
C	5

Soil chemical data (Table A1.9) show that all A horizons have a medium carbon content and medium to high percent nitrogen. The pH in water is strongly acid at sites I and II but moderately acid at the ponded sites (low lying areas of effluent accumulation during irrigation). The A horizon at site I (no effluent) has a higher C content and electrical conductivity than the ponded site. This is unexpected and it may be a reflection of the use of this site for stock holding not long prior to sampling. The data indicate that effluent irrigation is having little effect on the measured properties at this site.

Table A1.9 Soil chemical data - Taumarunui

Site/sample	pH(H ₂ O)	pH(KCl)	Electrical conductivity μS	%C	%N	C/N
Site I - no effluent						
Ap	4.9	4.4	360	10.4	0.6	17.3
Bw	5.4	4.4	10	2.7	0.2	13.5
Site II - effluent irrigated						
Ap	5.1	4.1	110	9.1	0.6	15.2
Bw	5.1	4.3	60	3.4	0.2	17.0
Pond edge	5.6	4.4	160	8.2	0.5	16.4
pond centre	5.9	4.7	200	8.4	0.7	12.0

Wakanui meat processing plant - sampled 18 December 1989

Effluent application: Deer chain - an unknown volume was spray irrigated over approximately 5 ha adjacent to the plant, lamb chain - 7000 m³/week was spray irrigated over approximately 150 ha using a travelling irrigator. The total available farm area is about 300 ha of which only about half was irrigated with effluent in 1989. The other half was water irrigated.

Climate: as for Fairton.

Parent material: as for Fairton.

Topography: Generally flat, some small undulations.

Soil type: Lismore sandy loam.

Soil classification: as for Fairton.

Wakanui, site I - water irrigated

About 60 mm of rain had fallen on the two days prior to sampling. site I was ploughed about 18 months prior to sampling (P. Guildford pers. comm. 1989). It was irrigated with water 11 days prior to sampling.

Location: 100 m west of site II in neighbouring paddock, approximately 60 m west of deer fence and "county water race" (NZMS260 L37 190976).

Vegetation: Common pasture grasses, clover, "wild" wheat.

Profile description:

Horizon	Depth cm	Description
Ap	0 - 20	Brownish black (10YR 2/3) gravelly sandy loam; moderately developed coarse blocky breaking to moderately developed medium nut structure; slightly sticky; slightly plastic; friable; common very fine roots; few unweathered, subrounded greywacke gravels and stones; distinct irregular boundary,
Bw	20 - 55	Brown (10YR 4/6) gravelly stony sandy loam; moderately developed fine granular structure; non-sticky, non-plastic; common very fine roots; abundant unweathered subrounded greywacke gravels and stones; diffuse smooth boundary,
C	55-100+	Unweathered subrounded greywacke gravels, stones and boulders with a sand matrix and occasional sand lenses.

Appendix 1: Data for Chapter four

Wakanui - site II, effluent irrigated

Site II had not been ploughed for at least three years prior to sampling, It was irrigated with effluent 11 days prior to sampling.

Location: Second paddock south of the main race, 140 m south of east/west trending pine hedge, 40 m east of "county water race" and deer fence, in paddock irrigated with effluent (NZMS260 L37 192976).

Vegetation: Common pasture grasses, thistles in low-lying areas, no clover present, grass approx 30 cm long.

Topography and Parent material as for site I.

Profile description as for site I except A horizon was noticeably less dense, more porous, and less consolidated than that for site I.

Table A1.10 Soil permeability estimates and K_{40} measurements - Wakanui

Site/ sample	K_{40} mm hr ⁻¹			Permeability class estimate
	mean	SD	no	
Site I - water irrigated				
surface	9	2	2	
Ap				7
Bw				6
C				7
Site II - effluent irrigated				
surface	8.5	0.3	2	
Ap				7
Bw				6
C				7

Table A1.11 Soil chemical data - Wakanui

Site/ sample	pH (H ₂ O)	pH (KCl)	electrical conductivity μ S	C%	N%	C/N	
Site I - Water irrigated							
Ap	6.3	5.3	55		3.1	0.2	15.5
Bw	5.6	4.4	20		0.9	0.1	9.0
Site II - effluent irrigated							
Ap	6.5	5.7	130		3.3	0.2	16.5
Bw	5.4	4.4	110		0.8	0.1	8.0

Appendix 1: Data for Chapter four

Appendix 2: Data for Chapter 5

Table A2.1 Factorial trial design.

Core (10°C)	eff.*	soil	rain	time	vol.	Core (25°C)	eff.	soil	rain	time	vol.
1001	W	K	Hi	9	Lo	2001	W	K	Lo	3	Hi
1002	W	K	Lo	3	Lo	2002	W	K	Hi	9	Hi
1003	W	K	Hi	3	Hi	2003	W	K	Lo	9	Lo
1004	W	K	Lo	9	Hi	2004	W	K	Hi	3	Lo
1101	W	B	Lo	3	Hi	2101	W	B	Hi	9	Lo
1102	W	B	Hi	9	Hi	2102	W	B	Lo	3	Lo
1103	W	B	Lo	9	Lo	2103	W	B	Hi	3	Hi
1104	W	B	Hi	3	Lo	2104	W	B	Lo	9	Hi
1005	P	K	Lo	3	Hi	2005	P	K	Hi	9	Lo
1006	P	K	Hi	9	Hi	2006	P	K	Lo	3	Lo
1007	P	K	Lo	9	Lo	2007	P	K	Hi	3	Hi
1008	P	K	Hi	3	Lo	2008	P	K	Lo	9	Hi
1105	P	B	Hi	9	Lo	2105	P	B	Lo	3	Hi
1106	P	B	Lo	3	Lo	2106	P	B	Hi	9	Hi
1107	P	B	Hi	3	Hi	2107	P	B	Lo	9	Lo
1108	P	B	Lo	9	Hi	2108	P	B	Hi	3	Lo
1009	F	K	Hi	3	Hi	2009	F	K	Lo	9	Lo
1010	F	K	Lo	9	Hi	2010	F	K	Hi	3	Lo
1011	F	K	Hi	9	Lo	2011	F	K	Lo	3	Hi
1012	F	K	Lo	3	Lo	2012	F	K	Hi	9	Hi
1109	F	B	Lo	9	Lo	2109	F	B	Hi	3	Hi
1110	F	B	Hi	3	Lo	2110	F	B	Lo	9	Hi
1111	F	B	Lo	3	Hi	2111	F	B	Hi	9	Lo
1112	F	B	Hi	9	Hi	2112	F	B	Lo	3	Lo
1013	A	K	Lo	9	Lo	2013	A	K	Hi	3	Hi
1014	A	K	Hi	3	Lo	2014	A	K	Lo	9	Hi
1015	A	K	Lo	3	Hi	2015	A	K	Hi	9	Lo
1016	A	K	Hi	9	Hi	2016	A	K	Lo	3	Lo
1113	A	B	Hi	3	Hi	2113	A	B	Lo	9	Lo
1114	A	B	Lo	9	Hi	2114	A	B	Hi	3	Lo
1115	A	B	Hi	9	Lo	2115	A	B	Lo	3	Hi
1116	A	B	Lo	3	Lo	2116	A	B	Hi	9	Hi

* **Effluents** (eff.): W = water, P = primary treated, F = primary + fellmongery, A = anaerobic. **Soils**; K = Kopua sandy loam, B = Bruntwood sandy loam. **Rain**; Lo = low volume (11 mm/application), Hi = high volume (70 mm/application). **Time**; 3 = 3 days between effluent applications, 9 = 9 days between effluent applications. **Volume** (vol.): Hi = high volume (45 mm/application every three days or 135 mm/application every 9 days) and Lo = low volume (15 mm/application every 3 days or 45 mm/application every 9 days).

Table A2.2 Core permeability data

Core	MBE* (mm hr ⁻¹)	SD (mm hr ⁻¹)	K _{sat} 2 (mm hr ⁻¹)	K _{sat} 13 (mm hr ⁻¹)	ΔK _{sat} 2 %	ΔK _{sat} 13 %
1001	266	66	83	229	31	86
1002	179	57	48	174	27	97
1003	297	57	148	268	50	90
1004	185	61	83	143	45	77
1005	331	35	94	157	28	48
1006	91	11	39	44	42	48
1007	141	28	33	101	23	71
1008	219	62	212	272	97	124
1009	119	48	41	210	34	176
1010	170	17	33	85	19	50
1011	220	47	12	63	5	29
1012	221	41	44	261	20	118
1013	131	32	100	143	76	110
1014	226	91	169	230	75	102
1015	216	12	2	43	1	20
1016	220	44	29	60	13	27
1101	879	93	668	920	76	105
1102	1261	469	1209	1717	96	136
1103	786	272	620	593	79	75
1104	464	96	461	615	99	133
1105	1782	225	787	1431	44	80
1106	1132	236	987	1094	87	97
1107	623	103	0.5	4	0.08	0.6
1108	1131	106	114	446	10	39
1109	1151	208	801	1043	70	91
1110	745	103	1169	1383	157	186
1111	939	256	52	233	6	0.3
1112	498	98	232	397	47	80
1113	412	125	608	787	148	190
1114	696	82	620	906	89	130
1115	829	247	692	465	83	56
1116	660	169	859	859	130	130
2001	92	17	72	191	78	208
2002	145	41	100	176	69	121
2003	81	18	80	30	99	37
2004	116	29	102	120	88	104
2005	165	34	155	200	94	122
2006	92	22	307	181	335	198
2007	296	97	0.01	158	0.003	54
2008	440	66	212	716	48	163
2009	282	31	170	328	60	117
2010	246	70	233	334	94	136
2011	141	46	0.01	58	0.006	41
2012	561	58	116	161	21	29
2013	355	50	2	358	0.4	101
2014	430	69	313	405	73	94
2015	202	60	136	224	67	111
2016	600	96	787	1288	131	215
2101	2447	631	2576	3148	105	129
2102	1507	164	1574	1431	104	95
2103	2057	337	1682	2290	82	111
2104	1305	334	1091	2647	84	203
2105	1783	270	954	2433	54	73
2106	1008	308	859	1240	85	123
2107	1258	202	1207	1383	96	110
2108	2153	190	2218	3148	103	146
2109	1411	379	0.1	537	0.009	38
2110	1820	254	0.7	2969	0.04	163
2111	1083	358	1055	1002	97	93
2112	1336	146	2147	2004	161	150
2113	1706	300	1610	2433	94	143
2114	2579	416	2017	3721	78	144
2115	1526	308	1431	1932	94	127
2116	802	183	1002	2290	125	286

* MBE is the mean of seven permeability measurements made prior to effluent application. K_{sat} 2 is the K_{sat} two days after the last effluent application. K_{sat} 13 is K_{sat} 13 days after the last effluent application. ΔK_{sat}2 was calculated as K_{sat}2/MBE x 100 - ie the percentage of the measured value compared to the initial value. This eliminates the effects of initial between-core differences and is the value used for the statistical analysis. Similarly, ΔK_{sat}13 is K_{sat}13/MBE x 100.

Table A2.3 Core soil properties at conclusion of experiment

Core no.	bulk density g cm ⁻³	pH (H ₂ O)	pH (CaCl ₂)	electrical conductivity μS cm ⁻¹	C%	aggregate stability %	surface coat ratings		
							day 2	day 13	day 35
1001	1.06	5.1	4.1	50	6.7	88	0	0	0
1002	0.96	5.2	4.0	50	6.5	91	0	0	0
1003	1.08	5.3	4.1	50	7.2	*	0	0	1
1004	0.88	5.4	4.0	50	7.3	84	0	0	1
1005	0.94	4.8	3.9	180	7.3	84	3	2	1
1006	1.10	4.6	4.0	140	7.6	83	3	2	1
1007	1.08	4.9	4.1	150	7.4	87	2	2	1
1008	1.15	5.2	4.1	100	6.7	84	0	0	1
1009	1.10	5.1	4.3	260	7.1	88	1	0	1
1010	1.16	5.2	4.4	160	7.0	80	*	1	1
1011	1.24	5.1	4.1	150	5.9	85	2	2	2
1012	1.04	5.1	4.0	150	6.4	85	0	0	1
1013	0.99	4.5	3.9	250	6.6	85	3	3	2
1014	1.34	4.7	4.0	110	6.9	89	2	2	#
1015	1.07	4.2	3.8	450	7.4	85	3	3	3
1016	0.98	4.2	3.6	300	6.5	*	3	3	3
1101	0.73	5.4	4.2	60	6.4	*	0	0	0
1102	0.71	4.9	4.0	60	6.6	87	0	0	0
1103	0.71	5.1	4.1	80	7.8	86	0	0	0
1104	0.73	5.0	4.0	70	7.8	84	0	0	0
1105	0.70	4.8	3.9	150	7.5	82	1	1	1
1106	0.70	4.8	4.0	250	7.3	82	1	1	1
1107	0.73	4.5	3.9	250	7.6	85	3	2	2
1108	0.67	4.3	3.8	300	7.6	80	3	2	2
1109	0.68	5.0	4.2	240	7.4	87	2	1	0
1110	0.71	5.0	4.1	280	6.4	80	0	0	0
1111	0.69	5.3	4.3	300	7.8	85	1	1	1
1112	0.70	5.2	4.5	320	6.3	76	3	2	2
1113	0.72	4.3	3.8	300	7.4	79	3	3	3
1114	0.71	4.4	3.9	280	7.2	86	3	3	3
1115	0.67	4.2	3.8	240	7.4	84	3	2	2
1116	0.68	4.5	4.0	200	7.8	81	2	2	1
2001	1.16	5.5	4.7	50	6.1	91	0	0	0
2002	1.33	5.6	4.8	50	6.0	89	0	0	0
2003	1.33	5.6	4.8	50	5.8	*	0	0	0
2004	1.16	5.5	4.7	70	5.8	86	0	0	0
2005	1.28	5.5	4.7	100	5.2	93	2	1	1
2006	1.16	5.4	4.7	100	5.9	87	0	0	1
2007	1.12	5.2	4.8	250	6.8	87	3	2	2
2008	1.03	5.2	4.5	180	6.8	88	3	2	2
2009	1.01	5.4	4.8	200	6.4	87	1	1	1
2010	1.16	5.5	4.8	150	6.2	84	1	0	1
2011	1.04	5.6	5.0	400	7.2	93	3	3	3
2012	1.30	5.5	4.9	300	7.5	92	2	1	1
2013	1.12	5.0	4.6	300	7.4	87	3	3	3
2014	1.34	4.9	4.5	250	6.1	88	3	3	3
2015	1.12	5.1	4.6	180	6.6	80	3	3	3
2016	1.36	5.4	4.8	100	6.7	85	1	1	1
2101	0.63	5.4	4.7	100	6.8	86	0	0	0
2102	0.64	5.4	4.8	100	7.2	84	0	0	0
2103	0.63	5.6	4.8	100	7.5	89	0	0	0
2104	0.66	5.5	4.8	100	6.6	82	0	0	0
2105	0.69	5.4	4.7	200	7.4	86	2	1	2
2106	0.68	5.0	4.5	200	7.3	86	*	1	2
2107	0.70	5.3	4.8	200	7.2	83	1	1	2
2108	0.68	5.3	4.7	200	7.2	82	0	0	0
2109	0.67	5.4	4.7	300	7.3	81	3	1	0
2110	0.68	5.6	5.0	300	6.9	86	3	3	2
2111	0.66	5.5	4.8	260	8.0	90	1	0	0
2112	0.69	5.5	4.9	250	7.5	94	0	0	0
2113	0.66	5.2	4.8	300	8.4	87	3	3	3
2114	0.66	5.1	4.7	200	7.2	77	0	0	0
2115	0.70	5.0	4.6	250	7.6	81	3	3	3
2116	0.65	5.0	4.7	350	7.1	82	3	3	3

= lots of activity/mixing due to grass grub.

Table A2.4 Effluent leachate data

Core no	Effluent	pH	Electrical conductivity $\mu\text{S cm}^{-1}$	Total Solids g m^{-3}	Colour
1001	w	6.3	180	200	clear
1002	w	6.3	200	200	clear
1003	w	6.2	200	200	clear
1004	w	6.3	160	<100	clear
1005	p	6.2	980	800	5Y8/2
1006	p	6.4	660	600	5Y8/1
1007	p	6.5	600	400	5Y8/1
1008	p	6.7	620	800	2.5Y6/6
1009	F	7.0	1350	1200	5Y8/2
1010	F	7.2	880	900	5Y7/6
1011	F	7.0	1500	-	clear
1012	F	6.8	700	500	5Y8/3
1013	A	6.6	780	600	5Y8/2
1014	A	6.6	600	400	5Y8/1
1015	A	6.4	1200	1000	clear
1016	A	6.7	1200	1000	5Y8/1
1101	w	6.2	200	200	clear
1102	w	6.5	160	100	5Y8/1
1103	w	6.1	200	100	clear
1104	w	6.1	200	100	clear
1105	p	6.4	600	500	5Y7/6
1106	p	6.4	600	400	5Y8/2
1107	p	6.0	950	600	*
1108	p	6.4	700	500	5Y8/1
1109	F	6.8	750	600	*
1110	F	7.4	800	700	5Y7/6
1111	F	6.8	1200	900	5Y8/3
1112	F	6.5	1050	900	5Y8/4
1113	A	5.5	1100	800	5Y8/1
1114	A	6.4	1000	700	5Y8/1
1115	A	6.9	1000	600	5Y8/1
1116	A	6.8	850	500	5Y8/2
2001	w	6.8	250	200	clear
2002	w	6.9	190	100	clear
2003	w	6.7	300	200	clear
2004	w	6.8	250	200	clear
2005	p	6.7	800	500	5Y8/2
2006	p	6.7	1500	1000	5Y8/1
2007	p	7.0	1300	1000	5Y7/4
2008	p	7.1	1100	800	5Y8/1
2009	F	7.1	2000	1500	5Y7/5
2010	F	6.9	900	600	5Y8/4
2011	F	7.3	2400	2100	5Y7/6
2012	F	7.0	2400	1900	5Y8/4
2013	A	6.6	1600	1200	5Y8/2
2014	A	6.9	1600	1000	5Y8/2
2015	A	7.0	1000	600	5Y8/3
2016	A	6.9	1100	700	5Y8/0
2101	w	7.1	400	400	clear
2102	w	6.9	500	400	clear
2103	w	6.9	320	500	clear
2104	w	7.1	250	300	clear
2105	p	7.2	950	900	5Y7/6
2106	p	7.1	1200	900	5Y8/1
2107	p	7.0	1000	800	5Y8/3
2108	p	7.2	850	1000	5Y7/6
2109	F	8.0	1900	1800	5Y7/6
2110	F	7.7	2500	2000	5Y8/4
2111	F	7.3	1400	1300	5Y7/5
2112	F	7.0	2400	1700	5Y8/4
2113	A	7.2	1500	900	5Y8/3
2114	A	7.5	1600	900	5Y8/3
2115	A	7.3	1500	900	5Y8/3
2116	A	7.3	1250	900	5Y8/2

Table A2.5 Statistical analysis of soil permeability measurements

***** ANALYSIS OF VARIANCE *****

A2.5a: SOIL K_{sat} 2 DAYS AFTER END OF EFFLUENT APPLICATION

SOURCE OF VARIATION	DF	SS	SS%	MS	VR	F	PR
UNITS STRATUM							
TEMP	1	0.63582	8.15	0.63582	8.127	0.010	
EFF	2	0.57587	7.38	0.28793	3.680	0.045	
REG1	1	0.51220	6.57	0.51220	6.547	0.019	
DEVIATIONS	1	0.06366	0.82	0.06366	0.814	0.378	
SOIL	1	0.61928	7.94	0.61928	7.916	0.011	
RAIN	1	0.04470	0.57	0.04470	0.571	0.459	
TIME	1	0.07981	1.02	0.07981	1.020	0.325	
VOL	1	2.04677	26.25	2.04677	26.162	<0.001	
TEMP.EFF	2	0.12074	1.55	0.06037	0.772	0.476	
DEV.REG1	1	0.00502	0.06	0.00502	0.064	0.803	
DEVIATIONS	1	0.11572	1.48	0.11572	1.479	0.239	
TEMP.SOIL	1	0.04775	0.61	0.04775	0.610	0.444	
EFF.SOIL	2	0.23716	3.04	0.11858	1.516	0.245	
REG1.DEV	1	0.02927	0.38	0.02927	0.374	0.548	
DEVIATIONS	1	0.20790	2.67	0.20790	2.657	0.120	
TEMP.RAIN	1	0.16233	2.08	0.16233	2.075	0.166	
EFF.RAIN	2	0.05128	0.66	0.02564	0.328	0.725	
REG1.DEV	1	0.00402	0.05	0.00402	0.051	0.823	
DEVIATIONS	1	0.04725	0.61	0.04725	0.604	0.447	
SOIL.RAIN	1	0.00237	0.03	0.00237	0.030	0.864	
TEMP.TIME	1	0.04266	0.55	0.04266	0.545	0.469	
EFF.TIME	2	0.07928	1.02	0.03964	0.507	0.610	
REG1.DEV	1	0.04444	0.57	0.04444	0.568	0.460	
DEVIATIONS	1	0.03484	0.45	0.03484	0.445	0.513	
SOIL.TIME	1	0.00263	0.03	0.00263	0.034	0.857	
RAIN.TIME	1	0.00770	0.10	0.00770	0.098	0.757	
TEMP.VOL	1	0.36453	4.67	0.36453	4.659	0.044	
EFF.VOL	2	0.77462	9.93	0.38731	4.951	0.019	
REG1.DEV	1	0.71356	9.15	0.71356	9.121	0.007	
DEVIATIONS	1	0.06107	0.78	0.06107	0.781	0.388	
SOIL.VOL	1	0.23827	3.06	0.23827	3.046	0.097	
RAIN.VOL	1	0.00723	0.09	0.00723	0.092	0.764	
TIME.VOL	1	0.54707	7.02	0.54707	6.993	0.016	
RESIDUAL	19 (1)	1.48643	19.06	0.07823			
TOTAL	46	8.17430	104.83	0.17770			
GRAND TOTAL	46	8.17430	104.83				
GRAND MEAN		0.612					
TOTAL NUMBER OF OBSERVATIONS		48					
NUMBER OF MISSING VALUES		1					
MAXIMUM NUMBER OF ITERATIONS		5					
UNIT		ESTIMATED					
NUMBER		VALUE					
38		1.213					

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR SOIL PERMEABILITY 2 DAYS AFTER EFFLUENT *****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP	TEMP
SOIL								EFF
REP	24	16	24	24	24	24	8	12
SED	0.0807	0.0989	0.0807	0.0807	0.0807	0.0807	0.1399	0.1142
TABLE	EFF	TEMP	EFF	SOIL	TEMP	EFF	SOIL	RAIN
	SOIL	RAIN	RAIN	RAIN	TIME	TIME	TIME	TIME
REP	8	12	8	12	12	8	12	12
SED	0.1399	0.1142	0.1399	0.1142	0.1142	0.1399	0.1142	0.1142
TABLE	TEMP	EFF	SOIL	RAIN	TIME			
	VOL	VOL	VOL	VOL	VOL			
REP	12	8	12	12	12			
SED	0.1142	0.1399	0.1142	0.1142	0.1142			

(NOT ADJUSTED FOR MISSING VALUES)

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	19	0.2797	45.7

Appendix 2: Data for Chapter 5

A2.5b: SOIL PERMEABILITY 13 DAYS AFTER THE END OF EFFLUENT APPLICATION

SOURCE OF VARIATION	DF	SS	SS%	MS	VR	F PR
UNITS STRATUM						
TEMP	1	1.2140	10.10	1.2140	7.243	0.014
EFF	2	0.3048	2.54	0.1524	0.909	0.419
REG1	1	0.2998	2.49	0.2998	1.789	0.196
DEVIATIONS	1	0.0050	0.04	0.0050	0.030	0.865
SOIL	1	0.0845	0.70	0.0845	0.504	0.486
RAIN	1	0.0416	0.35	0.0416	2.48	0.624
TIME	1	0.2492	2.07	0.2492	1.487	0.237
VOL	1	0.2636	2.19	0.2636	1.573	0.224
TEMP.EFF	2	0.9021	7.51	0.4511	2.691	0.092
DEV.REG1	1	0.0208	0.17	0.0208	0.124	0.728
DEVIATIONS	1	0.8813	7.33	0.8813	5.258	0.033
TEMP.SOIL	1	0.0393	0.33	0.0393	0.234	0.634
EFF.SOIL	2	0.2472	2.06	0.1236	0.738	0.491
REG1.DEV	1	0.0914	0.76	0.0914	0.546	0.469
DEVIATIONS	1	0.1558	1.30	0.1558	0.929	0.347
TEMP.RAIN	1	1.0002	8.32	1.0002	5.968	0.024
EFF.RAIN	2	0.1298	1.08	0.0649	0.387	0.684
REG1.DEV	1	0.0325	0.27	0.0325	0.194	0.664
DEVIATIONS	1	0.0973	0.81	0.0973	0.580	0.455
SOIL.RAIN	1	0.0112	0.09	0.0112	0.067	0.799
TEMP.TIME	1	0.2215	1.84	0.2215	1.321	0.264
EFF.TIME	2	0.1062	0.88	0.0531	0.317	0.732
REG1.DEV	1	0.0124	0.10	0.0124	0.074	0.788
DEVIATIONS	1	0.0938	0.78	0.0938	0.559	0.463
SOIL.TIME	1	0.6202	5.16	0.6202	3.700	0.069
RAIN.TIME	1	0.0217	0.18	0.0217	0.130	0.723
TEMP.VOL	1	0.1499	1.25	0.1499	0.894	0.356
EFF.VOL	2	1.6231	13.50	0.8116	4.842	0.019
REG1.DEV	1	1.6217	13.49	1.6217	9.676	0.006
DEVIATIONS	1	0.0014	0.01	0.0014	0.008	0.928
SOIL.VOL	1	0.0171	0.14	0.0171	0.102	0.752
RAIN.VOL	1	0.2732	2.27	0.2732	1.630	0.216
TIME.VOL	1	1.1475	9.55	1.1475	6.846	0.017
RESIDUAL	20	3.3521	27.89	0.1676		
TOTAL	47	12.0199	100.00	0.2557		
GRAND TOTAL	47	12.0199	100.00			
GRAND MEAN		1.018				
TOTAL NUMBER OF OBSERVATIONS		48				

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR SOIL PERMEABILITY 13 DAYS AFTER END OF EFFLUENT*****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP EFF	TEMP SOIL
REP	24	16	24	24	24	24	8	12
SED	0.1182	0.1447	0.1182	0.1182	0.1182	0.1182	0.2047	0.1671
TABLE	EFF SOIL	TEMP RAIN	EFF RAIN	SOIL RAIN	TEMP TIME	EFF TIME	SOIL TIME	RAIN TIME
REP	8	12	8	12	12	8	12	12
SED	0.2047	0.1671	0.2047	0.1671	0.1671	0.2047	0.1671	0.1671
TABLE	TEMP VOL	EFF VOL	SOIL VOL	RAIN VOL	TIME VOL			
REP	12	8	12	12	12			
SED	0.1671	0.2047	0.1671	0.1671	0.1671			

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	20	0.4094	40.2

Table A2.6 Statistical analysis of soil properties measured at the conclusion of the experiment.

***** ANALYSIS OF VARIANCE *****

A2.6a: SOIL BULK DENSITY

SOURCE OF VARIATION	DF	SS	SS%	MS	VR	F PR
UNITS STRATUM						
TEMP	1	0.026002	0.70	0.026002	3.403	0.075
EFF	3	0.005555	0.15	0.001852	0.242	0.866
REG1	1	0.000827	0.02	0.000827	0.108	0.745
DEVIATIONS	2	0.004728	0.13	0.002364	0.309	0.736
SOIL	1	3.181764	85.52	3.181764	416.396	<.001
RAIN	1	0.016577	0.45	0.016577	2.169	0.151
TIME	1	0.000127	0.00	0.000127	0.017	0.898
VOL	1	0.005077	0.14	0.005077	0.664	0.421
TEMP.EFF	3	0.020867	0.56	0.006956	0.910	0.448
DEV.REG1	1	0.014702	0.40	0.014702	1.924	0.176
DEVIATIONS	2	0.006166	0.17	0.003083	0.403	0.672
TEMP.SOIL	1	0.090752	2.44	0.090752	11.877	0.002
EFF.SOIL	3	0.010005	0.27	0.003335	0.436	0.729
REG1.DEV	1	0.004064	0.11	0.004064	0.532	0.471
DEVIATIONS	2	0.005941	0.16	0.002970	0.389	0.681
TEMP.RAIN	1	0.016577	0.45	0.016577	2.169	0.151
EFF.RAIN	3	0.024267	0.65	0.008089	1.059	0.381
REG1.DEV	1	0.015939	0.43	0.015939	2.086	0.159
DEVIATIONS	2	0.008328	0.22	0.004164	0.545	0.586
SOIL.RAIN	1	0.020664	0.56	0.020664	2.704	0.111
TEMP.TIME	1	0.008789	0.24	0.008789	1.150	0.292
EFF.TIME	3	0.027567	0.74	0.009189	1.203	0.326
REG1.DEV	1	0.007877	0.21	0.007877	1.031	0.318
DEVIATIONS	2	0.019691	0.53	0.009845	1.288	0.291
SOIL.TIME	1	0.003164	0.09	0.003164	0.414	0.525
RAIN.TIME	1	0.000000	0.00	0.000000	0.000	
TEMP.VOL	1	0.002139	0.06	0.002139	0.280	0.601
EFF.VOL	3	0.013692	0.37	0.004564	0.597	0.622
REG1.DEV	1	0.000189	0.01	0.000189	0.025	0.876
DEVIATIONS	2	0.013503	0.36	0.006752	0.884	0.424
SOIL.VOL	1	0.010252	0.28	0.010252	1.342	0.256
RAIN.VOL	1	0.000127	0.00	0.000127	0.017	0.898
TIME.VOL	1	0.007439	0.20	0.007439	0.974	0.332
RESIDUAL	30	0.229236	6.16	0.007641		
TOTAL	63	3.720636	100.00	0.059058		
GRAND TOTAL	63	3.720636	100.00			
GRAND MEAN		0.908				
TOTAL NUMBER OF OBSERVATIONS		64				

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR SOIL BULK DENSITY *****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP	TEMP
							EFF	EFF
SOIL								
REP	32	16	32	32	32	32	8	16
SED	0.0219	0.0309	0.0219	0.0219	0.0219	0.0219	0.0437	0.0309
TABLE	EFF	TEMP	EFF	SOIL	TEMP	EFF	SOIL	RAIN
	SOIL	RAIN	RAIN	RAIN	TIME	TIME	TIME	TIME
REP	8	16	8	16	16	8	16	16
SED	0.0437	0.0309	0.0437	0.0309	0.0309	0.0437	0.0309	0.0309
TABLE	TEMP	EFF	SOIL	RAIN	TIME			
	VOL	VOL	VOL	VOL	VOL			
REP	16	8	16	16	16			
SED	0.0309	0.0437	0.0309	0.0309	0.0309			

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	30	0.0874	9.6

Appendix 2: Data for Chapter 5

A2.6b: SOIL pH(H₂O)

SOURCE OF VARIATION	DF	SS	SS%	MS	VR	F	PR
UNITS STRATUM							
TEMP	1	3.90063	40.13	3.90063	256.479	<.001	
EFF	3	3.97125	40.86	1.32375	87.041	<.001	
REG1	1	0.25000	2.57	0.25000	16.438	<.001	
DEVIATIONS	2	3.72125	38.28	1.86063	122.342	<.001	
SOIL	1	0.10562	1.09	0.10562	6.945	0.013	
RAIN	1	0.04000	0.41	0.04000	2.630	0.115	
TIME	1	0.06250	0.64	0.06250	4.110	0.052	
VOL	1	0.07562	0.78	0.07562	4.973	0.033	
TEMP.EFF	3	0.35813	3.68	0.11938	7.849	<.001	
DEV.REG1	1	0.01563	0.16	0.01563	1.027	0.319	
DEVIATIONS	2	0.34250	3.52	0.17125	11.260	<.001	
TEMP.SOIL	1	0.02250	0.23	0.02250	1.479	0.233	
EFF.SOIL	3	0.07312	0.75	0.02437	1.603	0.209	
REG1.DEV	1	0.00062	0.01	0.00062	0.041	0.841	
DEVIATIONS	2	0.07250	0.75	0.03625	2.384	0.109	
TEMP.RAIN	1	0.00063	0.01	0.00063	0.041	0.841	
EFF.RAIN	3	0.01625	0.17	0.00542	0.356	0.785	
REG1.DEV	1	0.01000	0.10	0.01000	0.658	0.424	
DEVIATIONS	2	0.00625	0.06	0.00312	0.205	0.815	
SOIL.RAIN	1	0.03062	0.32	0.03062	2.014	0.166	
TEMP.TIME	1	0.01563	0.16	0.01563	1.027	0.319	
EFF.TIME	3	0.03625	0.37	0.01208	0.795	0.507	
REG1.DEV	1	0.00000	0.00	0.00000	0.000		
DEVIATIONS	2	0.03625	0.37	0.01812	1.192	0.318	
SOIL.TIME	1	0.00063	0.01	0.00063	0.041	0.841	
RAIN.TIME	1	0.00000	0.00	0.00000	0.000		
TEMP.VOL	1	0.00000	0.00	0.00000	0.000		
EFF.VOL	3	0.49813	5.12	0.16604	10.918	<.001	
REG1.DEV	1	0.00563	0.06	0.00563	0.370	0.548	
DEVIATIONS	2	0.49250	5.07	0.24625	16.192	<.001	
SOIL.VOL	1	0.04000	0.41	0.04000	2.630	0.115	
RAIN.VOL	1	0.01563	0.16	0.01563	1.027	0.319	
TIME.VOL	1	0.00063	0.01	0.00063	0.041	0.841	
RESIDUAL	30	0.45625	4.69	0.01521			
TOTAL	63	9.72000	100.00	0.15429			
GRAND TOTAL	63	9.72000	100.00				
GRAND MEAN	5.100						
TOTAL NUMBER OF OBSERVATIONS	64						

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR SOIL pH*****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP EFF	TEMP SOIL
REP	32	16	32	32	32	32	8	16
SED	0.0308	0.0436	0.0308	0.0308	0.0308	0.0308	0.0617	0.0436
TABLE	EFF SOIL	TEMP RAIN	EFF RAIN	SOIL RAIN	TEMP TIME	EFF TIME	SOIL TIME	RAIN TIME
REP	8	16	8	16	16	8	16	16
SED	0.0617	0.0436	0.0617	0.0436	0.0436	0.0617	0.0436	0.0436
TABLE	TEMP VOL	EFF VOL	SOIL VOL	RAIN VOL	TIME VOL			
REP	16	8	16	16	16			
SED	0.0436	0.0617	0.0436	0.0436	0.0436			

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	30	0.1233	2.4

Appendix 2: Data for Chapter 5

A2.6c: SOIL pH_{calc1}

SOURCE OF VARIATION	DF	SS	SS%	MS	VR	F	PR
UNITS STRATUM							
TEMP	1	8.122500	83.87	8.122500	906.697	<.001	
EFF	3	0.783125	8.09	0.261042	29.140	<.001	
REG1	1	0.160000	1.65	0.160000	17.860	<.001	
DEVIATIONS	2	0.623125	6.43	0.311563	34.779	<.001	
SOIL	1	0.002500	0.03	0.002500	0.279	0.601	
RAIN	1	0.015625	0.16	0.015625	1.744	0.197	
TIME	1	0.002500	0.03	0.002500	0.279	0.601	
VOL	1	0.002500	0.03	0.002500	0.279	0.601	
TEMP.EFF	3	0.071250	0.74	0.023750	2.651	0.067	
DEV.REG1	1	0.030625	0.32	0.030625	3.419	0.074	
DEVIATIONS	2	0.040625	0.42	0.020312	2.267	0.121	
TEMP.SOIL	1	0.000625	0.01	0.000625	0.070	0.793	
EFF.SOIL	3	0.033750	0.35	0.011250	1.256	0.307	
REG1.DEV	1	0.015625	0.16	0.015625	1.744	0.197	
DEVIATIONS	2	0.018125	0.19	0.009062	1.012	0.376	
TEMP.RAIN	1	0.002500	0.03	0.002500	0.279	0.601	
EFF.RAIN	3	0.013125	0.14	0.004375	0.488	0.693	
REG1.DEV	1	0.002500	0.03	0.002500	0.279	0.601	
DEVIATIONS	2	0.010625	0.11	0.005313	0.593	0.559	
SOIL.RAIN	1	0.040000	0.41	0.040000	4.465	0.043	
TEMP.TIME	1	0.000625	0.01	0.000625	0.070	0.793	
EFF.TIME	3	0.051250	0.53	0.017083	1.907	0.150	
REG1.DEV	1	0.005625	0.06	0.005625	0.628	0.434	
DEVIATIONS	2	0.045625	0.47	0.022812	2.547	0.095	
SOIL.TIME	1	0.005625	0.06	0.005625	0.628	0.434	
RAIN.TIME	1	0.002500	0.03	0.002500	0.279	0.601	
TEMP.VOL	1	0.005625	0.06	0.005625	0.628	0.434	
EFF.VOL	3	0.248750	2.57	0.082917	9.256	<.001	
REG1.DEV	1	0.030625	0.32	0.030625	3.419	0.074	
DEVIATIONS	2	0.218125	2.25	0.109063	12.174	<.001	
SOIL.VOL	1	0.000625	0.01	0.000625	0.070	0.793	
RAIN.VOL	1	0.010000	0.10	0.010000	1.116	0.299	
TIME.VOL	1	0.000625	0.01	0.000625	0.070	0.793	
RESIDUAL	30	0.268750	2.78	0.008958			
TOTAL	63	9.684371	100.00	0.153720			
GRAND TOTAL	63	9.684371	100.00				
GRAND MEAN		4.384					
TOTAL NUMBER OF OBSERVATIONS		64					

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR SOIL pH_{calc12} *****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP EFF	TEMP SOIL
REP	32	16	32	32	32	32	8	16
SED	0.0237	0.0335	0.0237	0.0237	0.0237	0.0237	0.0473	0.0335
TABLE	EFF SOIL	TEMP RAIN	EFF RAIN	SOIL RAIN	TEMP TIME	EFF TIME	SOIL TIME	RAIN TIME
REP	8	16	8	16	16	8	16	16
SED	0.0473	0.0335	0.0473	0.0335	0.0335	0.0473	0.0335	0.0335
TABLE	TEMP VOL	EFF VOL	SOIL VOL	RAIN VOL	TIME VOL			
REP	16	8	16	16	16			
SED	0.0335	0.0473	0.0335	0.0335	0.0335			

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	30	0.0946	2.2

A2.6d: SOIL ELECTRICAL CONDUCTIVITY

SOURCE OF VARIATION	DF	SS	SS%	MS	VR	F PR
UNITS STRATUM						
TEMP	1	400	0.07	400	0.156	0.695
EFF	3	363188	59.08	121063	47.305	<.001
REG1	1	51756	8.42	51756	20.224	<.001
DEVIATIONS	2	311431	50.66	155716	60.846	<.001
SOIL	1	33306	5.42	33306	13.014	0.001
RAIN	1	900	0.15	900	0.352	0.558
TIME	1	25	0.00	25	0.010	0.922
VOL	1	60025	9.76	60025	23.455	<.001
TEMP.EFF	3	9638	1.57	3213	1.255	0.307
DEV.REG1	1	1056	0.17	1056	0.413	0.525
DEVIATIONS	2	8581	1.40	4291	1.677	0.204
TEMP.SOIL	1	156	0.03	156	0.061	0.807
EFF.SOIL	3	5931	0.96	1977	0.773	0.518
REG1.DEV	1	5625	0.91	5625	2.198	0.149
DEVIATIONS	2	306	0.05	153	0.060	0.942
TEMP.RAIN	1	2500	0.41	2500	0.977	0.331
EFF.RAIN	3	1563	0.25	521	0.204	0.893
REG1.DEV	1	56	0.01	56	0.022	0.883
DEVIATIONS	2	1506	0.25	753	0.294	0.747
SOIL.RAIN	1	506	0.08	506	0.198	0.660
TEMP.TIME	1	900	0.15	900	0.352	0.558
EFF.TIME	3	5938	0.97	1979	0.773	0.518
REG1.DEV	1	3906	0.64	3906	1.526	0.226
DEVIATIONS	2	2031	0.33	1016	0.397	0.676
SOIL.TIME	1	2256	0.37	2256	0.882	0.355
RAIN.TIME	1	25	0.00	25	0.010	0.922
TEMP.VOL	1	100	0.02	100	0.039	0.845
EFF.VOL	3	30638	4.98	10213	3.991	0.017
REG1.DEV	1	1056	0.17	1056	0.413	0.525
DEVIATIONS	2	29581	4.81	14791	5.779	0.008
SOIL.VOL	1	11556	1.88	11556	4.516	0.042
RAIN.VOL	1	1225	0.20	1225	0.479	0.494
TIME.VOL	1	7225	1.18	7225	2.823	0.103
RESIDUAL	30	76775	12.49	2559		
TOTAL	63	614775	100.00	9758		
GRAND TOTAL	63	614775	100.00			
GRAND MEAN		189.4				
TOTAL NUMBER OF OBSERVATIONS		64				

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR SOIL ELECTRICAL CONDUCTIVITY

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP EFF	TEMP SOIL
REP	32	16	32	32	32	32	8	16
SED	12.65	17.89	12.65	12.65	12.65	12.65	25.29	17.89
TABLE	EFF	TEMP	EFF	SOIL	TEMP	EFF	SOIL	RAIN
	SOIL	RAIN	RAIN	RAIN	TIME	TIME	TIME	TIME
REP	8	16	8	16	16	8	16	16
SED	25.29	17.89	25.29	17.89	17.89	25.29	17.89	17.89
TABLE	TEMP	EFF	SOIL	RAIN	TIME			
	VOL	VOL	VOL	VOL	VOL			
REP	16	8	16	16	16			
SED	17.89	25.29	17.89	17.89	17.89			

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	30	50.59	26.7

Appendix 2: Data for Chapter 5

A2.6e: Soil Carbon ‡

SOURCE OF VARIATION	DF	SS	SS‡	MS	VR	F PR
UNITS STRATUM						
TEMP	1	0.7877	3.14	0.7877	4.433	0.044
EFF	3	1.3167	5.25	0.4389	2.470	0.081
REG1	1	0.0452	0.18	0.0452	0.254	0.618
DEVIATIONS	2	1.2716	5.07	0.6358	3.578	0.040
SOIL	1	6.5664	26.19	6.5664	36.953	<.001
RAIN	1	0.1914	0.76	0.1914	1.077	0.308
TIME	1	0.1914	0.76	0.1914	1.077	0.308
VOL	1	0.4389	1.75	0.4389	2.470	0.127
TEMP.EFF	3	2.6242	10.47	0.8747	4.923	0.007
DEV.REG1	1	0.0689	0.27	0.0689	0.388	0.538
DEVIATIONS	2	2.5553	10.19	1.2777	7.190	0.003
TEMP.SOIL	1	1.2377	4.94	1.2377	6.965	0.013
EFF.SOIL	3	0.1380	0.55	0.0460	0.259	0.854
REG1.DEV	1	0.0564	0.22	0.0564	0.317	0.577
DEVIATIONS	2	0.0816	0.33	0.0408	0.229	0.796
TEMP.RAIN	1	0.2139	0.85	0.2139	1.204	0.281
EFF.RAIN	3	0.2330	0.93	0.0777	0.437	0.728
REG1.DEV	1	0.0827	0.33	0.0827	0.465	0.500
DEVIATIONS	2	0.1503	0.60	0.0752	0.423	0.659
SOIL.RAIN	1	0.0564	0.22	0.0564	0.317	0.577
TEMP.TIME	1	0.0189	0.08	0.0189	0.106	0.747
EFF.TIME	3	0.2755	1.10	0.0918	0.517	0.674
REG1.DEV	1	0.1702	0.68	0.1702	0.958	0.336
DEVIATIONS	2	0.1053	0.42	0.0527	0.296	0.746
SOIL.TIME	1	0.0127	0.05	0.0127	0.071	0.791
RAIN.TIME	1	0.1914	0.76	0.1914	1.077	0.308
TEMP.VOL	1	0.0452	0.18	0.0452	0.254	0.618
EFF.VOL	3	1.1680	4.66	0.3893	2.191	0.110
REG1.DEV	1	1.1289	4.50	1.1289	6.353	0.017
DEVIATIONS	2	0.0391	0.16	0.0195	0.110	0.896
SOIL.VOL	1	3.0189	12.04	3.0189	16.989	<.001
RAIN.VOL	1	0.3164	1.26	0.3164	1.781	0.192
TIME.VOL	1	0.7014	2.80	0.7014	3.947	0.056
RESIDUAL	30	5.3309	21.26	0.1777		
TOTAL	63	25.0748	100.00	0.3980		
GRAND TOTAL	63	25.0748	100.00			
GRAND MEAN		6.977				
TOTAL NUMBER OF OBSERVATIONS		64				

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR SOIL C ‡ *****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP EFF	TEMP SOIL
REP	32	16	32	32	32	32	8	16
SED	0.1054	0.1490	0.1054	0.1054	0.1054	0.1054	0.2108	0.1490
TABLE	EFF SOIL	TEMP RAIN	EFF RAIN	SOIL RAIN	TEMP TIME	EFF TIME	SOIL TIME	RAIN TIME
REP	8	16	8	16	16	8	16	16
SED	0.2108	0.1490	0.2108	0.1490	0.1490	0.2108	0.1490	0.1490
TABLE	TEMP VOL	EFF VOL	SOIL VOL	RAIN VOL	TIME VOL			
REP	16	8	16	16	16			
SED	0.1490	0.2108	0.1490	0.1490	0.1490			

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV‡
UNITS	30	0.4215	6.0

A2.6f: AGGREGATE STABILITY

SOURCE OF VARIATION	DF (MV)	SS	SS%	MS	VR	F PR
UNITS STRATUM						
TEMP	1	28.30	3.28	28.30	2.440	0.130
EFF	3	87.14	10.09	29.05	2.505	0.081
REG1	1	0.48	0.06	0.48	0.041	0.841
DEVIATIONS	2	86.67	10.04	43.33	3.737	0.037
SOIL	1	132.60	15.36	132.60	11.434	0.002
RAIN	1	3.04	0.35	3.04	0.262	0.613
TIME	1	1.79	0.21	1.79	0.154	0.698
VOL	1	2.82	0.33	2.82	0.243	0.626
TEMP.EFF	3	133.68	15.49	44.56	3.842	0.021
DEV.REG1	1	125.00	14.48	125.00	10.778	0.003
DEVIATIONS	2	8.69	1.01	4.34	0.375	0.691
TEMP.SOIL	1	2.16	0.25	2.16	0.186	0.669
EFF.SOIL	3	7.86	0.91	2.62	0.226	0.878
REG1.DEV	1	1.03	0.12	1.03	0.089	0.768
DEVIATIONS	2	6.83	0.79	3.41	0.294	0.747
TEMP.RAIN	1	3.12	0.36	3.12	0.269	0.609
EFF.RAIN	3	49.49	5.73	16.50	1.423	0.259
REG1.DEV	1	5.09	0.59	5.09	0.439	0.514
DEVIATIONS	2	44.41	5.14	22.20	1.915	0.168
SOIL.RAIN	1	29.49	3.42	29.49	2.543	0.123
TEMP.TIME	1	11.20	1.30	11.20	0.965	0.335
EFF.TIME	3	53.81	6.23	17.94	1.547	0.226
REG1.DEV	1	0.70	0.08	0.70	0.060	0.808
DEVIATIONS	2	53.11	6.15	26.56	2.290	0.121
SOIL.TIME	1	17.32	2.01	17.32	1.494	0.233
RAIN.TIME	1	20.96	2.43	20.96	1.808	0.190
TEMP.VOL	1	10.96	1.27	10.96	0.945	0.340
EFF.VOL	3	28.60	3.31	9.53	0.822	0.494
REG1.DEV	1	21.90	2.54	21.90	1.889	0.181
DEVIATIONS	2	6.70	0.78	3.35	0.289	0.752
SOIL.VOL	1	16.04	1.86	16.04	1.383	0.250
RAIN.VOL	1	10.66	1.23	10.66	0.919	0.346
TIME.VOL	1	34.18	3.96	34.18	2.947	0.098
RESIDUAL	26 (4)	301.52	34.93	11.60		
TOTAL	59	986.75	114.31	16.72		
GRAND TOTAL	59	986.75	114.31			

ESTIMATED GRAND MEAN 85.46
TOTAL NUMBER OF OBSERVATIONS 64
NUMBER OF MISSING VALUES 4
MAXIMUM NUMBER OF ITERATIONS 7

UNIT	ESTIMATED
NUMBER	VALUE
3	95.41
16	87.37
17	88.70
35	83.04

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR SOIL AGGREGATE STABILITY*****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP EFF	TEMP SOIL
REP	32	16	32	32	32	32	8	16
SED	0.851	1.204	0.851	0.851	0.851	0.851	1.703	1.204
TABLE	EFF SOIL	TEMP RAIN	EFF RAIN	SOIL RAIN	TEMP TIME	EFF TIME	SOIL TIME	RAIN TIME
REP	8	16	8	16	16	8	16	16
SED	1.703	1.204	1.703	1.204	1.204	1.703	1.204	1.204
TABLE	TEMP VOL	EFF VOL	SOIL VOL	RAIN VOL	TIME VOL			
REP	16	8	16	16	16			
SED	1.204	1.703	1.204	1.204	1.204			

(NOT ADJUSTED FOR MISSING VALUES)

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	26	3.405	4.0

Appendix 2: Data for Chapter 5

A2.6g: Core surface crust two days after effluent application stopped

SOURCE OF VARIATION	DF(MV)	SS	SS%	MS	VR	F PR
UNITS STRATUM						
TEMP	1	0.0540	0.05	0.0540	0.154	0.698
EFF	3	56.2576	53.36	18.7525	53.386	<.001
REG1	1	2.9006	2.75	2.9006	8.258	0.008
DEVIATIONS	2	53.3570	50.61	26.6785	75.950	<.001
SOIL	1	0.0540	0.05	0.0540	0.154	0.698
RAIN	1	0.0000	0.00	0.0000	0.000	
TIME	1	6.0178	5.71	6.0178	17.132	<.001
VOL	1	17.6663	16.76	17.6663	50.293	<.001
TEMP.EFF	3	1.4519	1.38	0.4840	1.378	0.270
DEV.REG1	1	0.2678	0.25	0.2678	0.763	0.390
DEVIATIONS	2	1.1841	1.12	0.5920	1.685	0.204
TEMP.SOIL	1	0.2991	0.28	0.2991	0.851	0.364
EFF.SOIL	3	0.3875	0.37	0.1292	0.368	0.777
REG1.DEV	1	0.0000	0.00	0.0000	0.000	
DEVIATIONS	2	0.3875	0.37	0.1938	0.552	0.582
TEMP.RAIN	1	0.0616	0.06	0.0616	0.175	0.679
EFF.RAIN	3	0.1619	0.15	0.0540	0.154	0.926
REG1.DEV	1	0.0716	0.07	0.0716	0.204	0.655
DEVIATIONS	2	0.0903	0.09	0.0452	0.129	0.880
SOIL.RAIN	1	0.0881	0.08	0.0881	0.251	0.620
TEMP.TIME	1	0.0540	0.05	0.0540	0.154	0.698
EFF.TIME	3	2.0487	1.94	0.6829	1.944	0.145
REG1.DEV	1	0.4944	0.47	0.4944	1.407	0.245
DEVIATIONS	2	1.5543	1.47	0.7772	2.213	0.128
SOIL.TIME	1	0.0716	0.07	0.0716	0.204	0.655
RAIN.TIME	1	0.0186	0.02	0.0186	0.053	0.820
TEMP.VOL	1	1.0354	0.98	1.0354	2.948	0.097
EFF.VOL	3	8.3748	7.94	2.7916	7.947	<.001
REG1.DEV	1	6.0178	5.71	6.0178	17.132	<.001
DEVIATIONS	2	2.3570	2.24	1.1785	3.355	0.049
SOIL.VOL	1	0.2678	0.25	0.2678	0.763	0.390
RAIN.VOL	1	0.0716	0.07	0.0716	0.204	0.655
TIME.VOL	1	3.2288	3.06	3.2288	9.192	0.005
RESIDUAL	28 (2)	9.8354	9.33	0.3513		
TOTAL	61	107.5066	101.96	1.7624		
GRAND TOTAL	61	107.5066	101.96			
ESTIMATED GRAND MEAN	1.494					
TOTAL NUMBER OF OBSERVATIONS	64					
NUMBER OF MISSING VALUES	2					
MAXIMUM NUMBER OF ITERATIONS	4					

UNIT	ESTIMATED
NUMBER	VALUE
10	1.742
54	2.883

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR SOIL CRUST 2 DAYS AFTER END OF EFFLUENT APPLICATION*****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP EFF	TEMP SOIL
REP	32	16	32	32	32	32	8	16
SED	0.1482	0.2095	0.1482	0.1482	0.1482	0.1482	0.2963	0.2095
TABLE	EFF SOIL	TEMP RAIN	EFF RAIN	SOIL RAIN	TEMP TIME	EFF TIME	SOIL TIME	RAIN TIME
REP	8	16	8	16	16	8	16	16
SED	0.2963	0.2095	0.2963	0.2095	0.2095	0.2963	0.2095	0.2095
TABLE	TEMP VOL	EFF VOL	SOIL VOL	RAIN VOL	TIME VOL			
REP	16	8	16	16	16			
SED	0.2095	0.2963	0.2095	0.2095	0.2095			

(NOT ADJUSTED FOR MISSING VALUES)

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	28	0.5927	39.7

Appendix 2: Data for Chapter 5

A2.6h: Soil surface crust 13 days after effluent application was stopped

SOURCE OF VARIATION	DF	SS	SS%	MS	VR	F PR
UNITS STRATUM						
TEMP	1	0.2500	0.28	0.2500	0.638	0.431
EFF	3	50.7500	57.83	16.9167	43.191	<.001
REG1	1	0.2500	0.28	0.2500	0.638	0.431
DEVIATIONS	2	50.5000	57.55	25.2500	64.468	<.001
SOIL	1	0.2500	0.28	0.2500	0.638	0.431
RAIN	1	1.0000	1.14	1.0000	2.553	0.121
TIME	1	4.0000	4.56	4.0000	10.213	0.003
VOL	1	9.0000	10.26	9.0000	22.979	<.001
TEMP.EFF	3	1.2500	1.42	0.4167	1.064	0.379
DEV.REG1	1	0.0000	0.00	0.0000	0.000	
DEVIATIONS	2	1.2500	1.42	0.6250	1.596	0.219
TEMP.SOIL	1	0.2500	0.28	0.2500	0.638	0.431
EFF.SOIL	3	0.2500	0.28	0.0833	0.213	0.887
REG1.DEV	1	0.0000	0.00	0.0000	0.000	
DEVIATIONS	2	0.2500	0.28	0.1250	0.319	0.729
TEMP.RAIN	1	0.2500	0.28	0.2500	0.638	0.431
EFF.RAIN	3	0.5000	0.57	0.1667	0.426	0.736
REG1.DEV	1	0.2500	0.28	0.2500	0.638	0.431
DEVIATIONS	2	0.2500	0.28	0.1250	0.319	0.729
SOIL.RAIN	1	0.2500	0.28	0.2500	0.638	0.431
TEMP.TIME	1	0.0000	0.00	0.0000	0.000	
EFF.TIME	3	1.5000	1.71	0.5000	1.277	0.300
REG1.DEV	1	0.2500	0.28	0.2500	0.638	0.431
DEVIATIONS	2	1.2500	1.42	0.6250	1.596	0.219
SOIL.TIME	1	0.0000	0.00	0.0000	0.000	
RAIN.TIME	1	0.0000	0.00	0.0000	0.000	
TEMP.VOL	1	1.0000	1.14	1.0000	2.553	0.121
EFF.VOL	3	3.0000	3.42	1.0000	2.553	0.074
REG1.DEV	1	1.0000	1.14	1.0000	2.553	0.121
DEVIATIONS	2	2.0000	2.28	1.0000	2.553	0.095
SOIL.VOL	1	0.2500	0.28	0.2500	0.638	0.431
RAIN.VOL	1	0.0000	0.00	0.0000	0.000	
TIME.VOL	1	2.2500	2.56	2.2500	5.745	0.023
RESIDUAL	30	11.7500	13.39	0.3917		
TOTAL	63	87.7500	100.00	1.3929		
GRAND TOTAL	63	87.7500	100.00			
GRAND MEAN		1.188				
TOTAL NUMBER OF OBSERVATIONS		64				

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR SOIL CRUSTS 13 DAYS AFTER EFFLUENT APPLICATION *****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP EFF	TEMP SOIL
REP	32	16	32	32	32	32	8	16
SED	0.1565	0.2213	0.1565	0.1565	0.1565	0.1565	0.3129	0.2213
TABLE	EFF SOIL	TEMP RAIN	EFF RAIN	SOIL RAIN	TEMP TIME	EFF TIME	SOIL TIME	RAIN TIME
REP	8	16	8	16	16	8	16	16
SED	0.3129	0.2213	0.3129	0.2213	0.2213	0.3129	0.2213	0.2213
TABLE	TEMP VOL	EFF VOL	SOIL VOL	RAIN VOL	TIME VOL			
REP	16	8	16	16	16			
SED	0.2213	0.3129	0.2213	0.2213	0.2213			

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	30	0.6258	52.7

Appendix 2: Data for Chapter 5

A2.61: Soil surface crust 35 days after effluent application was stopped

SOURCE OF VARIATION	DF(MV)	SS	SS%	MS	VR	F	PR
UNITS STRATUM							
TEMP	1	0.0000	0.00	0.0000	0.000		
EFF	3	41.3793	55.68	13.7931	38.585	<.001	
REG1	1	0.0544	0.07	0.0544	0.152	0.699	
DEVIATIONS	2	41.3249	55.61	20.6624	57.802	<.001	
SOIL	1	0.9669	1.30	0.9669	2.705	0.111	
RAIN	1	0.2670	0.36	0.2670	0.747	0.395	
TIME	1	1.6045	2.16	1.6045	4.489	0.043	
VOL	1	9.1005	12.25	9.1005	25.458	<.001	
TEMP.EFF	3	0.5076	0.68	0.1692	0.473	0.703	
DEV.REG1	1	0.2336	0.31	0.2336	0.653	0.425	
DEVIATIONS	2	0.2741	0.37	0.1370	0.383	0.685	
TEMP.SOIL	1	0.0711	0.10	0.0711	0.199	0.659	
EFF.SOIL	3	2.0008	2.69	0.6669	1.866	0.157	
REG1.DEV	1	0.0000	0.00	0.0000	0.000		
DEVIATIONS	2	2.0008	2.69	1.0004	2.799	0.077	
TEMP.RAIN	1	1.5210	2.05	1.5210	4.255	0.048	
EFF.RAIN	3	0.2341	0.32	0.0780	0.218	0.883	
REG1.DEV	1	0.2336	0.31	0.2336	0.653	0.425	
DEVIATIONS	2	0.0006	0.00	0.0003	0.001	0.999	
SOIL.RAIN	1	0.5377	0.72	0.5377	1.504	0.230	
TEMP.TIME	1	0.2336	0.31	0.2336	0.653	0.425	
EFF.TIME	3	1.2468	1.68	0.4156	1.163	0.341	
REG1.DEV	1	0.0711	0.10	0.0711	0.199	0.659	
DEVIATIONS	2	1.1757	1.58	0.5878	1.644	0.211	
SOIL.TIME	1	0.9669	1.30	0.9669	2.705	0.111	
RAIN.TIME	1	0.0032	0.00	0.0032	0.009	0.925	
TEMP.VOL	1	0.0544	0.07	0.0544	0.152	0.699	
EFF.VOL	3	2.0677	2.78	0.6892	1.928	0.147	
REG1.DEV	1	0.0000	0.00	0.0000	0.000		
DEVIATIONS	2	2.0677	2.78	1.0338	2.892	0.072	
SOIL.VOL	1	0.5377	0.72	0.5377	1.504	0.230	
RAIN.VOL	1	0.0544	0.07	0.0544	0.152	0.699	
TIME.VOL	1	1.0337	1.39	1.0337	2.892	0.100	
RESIDUAL	29 (1)	10.3667	13.95	0.3575			
TOTAL	62	74.7558	100.59	1.2057			
GRAND TOTAL	62	74.7558	100.59				
ESTIMATED GRAND MEAN	1.217						
TOTAL NUMBER OF OBSERVATIONS	64						
NUMBER OF MISSING VALUES	1						
MAXIMUM NUMBER OF ITERATIONS	4						
UNIT	ESTIMATED						
NUMBER	VALUE						
14	1.866						

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR SOIL CRUST 35 DAYS AFTER END OF EFFLUENT APPLICATION *****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP EFF	TEMP SOIL
REP	32	16	32	32	32	32	8	16
SED	0.1495	0.2114	0.1495	0.1495	0.1495	0.1495	0.2989	0.2114
TABLE	EFF SOIL	TEMP RAIN	EFF RAIN	SOIL RAIN	TEMP TIME	EFF TIME	SOIL TIME	RAIN TIME
REP	8	16	8	16	16	8	16	16
SED	0.2989	0.2114	0.2989	0.2114	0.2114	0.2989	0.2114	0.2114
TABLE	TEMP VOL	EFF VOL	SOIL VOL	RAIN VOL	TIME VOL			
REP	16	8	16	16	16			
SED	0.2114	0.2989	0.2114	0.2114	0.2114			

(NOT ADJUSTED FOR MISSING VALUES)

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	29	0.5979	49.1

Table A2.7 Statistical analysis of core leachate

***** ANALYSIS OF VARIANCE *****

2.7a: Core leachate pH

SOURCE OF VARIATION	DF	SS	SS%	MS	VR	F PR
UNITS STRATUM						
TEMP	1	4.95062	41.00	4.95062	85.478	<.001
EFF	3	2.57188	21.30	0.85729	14.802	<.001
REG1	1	0.76562	6.34	0.76562	13.219	0.001
DEVIATIONS	2	1.80625	14.96	0.90313	15.594	<.001
SOIL	1	0.18063	1.50	0.18063	3.119	0.088
RAIN	1	0.00250	0.02	0.00250	0.043	0.837
TIME	1	0.05062	0.42	0.05062	0.874	0.357
VOL	1	0.01000	0.08	0.01000	0.173	0.681
TEMP.EFF	3	0.23188	1.92	0.07729	1.335	0.282
DEV.REG1	1	0.07563	0.63	0.07563	1.306	0.262
DEVIATIONS	2	0.15625	1.29	0.07812	1.349	0.275
TEMP.SOIL	1	0.85562	7.09	0.85562	14.773	<.001
EFF.SOIL	3	0.03188	0.26	0.01063	0.183	0.907
REG1.DEV	1	0.00062	0.01	0.00062	0.011	0.918
DEVIATIONS	2	0.03125	0.26	0.01563	0.270	0.765
TEMP.RAIN	1	0.00250	0.02	0.00250	0.043	0.837
EFF.RAIN	3	0.02750	0.23	0.00917	0.158	0.924
REG1.DEV	1	0.00250	0.02	0.00250	0.043	0.837
DEVIATIONS	2	0.02500	0.21	0.01250	0.216	0.807
SOIL.RAIN	1	0.00250	0.02	0.00250	0.043	0.837
TEMP.TIME	1	0.03063	0.25	0.03063	0.529	0.473
EFF.TIME	3	0.13688	1.13	0.04563	0.788	0.510
REG1.DEV	1	0.10562	0.87	0.10562	1.824	0.187
DEVIATIONS	2	0.03125	0.26	0.01563	0.270	0.765
SOIL.TIME	1	0.00562	0.05	0.00562	0.097	0.757
RAIN.TIME	1	0.00250	0.02	0.00250	0.043	0.837
TEMP.VOL	1	0.42250	3.50	0.42250	7.295	0.011
EFF.VOL	3	0.46500	3.85	0.15500	2.676	0.065
REG1.DEV	1	0.12250	1.01	0.12250	2.115	0.156
DEVIATIONS	2	0.34250	2.84	0.17125	2.957	0.067
SOIL.VOL	1	0.04000	0.33	0.04000	0.691	0.413
RAIN.VOL	1	0.22563	1.87	0.22563	3.896	0.058
TIME.VOL	1	0.09000	0.75	0.09000	1.554	0.222
RESIDUAL	30	1.73750	14.39	0.05792		
TOTAL	63	12.07438	100.00	0.19166		
GRAND TOTAL	63	12.07438	100.00			
GRAND MEAN		6.791				
TOTAL NUMBER OF OBSERVATIONS		64				

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR EFFLUENT OUTFLOW pH*****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP EFF	TEMP SOIL
REP	32	16	32	32	32	32	8	16
SED	0.0602	0.0851	0.0602	0.0602	0.0602	0.0602	0.1203	0.0851
TABLE	EFF SOIL	TEMP RAIN	EFF RAIN	SOIL RAIN	TEMP TIME	EFF TIME	SOIL TIME	RAIN TIME
REP	8	16	8	16	16	8	16	16
SED	0.1203	0.0851	0.1203	0.0851	0.0851	0.1203	0.0851	0.0851
TABLE	TEMP VOL	EFF VOL	SOIL VOL	RAIN VOL	TIME VOL			
REP	16	8	16	16	16			
SED	0.0851	0.1203	0.0851	0.0851	0.0851			

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	30	0.2407	3.5

Appendix 2: Data for Chapter 5

2.7b: Core Leachate Electrical Conductivity

SOURCE OF VARIATION	DF	SS	SS%	MS	VR	F PR
UNITS STRATUM						
TEMP	1	3534400	15.32	3534400	47.603	<.001
EFF	3	13760306	59.63	4586769	61.777	<.001
REG1	1	3851406	16.69	3851406	51.872	<.001
DEVIATIONS	2	9908900	42.94	4954450	66.729	<.001
SOIL	1	2256	0.01	2256	0.030	0.863
RAIN	1	84100	0.36	84100	1.133	0.296
TIME	1	9025	0.04	9025	0.122	0.730
VOL	1	566256	2.45	566256	7.627	0.010
TEMP.EFF	3	1489788	6.46	496596	6.688	0.001
DEV.REG1	1	616225	2.67	616225	8.300	0.007
DEVIATIONS	2	873563	3.79	436781	5.883	0.007
TEMP.SOIL	1	25600	0.11	25600	0.345	0.561
EFF.SOIL	3	78331	0.34	26110	0.352	0.788
REG1.DEV	1	66306	0.29	66306	0.893	0.352
DEVIATIONS	2	12025	0.05	6013	0.081	0.922
TEMP.RAIN	1	339306	1.47	339306	4.570	0.041
EFF.RAIN	3	78488	0.34	26163	0.352	0.788
REG1.DEV	1	42025	0.18	42025	0.566	0.458
DEVIATIONS	2	36463	0.16	18231	0.246	0.784
SOIL.RAIN	1	1600	0.01	1600	0.022	0.884
TEMP.TIME	1	0	0.00	0	0.000	
EFF.TIME	3	116213	0.50	38738	0.522	0.671
REG1.DEV	1	900	0.00	900	0.012	0.913
DEVIATIONS	2	115313	0.50	57656	0.777	0.469
SOIL.TIME	1	21025	0.09	21025	0.283	0.599
RAIN.TIME	1	43056	0.19	43056	0.580	0.452
TEMP.VOL	1	2500	0.01	2500	0.034	0.856
EFF.VOL	3	457256	1.98	152419	2.053	0.128
REG1.DEV	1	138756	0.60	138756	1.869	0.182
DEVIATIONS	2	318500	1.38	159250	2.145	0.135
SOIL.VOL	1	127806	0.55	127806	1.721	0.199
RAIN.VOL	1	78400	0.34	78400	1.056	0.312
TIME.VOL	1	32400	0.14	32400	0.436	0.514
RESIDUAL	30	2227431	9.65	74248		
TOTAL	63	23075546	100.00	366279		
GRAND TOTAL	63	23075546	100.00			
GRAND MEAN	959					
TOTAL NUMBER OF OBSERVATIONS	64					

***** STANDARD ERRORS OF DIFFERENCES OF MEANS *****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP EFF	TEMP SOIL
REP	32	16	32	32	32	32	8	16
SED	68.1	96.3	68.1	68.1	68.1	68.1	136.2	96.3
TABLE	EFF SOIL	TEMP RAIN	EFF RAIN	SOIL RAIN	TEMP TIME	EFF TIME	SOIL TIME	RAIN TIME
REP	8	16	8	16	16	8	16	16
SED	136.2	96.3	136.2	96.3	96.3	136.2	96.3	96.3
TABLE	TEMP VOL	EFF VOL	SOIL VOL	RAIN VOL	TIME VOL			
REP	16	8	16	16	16			
SED	96.3	136.2	96.3	96.3	96.3			

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	30	272.5	28.4

Appendix 2: Data for Chapter 5

A2.7c: Core leachate Total Solids content

SOURCE OF VARIATION	DF	SS	SS%	MS	VR	F PR
UNITS STRATUM						
TEMP	1	2102500	14.81	2102500	79.340	<.001
EFF	3	7690000	54.16	2563333	96.730	<.001
REG1	1	3240000	22.82	3240000	122.264	<.001
DEVIATIONS	2	4450000	31.34	2225000	83.962	<.001
SOIL	1	10000	0.07	10000	0.377	0.544
RAIN	1	10000	0.07	10000	0.377	0.544
TIME	1	62500	0.44	62500	2.358	0.135
VOL	1	810000	5.71	810000	30.566	<.001
TEMP.EFF	3	1250000	8.80	416667	15.723	<.001
DEV.REG1	1	640000	4.51	640000	24.151	<.001
DEVIATIONS	2	610000	4.30	305000	11.509	<.001
TEMP.SOIL	1	160000	1.13	160000	6.038	0.020
EFF.SOIL	3	62500	0.44	20833	0.786	0.511
REG1.DEV	1	0	0.00	0	0.000	
DEVIATIONS	2	62500	0.44	31250	1.179	0.321
TEMP.RAIN	1	90000	0.63	90000	3.396	0.075
EFF.RAIN	3	102500	0.72	34167	1.289	0.296
REG1.DEV	1	22500	0.16	22500	0.849	0.364
DEVIATIONS	2	80000	0.56	40000	1.509	0.237
SOIL.RAIN	1	22500	0.16	22500	0.849	0.364
TEMP.TIME	1	0	0.00	0	0.000	
EFF.TIME	3	95000	0.67	31667	1.195	0.328
REG1.DEV	1	10000	0.07	10000	0.377	0.544
DEVIATIONS	2	85000	0.60	42500	1.604	0.218
SOIL.TIME	1	2500	0.02	2500	0.094	0.761
RAIN.TIME	1	0	0.00	0	0.000	
TEMP.VOL	1	2500	0.02	2500	0.094	0.761
EFF.VOL	3	707500	4.98	235833	8.899	<.001
REG1.DEV	1	122500	0.86	122500	4.623	0.040
DEVIATIONS	2	585000	4.12	292500	11.038	<.001
SOIL.VOL	1	160000	1.13	160000	6.038	0.020
RAIN.VOL	1	40000	0.28	40000	1.509	0.229
TIME.VOL	1	22500	0.16	22500	0.849	0.364
RESIDUAL	30	795000	5.60	26500		
TOTAL	63	14197500	100.00	225357		
GRAND TOTAL	63	14197500	100.00			
GRAND MEAN	731					
TOTAL NUMBER OF OBSERVATIONS	64					

***** STANDARD ERRORS OF DIFFERENCES OF MEANS FOR EFFLUENT OUTFLOW TOTAL SOLIDS *****

TABLE	TEMP	EFF	SOIL	RAIN	TIME	VOL	TEMP EFF	TEMP SOIL
REP	32	16	32	32	32	32	8	16
SED	40.7	57.6	40.7	40.7	40.7	40.7	81.4	57.6
TABLE	EFF SOIL	TEMP RAIN	EFF RAIN	SOIL RAIN	TEMP TIME	EFF TIME	SOIL TIME	RAIN TIME
REP	8	16	8	16	16	8	16	16
SED	81.4	57.6	81.4	57.6	57.6	81.4	57.6	57.6
TABLE	TEMP VOL	EFF VOL	SOIL VOL	RAIN VOL	TIME VOL			
REP	16	8	16	16	16			
SED	57.6	81.4	57.6	57.6	57.6			

***** STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION *****

STRATUM	DF	SE	CV%
UNITS	30	162.8	22.3

Appendix 3. Data for chapter 6.

Soil description - Bruntwood sandy loam

Location: Farm paddock approximately 300 m south of Horotiu Road, 70 m north of silage pit, 10 m west of fence (Grid. Ref. NZMS260 S14 140779).
Elevation: 40 m.

Slope/aspect: 0 - 5° slope towards north east, flat to low-rolling terrace with some stream dissection.

Vegetation/landuse: Pasture grasses and thistles, grazing, mainly lamb and beef fattening.

Climate: Mean annual rainfall 1201 mm; mean annual temperature range 8.3 - 18.1 °C (New Zealand Meteorological Service, 1983).

Parent material: Alluvium dominated by rhyolitic materials.

Soil Classification: Typic impeded Allophanic Soil (Hewitt 1992); Yellow-brown loam (Taylor and Pohlen, 1979); Aquic Udivitrant (Soil Survey Staff, 1990).

Horizon	Depth (cm)	Description
Ap	0-20	Very dark brown (10YR2/2) sandy loam; moderately developed coarse block structure breaking to moderately developed fine to medium nut structure; slightly sticky; slightly plastic; very friable when moist; friable when dry; many very fine roots; allophanic reaction; distinct irregular boundary,
Bw1	20-40	yellowish brown (10YR5/6) sandy clay loam with few faint iron concretions; massive <i>in situ</i> breaking to moderately developed coarse block structure breaking to weakly developed very fine to fine granular to crumb structure; sticky; plastic; very friable when moist; friable when dry; no allophane reaction; diffuse smooth boundary,
Bw2	40-65	yellowish brown (10YR5/8) sandy clay loam with greyish yellow brown (10YR6/2) distinct medium sized mottles; massive <i>in situ</i> breaking to moderately developed coarse block structure breaking to weakly

developed fine crumb structure; sticky; plastic; very friable when moist; friable when dry; very firm *in situ*; few fine roots; no allophane reaction; indistinct smooth boundary,

Bg 65 + greyish yellow brown (10YR6/2) sandy clay loam with many medium distinct bright brown (7.5YR5/6) mottles and few medium distinct reddish brown (5YR4/8) mottles; massive *in situ* breaking to weakly developed fine block structure; sticky to very sticky; plastic; friable when moist; few fine roots; no allophane reaction.

Table A3.1 Moisture retention data for soil cores

Tension m	grav water	vol. water	Equivalent pore diameter μm
-0.04	0.95	0.67	375
-0.09	0.89	0.62	166
-0.2	0.78	0.54	75
-0.3	0.74	0.52	50
-1.0	0.62	0.44	15
-3.3	0.55	0.39	4.5
-10	0.46	0.32	1.5
-30	0.44	0.31	0.5
-150	0.26	0.18	0.1

Table A3.2 Infiltration data for effluent infiltration trial (Chapter 6)

Series	Time sec	K mm hr ⁻¹	K m s ⁻¹	SE mm hr ⁻¹	SE m s ⁻¹
Water 1 SS = 10 g m ⁻³	0	70	1.94e-05		
	3600	58	1.61e-05	12	3.33e-06
	7200	44	1.22e-05	6	1.67e-06
	9900	44	1.22e-05	5	1.39e-06
	13500	40	1.11e-05	9	2.50e-06
	17100	36	1.00e-05	6	1.67e-06
Water 2 SS = 10 g m ⁻³	0	70	1.94e-05		
	7200	63	1.75e-05	4	1.11e-06
	10800	69	1.92e-05	7	1.94e-06
	14400	75	2.08e-05	15	4.17e-06
	18000	61	1.69e-05	5	1.39e-06
	20700	56	1.56e-05	4	1.11e-06
Water 3 SS = 15 g m ⁻³	0	70	1.94e-05		
	3600	42	1.17e-05	8	2.22e-06
	7200	44	1.22e-05	10	2.78e-06
	10800	46	1.28e-05	9	2.50e-06
	14400	39	1.08e-05	11	3.06e-06
	16200	37	1.03e-05	9	2.50e-06
	19800	32	8.89e-06	13	3.61e-06
Untreated SS = 1400 g m ⁻³	0	70	1.94e-05		
	3600	26	7.22e-06	4	1.11e-06
	9900	11	3.06e-06	3	8.33e-07
	13500	11	3.06e-06	1	2.78e-07
	17100	9	2.50e-06	1	2.78e-07
	18000	5	1.39e-06	1	2.78e-07
Primary SS = 550 g m ⁻³	0	70	1.94e-05		
	7200	50	1.39e-05	6	1.67e-06
	10800	31	8.61e-06	3	8.33e-07
	14400	25	6.94e-06	3	8.33e-07
	18000	20	5.56e-06	3	8.33e-07
	21600	14	3.89e-06	3	8.33e-07
	24300	16	4.44e-06	3	8.33e-07
Anaerobic SS = 15 g m ⁻³	0	70	1.94e-05		
	3600	75	2.08e-05	13	3.61e-06
	7200	64	1.78e-05	12	3.33e-06
	9000	62	1.72e-05	10	2.78e-06
	12600	46	1.28e-05	13	3.61e-06
	16200	53	1.47e-05	7	1.94e-06
	18000	41	1.14e-05	8	2.22e-06

Appendix 4 : Data for Chapter 7

Table A4.1 Data for core recovery trial, 25 degree C

Core number	Mean pre effluent	Permeability mm hr ⁻¹						
		day 1.5	day 4	day 7	day 10	day 13	day 17	day 23
Effluent treated cores								
6	47.6	25.3	16.4	17.8	24.9	39.1	33.5	43.4
11	79.9	48	35.2	40	61.4	48.1	67.9	63.6
13	39.8	3.5	2	2.7	9.1	8.9	14.3	28
21	39.9		11.8	11.9	21.3	29.7	36.3	44.1
22	33.6	19.8	17.66	22.4	27.9	24.9	29.4	31.5
26	38.1	7.2	3	1.4	1.9	2.7	4.2	20.6
28	52	20.8	14.5	11.1	25.9	16.4	21.2	29
29	50.7	30.1	19.2	29.7	35.6	36	47.7	60.1
32	30.7	11.4	11.6	12.2	20.4	28.6	12.2	25.9
34	48.8	21.3	22	29.4	50.1	50.7	51.1	55.9
Mean	46.11	20.82	15.34	17.86	27.85	28.51	31.78	40.21
Std. Dev.	13.20	12.56	9.04	11.82	16.78	15.02	18.77	14.68
Std. Err.	4.40	4.44	3.01	3.94	5.59	5.01	6.26	4.89
Water treated cores								
2	57.3	53.5	38.6	52.1	52.5	41.2	44.9	30
3	64.8	68.4	54.2	64.6	53	53.7	60.4	43.8
4	40.5	46.8	43.5	45.5	50.3	45.6	48.5	40.5
7	20.1	20.9	38.7	31.8	24.9	25.9	30.8	27.5
9	65.6	81.8	77.1	72.9	86.2	87	81.4	78.8
10	44.3	54.7	47.1	54.7	55.4	46.4	52.7	47.9
12	46.5	47.6	45.1	48.6	42.1	45.9	42.3	36
15	33.5	37.3	34.9	42.4	48.1	32.9	52.1	45.6
16	53.7	58.5	50.7	72.9	81.3	67.5	81.6	66.7
17	85.6	86.1	84.5	80.4	79.6	80.8	86.8	74.1
Mean	51.19	55.56	51.44	56.59	57.34	52.69	58.15	49.09
Std. Dev.	17.56	18.64	15.76	14.80	18.35	18.88	18.03	17.13
Std. Err.	5.85	6.21	5.25	4.93	6.12	6.29	6.01	5.71
T Test probability - comparison between water and effluent treated cores								
T test	0.50	0.00	0.00	0.00	0.00	0.01	0.01	0.25
Signif. %	50.32	99.97	100.0	100.00	99.78	99.24	99.30	74.70
Paired t test probability - comparison between mean pre effluent and each measurement for effluent treated cores								
Paired t test		0.00	0.00	0.00	0.00	0.00	0.01	0.12
Significance %		100.00	100.0	100.00	99.93	99.62	99.43	87.52
Paired t test probability - comparison between mean pre effluent and each measurement day for water treated cores								
Paired t test		0.04	0.94	0.05	0.16	0.68	0.10	0.66
Significance %		96.33	5.90	94.54	83.62	32.26	89.63	33.81

Table A4.2 Normalised data for core recovery trial, 25 degree C

Core number	Percent change in permeability						
	day 1.5	day 4	day 7	day 10	day 13	day 17	day 23
Effluent treated cores							
6	53	34	37	52	82	70	91
11	60	44	50	77	60	84	79
13	9	5	7	23	22	35	70
21		30	29	53	74	90	110
22	59	53	66	83	74	88	94
26	19	8	4	5	7	11	54
28	40	28	21	50	32	41	56
29	59	38	59	70	71	94	119
32	37	38	40	66	93	40	84
34	43.6	45	60	103	103	105	115
Mean	42	32	37	58	62	66	87
Std. Dev.	17	15	21	27	30	30	22
Std. Err.	6.1	4.9	7.0	9.0	10.0	10.0	7.3
Water treated cores							
2	93	67	91	92	72	78	52
3	106	84	100	82	83	93	68
4	116	107	112	124	113	120	100
7	104	193	158	124	129	153	137
9	125	118	111	131	133	124	120
10	124	106	123	125	105	119	108
12	102	97	105	91	99	91	77
15	111	104	127	144	98	156	136
16	109	94	136	151	126	152	124
17	101	99	94	93	94	101	87
Mean	109	107	116	116	105	119	101
Std. Dev.	9.49	31	20	23.25	18.98	26.5	27.8
Std. Err.	3.2	10	6.6	7.7	6.3	8.8	9.3
T Test probability - comparison between water and effluent treated cores							
T test	0	0	0	0	0.00189	0.0009	0.2612
Signif. %	100	100	100	99.99	99.8106	99.906	73.877

Table A4.3 Data for core recovery trial 13 ° C, Permeability, mm hr⁻¹

core no.	1	2	3	4	mean pre	day 2	day 4	day 7	day 11	day 16	day 21	post effluent day 28	day 34	day 41	day 49	day 62	day 70	day 86	day 100
Group 1, effluent																			
2	88	64	90	68	77.5	36	42	50	66	70	80	86	81	96	92	113.5	115	104	110
22	74	74	64	64	69	29	30	47	42	49	55	48	50	51	47	39	51.7	42	34
38	43	27	41	34	36.25	21	17	18	20	19	20	22	22	20	18	23	23	22	21
52	116	139	87	83	106.25	31	53	31	31	27	31	18	37	29	26	29	29	38	32
63	97	67	83	61	77	33	39	35	33	34	43	42	42	41	53	54	55	63	71
mean	83.6	74	73	62	73.2	30	36.2	36.2	38.4	39.8	45.8	43.2	46.4	47.4	47.2	51.7	54.74	53.8	53.6
Group 1 water																			
3	79	81	94	79	83.25	80	87	82	86	90	55	91	92	80	90	70	80	80	77
26	9	10	11	16	11.5	14	13	13	13	13	15	15	14	12	11	11	12	15	11
39	36	43	59	47	46.25	38	32	42	43	37	31	42	42	52	37	40	39	34	41
53	102	73	108	104	96.75	70	89	101	82	100	84	83	93	91	88	80	92	90	
64	33	29	27	26	28.75	16	17	16	18	19	20	15	23	22	24	19	22	21	21
mean	51.8	47	59.8	54.4	53.3	43.6	47.6	50.8	48.4	51.8	41	49.2	52.8	51.8	50.6	45.6	46.6	48.4	48
Group 2, effluent																			
5	91	48	69	51	64.75		33	50	56	45	49	43		41	42	39	37	37	35
27	31	23	25	22	25.25		9	6	6	7	7	14	7	7	7	6	5	10	3
41	106	113	106	90	103.75		63	74	80	94	91	82	98	87	80	77	66	68	59
54	104	80	98	108	97.5		44	50	45	50	48	40	47	17	53	50	53	58	66
65	46	67	81	82	69		42	31	52	49	48	46	46	42	39	40	45	45	45
mean	75.6	66	75.8	70.6	72.05		38.2	42.2	47.8	49	48.6	45	49.5	38	44.8	42.2	40.2	43.6	41.6
Group 2, water																			
30	12	9	12	9	10.5		12	12	11	11	13	9	7	6	6	6	7	6	5
42	22	21	25	23	22.75		23	26	28	33	34	37	37	36	34	34	40	44	36
55	68	57	66	63	63.5		66	29	70	64	56	61	57	62	56	57	55	72	68
68			167	158	162.5		118	120	88	62	69	79	114	80	77	83	124	142	124
74	121	90	94	105	102.5		98	94	86	80	57	60	71	75	71	73	57	71	
mean	55.8	44	72.8	71.6	72.35		63.4	56.2	56.6	50	45.8	49.2	57.2	51.8	48.8	50.6	56.6	66	60.8
Group 3, effluent																			
8	120	111	123	100	113.5			68	52	77	86	91	75	114		106	86	97	89
32	59	34	53	39	46.25			15	13	11	16	18	18	19	24	27	22	23	20
44	12	11	14	16	13.25			4	2	2	2	2	2	2	2	1	1	4	3
56	134	89	161	148	133			97	105	103	198	114	112	145	138	149	100	159	167
69	95	78	135	106	103.5			54	51	49	44	40	47	44	43	50	52	59	60
mean	84	65	97.2	81.8	81.9			47.6	44.6	48.4	69.2	53	50.8	64.8	51.75	66.6	52.2	68.4	67.8
Group 3, water																			
9	17	15	16	11	14.75			18	20	21	20	18	17	16		13	14	16	15
33	39	28	31	25	30.75			33	39	35	36	30	34	30	30	27	26	30	24
45	68	62	59	51	60			64	64	64	55	50	60	48	50	49	30	44	43
57	47	35	36	32	37.5			24	22	25	30	27	22	30	32	25	31	29	29
70	86	53	88	62	72.25			60	48	40	38	37	38	37	33	34	33	37	27
mean	51.4	39	46	36.2	43.05			39.8	38.6	37	35.8	32.4	34.2	32.2	36.25	29.6	26.8	31.2	27.6
Group 4, effluent																			
13	71	48	72	59	62.5			34	36	46	46	43	47	52	47	45	37	59	52
34	87	68	78	68	75.25			31	28	64	56	50	50	15	59	66	67	65	61
46	53	65	92	69	69.75			76	75	74	91	82	93	94	88	80	89	96	
59	44	32	39	39	38.5			10	11	11	13	12	15	16	18	15	22	20	
7	107	122	139	70	109.5			118	136	142	154	135	161	172	162	174	181	169	
mean	72.4	67	84	61	71.1			53.8	57.2	67.4	71.4	65.2	67.2	77.6	75.8	74.6	83.2	79.6	
Group 4, water																			
20	136	147	156	138	144.25			202	176	198	96	204	90	83	59	75	60	45	
37	72	68	72	54	66.5			97	81	71	81	102	86	83	74	66	79	72	
47	21	14	21	16	18			16	17	18	15	13	12	12	10	9	9	7	
62	53	40	47	46	46.5			46	46	54	42	33	45	48	53	47	40		
83	129	105	140	122	124			114	102	119	107	82	80	116	83	105	85	100	
mean	82.2	75	87.2	75.2	79.85			95	84.4	92	68.2	86.8	62.6	73.5	54.8	61.6	56	52.8	
Overall Effluent Mean					74.56	30.00	37.20	42.00	46.15	48.60	57.75	53.15	53.16	57.33	55.53	59.08	55.44	62.25	60.65
Std. dev. effluent					31.20	5.06	15.11	25.06	30.57	34.28	45.85	37.83	35.15	46.14	42.63	43.45	40.21	44.75	45.67
Std. Err.					7.16	2.53	5.04	6.70	7.01	7.86	10.52	8.68	8.28	10.88	10.05	9.97	9.22	10.27	10.48
Overall Water Mean					62.14	43.60	56.22	48.93	59.65	55.80	53.65	49.75	57.75	49.60	52.00	45.15	47.90	49.58	47.30
Std. dev. water					43.72	27.17	36.66	34.43	45.07	39.76	42.00	29.94	46.14	28.44	31.59	26.41	31.68	34.00	32.38
Std. Err.					10.03	13.59	12.79	9.20	10.34	9.12	9.64	6.87	10.39	6.52	7.66	6.06	7.27	8.01	7.43
T Test - comparison between water and effluent treated cores																			
Ttest	0.13	0.16	0.25	0.44	0.32	0.35	0.20	0.55	0.29	0.55	0.78	0.76	0.74	0.66	0.78	0.24	0.53	0.34	0.31
Sig %	87.40	84.20	75.00	55.64	68.03	64.61	80.02	45.27	71.33	44.65	22.46	23.96	26.37	34.30	21.65	76.00	47.90	65.98	69.49

Table A4.4 Normalised data for core recovery trial, 13 °C, permeability %.

Core no	D2/meanpre	D4/meanpre	D7/meanpre	D11/pre	D16/pre	D21/pre	D28/pre	D34/pre	D41/pre	D49/pre	D62/pre	D70/pre	D86/pre	D100/pre
Group 1, effluent														
2	46	54	65	85	90	103	110	104	124	119	146	148	134	142
22	42	43	68	61	71	79	70	72	74	68	57	75	61	49
38	58	47	50	55	52	55	61	61	55	50	63	63	61	58
52	29	50	29	29	25	29	17	35	27	24	27	27	36	30
63	42	51	45	43	44	56	55	55	53	69	70	71	82	92
mean	44	49	51	55	57	65	63	65	67	66	73	77	75	74
Group 1, water														
3	96	105	98	103	108	66	109	111	96	108	84	96	96	92
26	122	113	113	113	113	130	130	122	104	96	96	104	130	96
39	82	69	91	93	80	67	91	91	112	80	86	84	74	89
53	72	92	104	85	103	87	86	96	96	94	91	83	95	93
64	56	59	56	63	66	70	52	80	77	83	66	77	73	73
mean	86	88	92	91	94	84	94	100	97	92	85	89	94	89
Group 2, effluent														
5		51	77	86	69	76	66		63	65	60	57	57	54
27		35	24	24	28	28	55	28	28	28	23	20	40	12
41		61	71	77	91	88	79	94	84	77	74	64	66	57
54		45	51	46	51	49	41	48	17	54	51	54	59	68
65		61	45	75	71	70	67	67		61	57	58	65	65
mean		51	54	62	62	62	62	59	58	57	53	51	57	51
Group 2 water														
30		114	114	105	105	124	86	67	57	57	57	67	57	48
42		101	114	123	145	149	163	163	158	149	149	176	193	158
55		104	45	110	101	88	96	90	98	88	90	87	113	107
68		73	73	54	38	42	49	70	49	47	51	76	87	76
74		96	91	84	78	56	59	69	73	69	71	56	69	69
mean		98	88	95	93	92	90	92	87	82	83	92	112	92
Group 3 effluent														
8			60	46	68	76	80	66	100		93	76	85	78
32			32	28	24	35	39	39	41	52	58	48	50	43
44			30	15	15	15	15	15	15	15	8	8	30	23
56			73	79	77	149	86	84	109	104	112	75	119	126
69			52	49	47	43	39	45	43	42	48	50	57	58
mean			50	43	46	63	52	50	62	53	64	51	68	66
Group 3 water														
9			122	136	142	136	122	115	108		88	95	108	102
33			107	127	114	117	98	111	98	98	88	85	98	78
45			107	107	107	92	83	100	80	83	82	50	73	72
57			64	39	67	80	72	59	80	85	67	83	77	77
70			83	66	55	53	51	53	51	46	47	46	51	37
mean			97	99	97	95	85	87	83	78	74	71	82	73
Group 4 effluent														
13				54	58	73	69	75	83	75	72	59	94	83
34				41	37	85	74	66	20	78	88	89	86	81
46				109	108	106	130	118	133	135	126	115	128	138
59				26	29	29	34	31	39	42	47	39	57	52
7				108	124	130	141	123	147	157	148	159	165	154
mean				68	71	85	90	83	84	97	96	92	106	102
Group 4 water														
20				140	122	137	67	141	62	58	41	52	42	31
37				146	122	107	122	153	129	125	111	99	119	108
47				89	94	100	83	72	67	67	56	50	50	39
62				99	99	116	90	71	97	103	114	101	101	86
83				92	82	96	86	66	65	94	67	85	69	81
mean				113	104	111	90	101	84	86	76	80	76	69
Overall effluent mean	44	50	52	57	59	68	66	65	69	69	72	68	77	74
Standard dev.	9	7	17	27	29	35	32	29	39	36	37	37	35	39
Standard error	5	2	4	6	7	8	7	7	9	9	9	8	8	9
Overall water mean	86	93	92	100	97	96	90	95	88	85	80	83	90	81
Standard deviation	22	17	23	26	27	30	28	31	27	26	25	29	34	28
Standard error	11	6	6	6	6	7	7	7	6	6	6	7	8	6
T Test - comparison between water and effluent treated cores, normalised data														
T test	0.008	0.000	0.000	0.000	0.000	0.014	0.023	0.004	0.058	0.150	0.436	0.159	0.252	0.502
Significance %	99.2	100.0	99.999	99.999	99.999	98.543	97.659	99.577	94.190	85	56	84	75	50

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