LAND TREATMENT OF WASTEWATER: WITH SPECIAL REFERENCE TO OVERLAND FLOW

by

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DECLARATION

Except where otherwise indicated, this dissertation is my own work

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ABSTRACT

Land treatment is considered as an alternative to conventional wastewater treatment systems. The economic and environmental advantages of land treatment are discussed. Overland flow, a method of land treatment is modelled using both a reductionist and holistic approach. The findings from the modelling exercises are presented along with a discussion of the modelling methods.

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CHAPTER 1
INTRODUCTION

1.1 Land Treatment

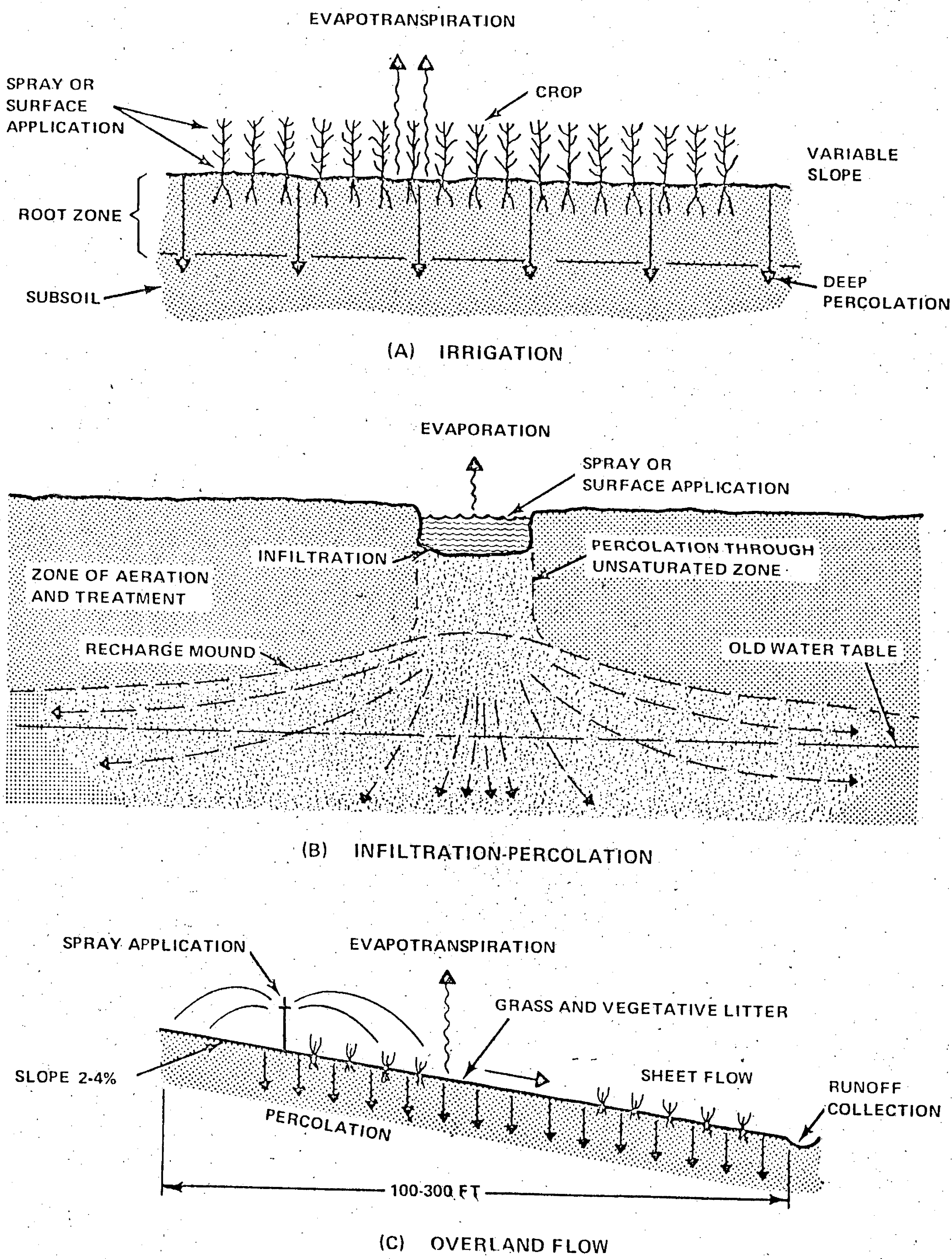
Land treatment is the application of either primary and/or secondary wastewater or sludge to areas of land for the purpose of wastewater renovation. Wastewater applied to land is treated by the physical, chemical, and biological components of the soil-plant matrix of the land treatment system. The three principal methods of land treatment, according to the literature (EPA 1977; Pound 1975) are irrigation, infiltration-percolation, and overland flow. For a detailed explanation of the basic methods of land treatment, see EPA (1977).

In irrigation, Figure 1.1A, wastewater is applied to permeable soil. Treatment occurs as the wastewater passes through the soil matrix. A large portion of the flow percolates to the groundwater. Surface runoff is normally not allowed. Crops or pastures are normally grown on the soil surface.

Infiltration-percolation, Figure 1.1B, is characterised by the fact that most of the wastewater applied to the system reaches groundwater. The method is restricted to very permeable soils such as sand and sandy loam. Physical, chemical, and biological mechanisms in the soil matrix are responsible for the treatment of the wastewater. Plants are seldom used as a renovation mechanism.

Overland flow, Figure 1.1C, is a treatment method in which wastewater is applied over the upper reaches of sloped terraces and allowed to flow across a vegetated surface to runoff collection ditches. Renovation is accomplished by physical, chemical, and biological means as the wastewater flows in a thin sheet down the relatively impervious slope (EPA 1976a, p.5).

FIGURE 1.1 METHODS OF LAND TREATMENT



(A) IRRIGATION

(B) INFILTRATION-PERCOLATION

(C) OVERLAND FLOW

In conventional treatment, wastewater is renovated by mechanical processes which incorporate chemical, physical, and biological principles. Conventional treatment can be composed of one or a combination of treatment phases, depending upon the standard of treated wastewater required. Such phases can be classified as primary, secondary, or tertiary. Primary treatment is simply crude filtering or sieving of wastewater. Secondary treatment involves the removal of organic matter and biostimulants such as phosphorus and nitrogen to a prescribed level. In terms of conventional treatment, the secondary phase is carried out by such processes as trickling filtration, activated sludge, or chemical precipitation. The tertiary phase is designed to remove the biostimulants such as phosphorus and nitrogen that remain in secondary treated wastewater. The prescribed standard of phosphorus and nitrogen in tertiary treated wastewater should not exceed 0.15 mg/litre and 2 mg/litre respectively (Caldwell, p.11). For a detailed explanation of conventional, also referred to as traditional, wastewater treatment systems refer to Ramalho (1977).

1.1.1 History

There is evidence to suggest that land treatment systems existed in western civilization as far back as the ancient Greeks (EPA 1977, p.1-1). In Bunzlau, Germany, a wastewater irrigation system started in 1559 is still in operation today (Pound 1975). The greatest proliferation of land treatment systems occurred in Europe in the mid-nineteenth century during the Industrial Revolution. Due to expanding cities and the lack of wastewater treatment facilities, wastewater was transported into rural areas for irrigation and disposal. As cities continued to expand, irrigated rural land, referred to as 'sewage farms', was lost due to development.

Remaining sewage farms not affected by development eventually failed due to over use and poor management.

1.1.2 An alternative technology

Land treatment can be used as either a primary-secondary and/or tertiary system. An example of a primary-secondary system is Werribee Farm, Werribee, Victoria (Scott 1977) and a tertiary system is Cannock Sewage Works, Cannock, United Kingdom (Hopper 1973).

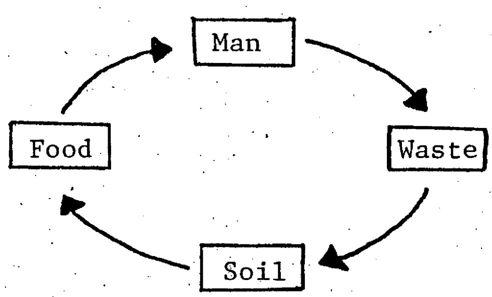
The Senate Select Committee on Water Pollution (1970, p.xiii) has stated unequivocably that the addition of wastewater both domestic and industrial to the nation's drainage pattern is a major factor in the deterioration of water quality in Australia. The Committee suggests that one way to improve water quality in respect to wastewater is for the States to pass tougher environmental legislation. In New South Wales, for example, The Clean Waters Act 1970, establishes machinery which enables various government departments to regulate and control the standard of wastewater entering various bodies of water (Butlin 1976).

If the pollution of water ways by wastewater in Australia is to decrease, it is inevitable that the number and effectiveness of wastewater treatment systems in Australia must increase. This means, to achieve the standard of wastewater effluent from treatment systems that will improve and maintain the level of water quality desired by government authorities, conventional secondary wastewater systems will need to contain a tertiary treatment component. In regards to conventional treatment, the tertiary component is, in comparison to the primary and secondary component, more energy intensive, technologically complex, and expensive (Ramalho 1977).

In most circumstances, land treatment, as a tertiary system, in comparison to conventional treatment, is a system of low energy input and simple technology. This holds assuming the effluent standard is identical. If the level of water quality in Australia is to be improved by the application of advanced wastewater treatment systems, it is only reasonable to suggest in the search for the most effective treatment system that both conventional and land treatment systems be seriously considered.

Land treatment is an ecologically sound way of renovating wastewater. It is a technology that maintains the nutrient recycling principle inherent in nature, see Figure 1.2. Once the wastewater is applied to the land, contaminants in the wastewater are disposed of in an environmentally sound way. For example, various contaminants are converted into naturally occuring gases which are lost to the atmosphere while other contaminants are either absorbed by plants and micro-organisms or 'fixed' to particles in the soil matrix. It is only when resources exist in their unnatural place in the environment that they are characterised as 'pollutants'.

FIGURE 1.2 SIMPLIFIED NUTRIENT CYCLE



At present in the United States and Australia, the most common and traditional wastewater treatment system is conventional primary-secondary. In the United States, federal legislation (Federal Water Pollution Control Act Amendments of 1972; Public Law 92-5000) has provided a statutory basis for the consideration and funding of land treatment systems in the treatment of municipal wastewater (Seabrook 1975).

Such legislation directs the top official administrators in the United States EPA to encourage the idea that land treatment be considered as a possible method for municipal wastewater treatment in projects funded by Federal grants. This is accomplished by requesting subordinates to:

1. require that submissions for construction of publicly-owned treatment works include proof that land treatment was given fair consideration as an alternative waste management scheme;
2. refuse to fund waste treatment projects if it can be demonstrated that land treatment is superior in terms of cost and ability to achieve set standards.

The United States Federal Water Pollution Control Act also directs the United States EPA to publish information on land treatment of wastewater. Such information (EPA 1977, 1976 b.c., 1975) is to be used in the education of the public on the practicality and suitability of land treatment as an alternative waste management scheme and by the United States EPA in evaluating the feasibility of land treatment as an alternative to proposed wastewater treatment projects.

Land treatment of either municipal or industrial wastewater as an alternative waste management scheme is supported by the United States Federal Government and EPA. Land treatment is flexible enough to be considered either as a primary-secondary treatment system (EPA 1977) or as a tertiary component in combination with a primary-secondary conventional system (Seabrook 1975).

At present, there are a number of successful operating land treatment systems throughout the world. In Paris, Texas, the Campbell Soup Company, on three hundred and sixty hectares using the overland flow method of land treatment, purifies waste from its food processing plant. Extensive monitoring programmes in 1968 showed that the wastewater leaving the system was of a high standard (EPA 1977, p.7-73).

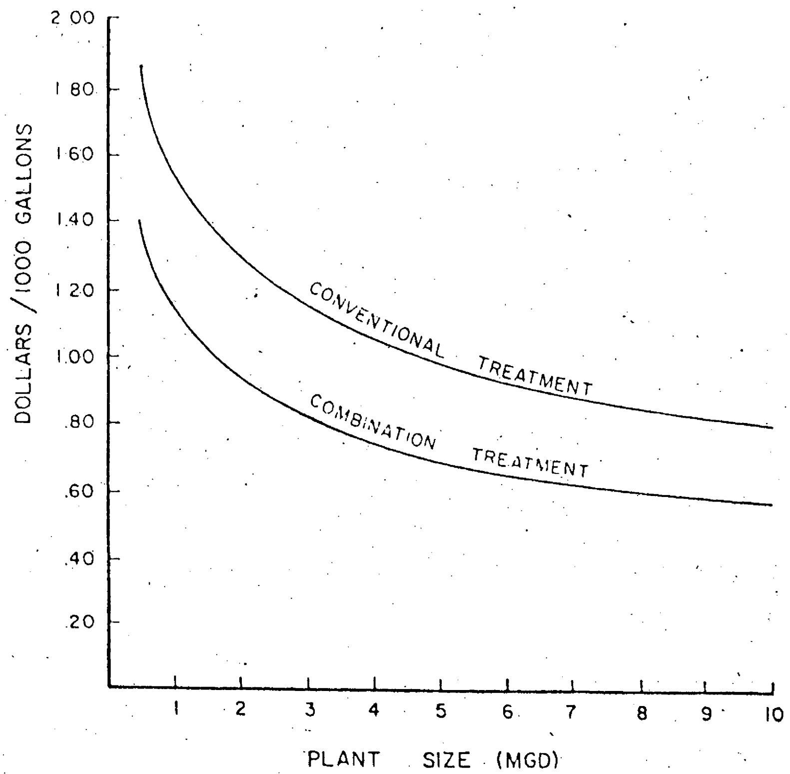
In Phoenix, Arizona, a land infiltration-percolation system has been in operation since 1973. The Phoenix project has been successful in demonstrating the renovation of secondary wastewater into water that has unrestricted use for irrigation and recreational purposes (Stevens 1974). Numerous examples of successful land treatment systems can be found in EPA (1977) and Stevens (1974).

To further demonstrate confidence in land treatment systems, the United States EPA, in co-operation with the United States Army Corps of Engineers, have set up extensive research projects to investigate the various methods of land treatment. For example, at the United States Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, experimentation on overland flow as an effective, low cost tertiary method of treating wastes on military reservations is under way. The study is being conducted to determine and clearly understand mechanisms involved in wastewater treatment by overland flow so that operational feasibility, design, and performance criteria can be accurately evaluated (Carlson 1974; Hoeppel 1974; Lee 1976).

1.2 Economics of Land Treatment

In a general sense, land treatment is not only ecologically sounder but more cost effective than conventional treatment systems. In terms of competitive systems for the treatment of municipal wastewater, Young (1974) studied the economics of land and conventional treatment in the south east United States. He concluded that there is an economic advantage in the use of land compared to conventional treatment, especially for small treatment plants, see Figure 1.3.

FIGURE 1.3 ESTIMATED COSTS OF LAND COMPARED TO CONVENTIONAL WASTEWATER TREATMENT SYSTEMS



According to Young (1975, p.2570) a 1,900 m^3/day plant will save \$10.80/m^3 while a 37,900 m^3/day plant will save \$5.05/m^3. Young obtained his results by using a cross sectional multiple regression analysis in which the average effect of key variables on treatment cost were evaluated. The method to cost treatment systems as used by Young (1975) will be referred to in this study as the model costing method.

Information on vital factors related to wastewater treatment must be obtained before costing of a treatment system can be undertaken. The factors that must be considered include: size of treatment plant, specific processes used, excess capacity existing at the plant, region of the country in which the plant is located, the point in time at which the cost estimates apply, the actual flow rates of wastewater into the plant, and the standard of treatment required.

In the model costing method, according to Young (1975, p.2567) a total cost function of the form $C = f_1 (Q_1, Q_2, S_1, P_L, P_k, P_f, P_e, P_r)$ is derived from a production function. The total cost function presented by Young (1975) represents the current level of technology for the type of wastewater treatment it characterises. The cost variables used to estimate f_1 are as follows:

C = total annual operating and construction cost;
Q_1 = average rate of wastewater flow;
Q_2 = final effluent concentration;
S_1 = size or capacity utilisation;
P_L = price of labour;
P_k = annual price of capital;
P_f = price of fuel;
P_e = price of chemicals; and
P_r = annual price of land.

Young (1974) obtained data on the given cost variables by the use of a survey. Using a log linear multiple regression analysis, coefficients for each variable were estimated, see Table 1.1. An estimated cost equation was determined by applying the coefficients to the cost function.

The cost equation, given the value of the various independent variables, may be used to obtain an estimate of the total cost of a wastewater treatment system. The cost equation may also be used to determine the extent to which an independent variable can effect the total cost. In reference to Table 1.1, equation 1, a 10 percent increase in flow results in an 8.304 percent increase in total cost. Estimated cost curves determined from a cost equation provide a vehicle for examining the cost of conventional compared to land treatment (Young 1974, p.22). So, the coefficients from a regression of a conventional treatment system may be compared with coefficients from a regression of a land treatment system.

TABLE 1.1 ESTIMATED COEFFICIENTS OF COST FUNCTION

Independent variables		Total cost				
		Without land				With land
		C_1	C_1	C_1	C_1	C_2
Equation number		1	2a[b]	2b[b]	3	4
Constant		7.7533	10.1153	4,3511	7.8962	7,8661
		(5.0217)	(4.6820)	(2.1278)	(4.4998)	(4.9570)
Flow	x_1	0.8304	0.8968	0.7073	0.7242	0.8302
		(18.8529)	(15.8338)	(9.9579)	(12.7344)	(18.3206)
Internal percent BOD_5 removal	x_2				0.2120	
					(1.3607)	
Proportion of capacity utilized	x_3	-0.3465	-0.2982	-0.5018	-0.1928	-0.3392
		(-2.2952)	(-1.3024)	(-2.8594)	(-1.2498)	(-2.2258)
Age of capital	x_4				-0.1067	
					(-1.6305)	
Industrial wastes	x_5				0.0824	
					(1.6137)	
Final inplant BOD land treatment	x_{12}					-0.0906
						(-1.5127)
Price of labor	P_1	0.6664	0.4041	1.1658	0.8264	0.6600
		(2.4417)	(1.0114)	(3.3617)	(2.9421)	(2.3954)
Price of electricity	P_3	0.2362	-0.5144	0.9846	0.1601	0.1105
		(0.5236)	(-0.7608)	(1.8218)	(0.1594)	(0.2420)
Price of capital (excluding subsidy)	P_5	0.4144	0.2260	0.7674	0.4078	0.3880
		(1.8240)	(0.6964)	(2.7063)	(1.6869)	(1.6782)
Sample size		125	73	52	125	125
R^2		0.7813	0.7608	0.7505	0.7684	0.7772

[a]Values in parenthesis are t values for test of significance from zero.

[b]Equation 2a was estimated using only those observations with less than 90 percent inplant BOD_5 removal. Equation 2b was estimated using only those observations with greater than or equal to 90 percent inplant BOD_5 removal.

Results in relation to the economics of land compared to conventional wastewater treatment obtained from the model costing method are as follows:

1. as treatment plant size increases costs increase at a decreasing rate; thus, suggesting that there are economies of scale in wastewater treatment plants (Young 1975, p.2566);
2. with reference to conditions, especially in relation to plant size, as stated by Young (1974, p.27), economies of scale for increasing flow are smaller when land treatment is utilised;
3. increasing the standard of treatment causes total costs to rise at an increasing rate (Young 1974, p.31);
4. the diseconomies to increasing the standard of treatment are smaller with land than with conventional treatment (Young 1975, p.2569);
5. increasing concentrations of contaminants in applied wastewater causes costs to increase;
6. a proportional increase in reserve capacity will cause a greater increase in costs for tertiary than for primary and secondary treatment (Young 1974, p.49);
7. land treatment has a higher elasticity of substitution between capital and labour, that is, the land treatment manager is able to vary labour-land-capital combinations as prices change more readily than those using conventional treatment technology.

When different types of wastewater treatment systems are to be costed for a specific site and an accurate cost function does not exist, a detailed engineering exercise may be applied. In the engineering exercise, the treatment system is divided into cost components. Table 1.2 represents the various cost components of a land treatment system (Pound 1975, p.53). Pound (1975, p.52) produces a procedure for

TABLE 1.2 COST CALCULATION SHEET

Alternative No. ____________ Average flow ____________ mgd
Type of system ____________ Analysis date ____________

Cost Component	Total Capital Cost, $	Amortized Capital Cost, ¢/1,000 gal.	O & M Cost ¢/1000 gal.	Total Cost, ¢/1,000 gal.
Preapplication treatment				
____________	____	____	____	____
____________	____	____	____	____
____________	____	____	____	____
Transmission conveyance				
______, ______ mi	____	____	____	____
Transmission - pumping	____	____	____	____
Storage period				
____________ wks	____	____	____	____
Application systems				
____________				
@ ________ in/wk	____	____	____	____
Underdrains	____	____	____	____
SUBTOTAL, BASE DATE	____	____	____	____
Trend factor	____	____	____	____
SUBTOTAL, ANALYSIS DATE	____	____	____	____
Crop revenues			( )	( )
Land cost	____	____	____	____
TOTAL COST	____	____	____	____

calculating the cost of a specific land treatment system from Table 1.2. By further subdividing the cost components, a more accurate cost of the specific treatment system is obtained, see Table 1.3 (Pound 1975, p.60).

The individual cost of each component is calculated by multiplying the quantity of the component by the unit price. The components that make up the costing sheet can be different, depending on the organization doing the costing and the type of wastewater treatment system being costed. Caldwell (1971, p.42) and Pound (1975, p.27) show examples of costing a conventional and land treatment system respectively for specific geographical sites.

The final capital cost of the treatment system is calculated by adding together all component costs. The costing is completed by calculating operating and maintenance costs in cents per quantity-volume, see Table 1.2. To take into account economic factors such as inflation, it is necessary to adjust the costs given, from the engineering exercise, to allow for the elapsed time between the date of compiling the costs and the actual date of construction of the proposed facility.

Land treatment produces saleable by-products (revenue producing benefits). Various components in wastewater such as nitrogen, phosphorus, potassium, water, and organic matter which contain potential energy are, in an economic sense, valuable (Young 1974, p.15; Sandford 1977,p.9). Revenue producing benefits that stem from the wastewater treatment method, that can be easily and accurately quantified, should be incorporated into the cost analysis (Pound 1975, p.137). In regards to land treatment, such benefits may include the production of crops and livestock from the irrigation of agricultural land and pastures, and the creation of functional recreational areas by the application of wastewater to various types of public land such as golf courses and parks.

TABLE 1.3 DETAILED LIST OF COST COMPONENTS OF A LAND TREATMENT SYSTEM

Category	Component
1. Land	a. Field area requirement
2. Preapplication treatment	a. Aerated lagoons b. Chlorination
3. Transmission	a. Gravity pipe b. Open channels c. Force main d. Effluent pumping
4. Storage	a. 0.05-10 million gallons b. 10-5,000 million gallons
5. Field preparation	a. Site clearing b. Land leveling for surface irrigation c. Overland flow terrace construction
6. Distribution	a. Solid set spraying (buried) b. Center pivot spraying c. Surface flooding using border strips d. Ridge and furrow application e. Overland flow f. Infiltration basins g. Distribution pumping
7. Recovery of renovated water	a. Underdrains b. Tailwater return c. Runoff collection for overland flow d. Chlorination and discharge for overland flow e. Recovery wells
8. Additional costs	a. Administrative and laboratory facilities b. Monitoring wells c. Service roads and fencing d. Planting, cultivation, and harvesting e. Yardwork f. Relocation of residents g. Purchase of water rights h. Service and interest factor

Controversy exists over how to handle social costs and in particular benefits that arise from a treatment method because they are 'difficult' to quantify. Pound (1975, p.138) suggests that social costs and benefits of a particular treatment method should be accounted for descriptively in the cost analysis. Another view suggests (Krutilla 1975) that an effort should be made to quantify social costs and benefits that stem from the treatment method. Exclusion of social cost, especially in a quantitative sense, from the costing exercise may be due to the fact that those responsible for the costing are not aware that such costs can be determined given adequate time and finance.

Methods exist for assessing and evaluating many of the social costs and benefits associated with land treatment; however, such a discussion is outside the scope of this study.

Not until a specific cost is calculated for each treatment system can it be determined as to which is least costly for the specific site.

CHAPTER 2

CASE STUDY OF A LAND TREATMENT SYSTEM WERRIBEE FARM

2.1 Introduction

In the following chapters, one of the methods of land treatment, namely overland flow, will be analysed using different modelling techniques. It is hoped that the information ascertained from the analysis will add further light to the understanding of land treatment systems. A brief description of the remaining chapters is provided as an introduction to the organisation of the study.

Chapter 2 - Case study of a land treatment system - Werribee Farm

A brief description of the Werribee Farm wastewater treatment plant is presented. Specific details of the Farm to be emphasised are its design, operational factors and performance. The observed data from Werribee used in the modelling exercises are presented and discussed.

Chapter 3 - Modelling of an overland flow wastewater treatment system

This chapter is divided into two sections. In section one, a deterministic model of an overland flow wastewater treatment system constructed using a reductionist modelling approach is presented. Observed data from Werribee are used to calibrate the model. Findings from the modelling exercise are presented and discussed. In section two, time series analysis, a holistic modelling approach, is applied to observed data from Werribee Farm. Findings of this modelling exercise are presented and discussed. A critique of the modelling methods and approaches used in the chapter is presented.

Chapter 4 - Summary of the study

Major findings from the modelling in chapter three are summarized. A further plea to seriously consider land treatment as a realistic, practical alternative wastewater management scheme is presented.

2.2 History

In 1892 James Mansergh, an eminent English sanitation engineer with wide experience in land treatment of wastewater was requested by the Victorian Government to come to Melbourne and set up a wastewater treatment system. In collaboration with William Thwaites, a local Australian engineer, it was decided to establish a land wastewater treatment system at Werribee, thirty-five kilometres south-west of Melbourne. In August 1897, the Werribee Farm became operational.

The Farm started by simply irrigating land with raw wastewater, but as time progressed, the city of Melbourne began to grow. The area of the Farm was increased and new methods of land treatment instigated. Today Werribee treats approximately 178,000 megalitres (ML) per year or roughly seventy-five percent of Melbourne's wastewater (Melbourne and Metropolitan Board of Works).

2.3 Objectives and Plant Description

The major objective of Werribee Farm is to purify raw wastewater into what might be called 'reconditioned' or treated wastewater which will meet the Victorian Environmental Protection Authority's (VEPA) standard for discharge into Port Phillip Bay. The philosophical bases of Werribee Farm are to realize and use to maximum benefit the potential value in wastewater while at the same time assuring that an adequate standard of treated wastewater is maintained.

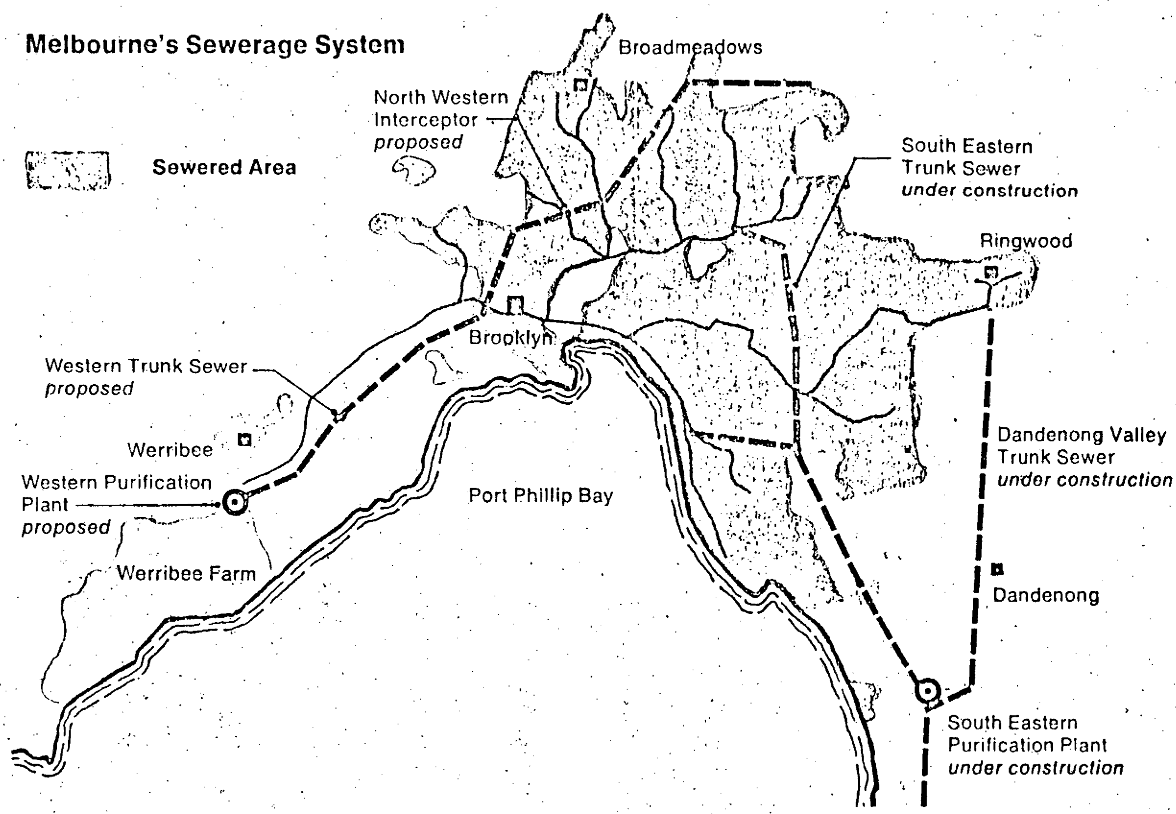
Werribee Farm covers an area of 10,800 hectares between the Geelong Road and Port Phillip Bay, see Figure 2.1 and 2.2. Figure 2.2 schematically represents the salient features of the land use of Werribee Farm. Features from Figure 2.2 of relevance to the study are as follows:

1. the two drains Lake Borrie and 145W where sampling took place to obtain data used in the study;
2. the location of the different methods of land treatment used at Werribee in relation to the drains;
3. the Little River channel connecting treatment areas to drains.

At Werribee, the methods used to treat wastewater are lagooning, land filtration, and grass filtration (overland flow).

Lagooning is used throughout the year to cater for wastewater flow in excess of 350 ML a day, the maximum amount of raw wastewater that either the land or grass filtration areas can handle. The wastewater moves through a series of eight to ten lagoons, and is purified by the processes of sedimentation and the biochemical activity of bacteria.

FIGURE 2.1 LOCATION MAP OF WERRIBEE FARM



Land filtration is used during the summer when the rate of evaporation is high in comparison to other times of the year. Graded pastures are irrigated with wastewater, the wastewater being purified by chemical, physical, and biological processes as it percolates through the soil. The lush plant growth in the pastures which is a response to the nutrients left in the soil from the filtered wastewater is eventually grazed by cattle.

FIGURE 2.2 LAND USE MAP WERRIBEE FARM

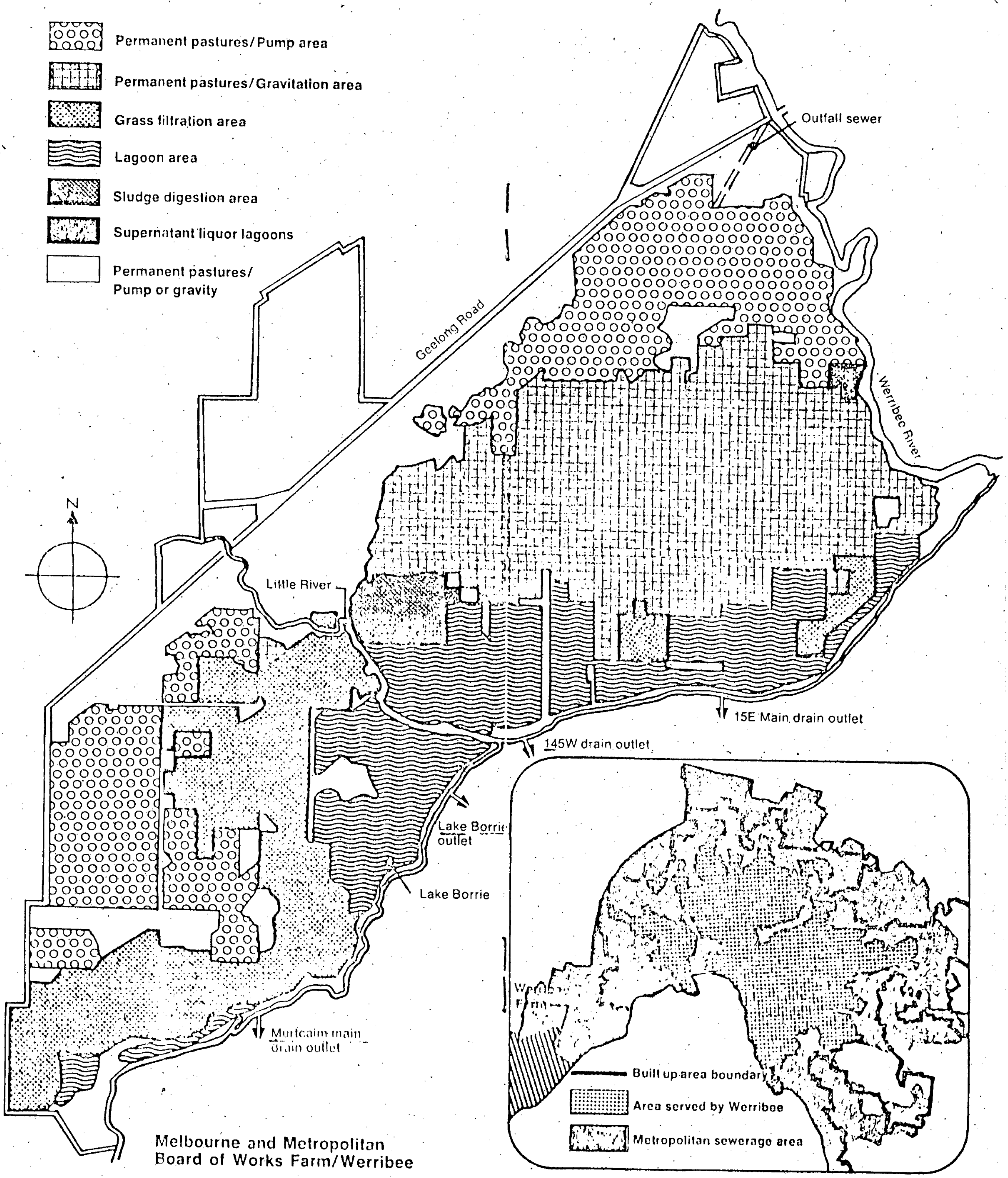


TABLE 2.1 A SUMMARY OF FACTS CONCERNING WERRIBEE FARM

	Method of Treatment		
	Grass filtration (overland flow)	Lagoon	Land filtration (irrigation)
Average flow, ML/day	Total for all three treatment methods 440		
Percent of total annual flow treated	34	47	19
Degree of preapplication treatment	Sedimentation ponds	Some sedimentation	Some sedimentation
Number of years in operation	81	81	81
Land preparation	Bays 400 metres long	8-10 ponds in series 4 x 8 x 1 metres	Bays 200 x 10 metres
Area used for purification of wastewater (ha)	1,463	1,499	4,281
Time sequence of wastewater application	6 months	60-70 days	18-20 days
Time of year for application	May - September	All year	October - April

A detailed explanation of overland flow (grass filtration) appears in section 2.5. For a summary of the essential statistics for the Werribee Wastewater Treatment Farm see Table 2.1.

In keeping with its philosophical principle, Werribee functions basically as a farm. During the year approximately 22,000 head of beef cattle, mainly Angus and Hereford, are grazed on pastures irrigated by wastewater. Roughly 1,500 tonnes of prime dressed beef are sold yearly (Scott 1977, p.9). During the spring and summer, some 20,000 to 50,000 sheep are fattened for the sale yards.

Due to shelter from predators and an ample supply of food in lagoons and pastures, Werribee has become a major bird sanctuary. Some two hundred species of birds have been identified by ornithologists.

2.4 Design Factors

Sections 2.4, 2.5 will concentrate on the method of treatment at Werribee referred to as grass filtration. Grass filtration and overland flow are two terms which describe the same treatment method.

The overland flow treatment is established on heavy red clay. The bays which make up the overland flow treatment system slope (1 in 1,000) naturally towards the sea. Table 2.2 gives a detailed list of design factors relating to the overland flow wastewater treatment system at Werribee.

2.5 Operation and Performance Overland Flow

The raw wastewater destined for the overland flow wastewater treatment system is channelled into sedimentation tanks where the heavy organic solids are allowed to settle out. The wastewater runs by way of open earth-lined channels to the overland flow bays. As the wastewater moves along the bay it slows down and spreads out. At the end of the bay, the wastewater is collected in open channels. The channels carry the treated wastewater to the appropriate outlet where it drains into Port Phillip Bay.

The bays are initially irrigated in February and March to promote the growth of Italian rye grass. By April the grass is some one hundred to one hundred and fifty millimetres high (Scott 1977, p.5). In April, small but continuous flows of wastewater are applied to build up bacterial populations. After two or three weeks, the rate of flow is increased in stages (over a period of a few weeks) until maximum flow is reached. Maximum flow is then maintained until the end of September.

TABLE 2.2 DESIGN FACTORS FOR OVERLAND FLOW WASTEWATER TREATMENT SYSTEM - WERRIBEE FARM

Type of system	Grass filtration (overland flow)
Average flow, ML/day/ha	0.22
Type of wastewater	80% domestic, 20% industrial
Preapplication treatment	Sedimentation ponds
Disinfection	None
Storage	Lagoon
Field area, ha	11,460
Crops	Italian Rye Grass
Application techniques	Drainage ditches
Routine monitoring	Yes (for EPA license)
Buffer zone	Yes
Application cycle	Winter (May to September)
Average annual precipitation, mm	490
Average annual evaporation, mm	1,140
Cost of treating 1,000 litres	2.7 cents

In October when overland flow ceases there is a change back to land filtration. The bays dry out and the Italian rye grass goes to seed. At this stage the cattle are permitted to take advantage of the fodder value of the dry vegetation. The grass seed falls to the ground where it remains until germinated by rain or irrigation in the autumn to provide for next winter's operation.

2.5.1 Costs

The revenue from the livestock sales, depending upon the market price, is some one million dollars a year (Scott 1977, p.9). The net cost of purifying wastewater in 1974/75 was some 4.5 million dollars which works out to a treatment cost of 2.7 cents per 1,000 litres (Scott 1977, p.9). Such a calculation ignores capital costs.

2.5.2 Observed data

See observed data from Werribee Farm (Figures 2.3, 2.4, 2.5 and 2.6).

There is a lack of water quality data especially with reference to the specific methods of wastewater treatment that exist at Werribee. The data that do exist from scientifically designed sampling programmes

FIGURE 2.3 CONCENTRATION OF AMMONIA LAKE BORRIE OUTLET

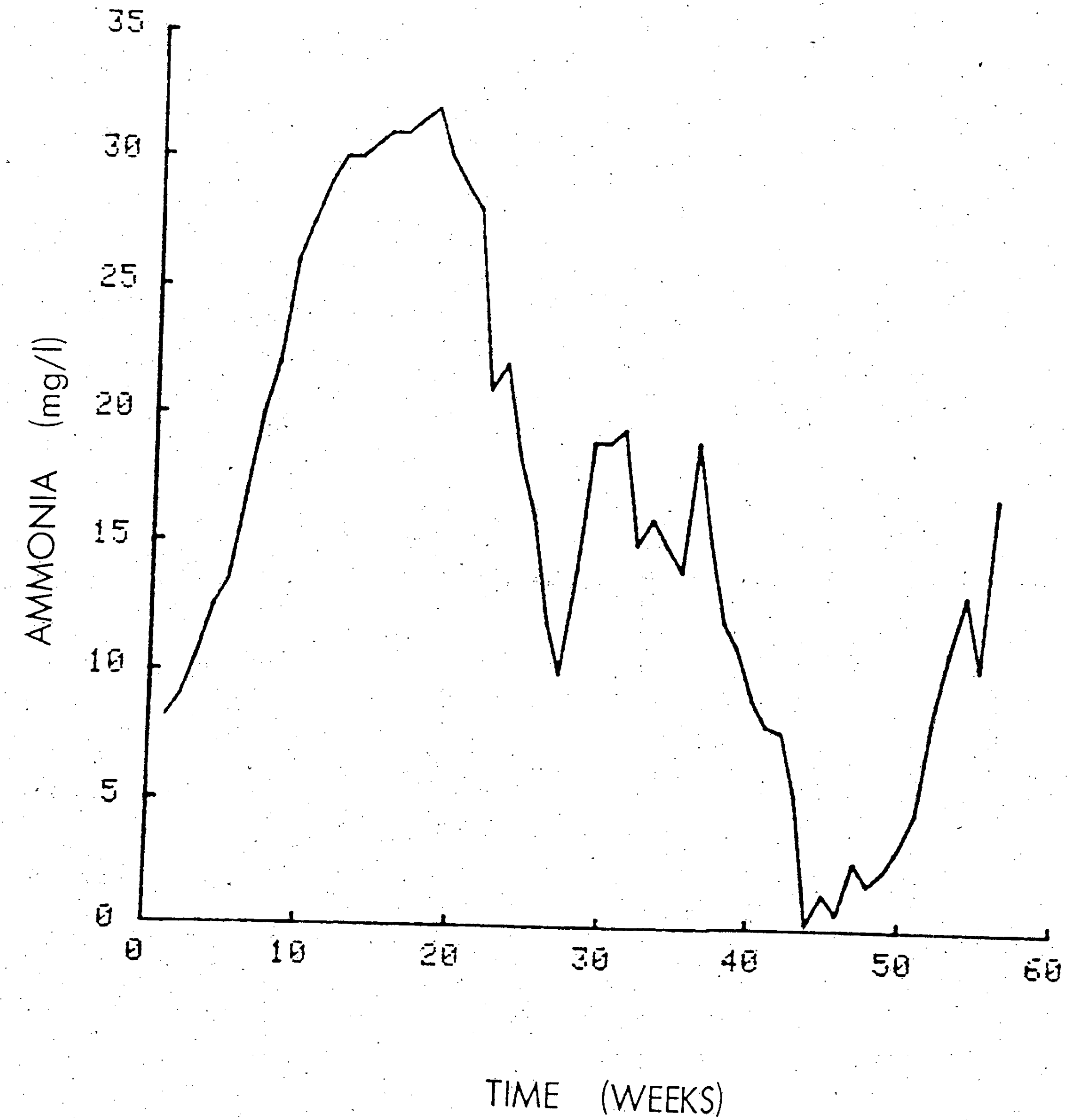


FIGURE 2.4 CONCENTRATION OF NITRITE, NITRATE LAKE BORRIE OUTLET

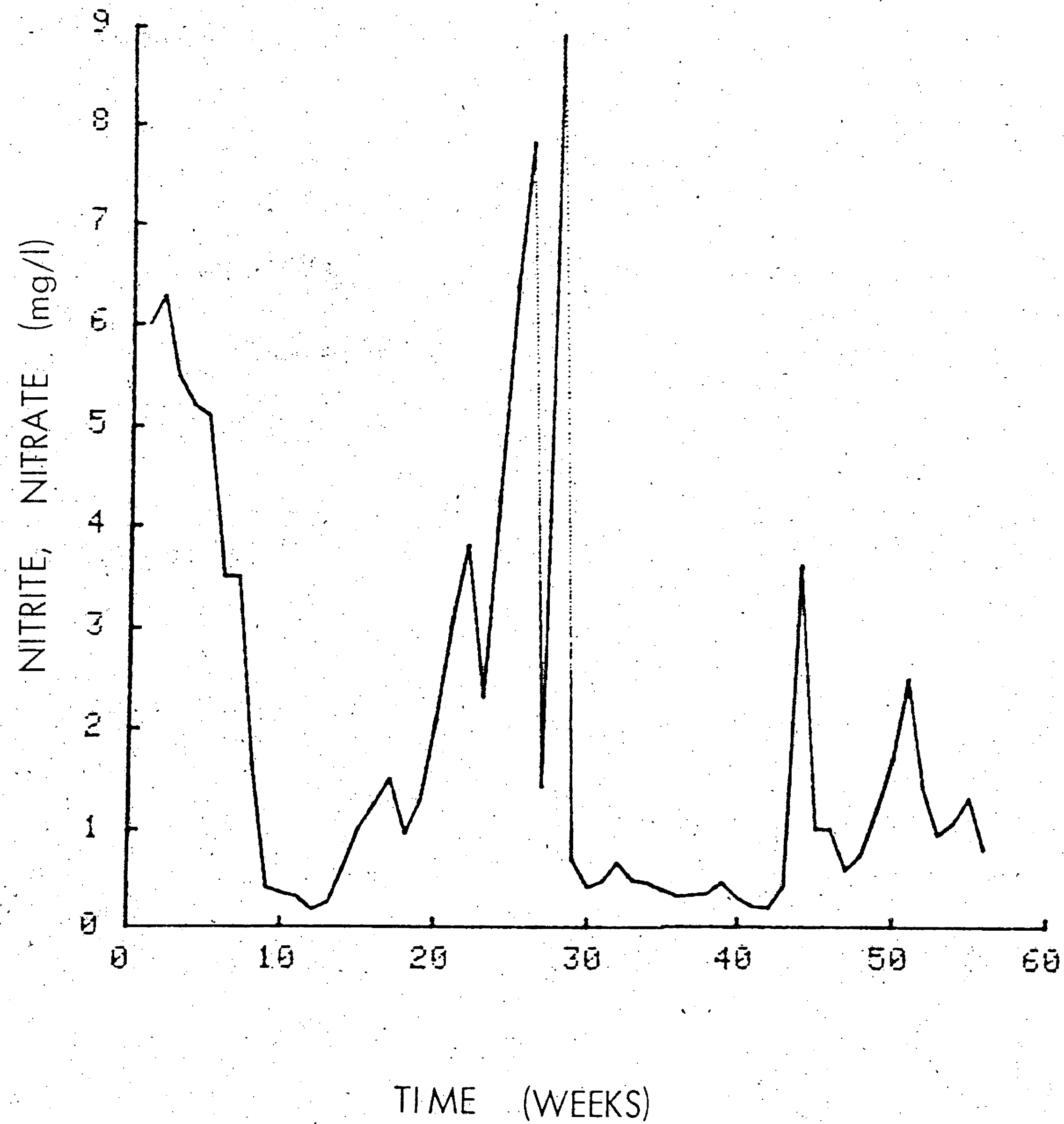
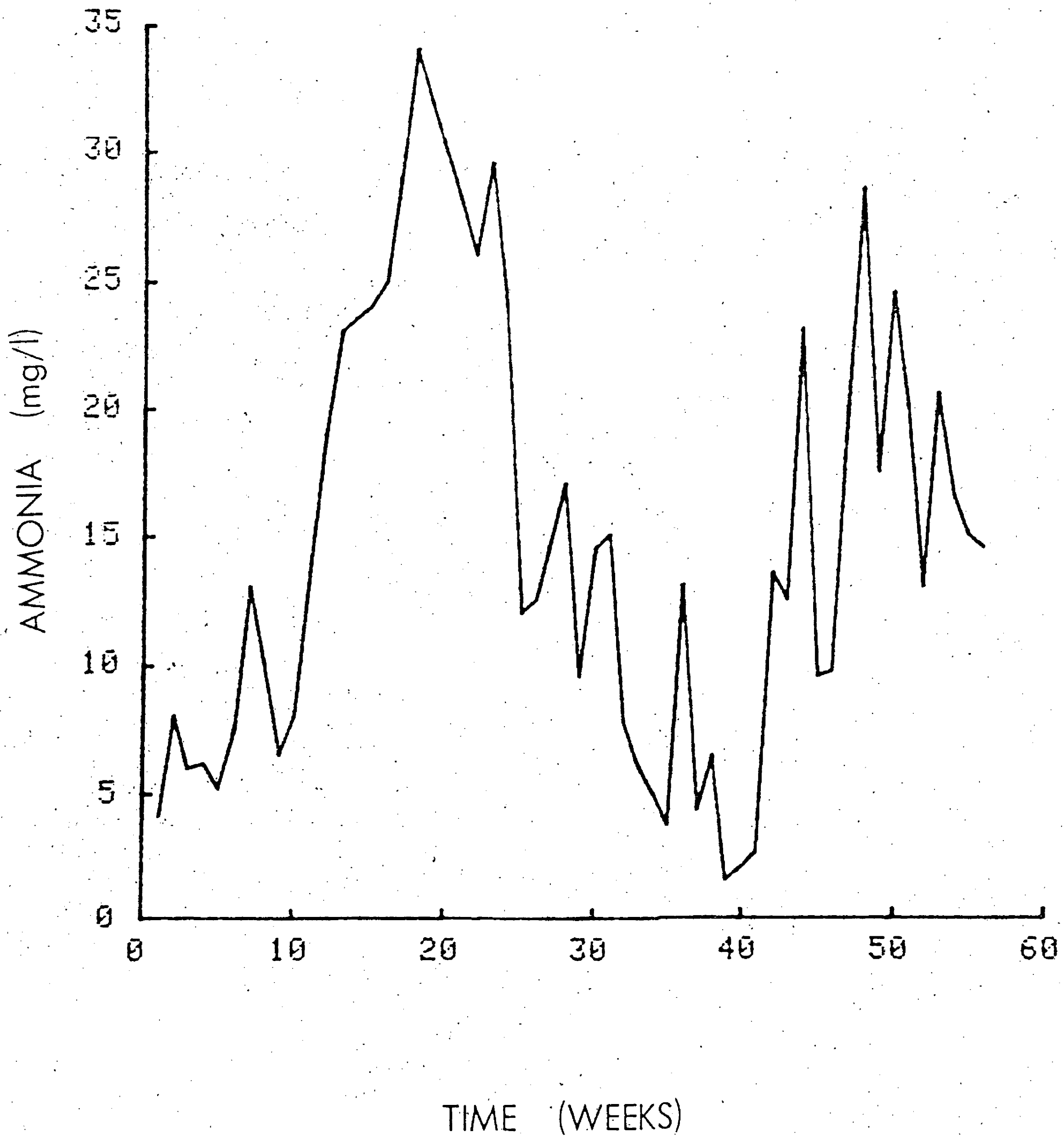


FIGURE 2.5 CONCENTRATION OF AMMONIA 145W OUTLET



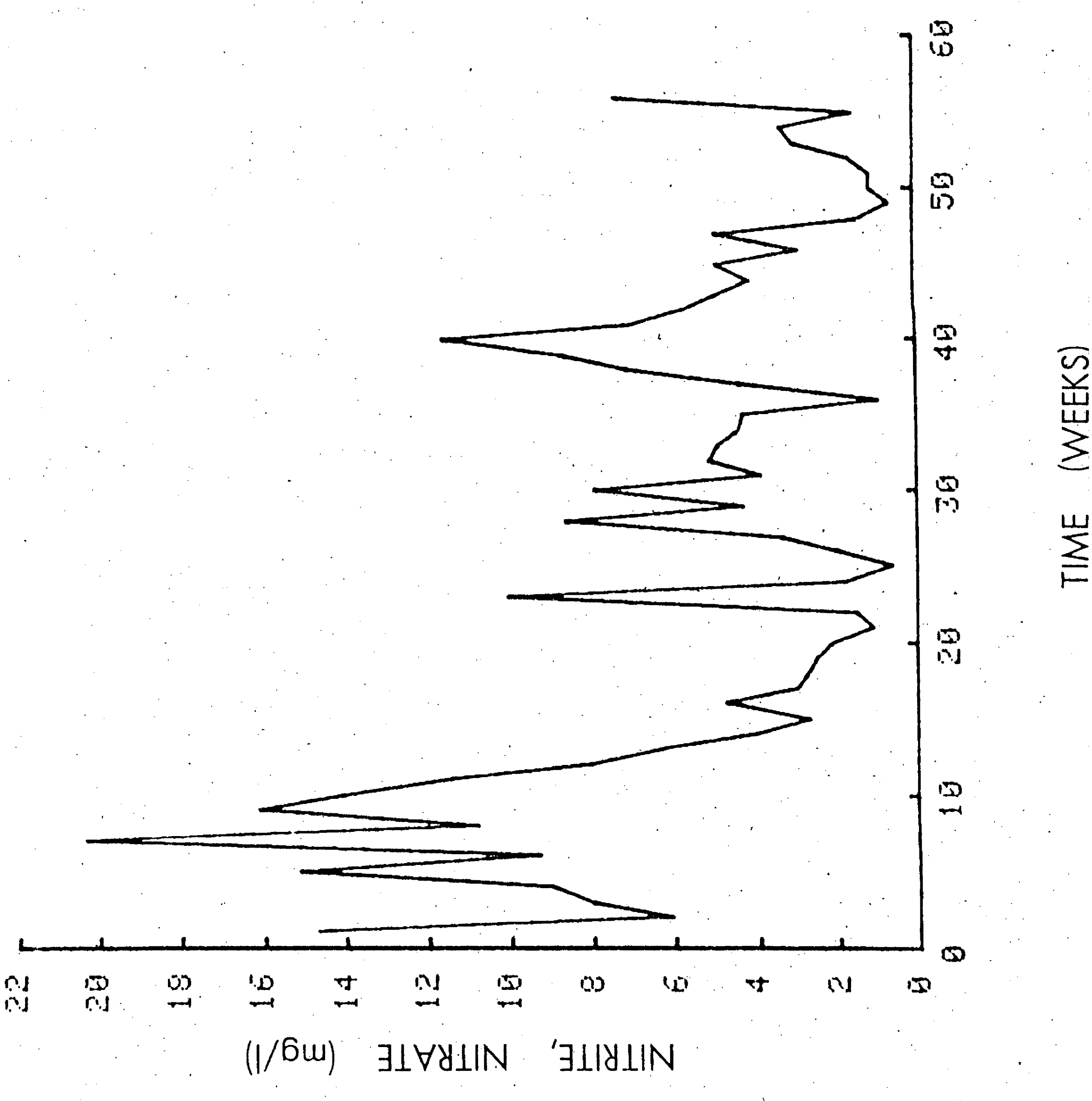


FIGURE 2.6 CONCENTRATION OF NITRITE, NITRATE 145W OUTLET

are under tight bureaucratic control and not accessible to the public. Werribee has been functioning as a wastewater treatment system for over eighty years, but not until the last two or three years have data collection programmes been in operation.

In order for Werribee to remain operational, it must have an Environmental Protection Authority licence; pursuant to section 20 of the Environmental Protection Act 1970. The EPA licence states clearly the type of data collection that must be carried out (see Appendix B). The observed data in Figures 2.3-2.6 are from such a sampling programme.

Deficiencies of the observed data used in the study are as follows:

1. the sampling programme used to obtain the data was not specifically designed for the purpose of the modelling exercises considered in this study;
2. data exist for only three of the outlet drains (145W, Lake Borrie, Murtcain main), no data exist for drain 15E;
3. data from drains 145W and Lake Borrie are based on weekly samples while data from Murtcain drain are as monthly averages;
4. The drainage from each outlet is a composite of at least two different types of land treatment methods;
5. the data set for outlet drains 145W and Lake Borrie has data points missing.

It was not possible to obtain the concentration of nutrients in the wastewater entering the Werribee treatment plant.

Werribee is fortunate in that the treated wastewater from the Farm drains into Port Phillip Bay. In his study, Axelrad (1977) reports that the general level of phytoplankton and biomass in Port Phillip Bay has not been greatly increased as a result of the wastewater discharge from Werribee Farm. It appears from this study that the effluent standard from Werribee could increase by as much as twenty percent before the nutrients from treated wastewater begin to affect the general ecology of Port Phillip Bay.

Even though Port Phillip Bay is not over sensitive to nutrient flux, Werribee is still concerned with the standard of treated wastewater. It would be reasonable to suggest that to either maintain or improve the standard of treated wastewater, an increase in the understanding of the treatment methods would be helpful; however, at Werribee very little scientific investigation into the mechanisms of the various treatment methods has taken place.

Statistics for the overall general performance of the overland flow method of wastewater treatment at Werribee are presented in Table 2.3.

TABLE 2.3 TREATMENT PERFORMANCE WERRIBEE, MELBOURNE

Constituents	Overland Flow Percent Removal
BOD	96
Suspended solids	95
Total nitrogen	40
Total phosphorous	15
E. coli	99.5
Heavy metals	90

CHAPTER 3

MODELLING OF OVERLAND FLOW WASTEWATER TREATMENT SYSTEM

3.1 Deterministic Model

In this section of the study, a reductionist approach is used to construct a deterministic model of an overland flow wastewater treatment system. In the reductionist approach, the system to be modelled is sub-divided into physical components and each component is modelled separately. The components are reassembled to provide a model of the complete system.

3.1.1 Objectives of modelling exercise

The objectives of the modelling exercise are as follows:

1. to construct a deterministic model of an overland flow wastewater treatment system which incorporates environmental factors which affect the various processes that make up the overland flow system;
2. to use the overland flow wastewater treatment system at Werribee Farm as a basis in validating the model;
3. to evaluate the deterministic model as a decision making tool in studying the feasibility of overland flow as a community wastewater treatment system.

3.1.2 Literature review

A search of the modelling literature of land treatment systems revealed three basic types of modelling that pertain indirectly to the modelling attempted in this study. The first type covers deterministic models concerned with spray irrigation systems and the concentration of various nutrients in ground water as applied to agriculture.

Dutt *et al.* (1972a, b) have devised deterministic models that predict in a quantitative way the concentration of various nutrients, such as nitrogen and phosphorus, in ground water after they have percolated through and interacted with a soil matrix. The models are designed to improve water quality by better management of non point source pollution.

Simulation studies on crop irrigation have been undertaken by Flinn (1971) and Anderson (1973). The output from these models can be used to maximize benefits, mostly in an economic sense, and to improve decision making in terms of irrigation schemes. Input data and processes modelled, parallel closely those used in land treatment systems. Such models have potential in the designing of efficient irrigation for land treatment systems.

In the second type of modelling, land treatment systems are modelled using linear programming techniques. An attempt is made, under the constraint of a given standard of runoff, to maximize amount of wastewater applied and minimize cost. In modelling the capacity of a lagoon spray irrigation system to assimilate nitrogen, Koening (1977) estimates the flow and concentration of wastewater that can be applied to the system given the standard of runoff as the constraint. By designing a land treatment system so that the full capacity of the system is utilized, the cost per given quantity of wastewater is minimized.

Haith (1977, 1973) has developed a linear programming model of a land treatment system incorporating equations that characterise specific nutrient transformations and removal processes. The model estimates the quantity and quality of wastewater that can be properly treated by the given land treatment system.

The third type comprises simulation models that are concerned mainly with the hydrological aspects of land treatment systems. Whiting (1975), using climatic data as an input, presents a hydrological design model, which identifies days favorable for the application of wastewater. One objective of the model is to calculate the maximum storage capacity of the system each year.

Lo (1976) simulated an infiltration-percolation land treatment system. He used climatic data as input to determine the area needed for such a system to function properly.

3.1.3 Description of Model

3.1.3.1 Definition of Model Type

The type of model presented in this section can be described as a deterministic, discrete time model. It is dynamic in the sense that certain variables such as plant growth and soil moisture capacity vary over time. In addition, it accounts for time varying inputs such as the flow and quality of applied wastewater and environmental factors such as temperature, evaporation, and rainfall.

3.1.3.2 Model Restrictions

Although there are a number of substances in wastewater that must be removed such as heavy metals (Carlson 1974), organic matter (EPA 1976b), and phosphorus (Thomas 1976), it was decided to focus attention on the inorganic nitrogen component (NH_3^+, NO_2^-, NO_3^-) of wastewater.

There are a number of researchers (for example, Koening (1977), Haith (1973), and Digiano (1977)) who, when faced with the problem of selecting a substance in wastewater to model have chosen nitrogen. Excess concentration of nitrogen in water ways can cause a number of environmental problems. The ability of an overland flow system to remove nitrogen will have an important effect upon the quality and quantity of wastewater that can be applied to the system.

FIGURE 3.1 PROCESSES INVOLVING NITROGEN IN AN OVERLAND FLOW SYSTEM

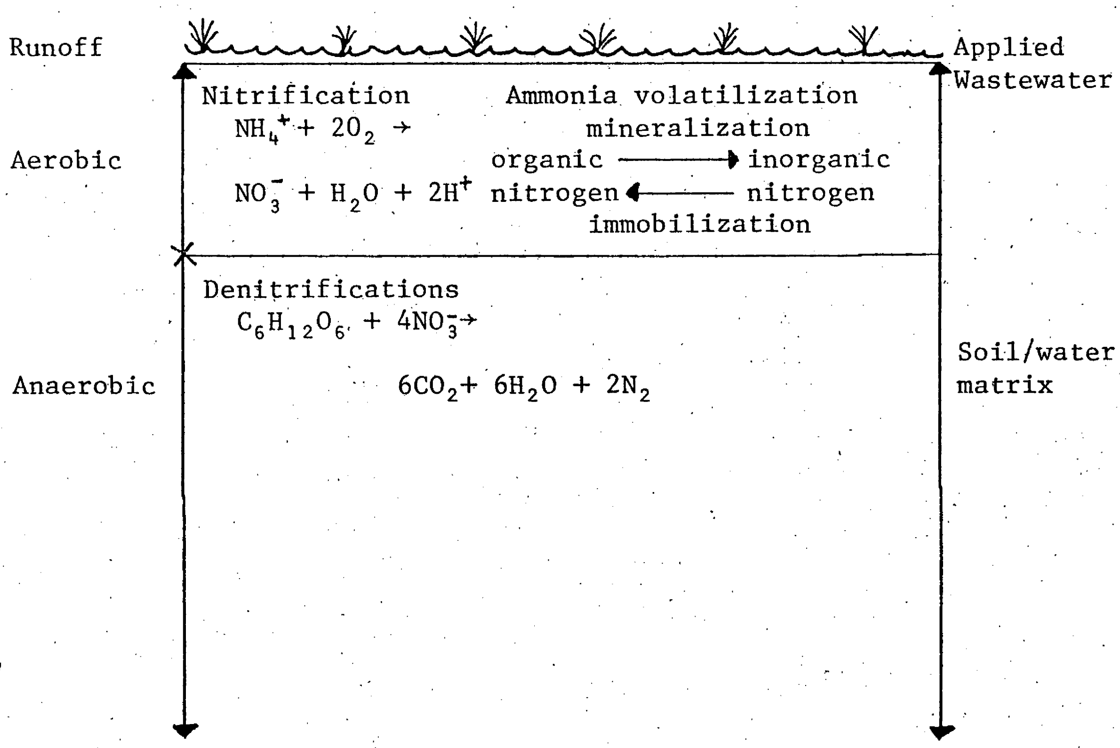
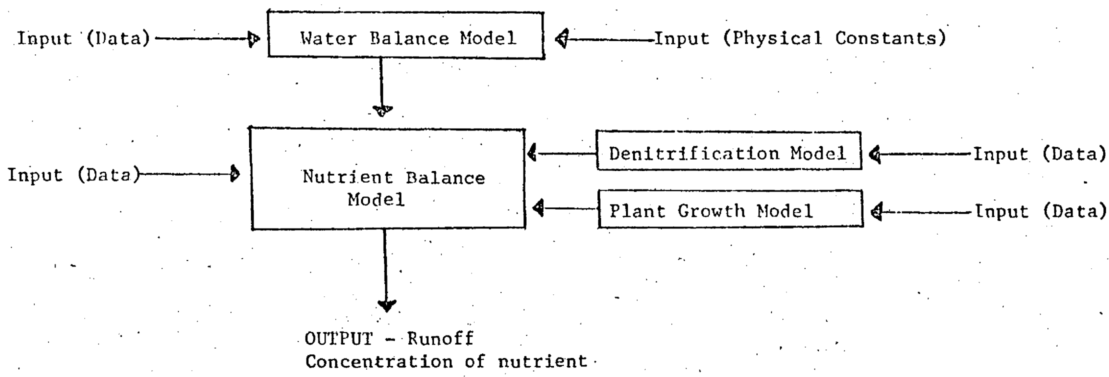


Figure 3.1 is a diagramatic representation of the processes involving nitrogen in an overland flow treatment system. For the purpose of the overland flow model, the reverse processes of mineralization and immobilization are assumed to be occuring with the rate of mineralization exceeding the rate of immobilization. This assumption is supported by Haith (1973, p.925). The processes considered in the deterministic overland flow model are those that have the most prominent affect on the movement of inorganic nitrogen. Processes not modelled are discussed in section 3.1.4.2.

3.1.3.3 Flow Diagram of Model

For a block diagram of the deterministic overland flow model, see Figure 3.2.

FIGURE 3.2 BLOCK DIAGRAM OF DETERMINISTIC OVERLAND FLOW WASTEWATER TREATMENT MODEL



3.1.3.4 Explanation of model

A computer programme has been written using the Tektronix 4051 graphic system (mini-computer) to simulate an overland flow wastewater treatment system. A detailed explanation of the modelling logic and a list and description of variables, parameters, and inputs is given in Appendix A.

A brief explanation of the overland flow model will be presented in this section. The overland flow model is composed of two sub models: the hydrological model and the nutrient balance model.

The hydrological or water balance model calculates the drainage of wastewater from the treatment system. The logic of the model is from a simple mass balance equation (1) (EPA 1977):

(1) $R + W = E + P + D$

where R = rainfall in mm/day, averaged from monthly rainfall data (converted to megalitres (ML)/day in model);

W = applied wastewater in ML/day, averaged from weekly figures of the flow of applied wastewater;

E = evapotranspiration in mm/day, averaged from monthly evaporation data (converted to ML/day in model);

P = percolation in per cent, (converted to ML/day in model) percolation is the movement of water through the soil matrix by gravity;

D = drainage in ML/day, drainage is the flow of wastewater from the treatment system.

In the overland flow model, rainfall and applied wastewater are represented as input data and drainage as output. Percolation is represented in terms of the soil moisture capacity variable. Evapotranspiration is calculated using the approach of Keig (1974) and the arithmetic constants used in the calculation come from McAlpine (1969, p.70). Further details of the evapotranspiration calculations are given in Appendix A.2.3.

The nutrient balance model is composed of the following series of models: ammonium ion adsorption model, influent model, denitrification model, plant growth model, and nutrient sink model.

The ammonium ion adsorption model calculates the mass of ammonium nitrogen the soil can adsorb. The calculation of the ammonium ion adsorption capacity is taken from the work of Lance (1972, p.1354). For further details, see Appendix A.2.1. The capacity of the soil to adsorb (fix) ammonium ion is used in the nutrient sink model.

The influent model, using the flow rate and concentration of inorganic nitrogen of the applied wastewater, calculates the nutrient mass entering the treatment system.

The denitrification model calculates the amount of nitrogen lost from the applied wastewater due to denitrification. The amount of nitrogen lost is dependent upon two environmental factors, namely soil moisture capacity and temperature. If the soil moisture capacity is equal to or less than sixty percent, the loss due to denitrification is zero (Broadbent 1965, p.349). Where soil moisture capacity is over sixty percent, denitrification proceeds. The relationship between temperature and percent denitrification is quantified on the basis of data from a paper by Nommik (1956, p.195). The mass of nitrogen lost due to denitrification is the product of the maximum percent lost (Lance 1972, p.1353) times the percent due to the temperature factor. For further details see Appendix A.2.5.

The plant growth model calculates the mass of nitrogen lost from the nutrient sink by the up-take of nitrogen due to plant growth. The logistic equation modified to a simple recursive form, see equation (2), is used to calculate plant yield. The equation to calculate plant yield in the overland flow model is:

(2) $$N_t = aN_{t-1}\frac{(K-N_{t-1})}{K} + N_{t-1}$$

where N_t = yield (biomass in dry weight) at present time period (kg/ha);

a = growth rate of plant species as a function of temperature (kg/kg/day);

N_{t-1} = yield (biomass in dry weight) at the previous time period (kg/ha);

K = maximum yield (biomass in dry weight), that is, the point at which the biomass is to be cut (kg/ha);

where the relative growth rate is a function of temperature, see equation (3) from Jeffery (1975, p.36):

(3) $$a = e^{-(2-X)^2}$$

where a = relative growth rate (kg/kg/day);

e = natural log;

x = temperature (degree C).

From the yield, the mass of nitrogen lost due to plant growth is calculated.

The important aspects of the nutrient sink model are the calculation of the exchangeable and fixed nitrogen in the soil matrix and the concentration of inorganic nitrogen in the runoff.

3.1.4. Discussion of Model

The following is a discussion of the problems incurred in the construction of the deterministic overland flow model.

The first problem arises when conflicting values for a specific parameter, such as the denitrification decay coefficient, are encountered in the literature. The process of denitrification in descriptive terms is well understood; however, due in part to experimental techniques, an accurate quantitative value under a given set of conditions in terms of the mass of nitrogen denitrified is not available. In the literature a wide range of values appear for nitrogen loss due to denitrification (Broadbent 1965). The problem may be resolved to some extent by selecting the average value from the literature and investigating the sensitivity of the model to the uncertainty in this parameter.

The second problem arises when attempting to choose the mathematical expression that will represent a specific process in the model. No matter how clearly a process is understood in descriptive terms there is uncertainty associated with the structure of mathematical models that represent such processes.

The third problem arises in regards to poorly understood, complex processes. In such complex processes quantitative values of many of the parameters and/or variables are not available. One example of this in the overland flow model is the relationship determining the mass of inorganic nitrogen lost from the applied nutrient mass to the nutrient sink. A number of complex independent integrated 'activities' make up the process whereby an amount of inorganic nitrogen moves into the soil matrix. Examples of such activities include: the lateral rate of wastewater movement along the soil surface; the vertical or percolation rate of water containing inorganic nitrogen moving down through the soil matrix; the amount of nitrification and denitrification which establish concentration gradients which in turn affect the diffusion rate of inorganic nitrogen down through the soil.

In this study, the percent of nitrogen lost to the nutrient sink was determined by simply calibrating the model with observed Werribee data. However, this approach is somewhat suspect due to the poor quality of the Werribee data.

Clearly, further research is required to improve the quantification of this loss of nitrogen to the nutrient sink. Such information can only be obtained from additional observations from Werribee or possibly from specific field experiments.

It is important to accurately quantify the percent of nitrogen entering the sink as this has a particularly significant effect on the concentration of inorganic nitrogen in the treated wastewater.

One approach to overcome such limited information is to conduct a sensitivity analysis. In such an analysis, an undefined parameter can be tested to see how sensitive the model output is to quantitative fluctuations of the parameter.

Many of the inadequate aspects of the overland flow model discussed in this section pertain to the deficiencies of the reductionist approach to modelling. These are further discussed in section 3.1.7.

3.1.4.1 Qualification of environmental factors

Each process in the overland flow model is affected by various environmental factors. Examples of such environmental factors are temperature, pH, oxidation potential, etc. Due to time restriction, only the environmental factors that have the most dramatic affect upon the various processes were incorporated into the overland flow model. For a more comprehensive list of environmental factors and their effect upon the various processes in the overland flow model, see Appendix A.4.

3.1.4.2 Processes not Modelled

Processes that do not appear in the overland flow model because their effect on the movement of inorganic nitrogen is minimal are discussed below.

Ammonia volatilization is the conversion of ammonium into gaseous ammonia. Researchers such as Lance (1972, p.1354) suggest that only small quantities of inorganic nitrogen are lost from the system by this process in comparison to other nitrogen removal processes in land treatment. However, growing support for ammonia volatilization as a significant process in nitrogen loss from pastures comes from the work of Simpson (1968) and Denmead (1974). Results from an experiment by Beauchamp *et al.* (1978) show that sixty percent of the ammoniacal nitrogen contained in sewage sludge when applied to a field was volatilized into gaseous ammonia.

The other process of negligible affect in terms of nitrogen movement is, according to Lance (1972, p.1357), chemodenitrification. Chemodenitrification is the process by which nitrites formed during nitrification may decompose or react with soil organic matter to yield gaseous nitrogen which is lost to the atmosphere.

3.1.5 Results

See results from deterministic overland flow model (Figures 3.3, 3.4, 3.5 and 3.6).

FIGURE 3.3 FLOW FROM TREATMENT SYSTEM AS A FUNCTION OF CLIMATIC FACTORS

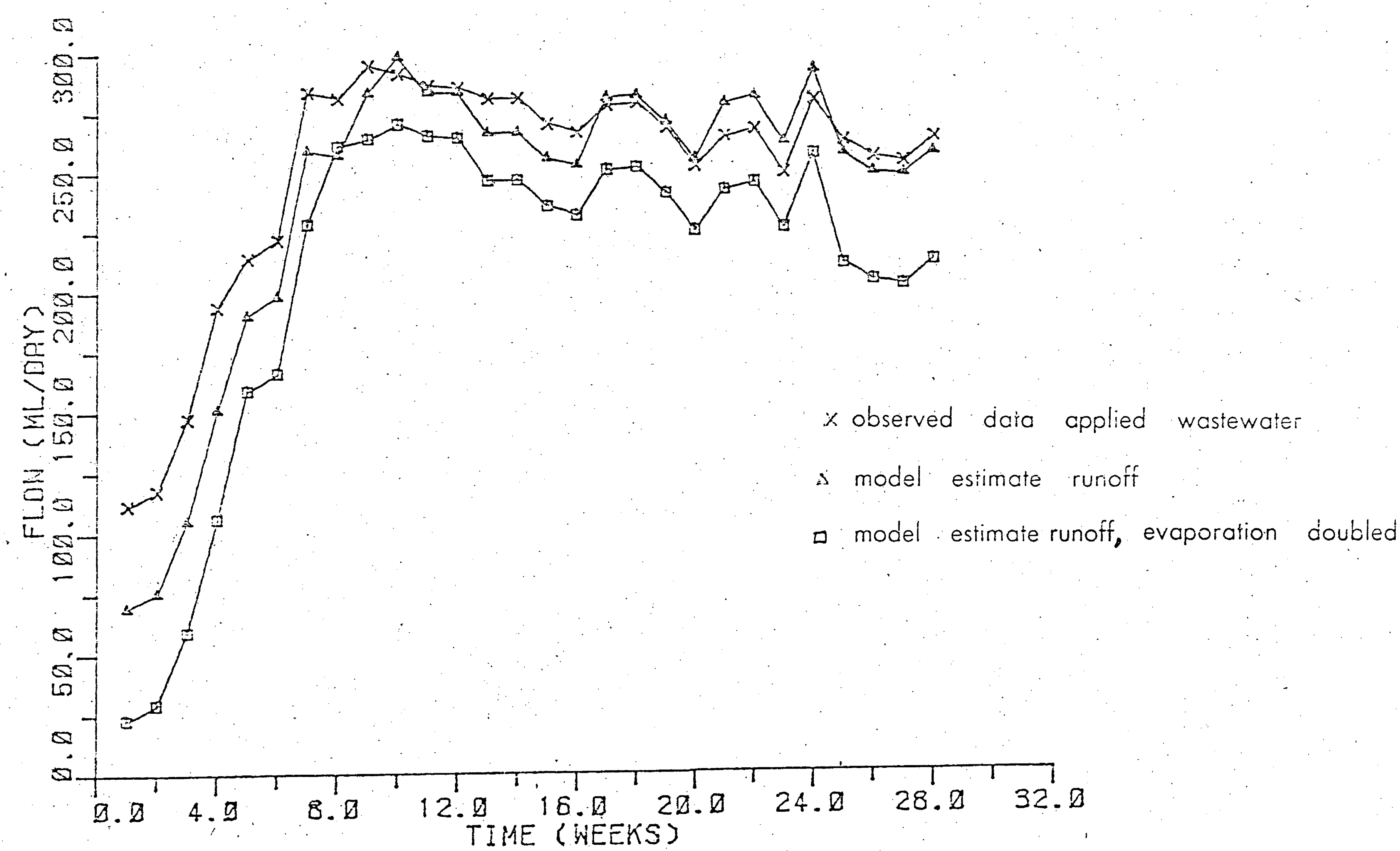


FIGURE 3.4 CONCENTRATION OF INORGANIC NITROGEN IN RUNOFF

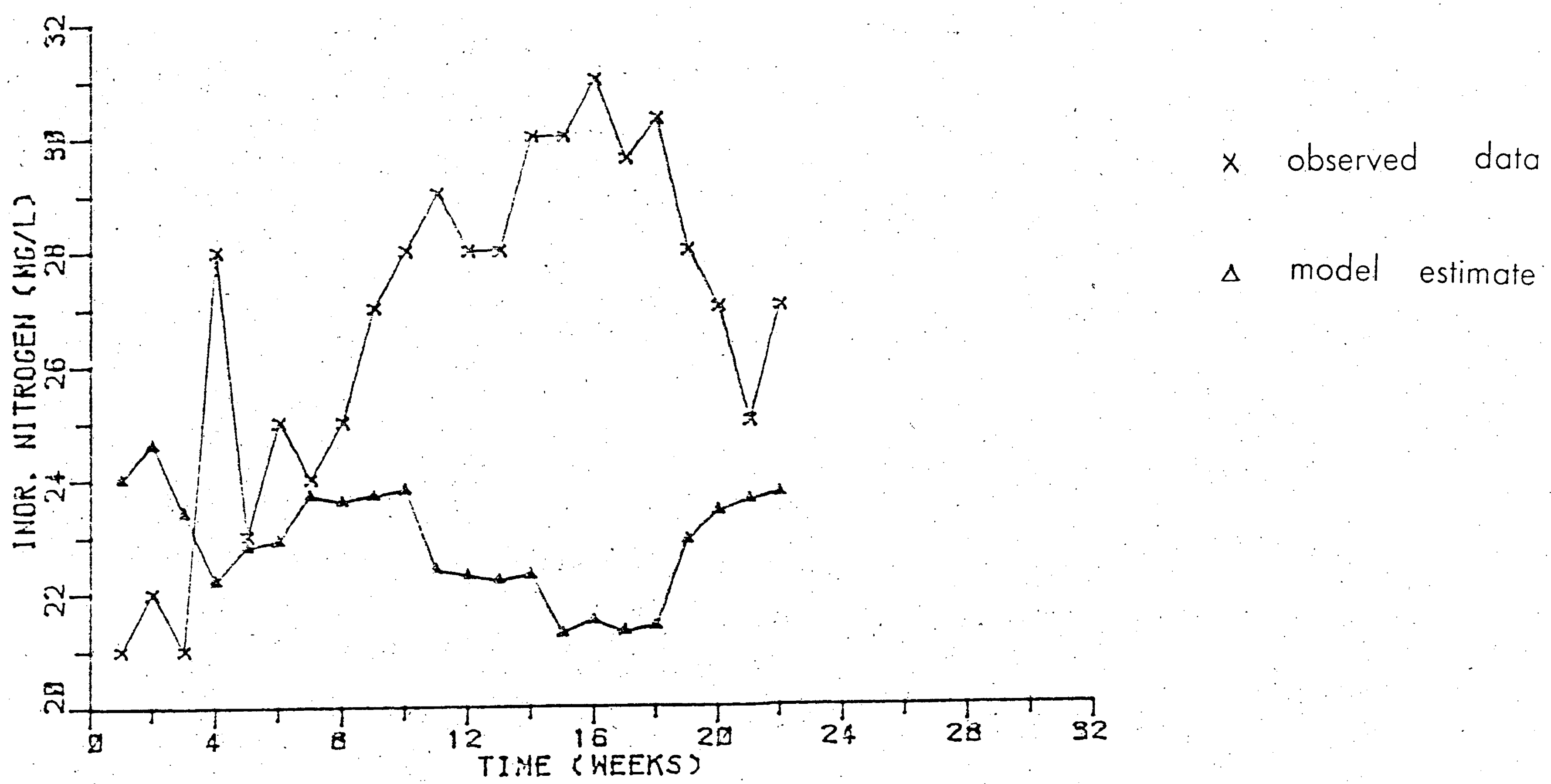


FIGURE 3.5 PLANT GROWTH

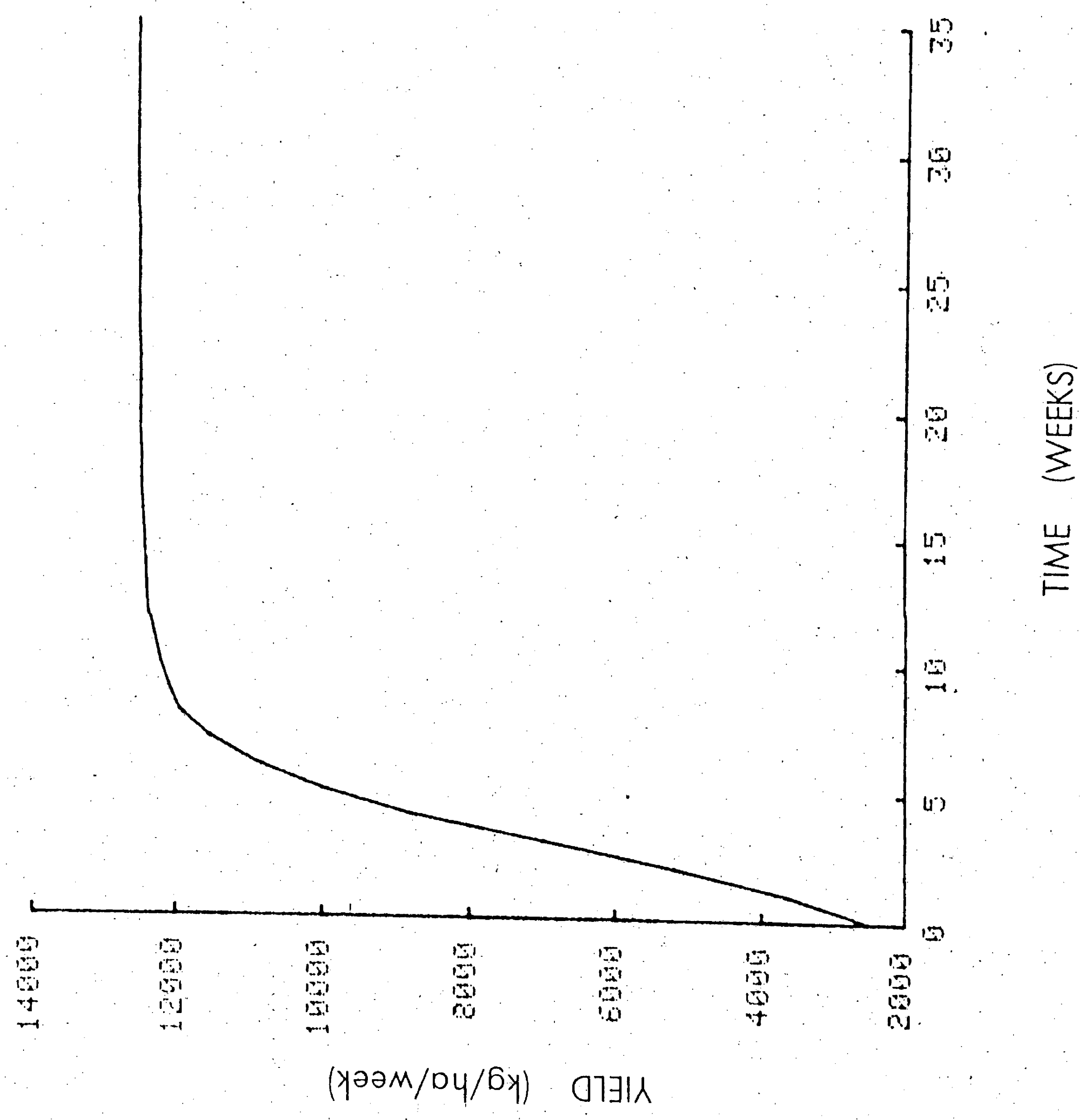
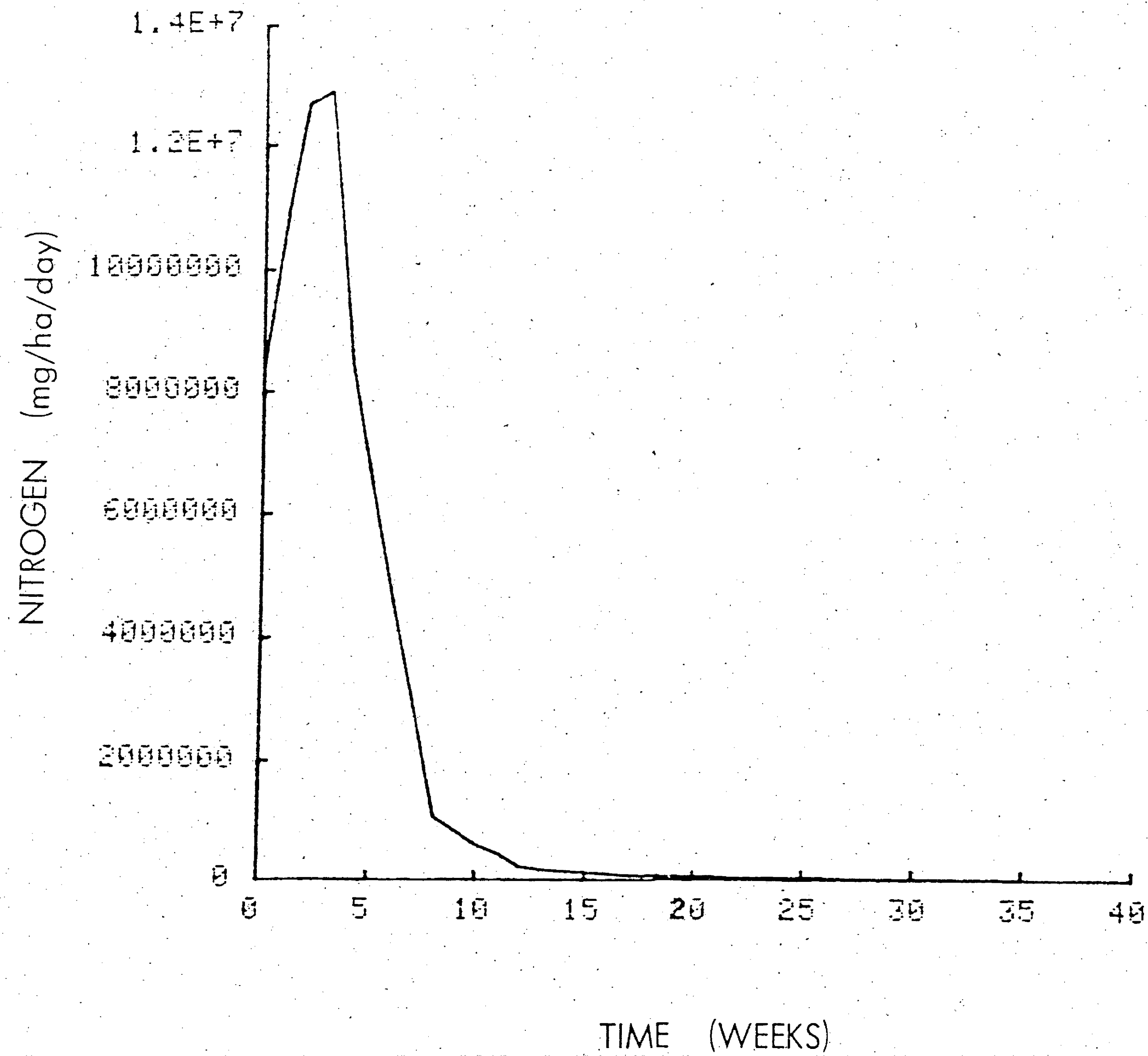


FIGURE 3.6 NITROGEN LOST DUE TO PLANT GROWTH



3.1.6 Discussion of Results

The concentration of nutrient in applied wastewater, the amount of applied wastewater, and the potential of the land treatment system to purify the applied wastewater are important factors in determining the area needed for an overland flow system.

In overland flow, the amount of water lost from the system due to evapotranspiration and especially percolation is much less in comparison to the other types of land treatment systems. However, given a constant concentration of nutrients, the general principle, that a decrease in the amount of wastewater applied means a decrease in the area of the treatment system, still holds for all treatment systems. Due to the fact that land is the single most expensive component of an overland flow system, it makes economic sense, when thinking about system feasibility to consider water loss potential, especially in terms of evapotranspiration.

Figure 3.3 shows the affect of climatic factors on the flow rate of runoff as estimated by the overland flow model. Assuming area of treatment system remains constant, the relationship between plot x and plot Δ accounts for the climatic characteristics inherent in the data set. For example, when evaporation exceeds rainfall, amount of applied wastewater exceeds runoff and when rainfall exceeds evaporation, runoff exceeds amount of applied wastewater.

To further investigate the climatic effect represented in Figure 3.3, a simulation run of the model was carried out in which the evaporation component of the data set was doubled. The results of the run appear on Figure 3.3 as plot □. From the relationship between plot x, Δ and □, the effect of water loss by the system in relation to climatic factors is apparent.

Simulation runs, in which initial conditions were varied such as soil moisture capacity and flow of applied wastewater, revealed interesting results. If initial conditions are such that one hundred percent soil moisture capacity is not reached, the effect is a lag in the system response to runoff. The time interval of the lag period is dependent upon such factors as the flow rate of applied wastewater, area of treatment system, soil moisture capacity, and climate.

In Figure 3.4 the model estimate is compared to the observed data from Werribee Farm of the concentration of inorganic nitrogen in the runoff. The discrepancy between model estimate and observed data is due, in part, to the fact that the model estimate was derived from an input in which the concentration of nitrogen was constant where as the observed data is a function of an input in which the concentration of nitrogen varied.

Simulation runs using the model were carried out to determine the relationship between the concentration of inorganic nitrogen in the runoff and area of treatment system. All other parameters were kept constant. The expected result from such runs was as follows: as the area increased, the concentration of inorganic nitrogen in the runoff decreased.

The simulation runs in general showed the expected results, but at times in a confusing way. The confusion was due to the model structure, that is, nitrogen loss due to plant growth is not a direct function of nutrient movement from applied nutrient mass to the nutrient sink. In the model, inorganic nitrogen lost through plant growth is expressed directly in the variation of the amount of exchangeable inorganic nitrogen in the nutrient sink. The nitrogen from the nutrient sink is therefore utilised by the plants and as might be expected as the treatment area increases the amount of exchangeable nitrogen in the nutrient sink decreases and again during the high plant growth period the nitrogen levels in the nutrient sink decrease.

The change in the mass of inorganic nitrogen in the nutrient sink due to plant growth will have an effect upon the movement of inorganic nitrogen from the applied nutrient mass into the nutrient sink. It follows that such movement would have the appropriate corresponding effect upon the concentration of inorganic nitrogen in the runoff. Such information as knowing the relationship between area and concentration of nutrient in runoff is important in determining the area needed for the treatment system.

The only other separate component of the model to be discussed is the plant growth model. The plant growth model is the second most important aspect of the overland flow model in respect to nitrogen loss from the system.

Figure 3.5 represents the yield due to plant growth given the various inputs. The value 12455 kg/ha is an estimate of the plant biomass at maturity and 2504 kg/ha is an estimate of the plant biomass after cutting. Yields obtained from the model compare favourably with yields from studies of pasture growth of the same grass species, perennial ryegrass, from the literature (Brougham, 1955)

Figure 3.6 represents the amount of inorganic nitrogen lost to plant growth. An interesting management concept arises from Figure 3.6. An improvement in the loss of inorganic nitrogen from the treatment system by plant growth could be achieved by increasing the number of cuttings per treatment period. From the results of Figure 3.6, to achieve improved inorganic nitrogen loss by plant growth, the grass should be cut approximately every seven to eight weeks. There may be practical limitations to an increased cutting rate. A discussion of such limitations is outside the scope of this study.

3.1.7 Discussion of Modelling Method

The basis of the discussion on the modelling method will be concerned with the deterministic model that was derived using the reductionist modelling approach and its application to the objectives stated in section 3.1.1. There are a number of positive aspects of the deterministic modelling method.

1. The attempt at quantifying a process improves the qualitative level of understanding of that process because it is necessary to carefully consider the relationships between variables.
2. Processes of the system being modelled that are either poorly defined or not well understood become readily apparent.
3. Assuming processes are accurately modelled, the method gives some indication of the relative importance and/or sensitivity of a particular process in reference to the other processes of the model.

There are a number of negative aspects of the deterministic modelling method.

1. In a reductionist form of modelling, problems may occur when processes defined and/or modelled in isolation are combined to formulate the behaviour of a complete system. It can be strongly argued (Young 1977) that for complex systems the overall system behaviour cannot be described by a combination of a large number of sub models.
2. The modelling method under study has modelling limitations, especially in regards to the model's ability to represent the real behaviour of a system, for example:

   a. simply increasing model complexity does not in the long run achieve further model realism, for there becomes a point when other factors such as model robustness begins to decline;

b. it is virtually impossible to define specifically all elements of an environmental system, due in part to the inherent stochastic nature of certain elements; thus, such elements may render deterministic projections inaccurate.

When dealing with a poorly defined system, it may be more appropriate to use alternative modelling techniques. One such example is the modelling work of Young (1977).

The conclusion drawn from the modelling exercise in relation to the set objectives is that overland flow has the 'theoretical' potential to function as a competitive wastewater treatment system. The model indicates that overland flow has the capacity to remove specific nutrients from wastewater.

Justification of the deterministic model in response to the set objectives cannot be evaluated until confidence in the model itself is determined. A practical approach to determine model confidence is to use a stochastic analysis to assess the uncertainty associated with the nominally 'deterministic' process and parameters that define the model. This approach has been used by Spear and Hornberger (1978) to test the sensitivity of various parameters of a phosphorus based model of nuisance algal growth, and could be applied to the overland flow model presented in section 3.1 of this study. This type of analysis would provide an indication of the sensitivity of predictions to uncertainty in the model and consequently could be used to assess whether current knowledge about processes is sufficient to use such a model as an aid in decision making.

3.2 Time Series Analysis

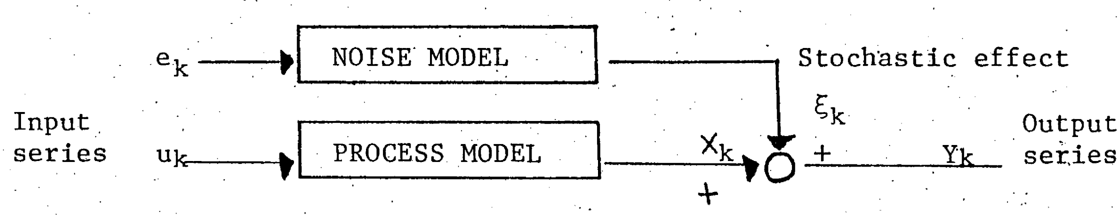
Time series analysis provide a holistic approach to the modelling of environmental systems. In the holistic approach, the system is modelled as a complete entity, and the models are derived directly from and validated against the observed data (Young 1977). In addition, time series models characterise the system's basic physical nature by describing the dominant modes of behaviour. The holistic approach has been widely used in the modelling of badly defined systems (Young 1977).

The model presented in this section can be referred to as a time series or black box model. The time series model is from a class of linear time series models introduced by Box and Jenkins (1970), and applied in modified form by Young (1977) and Whitehead (1976, 1977) to environmental systems. The black box model refers to a model in which it is assumed that all the complex mechanisms operating within a system combine to yield a relatively simple or low order system response.

3.2.1 Time Series Model

The time series transfer function or black box representation appears in Figure 3.7.

FIGURE 3.7 TIME SERIES TRANSFER FUNCTION REPRESENTATION



This black box representation is composed of two models - the 'process model' (also called the deterministic control model (Young 1977)) and the 'noise model'. The output of the black box model is a function of the inputs, u_k which is deterministic and measurable and e_k which is purely stochastic 'white noise'. The models which can be characterised by 'transfer functions' relate the input variables to output variables for each model respectively (Box and Jenkins 1970).

The 'process model' characterises the deterministic aspects of the system's behaviour. Information on the uncertainty of the model parameters is obtained using statistical methods of parameter estimation. The 'noise model' describes the stochastic nature of unavoidable uncertainties such as measurement error or system disturbances not explained by the process model. It is the addition of this stochastic component to the final model along with the statistical reference to uncertainty that differentiates time series analysis from other more conventional modelling techniques.

The mathematical details of the time series models are given elsewhere (Young 1974), but a simple first order representation of the process model is of the form:

$$X_k = -a_1 X_{k-1} + b_0 u_k$$

where X_k is the model output at time k;

u_k is the observed input at time k;

and a_1 and b_0 are parameters that characterise the model and have to be estimated from the observed input and output data.

The observed system output Y_k is the sum of the process output X_k and the stochastic noise component ξ_k, that is,

$$Y_k = X_k + \xi_k.$$

The time series model is identified and estimated using recursive methods of time series analysis (Young 1974) and a computer programme package CAPTAIN. CAPTAIN is an abbreviation for "Computer aided procedure for time series analysis and identification of noisy processes" (Mutch 1976) available in the Centre for Resource and Environmental Studies (CRES). For a more detailed explanation of time series analysis with examples of application to real problems see Young (1977) and Whitehead (1976).

3.2.2 Objectives of modelling exercise

Objectives of the time series analysis are as follows:

1. to develop simple models for an overland flow wastewater treatment system based on the analysis of observed data;
2. to analyse observed data from Werribee by time series analysis to extract information in respect to the overland flow wastewater treatment system;
3. to see how the holistic approach can be applied to the modelling of environmental systems.

3.2.3 Description of Input, Output Data

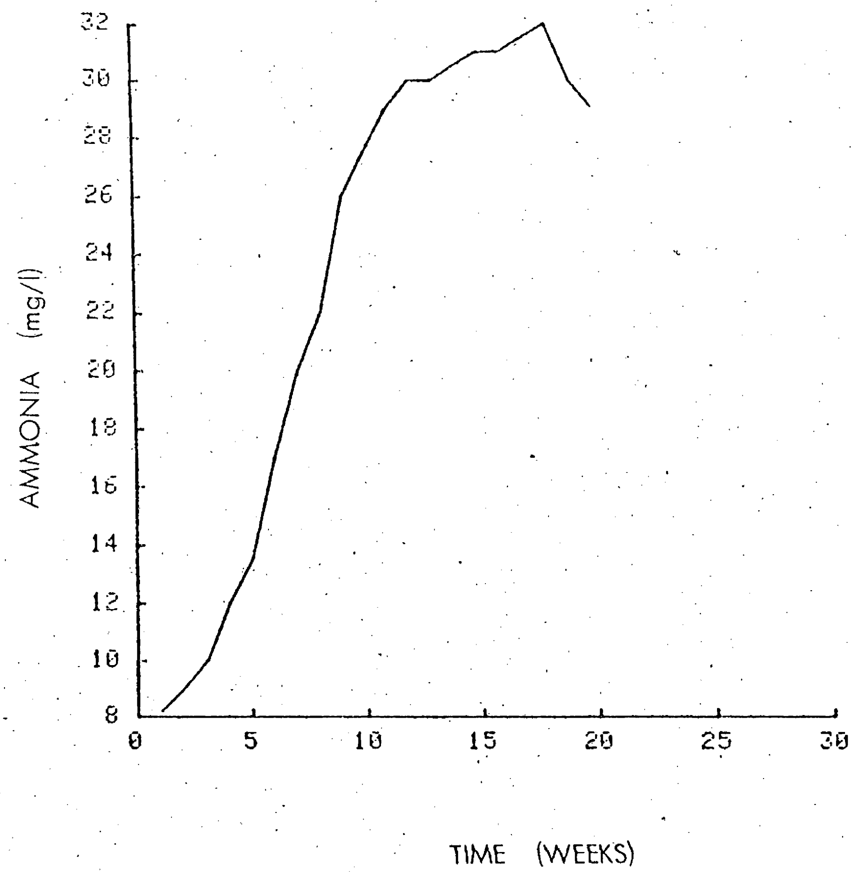
Figures 3.8 and 3.9 show the concentration of ammonia and nitrite added to nitrate (nitrite, nitrate) from the respective outlets during the period of overland flow at Werribee Farm. In wastewater an equilibrium exists between ammonium (NH_4^+) and ammonia (NH_3) as represented by equation (4) (Lance 1972, p.1353).

(4) $$NH_4^+ + OH^- \rightleftharpoons NH_3 + H_2O$$

The concentration of the substances in equilibrium that exist between ammonium and ammonia is dependent upon the pH of the wastewater. It is assumed that the equilibrium that exist between ammonium and ammonia is relatively constant due to stable pH levels in the wastewater. According to Sandford (1977 p.9) the pH of the wastewater entering Werribee Farm ranges between 6.0 and 7.0.

A discussion of the uncertainty that exists on the observed data appears in section 2.4.2. In order to further the justification of the modelling in this section, two assumptions in regards to the observed data are stated as follows:

FIGURE 3.8 CONCENTRATION OF AMMONIA AND NITRITE, NITRATE LAKE BORRIE OUTLET



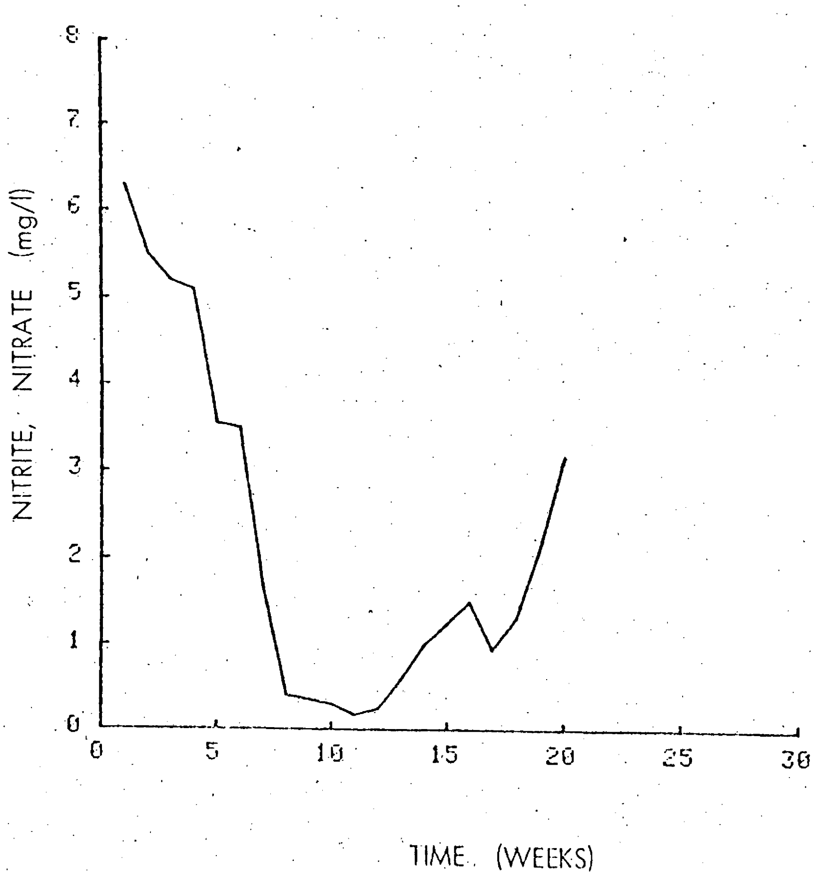
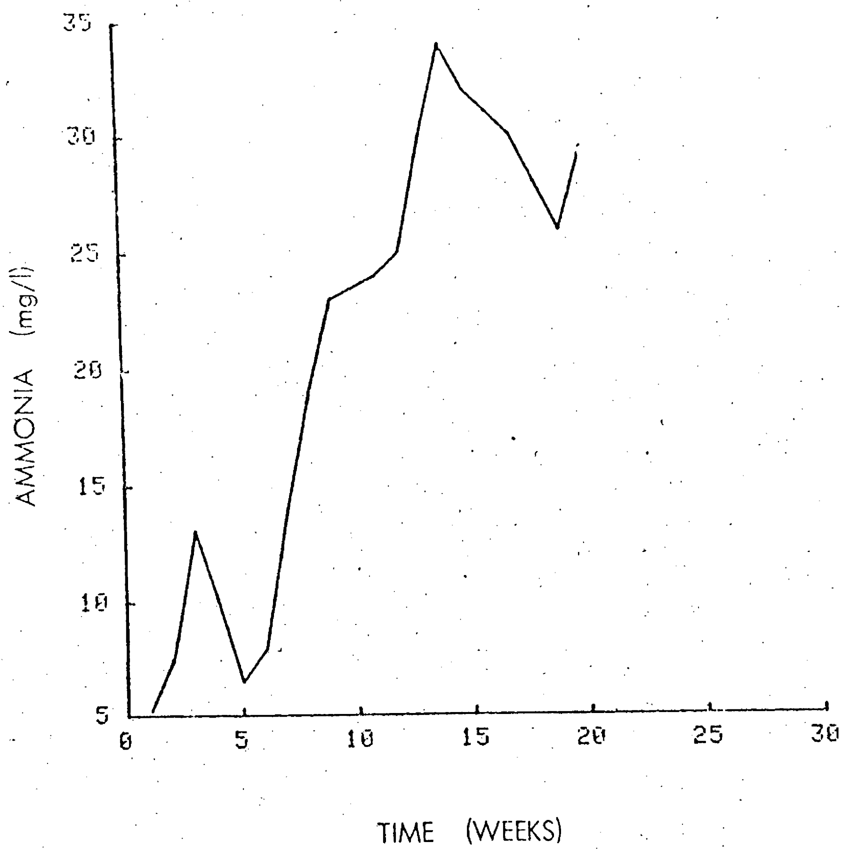
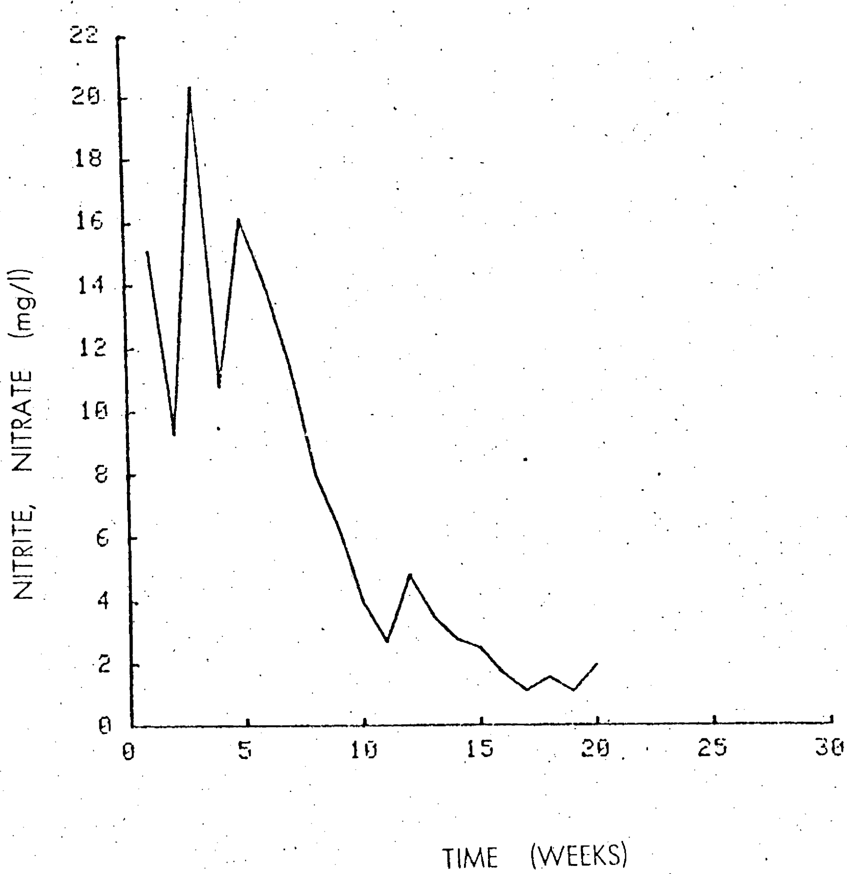


FIGURE 3.9 CONCENTRATION OF AMMONIA AND NITRITE, NITRATE 145W OUTLET





1. the concentration of nutrients in the wastewater applied to the given areas of lagoon and overland flow that drain to a common outlet are relatively constant;
2. the quantity of treated wastewater from the lagoon that drains to the given outlet under study is relatively small and constant.

If these two assumptions are correct, which from an initial analysis of the Werribee Farm treatment system seems to be the case, the results from the time series modelling exercise can be interpreted as representing the behaviour of the overland system under study.

The salient feature of Figures 3.8 and 3.9 are that the concentrations of ammonia and nitrite, nitrate are inversely related. An exception to the description just presented is that in Figure 3.8 the concentration of nitrite, nitrate mid way through the overland flow treatment period begins to increase. In studies by the United States Army Waterways Engineers, on overland flow treatment systems, under continuous flooding, the same variation in concentration between ammonia and nitrite, nitrate has been observed (Hoeppel 1974; Carlson 1974).

One hypothesis to explain such a reversal of concentration is based on the concentration of oxygen in the soil surface of the overland flow system. The process of nitrification, that is, the oxidation of ammonium to nitrite to nitrate proceeds under aerobic conditions. Relative to the rate of nitrification, the concentration of ammonium decreases and the concentration of nitrite, nitrate increases in the wastewater as it moves down the bay. In anaerobic conditions the process of nitrification does not occur; therefore, the concentration of ammonia increases and the concentration of nitrite, nitrate decreases.

If wastewater is continually applied to an overland flow system during the total treatment period, as is the case at Werribee Farm, conditions in the soil soon become anaerobic. Therefore, at the beginning of the overland flow treatment period at Werribee, the soil is basically aerobic and nitrification proceeds. As the soil column becomes more anaerobic, due to the continuous movement of wastewater into the soil surface, nitrification is reduced and eventually ceases when anaerobic conditions are complete. In such a situation, the concentration of ammonia increases and nitrite, nitrate decreases in respect to one another.

In anaerobic conditions, denitrification, that is, the reduction of nitrate to various forms of nitrogenous gas, occurs. Denitrification could be hypothesized as another factor in the decrease in the concentration of nitrite, nitrate during the overland flow treatment period.

In reference to Figures 3.8, 3.9, during the middle to end period of overland flow, the concentration of ammonia begins to decrease and the concentration of nitrite, nitrate increase in respect to one another except in outlet 145 W where a lag exists before the concentration of nitrite, nitrate increases. Such a reversal in concentrations at the end of the treatment period may be due to the change in the proportion of drainage from the overland flow and lagoon systems. The lagoon system at Werribee in general is aerobic; therefore, as the proportion of drainage from the lagoon system increases the concentration of ammonia and nitrite, nitrate at the outlet will change accordingly. The lag period in respect to increasing nitrite, nitrate concentrations in outlet 145W cannot be explained.

3.2.4 Analysis of Data

Only the deterministic structure of the observed data was modelled using the process model described in section 3.2.1. The time series models presented in this study do not characterise the stochastic noise model shown in Figure 3.7. Confidence in the results from the time series models could be weakened due to the small number of samples in the observed data. Small number of samples in observed data leads to relatively poor parameter estimates. In relation to analysis by the CAPTAIN package, as the data set becomes larger confidence in the estimated results increases.

3.2.4.1 Explanation of Time Series Modelling Exercise

For the Werribee outlets, Lake Borrie and 145W, two modelling exercises were set up. The first exercise was to model the system's response to a step input. The second exercise was to model the change in the concentration between ammonia and nitrite, nitrate.

In the first modelling exercise, the step input was the concentration of ammonia in the applied wastewater. Due to the lack of data from Werribee, the step input was characterised as a constant concentration of 45 mg/litre (Sandford 1977, p.9). The output was the concentration of ammonia in the wastewater runoff that drained from the outlet.

In the second modelling exercise, the input and output data were the concentration of nitrite, nitrate and ammonia respectively in the wastewater that drained from the given outlet.

In explanation for all graphs produced from the analysis by the CAPTAIN package, the string of dark circles represents the plot of the output data. The dark line 'attempting' to run through the output data is the plot of the model fit.

3.2.4.2 Results of Time Series Analysis

See results from time series modelling exercise (Figures 3.10, 3.11 and 3.12).

FIGURE 3.10 LAKE BORRIE OUTLET SYSTEM RESPONSE TO STEP INPUT

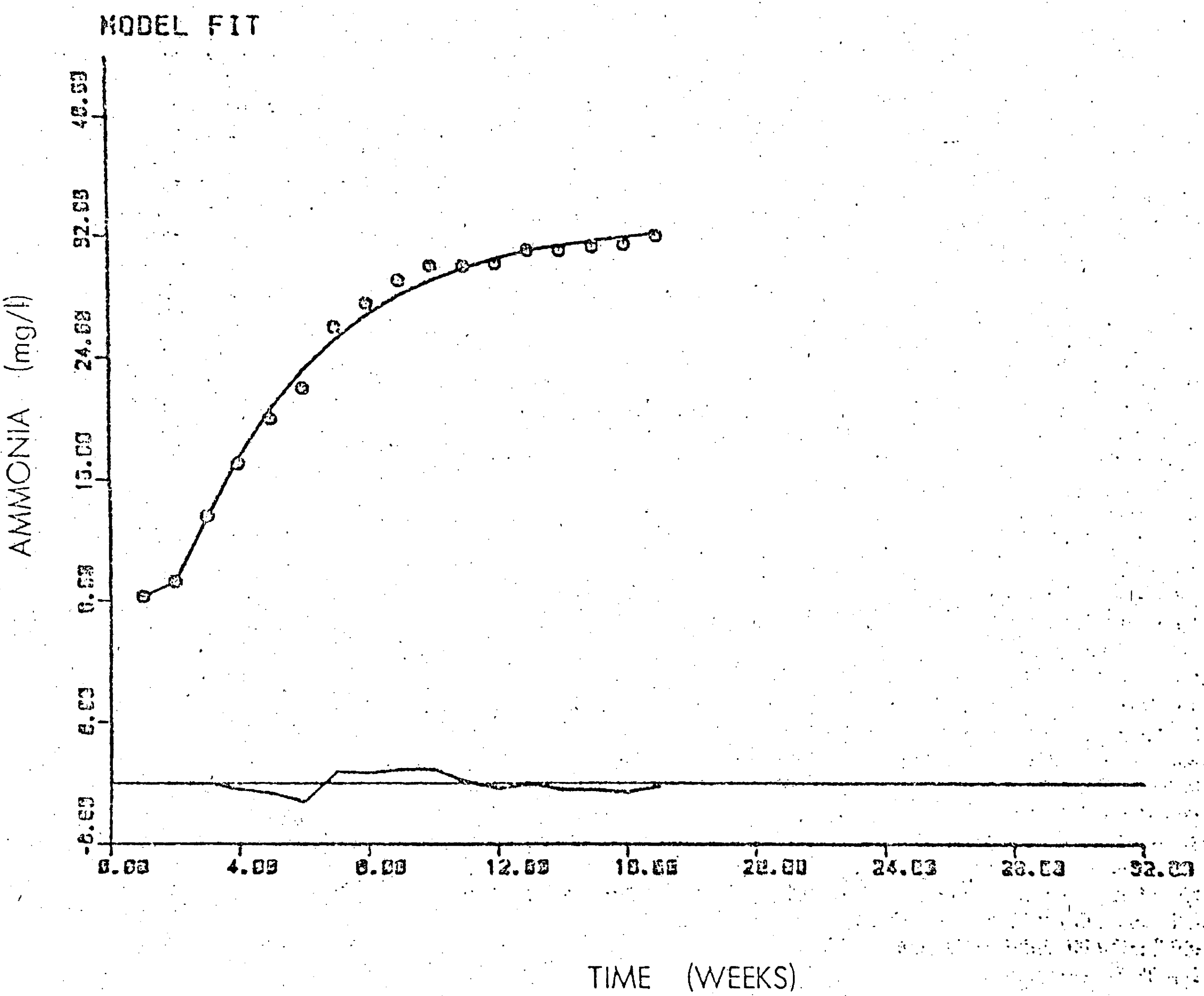


FIGURE 3.11 LAKE BORRIE OUTLET REVERSAL IN CONCENTRATION OF AMMONIA - NITRITE, NITRATE

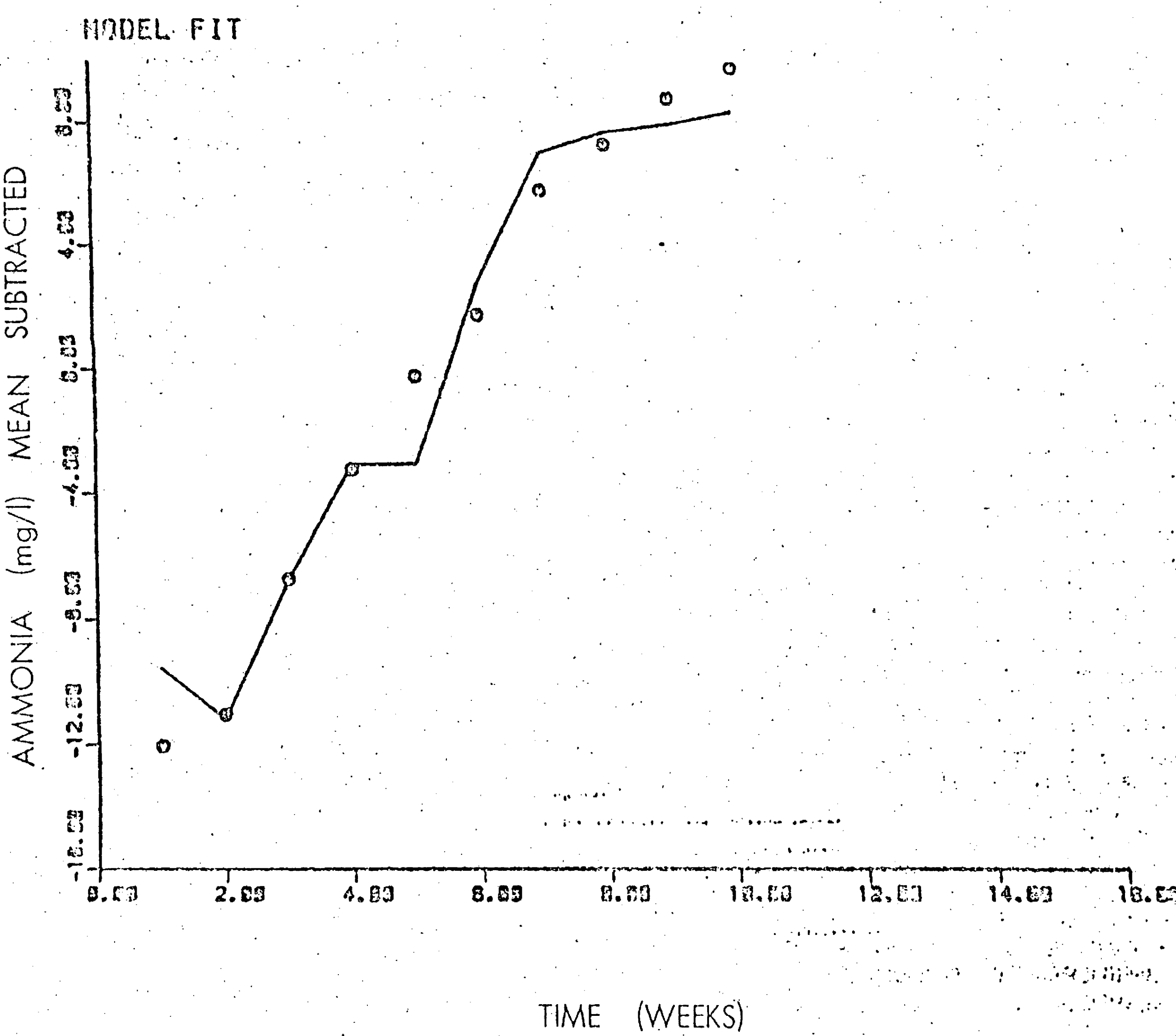
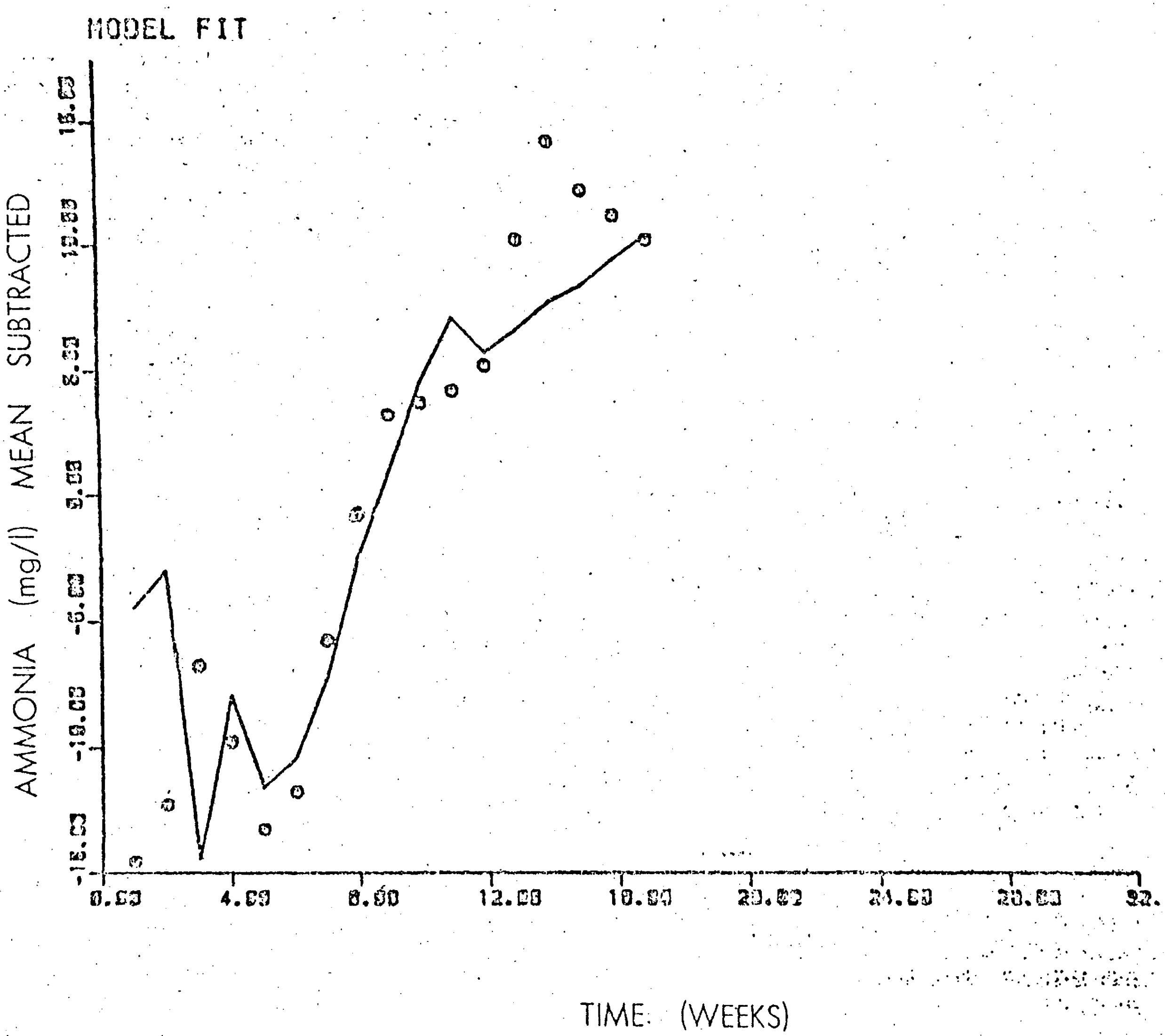


FIGURE 3.12 145W OUTLET

REVERSAL IN CONCENTRATION AMMONIA - NITRITE, NITRATE



3.2.4.3 Interpretation of Results from Time Series Analysis

Modelling exercise - step input to system response Lake Borrie outlet

As shown in Figure 3.10, the model output follows closely the observed system response, and the simple three parameter model adequately characterises the system behaviour. The time constant of 5.8 weeks represents the 'average' time it takes the ammonia to move through the overland flow treatment system. The movement of wastewater through the overland flow system is accurately described in section 2.4. A search of the literature did not reveal an estimate for the time it takes wastewater to move through the overland flow system at Werribee.

The steady state gain suggests that the overland flow treatment system at Werribee disposes of 28 percent of the ammonia applied to the system. Figures from Werribee Farm suggest that removal rates of ammonia from overland flow are between 60 (Seabrook 1975) and 40 (Scott 1977) percent. Kirby (1976, p.14) reports that a study in 1974/75 showed that the overland flow system at Werribee removed 17 percent of ammonia applied. A more reliable estimate of the ammonia lost to the system could have been obtained if actual concentration of ammonia entering the Werribee overland flow treatment system was used as input data.

Modelling exercise - the relationship between the change in the concentration of two substances in wastewater runoff.

Lake Borrie outlet

In order to estimate the parameters of the model, the mean of the input and output data was subtracted from each data set respectively. The mean of the input and output data for Lake Borrie outlet was 2.75 and 20.24 respectively. The fit of the model to the observed data, Figure 3.11 appears 'reasonable'; however, there are large standard errors associated with the estimated parameters, Table 3.1.

The 'average' time of 1.14 weeks for the relative concentration of the two substances to change in respect to one another can be inferred from the time constant of the model.

145W outlet

In order to obtain estimates of model parameters, the means of the input, output data were subtracted from each data set. The mean of the input data was 7.9 and the mean of the output data was 19.7. The fit of the model to the observed data is poor, see Figure 3.12. Considerable uncertainty is associated with parameter estimates as indicated by the standard error, Table 3.1

TABLE 3.1 RESULTS FROM TIME SERIES ANALYSIS MODEL STRUCTURE, TIME CONSTANT, STEADY STATE GAIN

	Mode Structure Parameter estimates (standard error)	Time Constant (weeks)	Steady State Gain
Lake Borrie (system response to step input)	$X_k = +0.96X_{k-1} - 0.133X_{k-2} + .125u_k$ (0.05) (0.05) (0.01)	5.8	0.73
Lake Borrie (Relationship between reversal in concentration)	$X_k = .12X_{k-1} - 2.8u_k$ (0.09) (0.28)	1.14	-3.23
145W (Relationship between reversal in concentration)	$X_k = 0.33X_{k-1} - 1.08u_k$ (0.2) (0.28)	1.48	-1.6

The 'average' time for the change in concentration of the two substances according to the time constant of the time series model was 1.49 weeks.

For the overland flow treatment systems that are drained by Lake Borrie and 145W outlets, the model order is identical but parameter estimates are different. This suggests that the two treatment systems differ by some unknown feature, be it chemical, physical, or biological.

For example, features that could modify the system's behaviour such that time constant and steady state gain of the estimated models of the two systems differ are land area, soil type, and/or vegetation cover. Further study is needed to investigate the features that exist between the treatment systems that might account for the difference in behaviour.

Time series models are derived directly from the data; therefore, they characterise the inherent dynamic nature that exists within the data. The description of the system's behaviour by the time series models presented in this section is based on available observed data. The model's description of the system can only be as good as the descriptive nature inherent in the data from which it was derived.

One method to improve model performance is to increase the number of samples in the data. In reference to the time series analysis in this section, to improve model description of the system's behaviour, a worth while exercise would be to increase the sampling interval to two samples per week. Such action would increase the number of samples and assurance that the dynamics of the system's behaviour is actually characterised in the data.

3.2.5 Extensions to Modelling Exercise

In order to maintain an accurate and correct characterisation and description of the system, continual reassessment of the time series model by new data from the system is required. Therefore, the models presented in section 3.2.4.3 must be continually evaluated by data, other than that used in the identification and estimation studies. Such a procedure is referred to in time series analysis as model validation.

Further information in regard to an increased understanding of the overland flow wastewater treatment system at Werribee could be obtained, assuming suitable data is available, by the application of time series analysis to the input, output data listed below:

a. flow of wastewater in ⟶ flow of treated wastewater out

b. total mass of substance in ⟶ total mass of substance out.

Substances of importance that could be considered in equation (b) are total nitrogen, phosphorus, organic matter, and heavy metals.

3.3 Conclusion to Modelling Section

In this section, the holistic and reductionist approach to the problems associated with the modelling of environmental systems is discussed.

Due to their size and complexity, environmental systems are subject to a wide degree of uncertainty. Such uncertainty exists in many forms, for example:

1. mechanisms which make up the total system are often poorly understood;
2. data which is collected to further improve understanding of the system is often inaccurate.

3.3.1 Holistic Modelling

The holistic approach circumvents to some extent the uncertainty problem of environmental systems by characterising the total physical nature of the system within a stochastic framework. The time series analysis approach does not describe each mechanism specifically, but integrates and aggregates mechanisms and variables respectively, and in a simple linear, dynamic model describes the dominant modes of behaviour. The techniques of parameter estimation and identification provide a statistical analysis of uncertainty and yield simple models with a low number of parameters.

The stochastic disturbances and measurement error associated with environmental systems are modelled using the 'noise model' of the time series transfer function. The noise model characterises the relationship between 'white noise' and the residual between the observed data and the output of the deterministic model. The stochastic model is combined with the deterministic model to formulate the complete time series model.

The formulation, that is identification and parameter estimation, and interpretation, in a physical sense, of the results from a time series model is not an easy task. In order to formulate and interpret time series models, the analyst must have a high level of expertise and experience in time series analysis.

Model identification and estimation may be difficult, if not impossible, if an analyst attempts to fit a linear time series model to a non-linear system. Difficulties can also occur when attempting to interpret the physical meaning of the results obtained from the time series model. The model's level of descriptive ability is strongly dependent upon the quantity of data available and the level of confidence associated with that data. Physical interpretation from time series models may be limited if behaviour originating from a specific process of the system is to be described or parameter estimates are statistically suspect.

3.3.2 Reductionist Modelling

Deterministic models constructed by the reductionist approach do not account for the stochastic nature or uncertainty of environmental systems. Normally there is no attempt to statistically evaluate parameters for uncertainty as done by Spear and Hornberger (1978). The classical methods of parameter tuning and deterministic sensitivity analysis have little effect upon reducing uncertainty in deterministic models constructed by the reductionist approach.

Models derived from the reductionist approach are often highly complicated; such complexity may lead to problems. There is the trap that the analytical construction of the model becomes so involved, interesting and challenging, that the analyst may become so absorbed in the model itself that model objectives are lost sight of. Other problems that may occur due to the complexity of models derived from the reductionist approach are as follows:

1. detail of the model often cannot be reconciled in relation to available data (Whitehead 1977, p.17);
2. it is often difficult to transform results from a complex model so that they can be effectively and efficiently used by planners and/or designers;
3. the analyst can at times be misled into believing that the model represents more than what it is truely capable of.

Modelling carried out carefully, sensibly, and intelligently, is one way to characterize and/or describe an environmental system. As stated by many authorities such as Newsome (1975, p.6), in order to achieve maximum benefit from the model, its limitations must be fully understood.

The most important criteria in selecting a model are the objectives established to resolve the specified problem. The model must be consistent with the objectives. For example, holistic models would most likely be better suited to objectives that emphasise general management and/or control; whereas, reductionist models would be better suited to objectives that emphasise a detailed physical mechanised analysis of a specific process.

It is also extremely important, in terms of modelling technique, to have a good general understanding of the physical make up of the system being modelled. Such an understanding will improve and simplify both model construction and interpretation of results. An accurate understanding of the environmental system under study will increase the assurance that the type of data, sampling time interval, and method of analysis is correct.

CHAPTER 4
CONCLUSION

4.1 Summary of Findings from the Modelling Chapter

Findings from the deterministic reductionist modelling section can be summarized as follows:

1. Climatic factors play an important part in the design of land treatment systems. The model demonstrates that the loss of water from the treatment system is dependent upon evaporation.
2. In a theoretical sense, the basis of which is scientific experimentation, the capacity exists in the overland flow system at Werribee Farm to remove nutrients in the form of nitrogenous compounds from wastewater. The actual amount that the system is capable of removing is questionable due to the level of uncertainty associated with the mechanisms of the system and the available data.
3. From the model analysis, a fruitful area to investigate in relation to overland flow treatment systems would be the movement of nitrogen from the applied wastewater into the soil matrix.
4. In a management sense, to increase the quantity of nitrogen removed by plants, the grass in the bays of the overland treatment system when reaching maximum biomass should be cut and removed. From the model analysis of Werribee, this should be done more than once a year.

Findings of the time series modelling section can be summarized as follows:

1. From the time series analysis the overland flow treatment system removed 28 percent of the ammonia applied.
2. According to the time series analysis, the time it takes ammonia to move through the complete overland flow system at Werribee is 5.8 weeks.
3. According to the time series analysis, the changes in the concentration of ammonia with respect to changes in the concentration of nitrite, nitrate, take place over a period of one to one and a half weeks.

4.2 Land Treatment of Wastewater

Land treatment is not a panacea for the treatment of wastewater, but a land treatment system, properly designed for a given environment, is worth considering as a vialable wastewater treatment system. Land treatment appeals to modern communities in that they are based on a simple re-cycling technology and have beneficial environmental effects. Compared to conventional treatment systems, assuming identical treatment standards are achieved, land treatment is cost effective either as a primary, secondary (Seabrook 1975) or tertiary (Young 1974, p.6) treatment unit. Conventional wastewater treatment systems compared to land treatment systems are also technologically more complex and energy intensive.

Many areas in Australia have suitable environmental conditions for the successful renovation of wastewater by land treatment. Essential conditions for land treatment systems include large areas of underdeveloped land, sunshine, and a need to conserve water.

Ample technical information exists for designing (EPA 1977), evaluating (EPA 1975) or gaining a general perspective (EPA 1976 a,b,c) on land treatment systems. The technology of land treatment is variable enough for effective land treatment systems to be established in a wide range of environments. For land treatment to be successful, it must be designed specifically for a given environment, and managed correctly.

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APPENDIX A
DETERMINISTIC MODEL

A.1 Listing and description of model variables and parameters.

WATER BALANCE PROGRAMME

A1	Actual evapotranspiration coefficient
T	Total amount of water added to the system per time unit (ML/ha/day)
M1	Soil moisture content in previous time period (ML/ha/day)
M	Soil moisture capacity (ML/ha)
M2	Dummy variable (%)
M7	Level of soil block saturated before wastewater applied (ML/ha)
M9	Dummy variable
W	Water loss (ML/ha/day)
S	Net water gain or loss to system (ML/ha/day)
D	Drainage flow from treatment system (ML/ha/day)
D1	Drainage flow from treatment system (l/ha/day)
D1	Drainage of total treatment system (l/day)
D2	Drainage of total treatment system (l/day)
P2	Potential evapotranspiration coefficient

AMMONIUM ION ADSORPTION PROGRAMME

B	"AAR" (ammonium ion adsorption ratio)
E2	"EAP" (exchange ammonia percentage)
N5	Number of mg-nitrogen (Ni)/100 gr of soil
V	Volume of block of soil
N6	Number of mg-Ni/fixed/ha
N7	Number of kg-Ni/fixed/ha

INFLUENT PROGRAMME

L	Flow of applied wastewater into the treatment system (1/day)
L2	Number of (1/ha/day) of applied wastewater
M4	Mass of applied nutrient for present time period (mg-Ni/ha/day)
K	Mass of applied nutrient for present time period (kg-Ni/ha/day)

DENITRIFICATION PROGRAMME

F1	Dummy variable
F2	Per cent of nitrogen lost with respect to temperature (mg-Ni/day)
N9	Loss of nitrogen from the system due to denitrifciation (mg-Ni/ha/day)
P	Remaining nitrogen in applied nutrient mass after loss of nitrogen due to denitrification (mg-Ni/ha/day)
P1	Nitrogen in applied nutrient mass lost to nutrient sink (mg-Ni/ha-day)
R2	Nitrogen runoff (mg-Ni/ha/day)

PLANT GROWTH PROGRAMME

F3	Function relating temperature to growth rate (kg/ha)
Y3	Yield in present time period (kg/ha)
D5	Weekly yield (kg/ha)
N8	Nitrogen lost due to plant growth (mg-Ni/ha/day)
N2	Nitrogen lost per week (kg/ha)
N9	Accumulated weekly nitrogen lost by plant growth (kg/ha)
N3	Accumulated total of nitrogen lost by plant growth (kg/ha)

NUTRIENT SINK

S2	Total exchangeable nitrogen in nutrient sink (mg-Ni/ha)
S1	Exchangeable nitrogen in nutrient sink after plant growth (mg-Ni/ha)
L3	Amount of nitrogen lost from nutrient sink (mg-Ni/ha)
L4	Nitrogen to ammonium adsorption (mg-Ni/ha)
L5	Excess ammonium adsorption capacity after nitrogen fixation (mg-Ni/ha)
A2	Calculated ammonium ion adsorption value (mg-Ni/ha)

NUTRIENT SINK (Continued)

R1 Nitrogen runoff due to ammonium ion adsorption capacity being filled (mg-Ni/ha)

R3 Total runoff (mg-Ni/ha/day)

R4 Concentration of nitrogen in runoff (mg-Ni/l)

INPUTS

WATER BALANCE PROGRAMME

Maximum soil storage water capacity (mm)

Soil block saturated (%)

Area of one hectare (sq m)

Total number of hectares of the treatment system

AMMONIUM ION ADSORPTION FIXATION PROGRAMME

Cation exchange capacity of soil (me/100 gr of soil)

Concentration of inorganic nitrogen in applied wastewater (me/l)

Concentration of calcium ion in applied wastewater (me/l)

Concentration of magnesium ion in applied wastewater (me/l)

Molecular weight of nitrogen

Density of soil (kg/l)

Depth of treatment system (m)

INFLUENT PROGRAMME

Concentration of nitrogen in applied wastewater (mg-Ni/l)

PLANT GROWTH PROGRAMME

Maximum growth rate of plant (kg/kg/day)

Maximum biomass of treatment system before cutting (kg/ha)

Minimum biomass of treatment system after cutting (kg/ha)

Percent of nitrogen in plant

NUTRIENT SINK

At start of programme, initial source of Ni in soil (mg-Ni/ha)

Initial source of nitrogen in soil (mg-Ni/ha)

At start of programme, maximum ammonium adsorption (mg-Ni/ha)

A.2 Detailed explanation of overland flow model

A.2.1 Calculation of constants used in the overland flow model

Water Balance Model

In this section of the overland flow model, the maximum soil moisture capacity of one hectare block (depth of block is determined by input parameter) is calculated. Table A.1 can be used to determine the point source maximum soil storage water capacity.

TABLE A.1 ESTIMATING AVAILABLE SOIL WATER STORAGE CAPACITY FOR DIFFERENT SOIL MATERIALS AND HORIZON THICKNESSES

Soil Material	Available Soil Water Storage Capacity per			
	12in	20in	25in	27in
Gravel	0.50	0.85	1.00	1.10
Sand	0.75	1.25	1.50	1.70
Loamy sand, coarse fibrous peat	1.00	1.70	2.00	2.25
Compact heavy clay	1.25	2.10	2.50	2.80
Sandy loam, compact clay loam to clay	1.50	2.50	3.00	3.40
Loam	1.75	3.00	3.50	4.00
Friable clay to heavy clay	2.00	3.40	4.00	4.50
Organic loamy sand to organic sandy loam	2.00	3.40	4.00	4.50
Friable clay-loam	2.25	3.85	4.50	5.10
Organic sandy clay-loam to organic clay	2.50	4.25	5.00	5.60
Peaty loam to peaty clay	2.75	4.65	5.50	6.20
Well decomposed peat	3.00	5.10	6.00	6.75

From Haantjens (1969)

To determine the initial level of soil block saturated before wastewater is applied, the maximum soil moisture capacity is multiplied by an input parameter - percent of soil block saturated. The level of the soil block saturated with water is obtained and transferred to the water balance programme where the parameter under discussion becomes the initial soil moisture capacity for the start of the programme.

Ammonium Ion Adsorption model

The ammonium ion adsorption model calculates the amount of ammonium ion that can be adsorbed (fixed) by the soil matrix. The method used in the model to calculate ammonium ion adsorption comes from Lance (1972, p.1354). A brief description of the method appears below. The value obtained from the calculation is used in the nutrient sink model.

AAR
Ammonium Ion Adsorption Ratio

$$\text{AAR} = \frac{[NH_4^+]}{\sqrt{\frac{1}{2}\left([Ca^{++}] + [Mg^{++}]\right)}}$$

EAP
Exchange Ammonia Percentage

$$\text{EAP} = \frac{100\ (0.036 + 0.1051 \times \text{AAR})}{1 + (0.036 + 0.1051 \times \text{AAR})}$$

$$\text{mg } NH_4\text{-} N/100 \text{ g Soil} = \text{EAP} \times \text{CEC} \times \text{AMU}$$

where CEC = Cation Exchange Capacity
AMU = Atomic Mass of nutrient under consideration

The product of the above equation is then converted into milligrams of nitrogen fixed per hectare.

A.2.3 Hydrological Model

The model structure is organized into three stages.

Stage 1

By adding together rainfall and flow of applied wastewater, the total amount of water added to the system per time period is calculated.

Stage 2

Water loss from the system, other than by drainage and percolation, is by evapotranspiration. Evapotranspiration is calculated using the programming logic in WATBAL (Keig 1974). For a good description of the logic see McAlpine (1970, p.484). The logic is as follows: to calculate evapotranspiration, pan evaporation is multiplied by the potential evapotranspiration coefficient as suggested by McAlpine (1969, p.70). To obtain a more accurate value of evapotranspiration, the value of evapotranspiration is multiplied by the actual evapotranspiration coefficient which is a step function relating evapotranspiration to soil moisture capacity.

Stage 3

Drainage from the system is dependent upon the following factors: amount of water added and lost per time period to the system; maximum soil moisture capacity and soil moisture in the previous time period. By subtracting water loss (evapotranspiration) from the water gain (applied wastewater and rainfall), net water loss or gain from or to the system is obtained. Drainage from the system is determined by subtracting the difference between maximum soil moisture capacity and soil moisture capacity in previous time period from net water loss or gain. If drainage is positive, soil moisture capacity for next time period is set equal to maximum soil moisture capacity.

If drainage is equal to or less than zero, the soil moisture content for the next time period is adjusted according to the value of net water loss or gain.

A.2.4 Influent Model

This section of the model calculates, given the flow and concentration of nutrient in the applied wastewater, the nutrient mass entering the overland flow system.

A.2.5 Denitrification Model

The denitrification model calculates the loss of inorganic nitrogen from the applied nutrient mass. In the model, the nitrogen loss due to denitrification is affected by two environmental factors - oxygen content of soil and temperature. If the soil moisture content is less than or equal to sixty percent, the loss of inorganic nitrogen by denitrification is zero. Studies by Wijler (1954, p.160) demonstrate that denitrification increases with increasing soil moisture content. The increase in soil moisture content affects the diffusion rate of oxygen. Broadbent (1965, p.349) states that even if other conditions are favorable, little loss of nitrogen occurs from denitrification until the soil moisture content is sixty percent or greater.

If soil moisture content is greater than sixty percent the effect of temperature on denitrification is calculated. The logic and data for quantifying the effect of temperature on denitrification occurs in the paper by Nommik (1956, p.195). Depending upon the temperature, the model selects the correct regression to calculate the percent of nitrogen lost. The actual loss of nitrogen by denitrification is obtained by multiplying the applied nutrient mass by the percent lost due to maximum denitrification by the temperature adjustment percentage. Many authorities Lance (1972, p.1353) and Broadbent (1965, p.349) have suggested that fifteen percent is a realistic value for the maximum amount of nitrogen lost from the applied nutrient mass due to denitrification.

Nitrogen loss from denitrification is then subtracted from the applied nutrient mass. A percentage of the remaining applied nutrient mass goes to the nutrient sink model; the remainder is runoff. If drainage from the water balance model is zero, no nutrients are lost to runoff. The total value of the remaining applied nutrient mass goes to the nutrient sink model.

A.2.6 Plant Growth Model

The plant growth model calculates the amount of inorganic nitrogen lost due to the growth of plants. The rate of plant growth and hence nitrogen uptake is dependent on the environmental factor temperature. The logistic equation modified to a simple recursive form is used in the model to calculate the yield. By subtracting the yield of the previous time period from the yield of the present time period, the weekly yield is obtained. Inorganic nitrogen lost by plant growth is obtained by multiplying the weekly yield by the percent nitrogen in the plants biomass.

A.2.7 Nutrient Sink Model

This model calculates the amount of inorganic nitrogen in the soil matrix and the concentration of inorganic nitrogen in the runoff that drains from the treatment system. The total exchangeable inorganic nitrogen in the soil matrix for the present time period is obtained by adding the percent of inorganic nitrogen lost from the applied nutrient mass from the denitrification model to the initial source of inorganic nitrogen present in the soil matrix. From the total exchangeable nitrogen in the nutrient sink is subtracted the amount of inorganic nitrogen lost due to plant growth. The difference from the above subtraction shall be referred to as the remaining inorganic nitrogen in the nutrient sink.

If the remaining nitrogen in the nutrient sink is less than the initial source of inorganic nitrogen, the difference is found and the value for the source of inorganic nitrogen in the nutrient sink for the next time period is adjusted. The nutrient mass runoff for the nutrient sink model becomes zero.

If the remaining inorganic nitrogen in the sink is greater than the initial source of nitrogen, the difference is found and the value of the initial source is reset to its input value. The 'excess' inorganic nitrogen from the subtraction in the first sentence of this paragraph is subtracted from the ammonium ion adsorption capacity of the system. If the ammonium ion adsorption capacity is exceeded, the calculated ammonium ion adsorption value of the present time period is subtracted from the ammonium ion adsorption capacity of the system, the difference being the inorganic nitrogen in runoff. If the calculated ammonium ion adsorption value is less than the ammonium ion adsorption capacity, runoff is zero.

To calculate the nutrient concentration of the final runoff, the runoff from the denitrification and nutrient sink programmes are added together. That sum is divided by the drainage from the hydrological model to obtain the final concentration of nitrogen in the runoff.

A.3 Programme Listing

See Listing of Programme, model output.

A.3 Programme Listing

```
100 REMARK DATA TRANS. TAPE TO MACHINE
110 PRINT "NO. OF ROWS FOR EACH ARRAY"
120 INPUT X
130 PRINT "NO. OF COLS FOR EACH ARRAY"
140 INPUT Y
150 DELETE R
160 DIM R(X,Y)
170 FIND 6
180 FOR Z=1 TO X
190 FOR Q=1 TO Y
200 READ @33:R(Z,Q)
210 NEXT Q
220 NEXT Z
230 F=0
240 DELETE F
250 DIM F(X,Y)
260 FOR Z=1 TO X
270 FOR Q=1 TO Y
280 READ @33:F(Z,Q)
290 NEXT Q
300 NEXT Z
310 E=0
320 DELETE E
330 DIM E(X,Y)
340 FOR Z=1 TO X
350 FOR Q=1 TO Y
360 READ @33:E(Z,Q)
370 NEXT Q
380 NEXT Z
390 H=0
400 DELETE H
410 DIM H(X,Y)
420 FOR Z=1 TO X
430 FOR Q=1 TO Y
440 READ @33:H(Z,Q)
450 NEXT Q
460 NEXT Z
469 REMARK ************************************************
470 [illegible]
471 REMARK ************************************************
480 REMARK WATER BALANCE PRO.
490 G1=0
500 D=0
510 D1=0
520 D2=0
530 M=0
540 M1=0
550 M2=0
551 M7=0
552 M9=0
560 P2=0.8
570 S=0
580 T=0
590 W=0
600 REMARK AMMONIUM ION ADSORPTION FIXED PRO.
610 B=0
620 E2=0
630 N5=0
640 REMARK CALCULATION OF NH4 AD (mg/kg/ha)
650 N6=0
660 N7=0
670 V=0
680 REMARK INFLUENT PRO.
690 K=0
700 L=0
710 L2=0
720 N1=0
730 REMARK PRO. TO CALCULATE DENITRIFICATION
740 F1=0
750 F2=0
760 N9=0
770 P=0
780 P1=0
781 R2=0
800 X0=3
810 X1=12
820 X2=55
830 Y0=0.05
840 Y1=0.82
850 Y2=8.44
860 REMARK NUTRIENT SINK
```

```
870 S1=0
880 S2=0
890 L3=0
900 L4=0
910 L5=0
920 R1=0
921 R3=0
922 R4=0
930 REMARK PLANT GROWTH PRO. DRY WT.
940 D5=0
950 E1=2.71
960 F3=0
970 N2=0
980 N3=0
990 N9=0
1000 N8=0
1010 Y3=0
1019 REMARK ************************************************
1020 REMARK INPUTS
1021 REMARK ************************************************
1030 REMARK WATER BALANCE PRO.
1040 PRINT 'MAX. SOIL STORAGE WATER CAPACITY (mm)'
1050 INPUT M6
1051 PRINT 'SOIL BLOCK SATURATED (%)'
1052 INPUT M8
1060 PRINT 'AREA OF ONE HA. (sq.m)'
1070 INPUT A
1080 PRINT 'TOTAL NO. OF HA. OF TREAT. SYS.'
1090 INPUT H1
1100 PRINT
1110 REMARK AMMONIUM ION ABSORPTION PRO. FIXED
1120 PRINT 'C.E.C. IN me/100g. OF SOIL'
1130 INPUT C
1140 PRINT 'CONCENTRATION OF Ni me/l'
1150 INPUT N4
1160 PRINT 'CONCENTRATION OF Ca++me/l'
1170 INPUT C1
1180 PRINT 'CONCENTRATION OF Mg++ me/l'
1190 INPUT M3
1200 PRINT 'MOLECULAR WT. OF Ni'
1210 INPUT M5
1220 PRINT
1230 REMARK AMMONIUM ABSORPTION CAL. Ni AD. (mg+kg/ha)
1240 PRINT 'DENSITY OF SOIL (kg/l)'
1250 INPUT D3
1260 PRINT 'DEPTH OF TREAT. SYS. (m)'
1270 INPUT D4
1280 PRINT
1290 REMARK INFLUENT PRO.
1300 PRINT 'CON; OF Ni IN INFLUENT (mg-Ni/l)'
1310 INPUT I
1320 PRINT
1330 REMARK NUTRIENT SINK PRO.
1340 PRINT 'START OF INITIAL COURCE OF Ni TO SOIL (mg-Ni/ha)'
1350 INPUT I2
1360 PRINT 'INITAL SOURCE OF NITRO. IN SOIL (mg-Ni/ha)'
1370 INPUT I1
1380 PRINT 'START OF MAX. AMMONIUM ION ABSORPTION (mg-Ni/ha)'
1390 INPUT A2
1400 PRINT
1410 REMARK PLANT GROWTH
1420 PRINT 'MAX. GROWTH RATE OF PLANT (mg/mg/day)'
1430 INPUT G1
1440 PRINT 'MAX. BIOMASS OF TREAT SYS. (kg/ha)'
1450 INPUT K1
1460 PRINT 'MIN. BIOMASS OF TREAT SYS. (kg/ha)'
1470 INPUT G
1480 PRINT 'PER CENT OF NITRO. IN PLANT'
1490 INPUT C2
1500 PRINT
1501 REMARK ************************************************************
1502 REMARK CALCULATION OF CONSTANTS
1503 REMARK ************************************************************
1504 REMARK WATER BALANCE PRO.
1505 M=HA*A/10^6
1506 M7=M*M8/100
1507 M1=M7
1508 PRINT
1509 REMARK ************************************************************
1510 REMARK PROGRAMMES
1511 REMARK ************************************************************
1520 PRINT 'NO. OF ROWS FOR PRO. TO RUN.'
```

```
1530 INPUT N
1540 PRINT 'NO. OF COLS. FOR PRO. TO RUN.'
1550 INPUT N1
1560 PRINT
1561 PRINT
1570 FOR Y=1 TO N
1580 FOR X=1 TO N1
1589 REMARK ***********************************************************
1590 REMARK WATER BALANCE PROGRAMME
1591 PRINT 'MONTH-WEEK';Y,X
1592 PRINT
1600 A1=1
1610 T=R(Y,X)*A/10^6+F(Y,X)/H1
1630 M2=T/M*100
1640 IF M2=>0.5 THEN 1660
1650 A1=0.5
1660 PRINT 'ACTUAL ET COEFF.';A1
1670 W=A1*P2*(E(Y,X)*A/10^6)
1680 PRINT 'WATER LOSS VAR. (M1/day/ha)';W
1690 S=T-W
1700 D=S-(M-M1)
1710 IF D>0 THEN 1740
1711 M9=M1
1720 M1=M9+S
1721 D=0
1730 GO TO 1770
1740 M1=M
1770 PRINT 'DRAINAGE (M1/ha/day)';D
1780 D1=D*10^6
1790 PRINT 'DRAINAGE (1/ha/day)';D1
1800 PRINT 'SOIL MOISTURE FOR NEXT MONTH (1/ day)';M1
1810 D2=D1*H1
1820 PRINT 'TOTAL RUN OFF (1/day)';D2
1830 PRINT
1840 PRINT
1849 REMARK ***********************************************************
1850 REMARK AMMONIUM ION ADSORPTION FIXED PRO .
1860 B=N4/SQR(0.5*(C1+M3))
1870 PRINT 'AAR';B
1880 E2=100*(0.036+0.1051*B)/1+(0.036+0.1051*B)
1890 PRINT 'EAP';E2
1900 N5=E2/100*C*M5
1910 PRINT 'ms-Ni/100sr. OF SOIL';N5
1920 PRINT
1930 PRINT
1940 REMARK AMMONIUM ADSORPTION CA,Ni AD.(ms;ks/ha)
1950 V=A*D4
1960 PRINT 'VOL.';V
1970 N6=V*D3/1.0E-3*10*N5
1980 PRINT 'ms Ni FIXED /ha';N6
1990 N7=N6/1000000
2000 PRINT 'ks Ni FIXED/ha';N7
2010 PRINT
2020 PRINT
2029 REMARK ***********************************************************
2030 REMARK INFLUENT PRO.
2040 REMARK CONVERT M1/day TO 1/day (WEEKLY AVER.)
2050 L=F(Y,X)*10^6
2060 PRINT 'FLOW RATE INFLUENT (1/day)';L
2070 L2=L/H1
2080 PRINT 'NO. 1/ha/day';L2
2090 N4=L2*I
2100 PRINT 'ms-Ni/ha/day';N4
2110 K=N4/10^6
2120 PRINT 'ks/ha/day';K
2130 PRINT
2140 PRINT
2149 REMARK ***********************************************************
2150 REMARK DENITRIFICATION PRO.
2151 IF M1/M*100>60 THEN 2160
2152 M9=0
```

```
2153 GO TO 2300
2160 IF X0>H(Y,X) THEN 2200
2170 IF (X0<=H(Y,X))*(H(Y,X)<=X1) THEN 2220
2180 IF (X1<H(Y,X))*(H(Y,X)<=X2) THEN 2240
2190 IF X2<H(Y,X) THEN 2260
2200 F1=0
2210 GO TO 2270
2220 F1=0.085*H(Y,X)-0.17
2230 GO TO 2270
2240 F1=0.177*H(Y,X)-1.3
2250 GO TO 2270
2260 F1=10
2270 F2=F1/10
2280 PRINT '%N. LOST RESPECT TO TEMP. (mg-Ni/day)';F2
2290 N9=M4*0.15*F2
2300 PRINT 'N. LOST DENITRI. (mg-Ni/ha/day)';N9
2310 P=M4-N9
2311 IF D1>0 THEN 2320
2312 P1=P
2313 GO TO 2330
2320 P1=P*0.5
2330 PRINT '% OF NITRO. TO NUTRIENT SINK (mg-Ni/ha/day)';P1
2340 R2=P-P1
2350 PRINT 'NITRO. RUN OFF (mg-Ni/ha/day)';R2
2360 PRINT
2370 PRINT
2379 REMARK ***************************************************************
2380 REMARK PLANT GROWHT PRO.
2390 F3=E1^-(2-H(Y,X)/10)^2
2400 PRINT 'F3';F3
2410 Y3=G1*F3*G*(K1-G)/K1+G
2420 PRINT 'YIELD (kg/ha)';Y3
2430 IF Y3>=G THEN 2450
2440 Y3=G
2450 D5=Y3-G
2460 PRINT 'WEEKLY YIELD (kg/ha)';D5
2470 G=Y3
2480 N2=C2*D5
2490 PRINT 'NITRO. LOST PER WEEK (kg/ha)';N2
2500 N8=N2*10^6/7
2510 PRINT 'NITRO. LOST (mg-Ni/ha/day)';N8
2520 N9=N3+N2
2530 PRINT 'ACCUM. WEEKLY NITRO. (kg/ha)';N9
2540 N3=N9
2550 PRINT
2560 PRINT
2569 REMARK ***************************************************************
2570 REMARK NUTRIENT SINK
2580 S2=P1+I2
2590 PRINT 'NITRO. IN SINK';S2
2600 S1=S2-N8
2601 PRINT 'S1 ';S1
2610 IF S1<=I1 THEN 2710
2620 L4=S1-I1
2630 PRINT 'N. TO AMMONIUM ADSORPTION';L4
2640 I2=I1
2650 L5=A2+L4
2660 A2=L5
2670 IF A2<N6 THEN 2721
2680 R1=A2-N6
2690 PRINT 'RUN OFF (mg-Ni/ha/day)';R1
2700 GO TO 2730
2710 L3=I1-S1
2720 I2=I1-L3
2721 R1=0
2730 PRINT
2740 R3=R1+R2
2750 PRINT 'TOTAL RUN OFF (mg-Ni/ha/day)';R3
2759 IF D1<=0 THEN 2762
2760 R4=R3/D1
2761 GO TO 2770
2762 R4=0
2770 PRINT 'CON. NITRO. RUN OFF (mg-Ni/l)';R4
2780 PRINT
2790 PRINT
2800 NEXT X
2810 NEXT Y
2820 END
```

PRINT OUT OF MODEL OUTPUT

```
RUN
NO. OF ROWS FOR EACH ARRAY
9
NO. OF COLS FOR EACH ARRAY
4
MAX. SOIL STORAGE WATER CAPACITY (mm)
50.3
AREA OF ONE HA. (sq.m)
10000
TOTAL NO. OF HA. OF TREAT. SYS.
1460

C.E.C. IN me 100g. OF SOIL
10
CONCENTRATION OF Ni me/l
2.5
CONCENTRATION OF Ca++me l
2.5
CONCENTRATION OF Mg++ me l
1.7
MOLECULAR WT. OF Ni
14

DENSITY OF SOIL (kg/l)
1.4
DEPTH OF TREAT. SYS. (m)
.125

CON. OF Ni IN INFLUENT (mg-Ni/l)
45.0

START OF INITIAL SOURCE OF Ni IN SOIL (mg-Ni/ha)
4.0E+9
```

```
INITAL SOURCE OF NITRO. IN SOIL (mg-Ni/ha)
4.0E+9
START OF MAX. AMMONIUM ION ADSORPTION (mg-Ni/ha)
2.7E+8

MAX. GROWTH RATE OF PLANT (mg/mg/day)
1.5
MAX. BIOMASS OF TREAT SYS. (kg/ha)
12544.0
MIN. BIOMASS OF TREAT SYS. (kg/ha)
2504.0
PER CENT OF NITRO. IN PLANT
.85

NO. OF ROWS FOR PRO. TO RUN.
9
NO. OF COLS. FOR PRO. TO RUN.
4


MONTH-WEEK1          1

ACTUAL ET COEFF.1
WATER LOSS VAR. (Ml/day/ha)0.05456
DRAINAGE (Ml/ha/day)0
DRAINAGE (l/ha/day)0
SOIL MOISTURE FOR NEXT MONTH (l/ day)0
TOTAL RUN OFF (l/day)0


AAR1.72516389836
EAP21.9487872974
mg-Ni/100gr. OF SOIL30.7283022164
```

```
VOL.1250
mg Ni FIXED /ha5.377452888E+8
kg Ni FIXED/ha537.745288787

FLOW RATE INFLUENT (l/day)9480000
NO. l/ha/day6493.15068493
mg-Ni/ha/day292191.780822
kg/ha/day0.292191780822

N. LOST DENITRI. (mg-Ni/ha/day)0
% OF NITRO. TO NUTRIENT SINK (mg-Ni/ha/day)292191.780822
NITRO. RUN OFF (mg-Ni/ha/day)0

F30.391749875011
YIELD (kg/ha)3681.69306494
WEEKLY YIELD (kg/ha)1177.69306494
NITRO. LOST PER WEEK (kg/ha)58.8846532472
NITRO. LOST (mg-Ni/ha/day)8412093.32102
ACCUM. WEEKLY NITRO. (kg/ha)58.8846532472

NITRO. IN SINK4.000292192E+9

TOTAL RUN OFF (mg-Ni/ha/day)0
CON. NITRO. RUN OFF (mg-Ni/l)0

MONTH-WEEK1          2

ACTUAL ET COEFF.1
WATER LOSS VAR. (Ml/day/ha)0.05456
```

A.4 Environmental Qualification

Below is a list of the processes of nitrogen removal in the land treatment model. Under each process is a list of those environmental factors that do not appear in the overland flow deterministic model. Following each environmental factor is a short, but accurate description of the affect of the factor upon the process it modifies.

Hydrological Model

Factors affecting evapotranspiration

1. type of crop,
2. humidity,
3. length of growing season, and
4. wind velocity.

Ammonium Ion Adsorption Model

The amount of ammonium-nitrogen fixed by the soil matrix can be altered by environmental factors not stated in the model.

	Environmental Factors	Affect on Ammonium Fixation
1.	Temperature	As temperature increases the amount of fixation increases for a temperature range of 0 degrees - 60 degrees C (Nommik 1965, p.209).
2.	Soil moisture	Basically, the drier the soil after application of the ammonium the more ammonium fixed (Nommik 1965, p.209).
3.	Other cations in particular potassium	The concentration of cations in particular potassium has an affect upon the calculation of AAR. Basically, potassium competes with ammonium for the fixation sites on the soil particles. As the concentration of potassium increases, the ability of ammonium to become fixed decreases (Nommik 1965, p.212).
4.	pH	Fixation increases with increasing pH of the soil.
5.	Organic matter	Organic matter in the soil increases the CEC; however, organic matter in the soil has a greater tendency to fix ammonia ions (Lance 1972, p.1354).

Denitrification Model

Environmental Factors	Affect on Denitrification
1. Organic factors $C_6H_{12}O + 4NO_3^- \rightarrow 2N_2\uparrow + 6H_2O + 6CO_2$	Increase in organic matter has an affect of increasing denitrification. Denitrifying bacteria need organic matter as an energy source to maintain metabolic activity to reduce nitrates in the absence of oxygen (Broadbent 1956, p.348).
2. pH	The rate of denitrification is rapid in soil of high pH and slow in soils of low pH.

Plant Growth

Environmental Factors

1. Soil moisture
2. Light intensity and day length

APPENDIX B

SAMPLING PROCEDURE FOR WERRIBEE FARM

(from Victoria EPA Licence)

1. The sampling point shall be as close as is practicable to the discharge point consistent with obtaining a true sample of the effluent.

2. Immediate access to the sampling point shall be available at all times to Officers of the Environment Protection Authority.

3. A figure for the volume of effluent discharged each week to Port Phillip Bay from the discharge point shall be forwarded weekly to the Environment Protection Authority.

4. A device to accurately record the flow of the waste at the point of discharge shall be installed by the first day of February 1976.

5. Within 30 days of the issue of this licence a sampling programme relevant to the waste discharged shall be implemented and carried out by the licencee. That programme shall incorporate the following features:

   (a) At least once in every seven days a grab sample of the effluent taken at the sampling point shall be analysed with respect to the following components or characteristics:

   i. Total organic carbon,
   ii. Biochemical oxygen demand (5 day) unfiltered sample,
   iii. Biochemical oxygen demand (5 day) filtered sample,
   iv. Suspended solids,
   v. Colour,
   vi. pH,
   vii. Nitrate as nitrogen,
   viii. Ammonia as nitrogen,
   ix. Organic nitrogen,
   x. Orthophosphate as phosphorus,
   xi. Total phosphorus.

   (b) At least once in every fourteen days a grab sample of the effluent taken at the sampling point shall be analysed with respect to the following components or characteristics:

   i. Volatile suspended solids,
   ii. Copper,
   iii. Chromium,
   iv. Cadmium,
   v. Iron,
   vi. Lead,
   vii. Mercury,
   viii. Nickel,
   ix. Zinc.

   (c) At least once in every thirty days a grap sample of the effluent taken at the sampling point shall be analysed with respect to the following components or characteristics:

i. Total dissolved solids,
ii. Anionic surfectants,
iii. Oil and grease.

(d) The samples referred to in paragraphs (a), (b) and (c) above shall be identified as to the time and date of sampling.