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Phosphorus and nitrate loss from horticulture on the Swan Coastal Plain

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Abstract

The extent of nutrient loss from nine horticultural properties located on the sandy soils of the Swan Coastal Plain was examined. On three of the properties phosphorus (P) loss was measured by monitoring nutrient loads in shallow drains. On the other six properties networks of monitoring bores were installed and both P and nitrate nitrogen (NO_3-N) concentrations were monitored. All of the properties except one were located on the low phosphate fixing Bassendean sands.

The level of nutrient loss was dependent on crop type, soil type and fertiliser history. Very high concentrations of phosphorus (7.5 to 38 mg/L) were found in the shallow groundwater or drains on six of the nine properties. On the newly developed properties P concentrations in the shallow groundwater increased to high levels within six months to a year. On three of the properties monitored P concentrations were low and similar to concentrations found under surrounding grazing properties. These three properties had either areas of higher phosphate fixing soils or the rate of fertiliser application was low resulting in low levels of residual phosphorus remaining in the soil.

Phosphorus concentrations in the groundwater at the bottom of the superficial aquifer were low under eight of the nine properties. The iron-organic pan or coffee rock layer was believed to have a major influence on the movement of phosphorus to the base of the aquifer.

High levels of P were detected in some of the monitoring bores 50 and 100 m down-gradient of the horticultural production areas.

High to very high NO_3-N concentrations were found in the shallow groundwater beneath the production areas on all of the properties. The World Health Limit for drinking water of 10 mg/L NO_3-N was exceeded under all but one of the properties. However, high NO_3-N concentrations occurred at the bottom of the superficial aquifer under only two of the properties. High NO_3-N concentrations were detected in the shallow groundwater 50 m and 100 m down-gradient of the horticultural production areas on four of the six properties. However, NO_3-N concentrations fell rapidly in the shallow groundwater as water moved away from the two properties located on Joel sands. Significant denitrification appeared to be occurring.

Contents

Introduction

Horticulture is an important industry on the Swan Coastal Plain worth over $100 million per year. A wide range of horticultural crops are grown including vegetables, native and greenhouse flowers, citrus, avocados, stonefruit, grapevines, turf and nursery crops. The majority of production is situated on the sandy soils of the Spearwood and Bassendean dune systems (Bettenay *et al.* 1960). The highest concentration of horticultural properties are located on the outskirts of Perth and in the Myalup and Guilderton areas. However, the total area of horticulture is small, covering less than 1 per cent of the coastal plain. Irrigation water is almost always obtained from the shallow unconfined aquifer.

The problems

Phosphorus and nitrogen enrichment of surface water

Estuaries, rivers, lakes and wetlands on the Swan Coastal Plain are often affected by algal blooms that choke the water, give off foul-smelling gases and may kill fish and wildlife. These blooms are caused by an excess of nutrients, with the major source being run-off and leaching from agricultural land. Horticulture, because it is a high fertiliser user has often been accused of being a major contributor to eutrophication of surface water bodies on the Swan Coastal Plain.

Nitrogen and phosphorus concentrations are two major factors which determine eutrophication of surface water bodies. Phosphorus is generally the limiting nutrient in freshwater ecosystems, while nitrogen may be the primary limiting nutrient in many coastal waters (Ryther and Dunstan 1971). However, this may vary seasonally, for example phytoplankton growth in the Peel–Harvey Estuary, Western Australia appeared to be limited by nitrogen in summer and autumn and by phosphorus in winter and spring (McComb *et al.* 1981).

It is not possible to recommend a single set of nitrogen and phosphorus concentrations that will prevent algal blooms in surface water bodies. However, eutrophication is likely to occur if nutrient concentrations exceed 0.4–0.6 mg/L and 0.04–0.06 mg/L for total N and/or total P, respectively (AEC, 1987).

The soils of the Spearwood Dune System have a significantly greater ability to hold excess P than the deep grey sands of the Bassendean Dune System. The Phosphate Retention Indices (PRI) of the Spearwood soils usually range from about 3 to 6 (Karrakatta sand) to about 7 to 20 (Cottesloe sand). The soils of the Bassendean Dune System generally have a poor ability to retain P (PRIs are close to 0). Phosphorus can readily leach through the soil profile and possibly into the shallow groundwater.

Run-off and associated loss of P attached to sediment rarely occurs on the sandy soils of the Swan Coastal Plain because of rapid infiltration.

Nitrate contamination of groundwater

The sandy soils of the Swan Coastal Plain have a poor ability to hold both water and nitrates. Excess irrigation or rainfall carries nitrates into the shallow groundwater system.

The leaching of nitrate from agricultural land and contamination of groundwater is a major concern. The World Health Limit for drinking water is 10 mg/L of nitrate nitrogen (NO_3-N). Drinking water with high nitrate levels can cause brain disorders, which especially affects infants. The expansion of horticulture over Public Water Supply areas is limited to prevent contamination, though in other areas people drink groundwater where intensive agriculture is pursued. Natural background NO_3-N concentrations within the groundwater under the Swan Coastal Plain are usually less than 0.2 mg/L.

High nitrate levels in the groundwater are also of concern to horticulturalists who use the water for irrigation. In some cases nitrate levels have built up to such levels that irrigation with this water can cause excessive growth or toxic effects on crops.

Past research

Previous monitoring of nutrient loss from horticulture on the sandy soils of the Swan Coastal Plain has been largely limited to groundwater monitoring. Few horticultural properties have a surface drainage system that can be monitored because the majority occur on elevated, well drained land. In 1991, an extensive program of water sampling in drains on the coastal plain was initiated by Agriculture Western Australia. This work included monitoring of the Peel Main Drain which flows through the Mandogalup horticultural area. In 1991 it was estimated that 0.68 kg of P was lost per hectare in this subcatchment (Heady *et al.* 1991). This figure and the P concentration of the water (0.66 mg/L) were lower than expected. Monitoring of drains in agricultural areas, containing beef, sheep and dairy properties showed P loads that usually ranged from 0.5 to 3 kg P/ha/year. In some cases the P loads from agricultural areas have been as high as 14 kg/ha/year with concentrations up to 6 mg/L (Summers *et al.* 1993).

The rate of nutrient loss depends on factors such as the size of the catchment, rainfall, extent of clearing, level of drainage, soil types and fertiliser application rates (Weaver and Summers 1997). Much of the P loss to drains on the Swan Coastal Plain appears to be via shallow groundwater rather than via overland flow bound to soil particles. Kinhill Engineers (1988) estimated that about 50 per cent of P reaching the Peel–Harvey Estuary was from shallow groundwater flow originating from Bassendean sands.

Considerably more work has been published examining the nutrient levels in the groundwater below horticultural properties. Pionke *et al.* (1990) examined the nutrient concentrations in water from horticulturalists' production bores in the Gnangara and Coogee areas. Both areas are located on the Spearwood Dune System. The NO_3-N concentrations in the bores averaged 31.2 mg/L and ranged from 9 to 79 mg/L. McPharlin and Pritchard (unpublished) examined the nutrient concentrations in the production bores of 34 vegetable growers around Perth and found similar results. These properties were located on both the Spearwood and Bassendean dune systems. NO_3-N concentrations ranged from 0.02 mg/L to 88 mg/L and averaged 13.7 mg/L. Phosphorus concentrations were low with a median value of 0.02 mg/L. However on one property a very high P concentration (44 mg/L) was obtained. This sample came from a soak on a market garden which was located on a Bassendean sand. The P concentrations in the production bores of all other market gardens located on Bassendean sands were low. Production bores usually draw water from about 10 m below the top of the aquifer. Nutrient concentrations taken from this depth may be considerably less than those in the top metre or so of the aquifer. Processes such as dilution and phosphate fixation by layers such as coffee rock may result in lower nutrient concentrations further down the aquifer.

Sharma *et al.* (1991) installed lysimeters on two vegetable farms to collect the leachate from below the root zone. On both properties about 40 per cent of the applied nitrogen was collected in the lysimeters. On Farm A, which had a grey phase Karrakatta sand, 12 per cent of the applied P was collected as leachate. On Farm B, which had a higher phosphate fixing Karrakatta sand, far less than 1 per cent of applied P was collected.

These workers also installed a network of monitoring bores up-gradient and down-gradient of the vegetable production area. The bores sampled the top 6 m of the watertable. On both properties the NO_3-N concentrations were high in the bores located under the production area (80 mg/L). However, the NO_3-N concentrations decreased rapidly with increasing distance from the production area, and on Farm A were less than 0.1 mg/L on the down-gradient boundary of the property. It was concluded that on Farm A there was negligible outflow of water and nutrients from the property because of considerable volumes of water pumped from the aquifer for irrigation. This, together with dilution as a result of recharge from pastured land, were used to explain nutrient concentrations in the down-gradient bores. The P concentrations were low in all bores, indicating that the soil was able to sorb all applied P, preventing it leaching into the watertable.

Previous groundwater monitoring of nutrients from horticultural properties has been largely limited to properties located on the Spearwood Dune System. The P retention ability of these soils has resulted in low P levels being detected in the groundwater.

The pale, sandy topsoils of the Bassendean Dune System have a poor ability to hold P. It is on these soils that the risk of P leaching and pollution of the groundwater is greatest.

Significant denitrification may occur under the soils of the Bassendean Dune System (Gerritse *et al.* 1990, Martin and Harris 1982). These soils have high levels of dissolved organic carbon and low redox potentials which create conditions suitable for denitrification. Losses by denitrification on the Bassendean sands may significantly lower groundwater nitrate levels.

Methodology

The extent of nutrient loss from nine horticultural properties was monitored for various lengths of time within the period from 1992 to 1997. The properties were located on the sandy soils of the Swan Coastal Plain around Perth, Western Australia. Eight of the properties were located on the Bassendean Dune System and one of the properties on the Spearwood Dune System. Five of the properties produced vegetables, two flowers, one fruit and one turf. Table 1 provides details of the properties and the methods of monitoring.

Estimates of the quantity of nutrient applied to each property were obtained from the grower. The approximate total amount of nitrogen and phosphorus applied per hectare over the life of the property was calculated.

Nutrient loss from horticultural properties was monitored by two methods. Where a surface drain which collected water from the property was present this was monitored to estimate a P load leaving the property (Properties 1, 2 and 3). Where surface drainage was not present networks of monitoring bores were installed to determine the concentration of nutrients in the groundwater (Properties 4 to 9). In this case a nutrient load leaving the property could not be calculated because the volume of ground-water leaving the property could not be accurately determined.

Samples were analysed at the Chemistry Centre of Western Australia (see Appendix 1 for methods of analysis).

Surface water monitoring

Monitoring sites were set up, within drains both at the exit point of the property and within any drains that entered the property. Property 1 was monitored in both 1992 and 1993 and Properties 2 and 3 were monitored in 1993. Prior to sampling the cross sectional area of the drain at the monitoring site was measured. A rating curve relating stage (water height in the drain) to discharge rate was developed. Once the drain began to flow in winter, water samples and stage were collected twice weekly. Additional tactical sampling was conducted where possible to catch peak flows. This frequency of collection was considered adequate because the sandy nature of the soils in the catchment meant that surface run-off rarely occurred and drain discharges rose and fell gradually.

Sampling concluded in October or November when the drain flows became minimal. The water samples were analysed for total P only. The samples were not filtered so as to measure both soluble and particulate P. Earlier testing showed that the majority of phosphorus in the drains was soluble rather than particulate.

Groundwater monitoring

Networks of monitoring bores were set up in and around Properties 4 to 9 in 1994 and 1995. Advice as to their design, location and installation was given by both the Water Authority of Western Australia and the Geological Survey of Western Australia.

The monitoring bores were installed using a cable tool, auger or rotary air blast drilling rig. They consisted of PVC pipe (40 or 80 mm diameter) with an end cap at the top and bottom. The bottom 2 m of pipe was slotted. Gravel packing was not necessary because the sandy nature of the aquifer meant the bores did not fill with sediment.

The bores were located so as to sample groundwater up-gradient, within the properties and at various distances down-gradient of the production area. The up-gradient bore was used to check whether significant concentrations of nutrient were entering the property. The majority of the bores were installed to sample the top 2 m of the watertable, though at each property one deeper bore was drilled to sample from the base of the superficial aquifer.

The bores were sampled every three months with a submersible electric pump. The sample bottles were kept on ice and taken at the end of the day to the laboratory for analysis. Samples were analysed for total phosphorus, total nitrogen, nitrate-nitrogen, ammonium-nitrogen, sulphate-sulphur, chloride and electrical conductivity. (See Appendix 1 for methods of analysis.)

Table 1. Details of properties which were monitored

Property	Method of monitoring	Soil type*	Depth to water-table	Years farmed	Crops grown
1	Drain	Joel, Gavin, Jandakot	1–5 m	10 years	Avocados Citrus Grapevines
2	Drain	Joel, Gavin	1–3 m	10 years	Vegetables
3	Drain	Joel, Gavin, Jandakot, Herdsman, Karrakatta	1–6 m	A number of properties 10–40 years	Vegetables
4	Bores	Gavin	3 m	2 years	Turf
5	Bores	Gavin, Joel	2–4 m	3 years (new section) 15 years (old section)	Vegetables
6	Bores	Jandakot, Gavin	3.5–7 m	20 years	Vegetables
7	Bores	Gavin	2–5.5 m	10 years	Native and greenhouse flowers
8	Bores	Gavin, Joel	1–2 m	10 years	Roses
9	Bores	Spearwood	1–2.5 m	2 years	Vegetables

* After Bettenay *et al.* (1960).

Results

Nutrient application rates

Table 2 gives the approximate rate of phosphorus and nitrogen applied to the nine properties. The rate of fertiliser applied to different types of horticulture varies greatly. Horticulturalists growing the same crop also apply considerably different amounts of nutrients. Appendices 2 and 3 give recommended upper phosphorus and nitrogen rates, crop removal and residual nutrient for different types of horticulture. The residual nutrient left in the soil after crop uptake is potentially available for leaching and contamination of groundwater. These figures provide a good overview of rates of nutrient that are applied to different types of horticulture and the respective nutrient pollution risks.

Surface water monitoring

Property 1. (Orchard and vineyard)

The P loads leaving Property 1 were monitored in both 1992 and 1993. Figures 1 and 2 show the discharge and P concentration at each sampling date for 1992 and 1993 respectively. In 1992 monitoring was only conducted from the end of July to the middle of September. Phosphorus concentrations ranged from 0.27 to 0.52 mg/L in 1992 and from 0.51 to 0.76 mg/L in 1993.

There was a higher discharge rate in 1992 due to heavy winter rainfall. Table 3 shows the extent of P loss over the monitoring period. In 1992 the P loss was 1.93 kg/ha/year and in 1993 it was 1.59 kg/ha/year.

Table 2. Rate of phosphorus and nitrogen applied to the nine properties

		Nutrient application rate (kg/ha/year)		Years farmed	Total nutrient applied (kg/ha/life of property)	
Property	Type of horticulture	Phosphorus	Nitrogen		Phosphorus	Nitrogen
1	Orchard and vineyard	25	76	10	250	760
2	Vegetables	70	424	10	700	4,240
3	Vegetables	307	1,214	10–40		
4	Turf farm	430	900	2	860	1,800
5	Vegetables	300	900	3 (new) 15 (old)	900 4,500	2,700 13,500
6	Vegetables	250	750	20	5,000	15,000
7	Native flowers Greenhouse flowers	11 136	100 1,600	10 10	110 1,360	1,000 16,000
8	Roses	236	714	10	2,360	7,140
9	Vegetables	300	900	2	600	1,800

Rates of fertiliser applied over the life of the property were often difficult to estimate because of change in ownership. These figures are approximations.

The amount of nitrogen available to the plant and for leaching may be considerably less than rates listed above for Properties 2, 3, 4, 5 and 6 because of volatilisation losses from poultry manure.

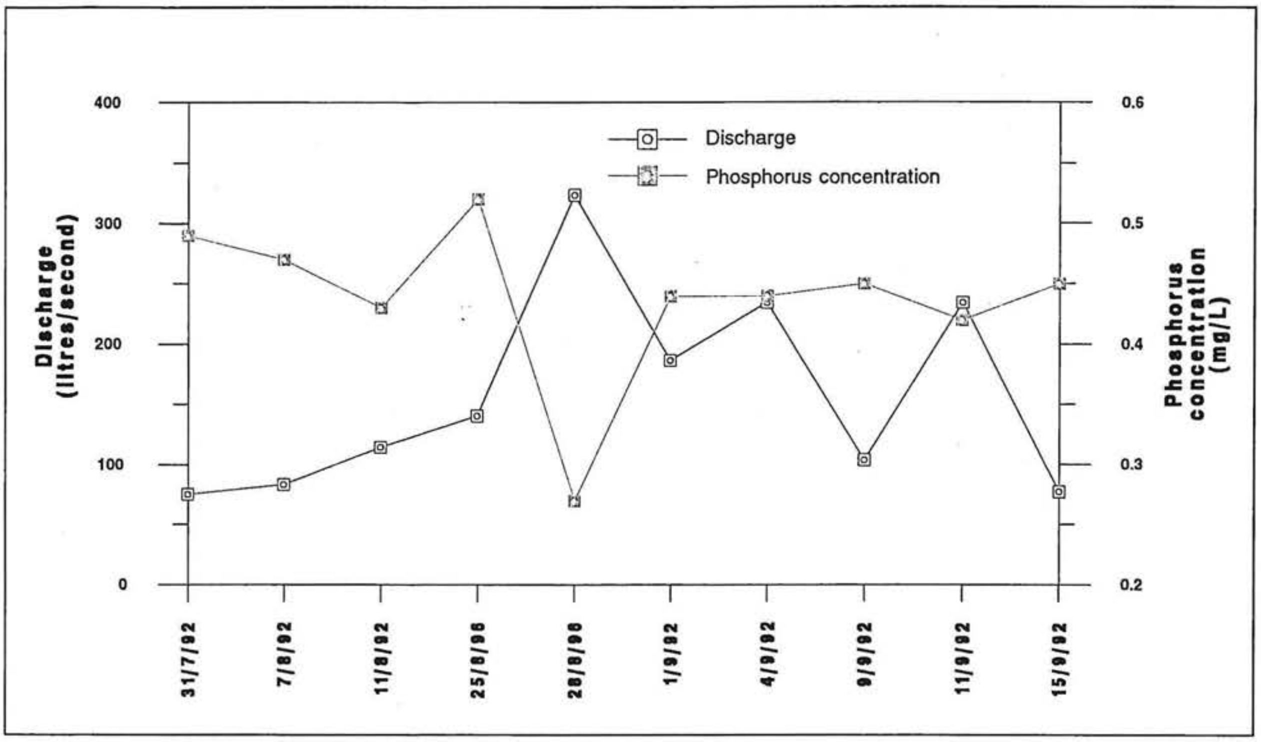

Figure 1. Discharge and phosphorus concentration of drainage water from Property 1 (August to September 1992).

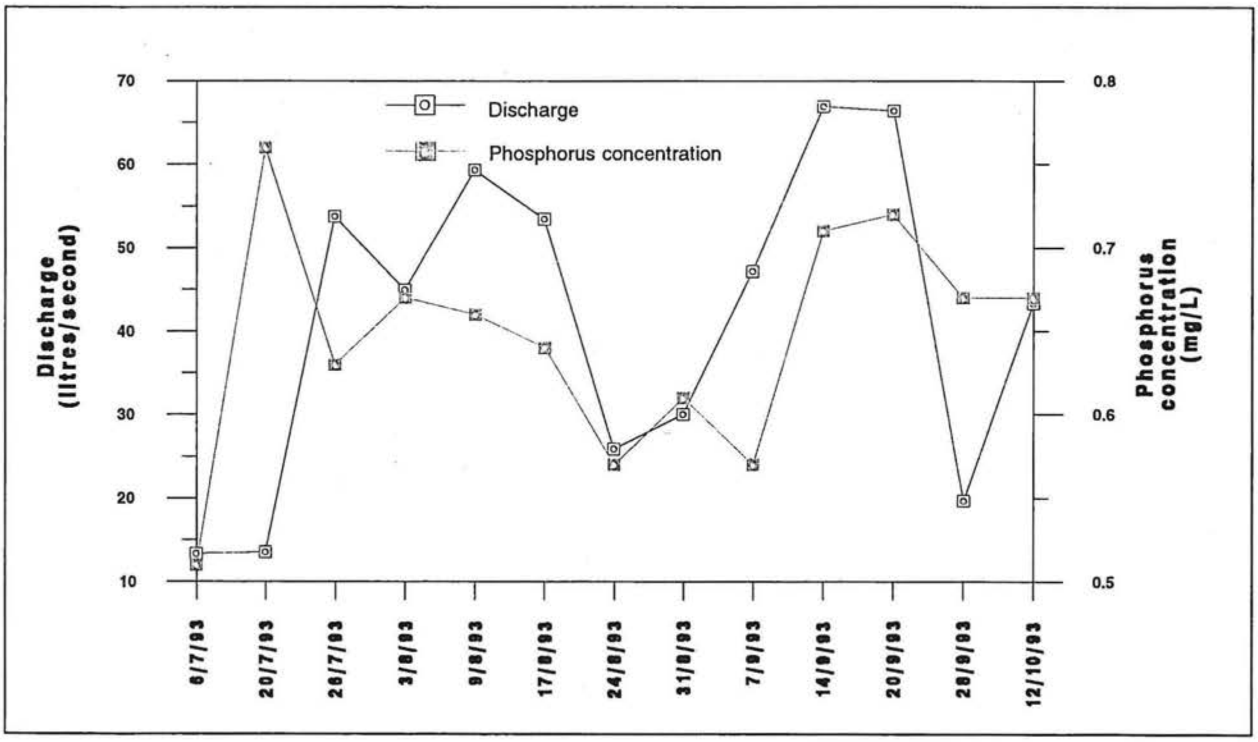

Figure 2. Discharge and phosphorus concentration in drainage water for Property 1 (1993).

Property 2. (Vegetable farm)

Figure 3 shows the discharge and P concentration at each sampling date for Property 2. Phosphorus concentrations reached a peak of 7.8 mg/L in late July and fell to 2.4 mg/L at the end of sampling in late October. Table 3 shows that 1320 kg of P were lost from the 50 ha property to give a loss rate of 27 kg/ha/year.

Property 3. (Vegetable farms)

Figure 4 shows the discharge and P concentrations at the exit drain at each sampling date for Property 3. Phosphorus concentrations reached a peak of 0.63 mg/L in winter before falling to 0.05 mg/L at the end of sampling in November. Table 3 shows that 326 kg of P left the subcatchment which contains about 140 ha of horticultural crops. This gives a P loss rate of 2.3 kg/ha/year.

Table 3. Phosphorus loss via surface drainage from horticultural properties

	Production area (ha)	Phosphorus load (kg/year)	Phosphorus loss (kg/ha/year)
Property 1* (1992)	120	232	1.93
Property 1 (1993)	120	191	1.59
Property 2 (1993)	50	1320	27
Property 3 (1993)	140	326**	2.3

* Only monitored from late July to mid-September.

** Exit drain 465 kg/year, entry drain 139 kg/year.

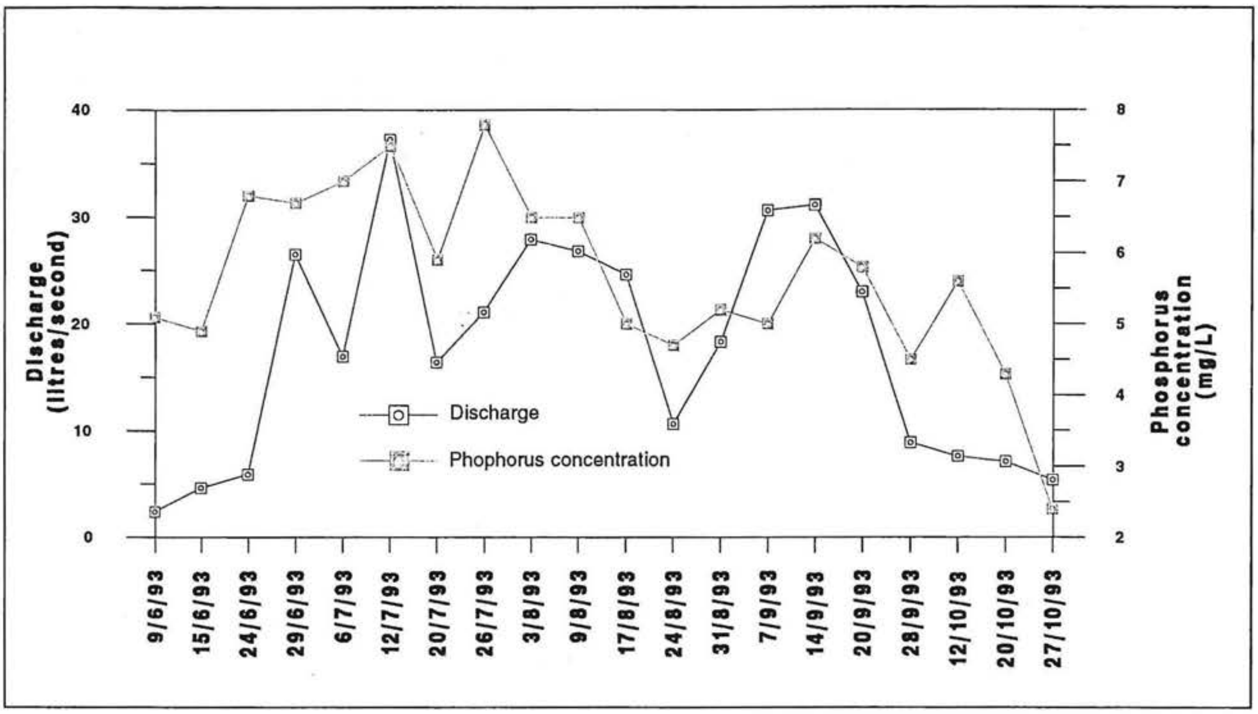

Figure 3. Discharge and phosphorus concentration of drainage water from Property 2.

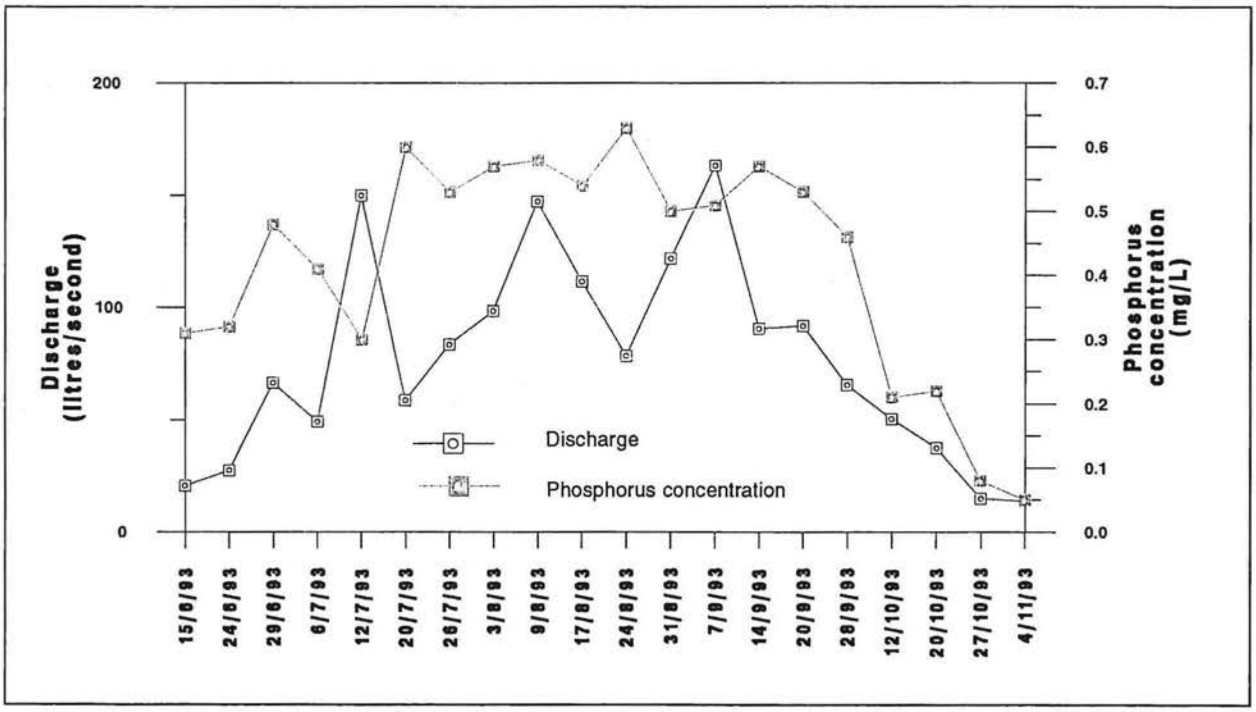

Figure 4. Discharge and phosphorus concentration of drainage water from Property 3.

Ground water monitoring

Property 4. (Turf farm)

Seven monitoring bores were installed to monitor nutrient concentrations. Figure 5 shows the location of the bores. Bores 4 and 5 are located up-gradient of the production area. Bores 1, 2 and 3 are on the immediate down-gradient edge of the production area. Bore 2 was designed to sample from the top 6 m of the watertable (as per Water and Rivers Commission bore license specifications). Bores 6 and 7 are 100 m down-gradient of the production area. The area between the turf and Bores 6 and 7 contains reasonably undisturbed native vegetation. Additional samples are taken from the farmer's production bore on three occasions.

The production area was fertilised and the turf planted in late January 1995. Prior to this the property was used for grazing cattle, with little or no fertiliser being applied in the recent past. The first water sampling was conducted before the addition of fertiliser by the turf farmer.

Phosphorus

Figure 6 shows the P concentrations in the monitoring bores. The P levels were very low before development of the turf property. Within two months the levels of P in the three bores on the edge of the turf (Bores 1, 2 and 3) had risen. The P levels continued to rise in these bores to a maximum of 16 mg/L.

The P concentrations in the two down-gradient bores (Bores 6 and 7) remained low for the eight months. From 20/2/96 onwards the P levels in these bores began to rise steadily, with Bore 7 reaching 7 mg/L on 26/2/97. The P concentrations in the up-gradient bores (Bores 4 and 5) remained low, indicating no significant amount of P was detected entering the property.

The level of P in water from the production bore was very low (< 0.01 mg/L) at every sampling date (data not shown).

Nitrogen

Figure 7 shows the NO_3-N concentrations in the monitoring bores. Prior to planting the turf the levels were low in all bores except Bore 5. Bore 5 occurs up-gradient of the turf and may indicate that some NO_3-N is entering the property. Bore 5 shows elevated NO_3-N levels throughout the monitoring period as compared with the other up-gradient bore, Bore 4. It is possible some nitrate from the vegetable property 600 m to the west is being detected in this bore.

NO_3-N concentration began to increase in Bore 1 within two months of turf farming starting (10/3/95). The NO_3-N concentration increased in the three bores located on the edge of the turf (Bores 1, 2 and 3) to a maximum of 29 mg/L on 26/2/97.

The NO_3-N concentration in the two down-gradient bores (Bores 6 and 7) remained low until the 20/2/96 sampling after which the NO_3-N concentration increased reaching a peak of about 10 mg/L in Bore 7. The NO_3-N concentration in the production bore did not increase (results not shown).

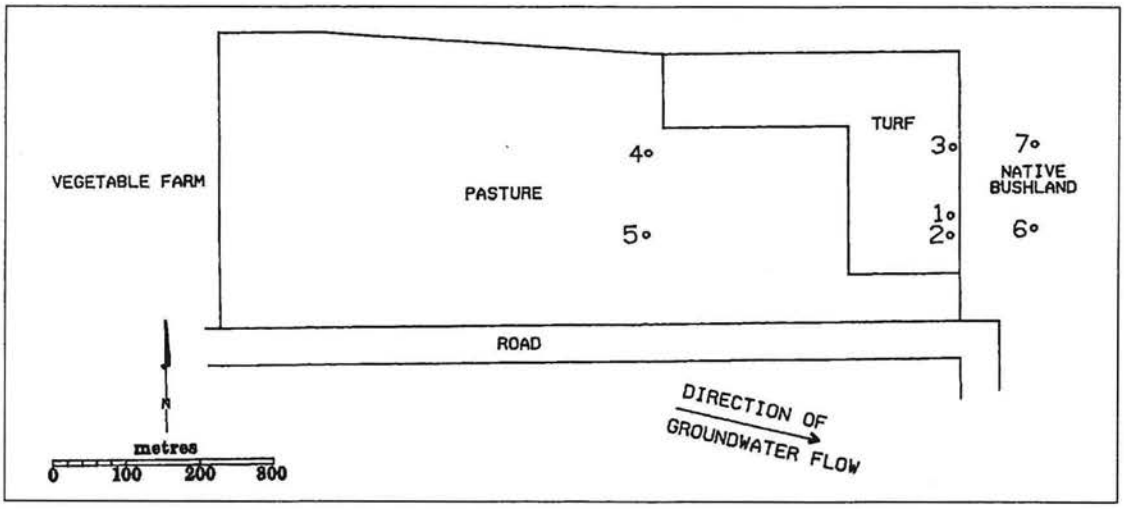

Figure 5. Location of monitoring bores on Property 4.

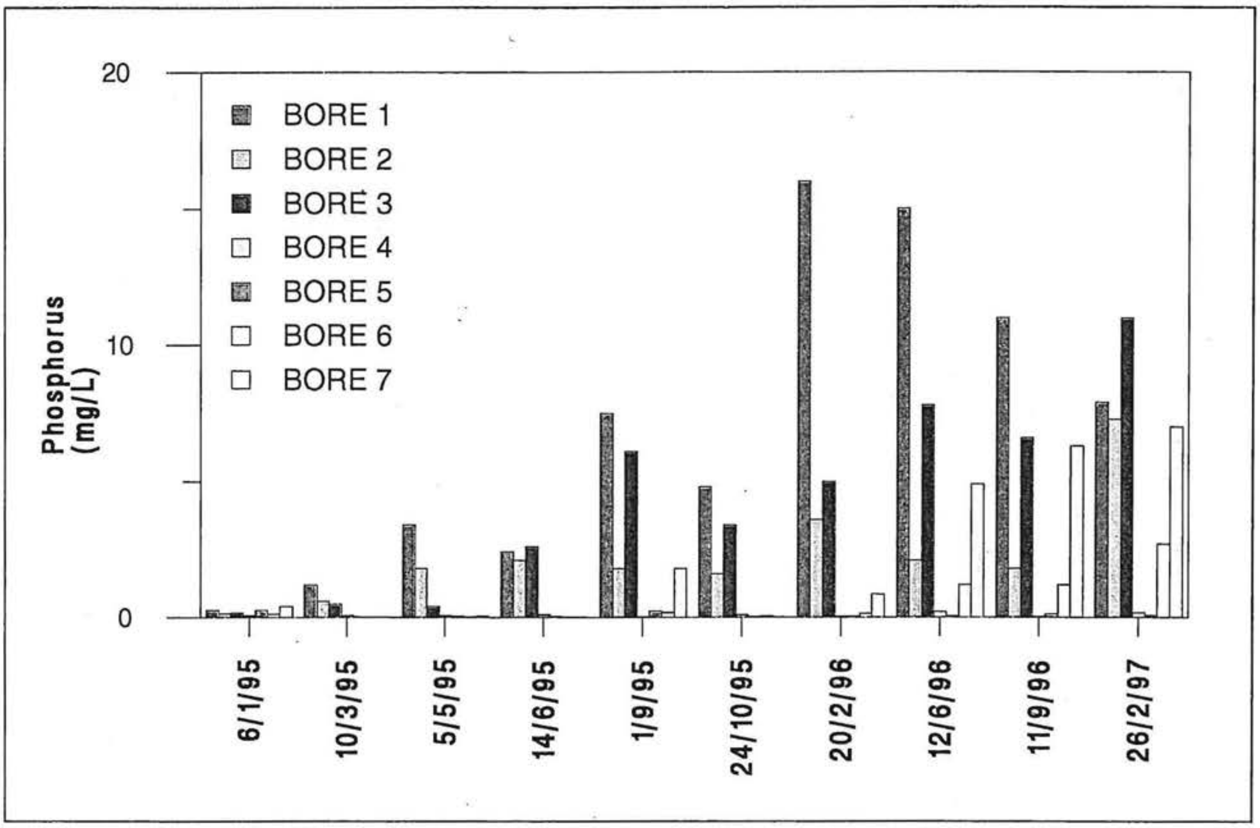

Figure 6. Phosphorus concentration in monitoring bores for Property 4.

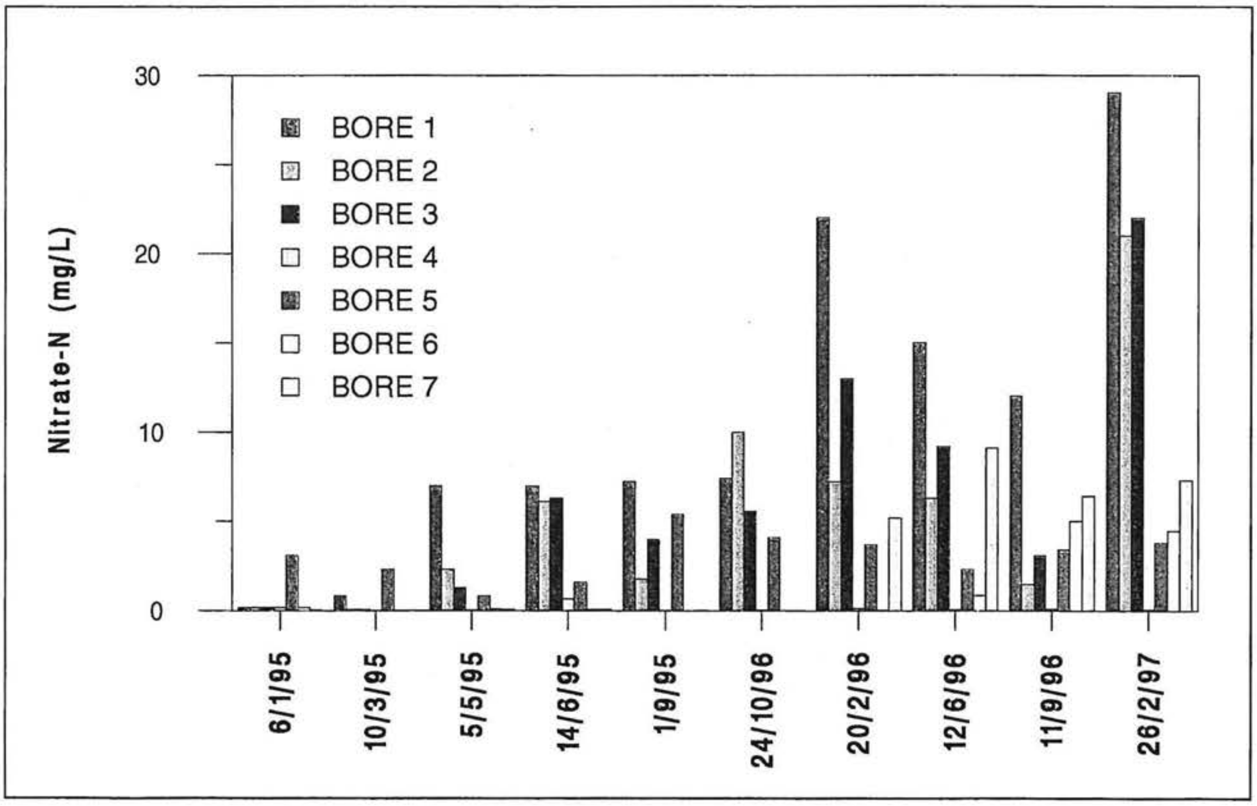

Figure 7. Nitrate-N concentration in monitoring bores for Property 4.

Property 5. (Vegetable farm)

Twelve bores were monitored for their nutrient concentrations. Figure 8 shows the location of the bores.

Transect A runs through the section of the garden which is three years old. Bore 9 is up-gradient of the property. This bore is also used in Transect B – one up-gradient bore was considered sufficient because of the vast areas of bushland to the west. Bore 1 occurs within the garden and Bores 4, 10, 12 and 18 are down-gradient. The down-gradient bores could not be located in a straight line because of dense scrub. Bore 15 was installed to the bottom of the superficial aquifer (18.5 m). Before being developed for vegetable production in early 1994, this area of the property contained pasture which was rarely fertilised.

Transect B runs through the 20-year-old section of the garden. Bore 9 is up-gradient and Bores 6, 13, 16, 17 and 19 various distances down-gradient of the garden. No monitoring bore could be installed within the garden because it would interfere with farming activities.

Bores 16, 17, 18 and 19 were installed at a later date than the other bores in order to gain a better understanding of nutrient concentrations in the groundwater down-gradient of the garden.

New section

Phosphorus

Figure 9 shows the P concentrations in the monitoring bores for the new section of the garden (Transect A). The P concentrations in the bore within the garden (Bore 1) were very high at each sampling date with a maximum of 38 mg/L. The P concentration in Bore 10 (100 m down-gradient) began to rise from 24/10/95 reaching 13 mg/L. The P concentrations in Bore 4 which is 50 m down-gradient did not increase above 0.34 mg/L. This area was more low lying, and the soil was an organic loamy sand which had a shallow coffee rock layer. Bore 15, which was installed to the bottom of the superficial aquifer, showed low P levels throughout the monitoring period (data not shown).

Nitrogen

Figure 10 shows the NO_3-N concentrations in the monitoring bores for the new section of the garden (Transect A). The NO_3-N levels in Bore 1 are very high at each sampling. Bore 4 shows elevated NO_3-N levels on 14/9/94 and 14/6/95. The NO_3-N concentrations in Bore 10 begin to rise from the 1/9/95 onwards. The other two down-gradient bores (Bores 12 and 18) show no increase in NO_3-N levels. NO_3-N levels did not increase in the deep bore (data not shown).

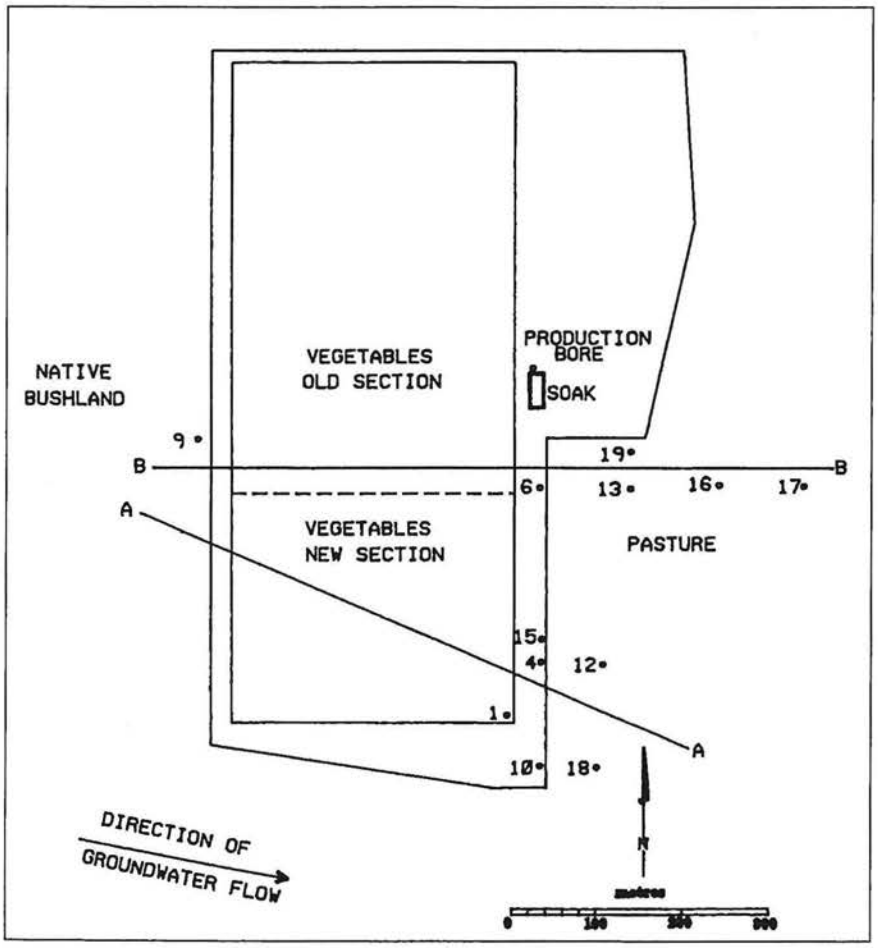

Figure 8. Location of monitoring bores on Property 5.

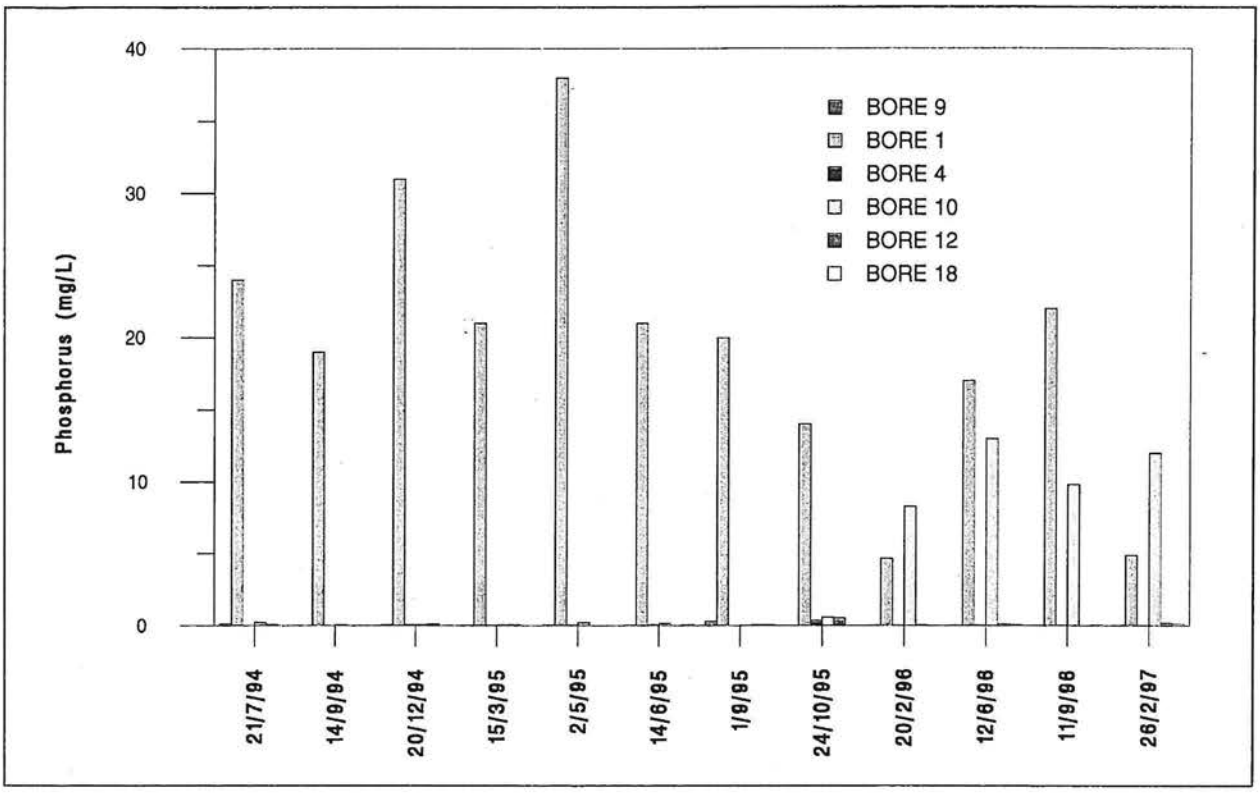

Figure 9. Phosphorus concentration in monitoring bores for Property 5 (new section).

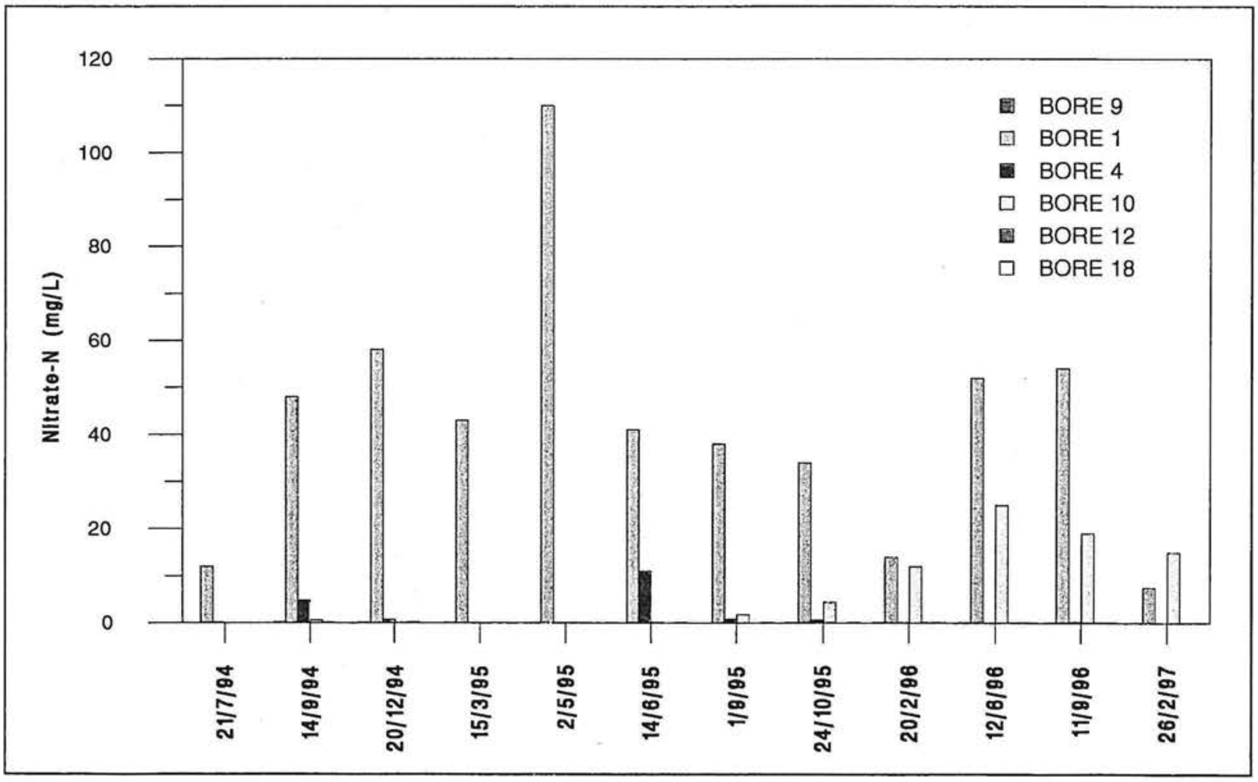

Figure 10. Nitrate-N concentration in monitoring bores for Property 5 (new section).

Old section

Phosphorus

Figure 11 shows the P concentrations in the monitoring bores in Transect B (old section of the garden). There was no bore within the garden with Bore 6 being 50 m down-gradient. It would be reasonable to assume that similarly very high P concentrations would be found beneath the garden in the old section as were found under the garden in the new section (i.e. Bore 1 – Figure 9).

Bore 6 shows increased levels of P but nowhere near as high as those levels found directly beneath the garden (Bore 1). Bore 13 located 100 m down-gradient from the garden initially showed increased levels of P. These levels fell and then rose towards the end of the monitoring period. The levels of P in Bore 19 did not increase despite being 150 m from the garden. This bore was located in a lower lying, more peaty soil type which had a well developed coffee rock layer.

The P concentrations in Bore 16 (250 m from garden) showed elevated P levels. Bore 17 (350 m from the garden) showed P concentrations as high as 0.65 mg/L. Phosphorus concentration had decreased very substantially in this bore as compared with that beneath the garden.

Nitrogen

Figure 12 shows the NO_3-N concentrations in the bores in Transect B (old section of the garden). There was no bore within the garden but it would be reasonable to assume that similarly high NO_3-N concentrations would be found beneath the garden in the old section as were found under the garden in the new section (i.e. Bore 1 – Figure 10).

Bore 6, located 50 m down-gradient of the garden, shows increased NO_3-N levels on the 21/7/94 (2.8 mg/L) and 14/6/95 (3.6 mg/L). These levels are markedly lower than those found under the garden (Bore 1). Bore 13, located 150 m down-gradient, shows increased NO_3-N levels on the first two sampling dates. Bore 17, located 350 m down-gradient of the garden, shows NO_3-N concentrations of up to 1.1 mg/L. This is markedly less than the NO_3-N concentration under the garden.

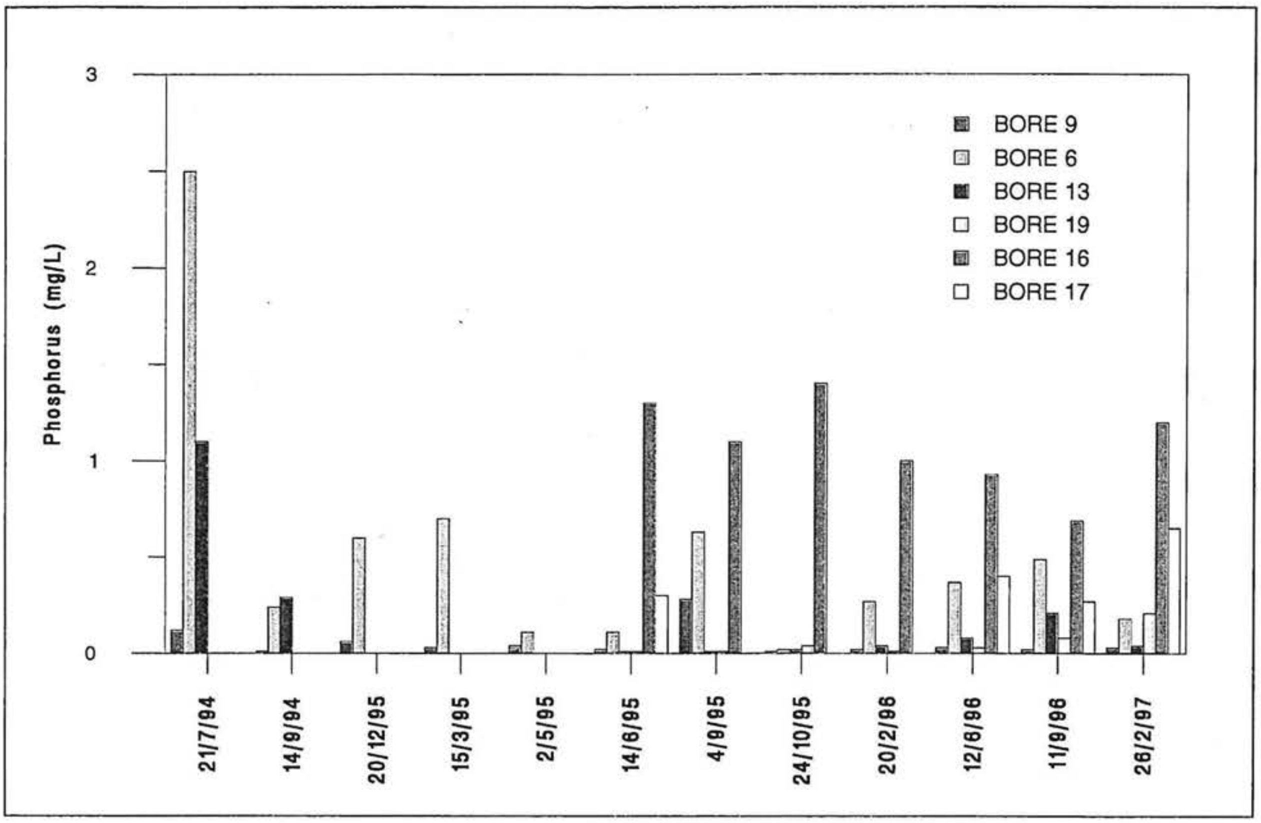

Figure 11. Phosphorus concentration in monitoring bores for Property 5 (old section).

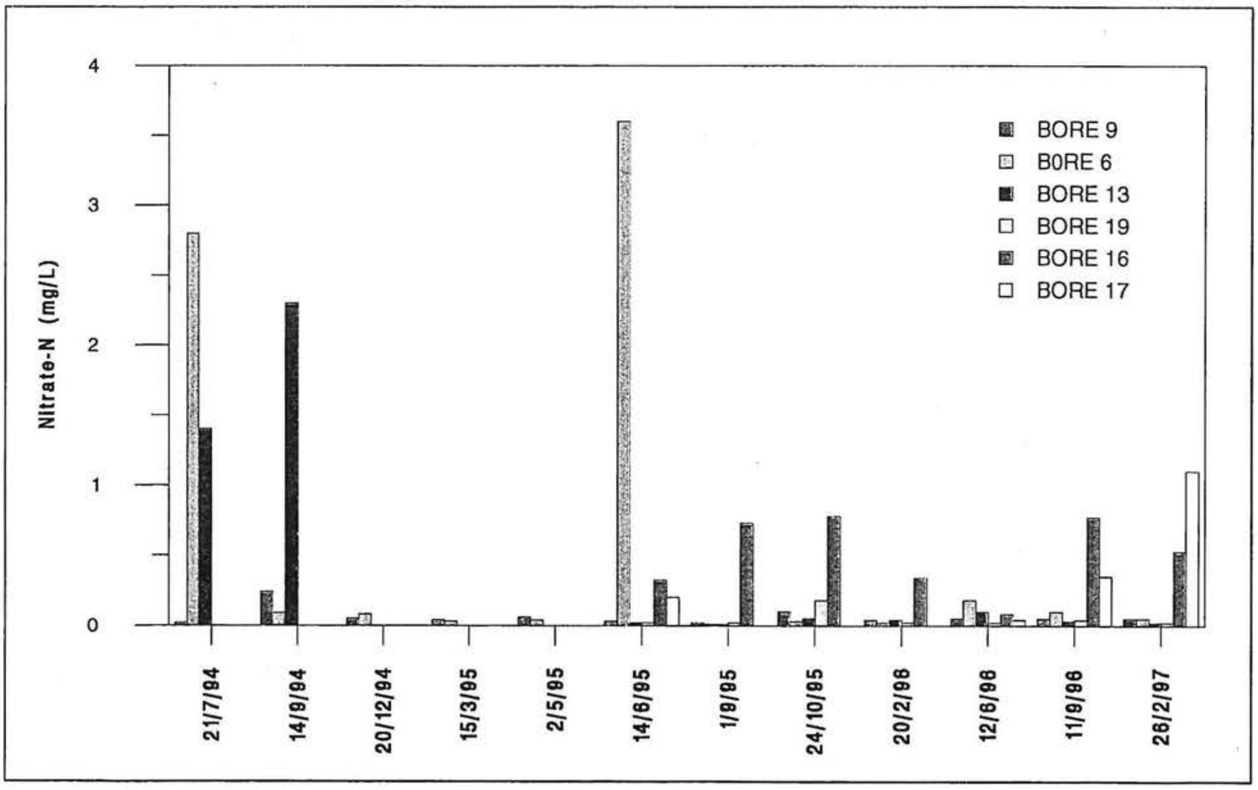

Figure 12. Nitrate-N concentration in monitoring bores for Property 5 (old section).

Property 6. (Vegetables)

Five monitoring bores were installed to monitor nutrient loss from Property 6. Figure 13 shows the location of the bores. Bore 5 was located up-gradient of the garden, Bores 2 and 4 within the garden and Bore 3, 50 m down-gradient. Bore 1 was installed to the bottom of the superficial aquifer (23 m). This property has been in vegetable production for over 20 years. In May 1995, the Australian Geological Survey Organisation monitored two of the bores on this property for a comprehensive range of chemical and microbiological contaminants. (Bauld *et al.* 1996.) The nutrient concentration in the production bore was not measured.

Phosphorus

Figure 14 shows the P concentrations in the monitoring bores. Low levels of P were detected in the up-gradient bore (Bore 5). The two bores located within the garden and sampling the top of the watertable (Bores 2 and 4) showed very high levels of P. Bore 1, which sampled from the bottom of the superficial aquifer beneath the garden, contained very low levels of P. Bore 3, which was 50 m down-gradient of the garden, showed high levels of P but lower than those detected within the garden.

Nitrogen

Figure 15 shows the NO_3-N concentrations in the monitoring bores. Significant levels of NO_3-N, up to 6 mg/L, were detected in the up-gradient bore (Bore 5). The origin of this NO_3-N may have been from the poultry farm to the east. Bores 2 and 4 within the garden show very high levels of NO_3-N (up to 100 mg/L). The deep bore (Bore 1) shows high levels of NO_3-N. Bore 3, which is located 50 m down-gradient, also shows elevated levels of NO_3-N. On the last sampling date the concentration in this bore is higher than that within the garden.

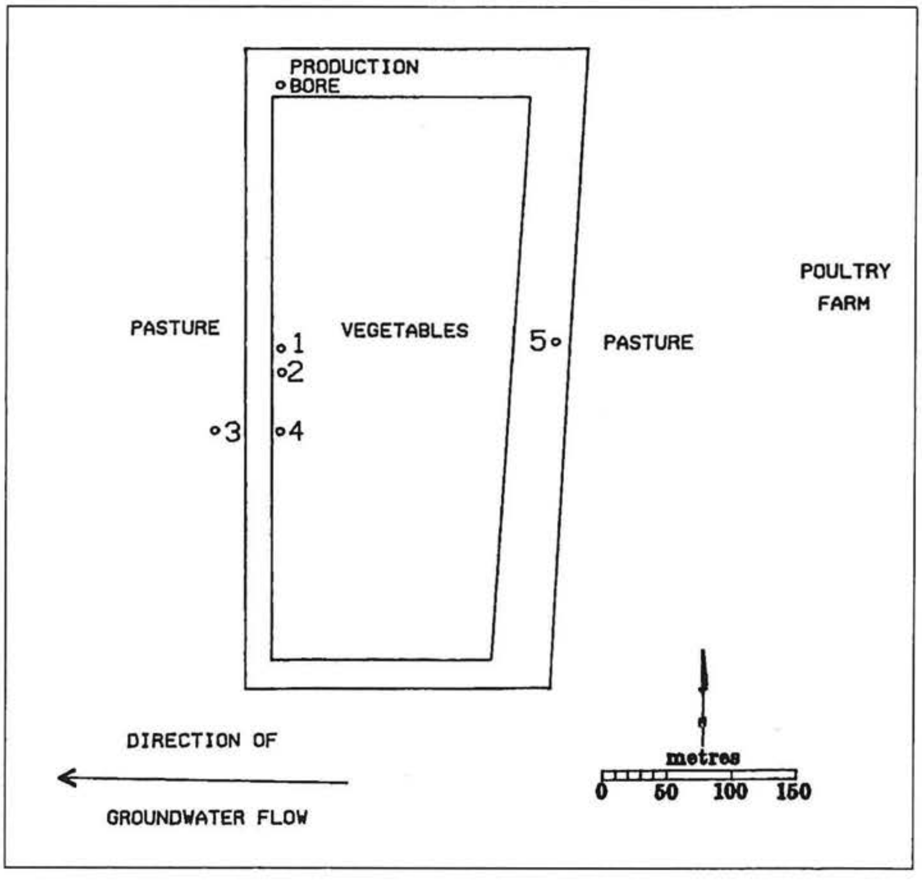

Figure 13. Location of monitoring bores on Property 6.

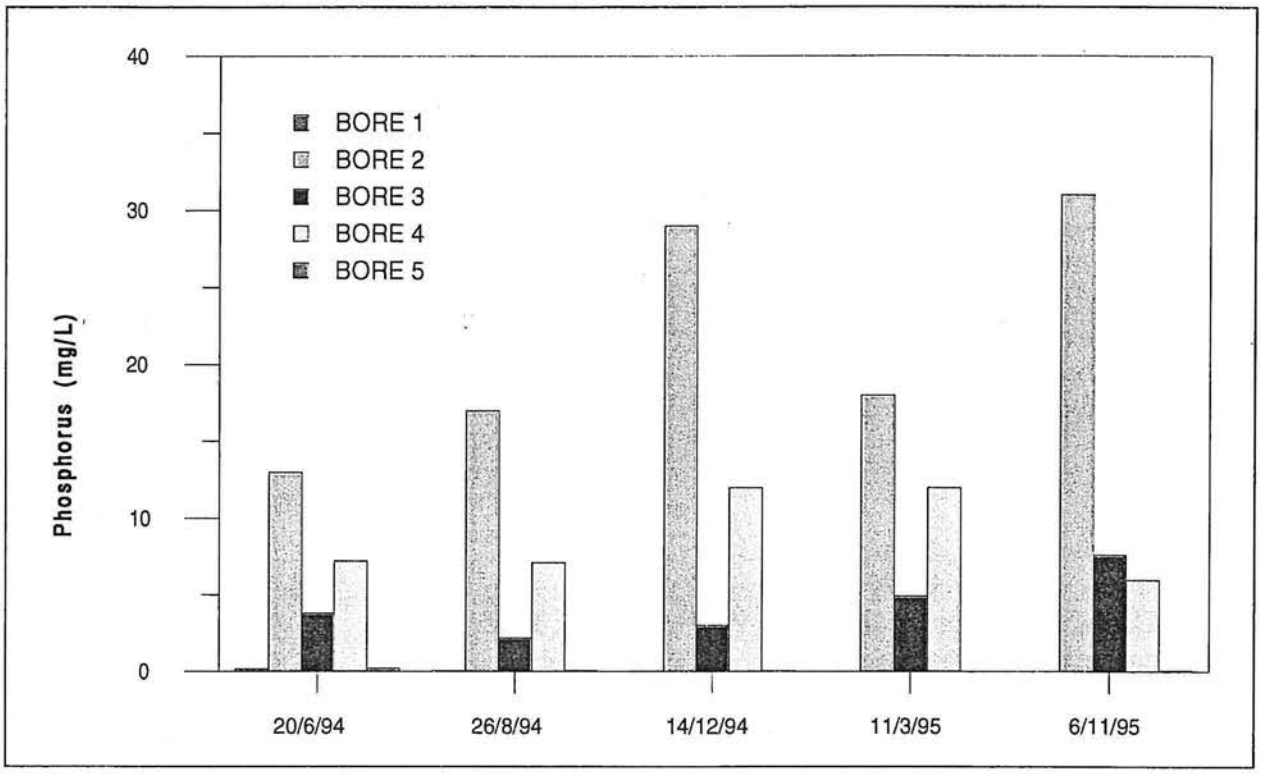

Figure 14. Phosphorus concentration in monitoring bores for Property 6.

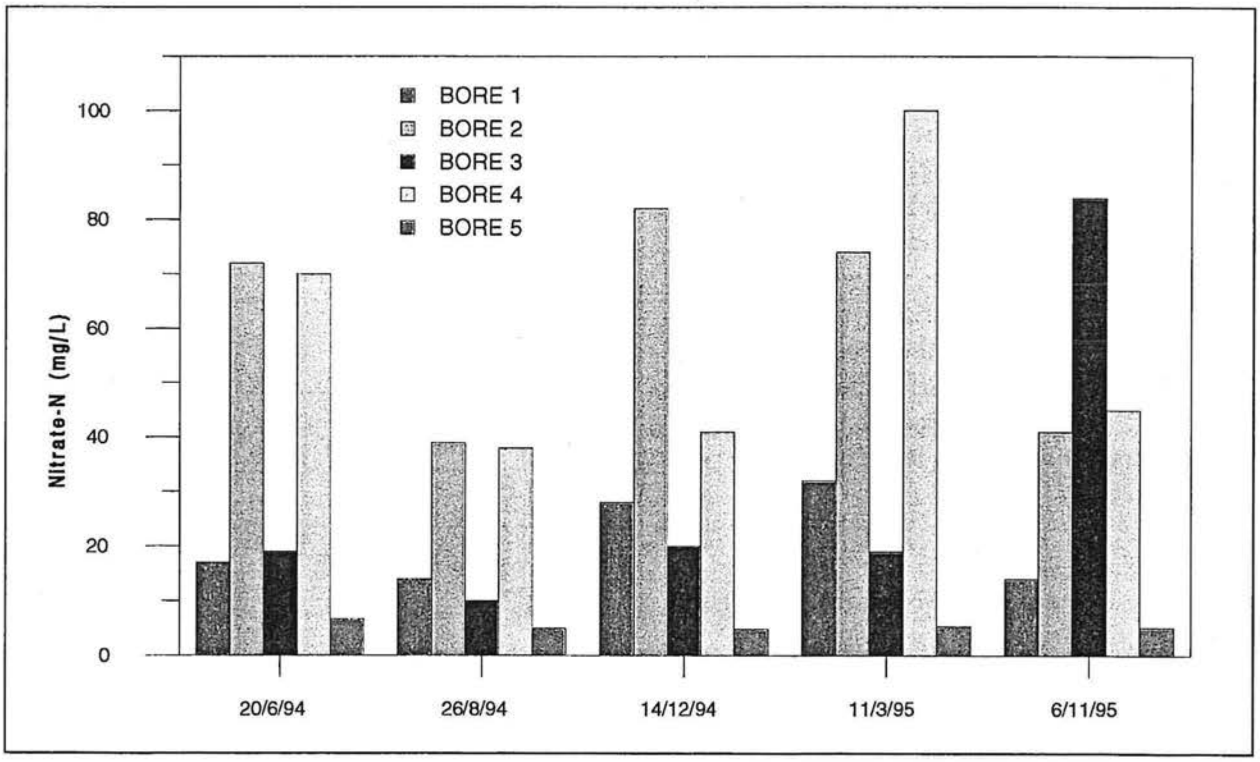

Figure 15. Nitrate-N concentration in monitoring bores for Property 6.

Property 7. (Native flowers and greenhouse flowers)

Ten monitoring bores were installed to monitor nutrient loss from Property 7. Figure 16 shows the location of the bores. Bore 7 is located up-gradient of the property to monitor any incoming nutrients. Bores 1, 2, 3, 6, 8, 9, 11 and 12 are located down-gradient of a range of floricultural crops (see Figure 16). Bore 10 is a deep bore sampling from the bottom of the superficial aquifer (16.3 m).

Phosphorus

Figure 17 shows the P concentrations in the monitoring bores on Property 7. The up-gradient bore, Bore 7, generally shows very low P concentrations, though on the 21/3/96 this bore contained a P concentration of 0.9 mg/L. Bore 1, located down-gradient of the boronia, showed P concentrations of between 0.5 and 1 mg/L. Bore 2, located adjacent to the tissue culture laboratory and propagation house, was initially high (3 mg/L) but fell after the first sampling date. The bores adjacent to the eucalyptus (Bore 3) and kangaroo paws (Bore 6) contained very low P concentrations throughout the monitoring period. The bores adjacent to the statice and lilium greenhouses (Bores 8, 9 and 11) showed moderate to high P concentrations. Bore 12, located 50 m down-gradient from a statice greenhouse, showed considerably lower P concentrations than those immediately adjacent to the greenhouse. The deep bore which was located adjacent to a statice greenhouse (Bore 10) contained P concentrations ranging from 0.2 mg/L to 7.5 mg/L.

Nitrogen

Figure 18 shows the NO_3-N concentrations in the monitoring bores for Property 7. The up-gradient bore, Bore 7, generally shows low NO_3-N concentrations throughout the monitoring period. Elevated NO_3-N levels were found in the Bore 1 which is located down-gradient of the boronia. Bore 2, which is adjacent to the tissue culture laboratory and propagation house, shows very high levels of NO_3-N initially after which the concentration declined. The bores down-gradient of the eucalyptus (Bore 3) and the kangaroo paws (Bore 6) generally show low NO_3-N concentrations. The bores adjacent to the statice greenhouses (Bores 8 and 11), contain high to very high NO_3-N concentrations. The bore adjacent to the liliums (Bore 9), however, contains low NO_3-N concentrations. Bore 12, which is 50 m down-gradient from a statice greenhouse shows high concentrations of NO_3-N. The deep bore (Bore 10) shows very low concentrations except on the first sampling date.

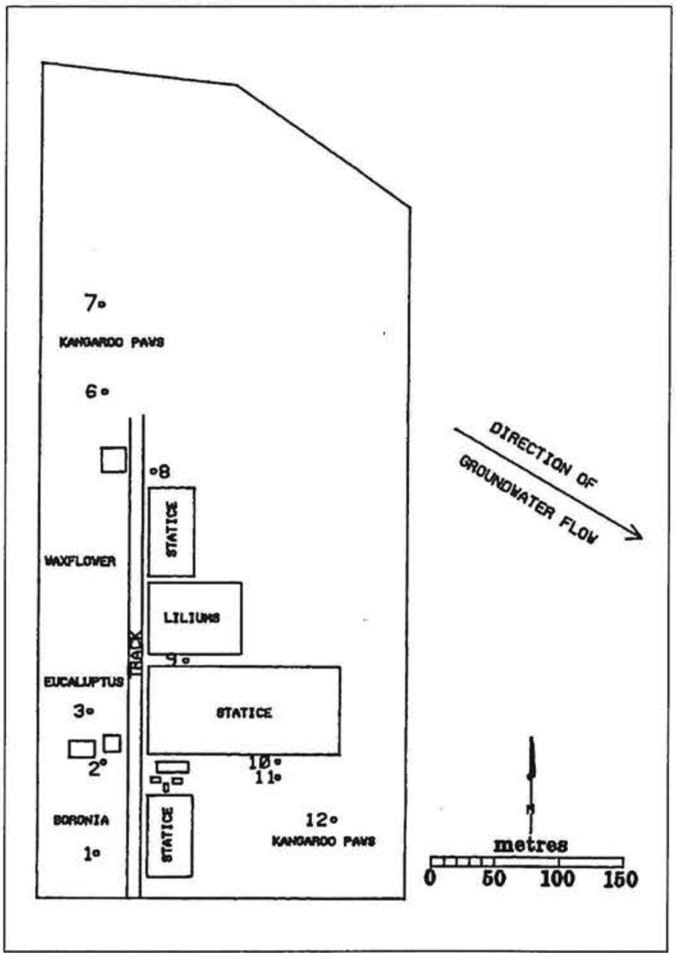

Figure 16. Location of monitoring bores on Property 7.

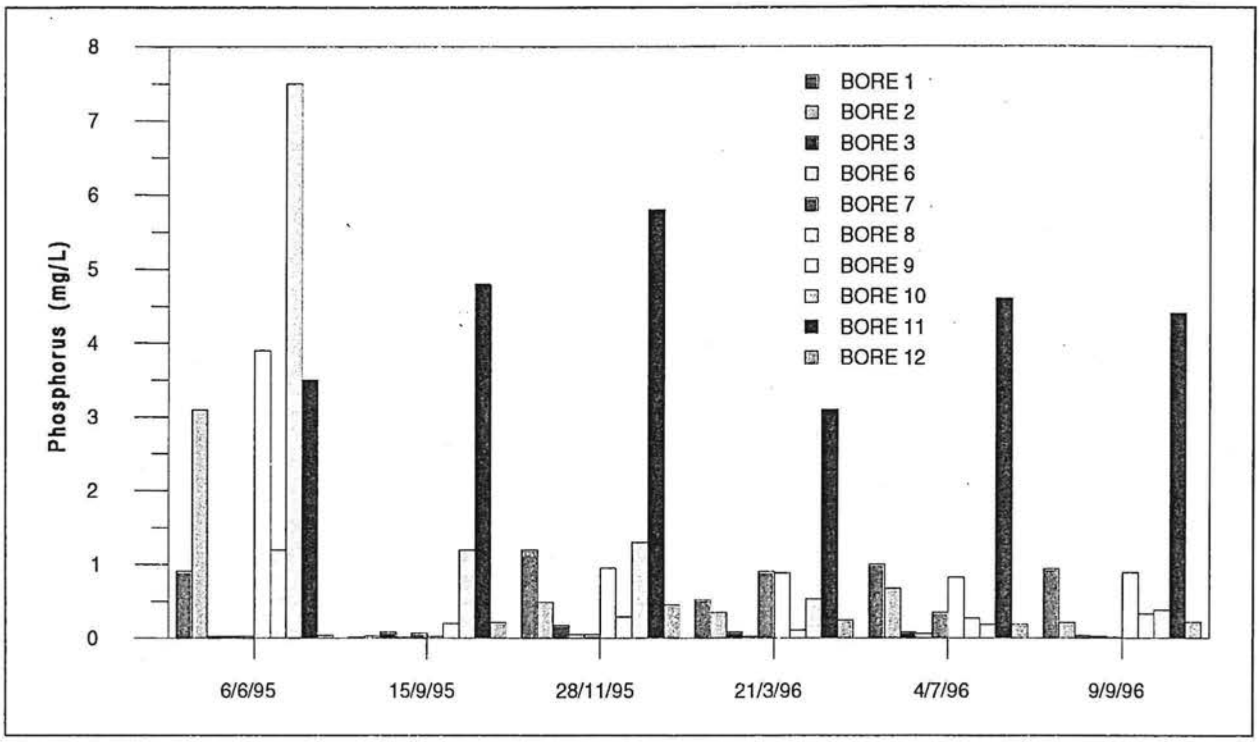

Figure 17. Phosphorus concentration in monitoring bores for Property 7.

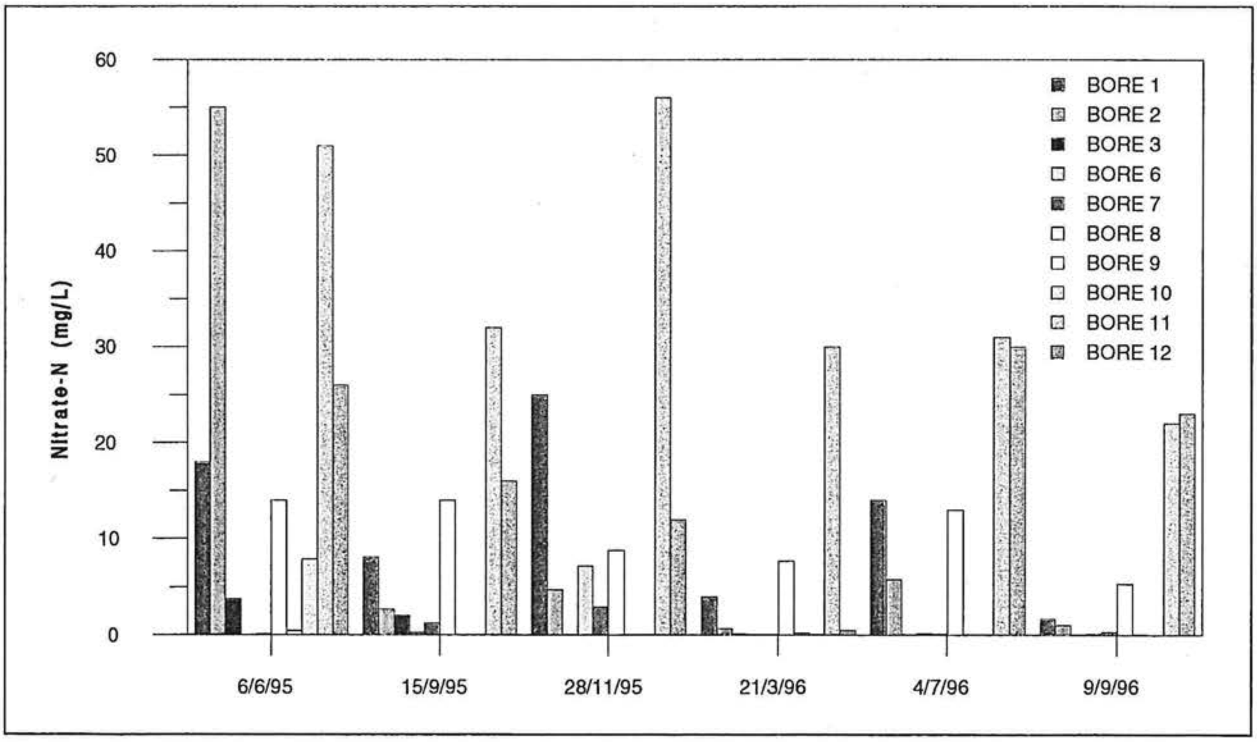

Figure 18. Nitrate-N concentration in monitoring bores for Property 7.

Property 8. (Roses)

Eight monitoring bores were installed to monitor nutrient loss from Property 8. Figure 19 shows the location of these bores. Bores 1 and 2 are located immediately up-gradient of the greenhouse, Bores 3 and 4 immediately down-gradient of the greenhouse and Bores 5 and 6, 50 m down-gradient. Bores 8 and 9 were installed 50 m up-gradient of the greenhouse in May 1995 because of concerns that Bores 1 and 2 were located too close to the greenhouse to accurately determine the extent of nutrient flow into the greenhouse.

Phosphorus

Figure 20 shows the P concentrations in the monitoring bores for Property 8. All bores contain significant levels of P. A market garden is located 100 m up-gradient of the property. It is likely that P from this property is masking any changes in P concentration as a result of farming activities on Property 8. Water from the production bore showed low P levels (< 0.1 mg/L) at all sampling dates (data not shown).

Nitrogen

Figure 21 shows the NO_3-N concentrations in the monitoring bores for Property 8. The two bores on the down-gradient edge of the greenhouse (Bores 3 and 4) showed elevated NO_3-N concentrations at most sampling dates. However, the NO_3-N concentration in the two bores located 50 m down-gradient (Bores 5 and 6) did not increase. These bores were located in an area of Joel sand.

The NO_3-N concentration in Bores 8 and 9 were high on some sampling dates, indicating movement of NO_3-N into the property from the market garden to the west. These bores were located in an area of Gavin sand.

Water from the production bore on Property 8 contained very low levels of NO_3-N (< 0.1 mg/L) at all sampling dates (data not shown).

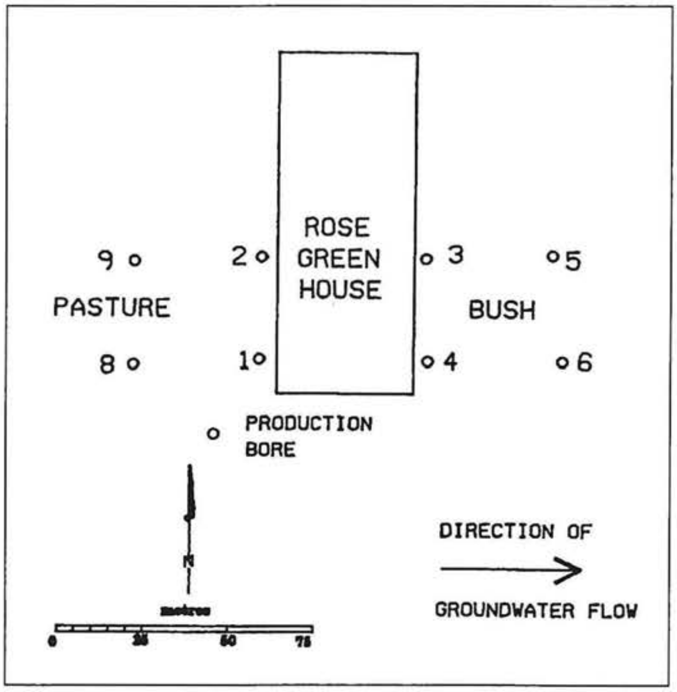

Figure 19. Location of monitoring bores on Property 8.

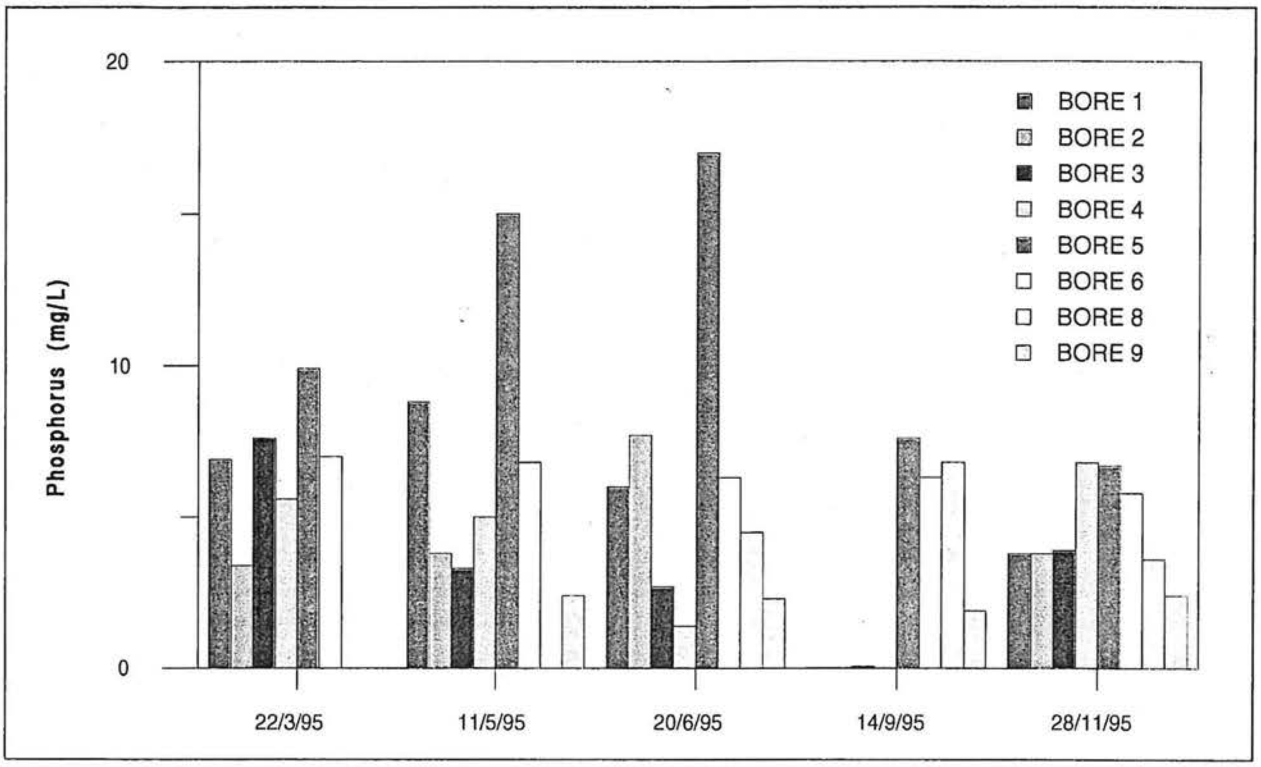

Figure 20. Phosphorus concentration in monitoring bores for Property 8.

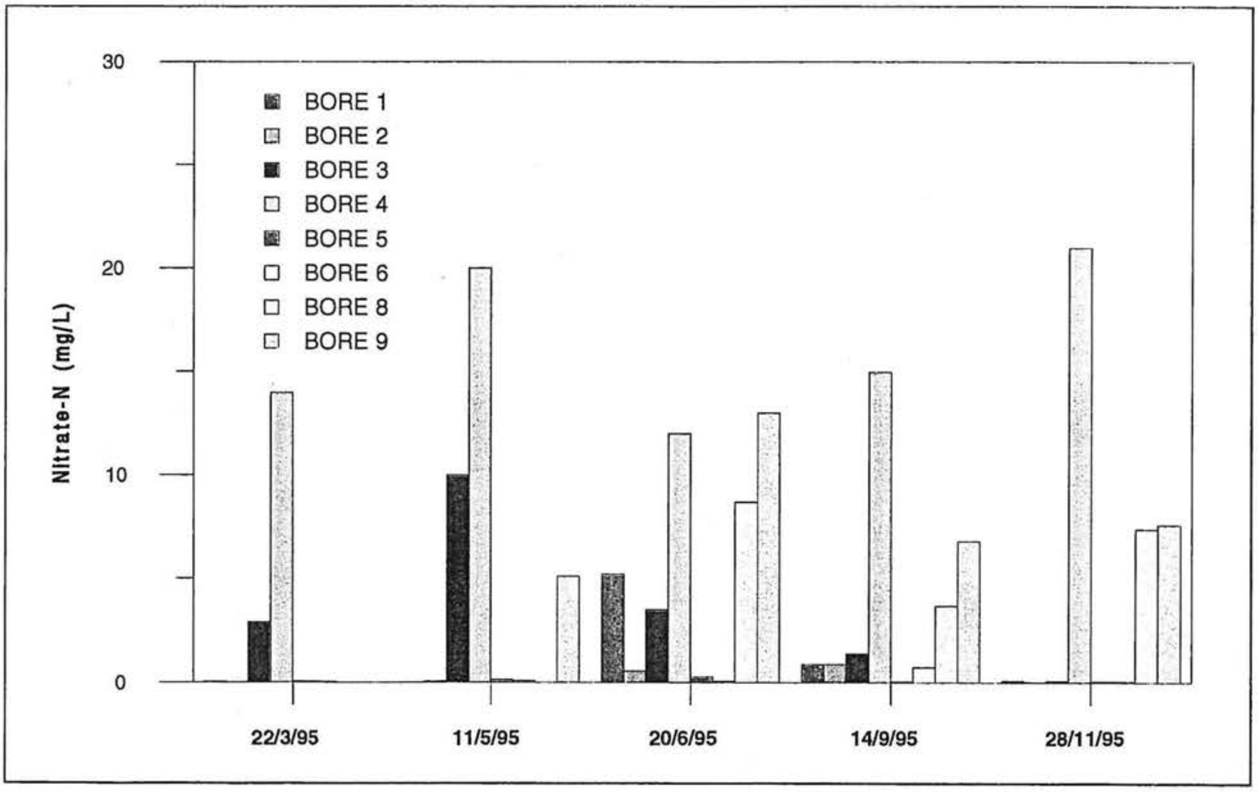

Figure 21. Nitrate-N concentration in monitoring bores for Property 8.

Property 9 (Vegetables)

Seven monitoring bores were installed to monitor nutrient loss from Property 9. Figure 22 shows the location of the bores. Bore 1 is located up-gradient, Bore 3 on the down-gradient edge of the garden and Bores 4, 5, 6 and 7 various distances down-gradient. Bore 2 was installed to sample from the bottom of the superficial aquifer (17 m). The market garden was developed in May 1995. Before this the property was used for grazing.

Unlike the other eight properties the soil type on this property is from the Spearwood Dune System.

Phosphorus

Very low P concentrations (< 0.05 mg/L) were detected in all the bores throughout the sampling period (data not shown).

Nitrogen

Figure 23 shows the NO_3-N concentrations in the bores on Property 9. The NO_3-N levels in the bore located on the down-gradient edge of the garden (Bore 3) began to rise within two months of the first fertiliser application. The concentration reached a peak of 7 mg/L on 12/9/95. Some NO_3-N was detected in the up-gradient bore (Bore 1) on the 12/9/95 and 16/11/95. Increased NO_3-N levels were found in two of the down-gradient bores located 50 m down-gradient of the garden (Bores 4 and 5). However, NO_3-N concentrations were less than 0.05 mg/L in the bores located 100 m down-gradient of the garden on all but one occasion (Bores 6 and 7). NO_3-N concentrations decreased in all bores on the last sampling date (18/3/97). This was possibly related to a fallow period.

The NO_3-N levels did not increase in the deep bore (Bore 2).

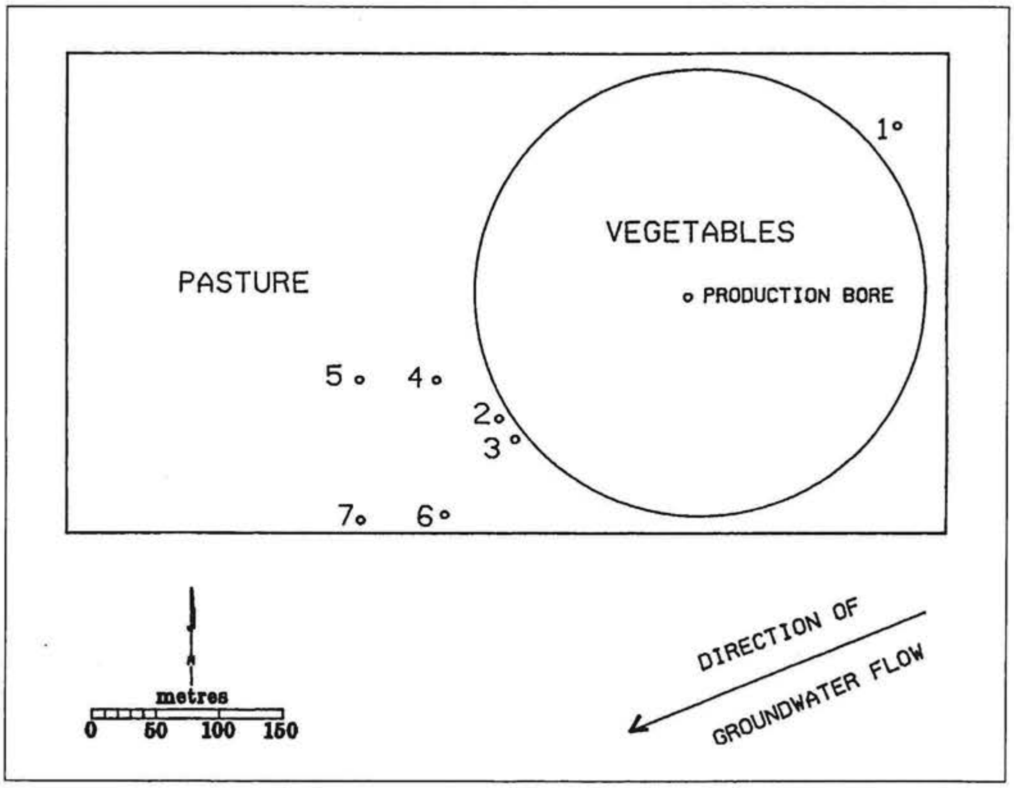

Figure 22. Location of monitoring bores on Property 9.

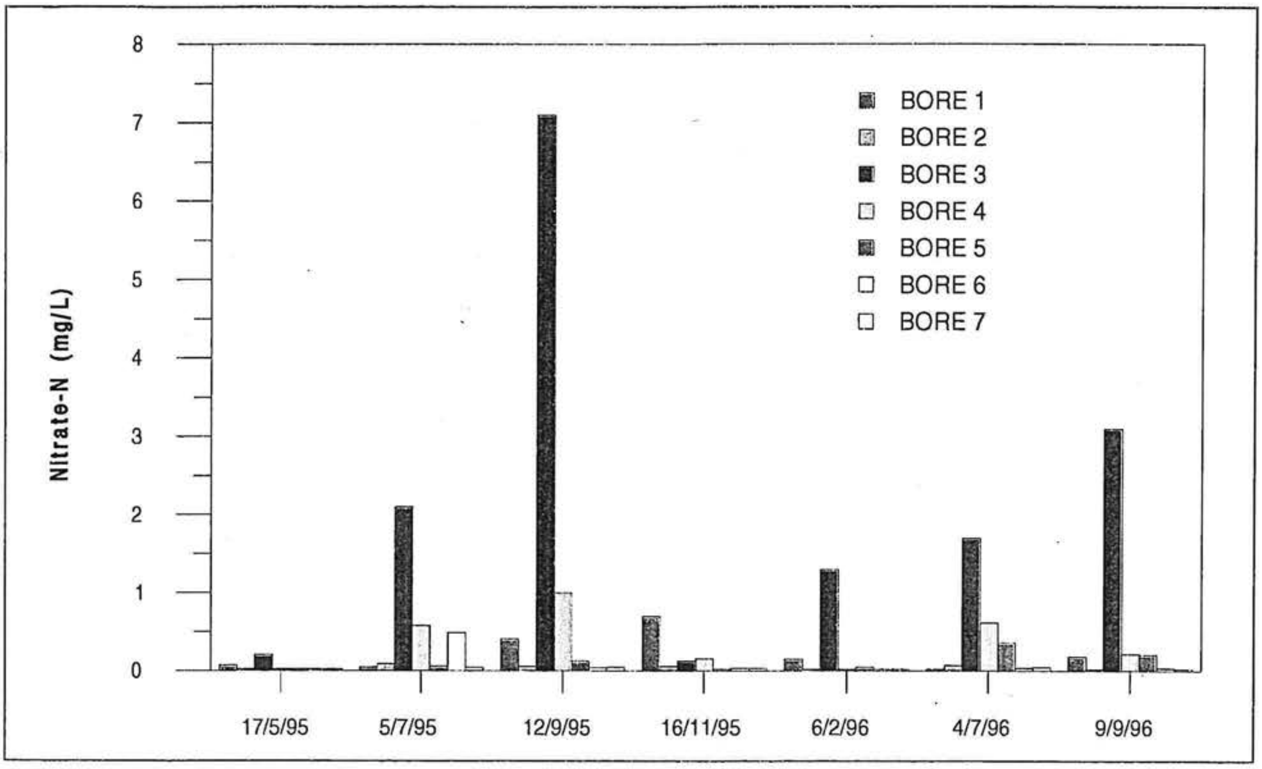

Figure 23. Nitrate-N concentration in monitoring bores for Property 9.

Nutrient loss rates for different horticultural activities

Tables 4 and 5 give maximum P and NO_3-N concentrations in the shallow groundwater beneath the properties monitored. A general trend exists where the nutrient concentrations are higher in the water leaving high fertiliser-using types of horticulture such as market gardens and greenhouse flowers than in lower fertiliser-using types of horticulture such as native flower production. Soil type differences from property to property also have a major influence on the concentration of nutrient in the drain or shallow groundwater.

The maximum P concentration in the bores under the turf property (Table 4) was high. However, the rate of P applied by the farmer (430 kg/ha/year) was much higher than that recommended in Appendix 2.

Table 4. Maximum phosphorus concentrations in shallow groundwater under the properties monitored

Crop	Property	Method of monitoring	Maximum phosphorus concentration in shallow groundwater beneath the production area (mg/L)
Vegetables	Property 2	Drain	7.8
	Property 3	Drain	0.63[A]
	Property 5	Bore	38
	Property 6	Bore	32
	Property 9	Bore	0.05[B]
Greenhouse flowers	Property 7	Bore	7.5
	Property 8	Bore	17[C]
Turf	Property 4	Bore	16
Fruit	Property 1	Drain	0.8
Native flowers	Property 7	Bore	0.9 (boronia) 0.02 (kangaroo paws)

A High phosphate fixing Herdsman Association occurs adjacent to drain.
B High phosphate fixing Spearwood Dune System.
C Results may be elevated due to additional phosphorus coming in from a vegetable property located 100 m up-gradient.

Phosphorus

The amount of residual P is considerably higher for market gardens and greenhouse flowers than for orchards and turf properties (Appendix 2). Residual P is very low for nurseries and native flower properties. Table 4 shows the maximum P concentrations in the water samples obtained from the nine horticultural properties which were monitored. Three of the five vegetable properties show high maximum P concentrations (Properties 2, 5 and 6). The other two vegetable properties are located on high phosphate fixing soils (Property 9) or have an area of high phosphate fixing soil immediately adjacent to the drain (Property 3).

The two properties on which greenhouse flowers were grown also showed high maximum P concentrations (Table 4). The concentrations in the bores on Property 8 may however be elevated due to inflow from a vegetable property 100 m up-gradient of the greenhouse.

The maximum P concentrations in the drain leaving the fruit farm (Property 1) and in the bores beneath the native flower farm (Property 7) were low.

The P concentrations in drains flowing through horticultural properties are likely to be lower than in bores located directly beneath the production area due to processes such as fixation and dilution.

Nitrogen

Appendix 3 gives approximate amounts of residual nitrogen remaining in the soil after crop removal for various types of horticulture. The amount of residual nitrogen is highest for market gardens. Greenhouse flower properties also have high residual nitrogen levels. Residual nitrogen is lower but still high for orchards, native flower properties, nurseries and turf farms.

Table 5 shows the maximum NO_3-N concentrations in the shallow monitoring bores beneath the production area. Two of the vegetable properties (Properties 5 and 6) showed extremely high NO_3-N levels. Property 9 showed an elevated but relatively lower level of NO_3-N. The reason for this was unclear.

High NO_3-N concentrations were also found in the bores located directly under the greenhouse flowers, turf and native flower properties.

Table 5. Maximum nitrate–nitrogen concentration in shallow groundwater under the properties monitored

Crop	Property	Method of monitoring	Maximum nitrate-nitrogen concentration in shallow groundwater beneath the production area (mg/L)
Vegetables	Property 5 Property 6 Property 9	Bore Bore Bore	110 100 7
Greenhouse flowers	Property 7 Property 8	Bore Bore	56 22*
Turf	Property 4	Bore	29
Native flowers	Property 7	Bore	25 (boronia) 7 (kangaroo paws)

* Results may be elevated due to inflow of NO_3-N from a vegetable property located 100 m up-gradient.

Nutrient concentrations in the shallow groundwater down-gradient of the production areas

Table 6 shows the maximum P and NO_3-N concentrations in monitoring bores 100 m down-gradient of the production area. Nutrient concentrations were lower than those under the production area but in the majority of cases were still high.

On Property 4 the P concentration rose to 7 mg/L in a bore located 100 m down-gradient of the turf. The dense bushland between the turf and this bore appeared to have little effect on reducing P concentrations. Phosphorus concentrations in excess of 7 mg/L were detected in a down-gradient bore located 50 m from the market garden on Property 6. Phosphorus concentrations were high in the shallow groundwater both up- and down-gradient of the rose greenhouse on Property 8. Phosphorus appears to be entering the property from the market garden located 100 m up-gradient. Phosphorus concentrations as great as 17 mg/L were detected 50 m down-gradient of the greenhouse. The dense area of bushland located between the greenhouse and the down-gradient bores had little effect in reducing P concentrations.

The down-gradient monitoring of Property 5 gave some interesting and conflicting results. Though P concentrations were very high (38 mg/L) in the groundwater directly under the garden, a number of the down-gradient bores showed low P concentrations (Figure 9). Bores 4 and 10 are both located 100 m down-gradient of the new section of the garden. The P concentration in Bore 4 did not increase above 0.34 mg/L while in Bore 10 concentrations reached 13 mg/L. Bore 4 was located in a lower lying Joel sand which had a peaty sand topsoil and a well developed coffee rock layer. Bore 10 was located on a slightly raised Gavin dune and had no layer of coffee rock. A possible explanation for the lower P concentrations in Bore 4 is that P was fixed by the coffee rock that occurred in this area.

The down-gradient monitoring in the old section of the garden gave similar results. Phosphorus concentrations were below 2.5 mg/L in all of the down-gradient bores. Again this area contained a well developed coffee rock layer.

The NO_3-N concentrations in the down-gradient bores on Properties 4, 6 and 7 did not fall greatly from those found under the production areas. On Properties 5 and 8 which contained Joel sands NO_3-N concentrations fell rapidly with increasing distance from the production area. The NO_3-N concentrations fell from 10 mg/L to 0.5 mg/L within 50 m on Property 8. Phosphorus concentrations did not fall over the same distance. On Property 5, NO_3-N concentrations fell from 110 mg/L under the garden to

11 mg/L (Bore 4) within 50 m. The shallow groundwater beneath both these areas contains large amounts of organic matter. Significant denitrification appears to have taken place. Bore 10 on Property 5 contained higher concentrations of NO_3-N (25 mg/L) than Bore 4. This bore was located on an area of Gavin sand which had less organic matter in the watertable.

The NO_3-N concentration in the bores 100 ı down-gradient of Property 9 only increase slightly.

Table 6. Maximum nutrient concentrations in the shallow groundwater under and down-gradient of the production area

	Maximum phosphorus concentration in shallow groundwater		Maximum nitrate-nitrogen concentration in shallow groundwater	
Property	Under production area	100 m down-gradient of production area	Under production area	100 m down-gradient of production area
4	16	7	29	9
5	38	13 (Bore 10) 0.34 (Bore 4)	110	25 (Bore 10) 11 (Bore 4)
6[B]	32	7.4	100	84
7	7.5	0.45	56	30
8[AB]	17	17	10	0.5
9[C]	0.03	0.04	7.1	0.36

Notes:

A Results may be elevated due to inflow of nutrients from a vegetable property located 100 m up-gradient.

B The down-gradient monitoring bores on Properties 6 and 8 were located 50 m down-gradient of the production area.

C Property 9 occurs on the Spearwood Dune System.

Discussion

Phosphorus

Phosphorus concentrations in shallow groundwater beneath the horticultural properties

Bassendean sands have a poor ability to hold P. The depth to the watertable beneath these soils is shallow and for many types of horticulture large amounts of residual P fertiliser are left in the soil after harvest (Appendix 2). This combination of factors creates a high potential for contamination of the shallow groundwater beneath horticultural properties.

This study found very high P concentı in the shallow groundwater beneath n the horticultural crops monitored (see Table 4). Where drains flowed directly through production areas on these soi concentrations in the drains were in s cases also very high (Property 2, Tabl

Phosphorus concentrations in the sha groundwater rapidly increased follov development of horticultural propert Bassendean sands. On Property 4 the concentrations increased from close t 0 mg/L to a maximum of 16 mg/L v months (Figure 6). Phosphorus in th toring bores on Property 5 increased to concentrations above 20 mg/L within six months. Phosphorus breakthrough times are very short on Bassendean sands when large amounts of phosphorus fertiliser are applied.

Not all of the properties monitored contained high P levels in the shallow groundwater or adjacent surface drains. In these cases P concentrations were often lower than those found in water leaving grazing properties (Summers *et al.* 1993). The low P concentration in the groundwater below these properties can be largely explained by soil type and lower rates of fertiliser application.

The shallow groundwater under the property which occurred on the soils of the Spearwood Dune System contained very low levels of P (Property 9, Table 4). This is consistent with the work of McPharlin and Pritchard (unpublished) and Sharma *et al.* (1991) which showed low P levels in the groundwater below horticultural properties located on the soils of the higher phosphate fixing Spearwood Dune System.

Both Properties 1 and 3 contain areas of higher phosphate fixing soils. This may help explain the lower P concentrations in water leaving these properties. The soil type surrounding the drain which was monitored on Property 3 is predominantly a peaty loam of the Herdsman Association. This soil has a very good ability to fix P (Appendix 4). The majority of the vegetable production in this catchment is located on the low phosphate fixing Bassendean sands. Phosphorus levels in the shallow groundwater directly under these areas are likely to be very high, however, the concentrations in the drain are relatively low reaching a peak of 0.6 mg/L.

The phosphorus retention properties of the area of soil immediately adjacent to the drain appear to be very important in determining the amount of P loss. Summers *et al.* (unpublished) found that the region closest to the drain was the most important area in determining the phosphorus concentration in the drain, probably because it is the area in which the water concentrates and any filtration that occurs is likely to be most effective there.

Phosphorus concentrations in the deep groundwater

High P concentrations were found in the top 2 m of the watertable on six properties (Properties 2, 4, 5, 6, 7 and 8). However, all of the deep bores on these properties, with the exception of Property 7, contained very low P concentrations. The iron-organic pan or coffee rock layer appears to have a major role in preventing or reducing P contamination of the deep groundwater. Coffee rock occurs beneath many of the properties and in particular under areas of the more low lying Joel sands. Coffee rock has a good to very good ability to fix phosphate (Appendix 4). The nature of coffee rock is variable. It varies from a very weakly cemented, organic sand through to a strongly cemented pan through which water does not pass. In more low lying areas it is continuous though it often disappears, becomes thinner and weaker or occurs at a greater depth from the surface under areas of Gavin sands. Generally, coffee rock occurs at a depth similar to, or just below, the level of the summer watertable. The difference in P content above and below the coffee rock layer appears to be due to three factors:

- Where the coffee rock is permeable, P can be stripped as it moves through this layer.
- Where the coffee rock is largely impermeable, P rich surface water can not move down the profile but is forced to flow laterally across the top of the coffee rock layer.
- Phosphorus rich water moving down the aquifer is greatly diluted by water coming in from outside the production area. The coffee rock layer may be poorly developed or is saturated with P resulting in little P fixation.

On Property 6 the coffee rock layer consisted of loose, organic stained sand with some lumps of coffee rock. High NO_3-N levels were found in the deep bore (Bore 1, Figure 15) but elevated P levels did not occur in the deep bore (Bore 1, Figure 14). This indicates that stripping of P by the coffee rock may have occurred.

Areas of Property 5 contained what appeared to be continuous, cemented layers of coffee rock. Drilling through this layer revealed different coloured water which had a piezometric head slightly above the watertable. This indicates that the water above the pan belonged to a different water body and that P rich water did not flow through the pan but laterally across the top of the pan.

Phosphorus concentrations in shallow groundwater down-gradient from the cropped area

Nutrient concentrations will decrease with increasing distance from the production area because of processes such as dilution and diffusion. Phosphorus concentrations will also decrease due to soil fixation, particularly if water flows through a high fixing layer.

High P concentrations were detected in the shallow groundwater 50 and 100 m down-gradient of the production area on four of the five properties located on Bassendean sands (Table 6).

Where the coffee rock is permeable and water flows across or through this layer, considerable P fixation may occur. Impermeable coffee rock layers appear to have limited ability to fix P from water flowing laterally across the top of this layer. In such a case there is little contact between the P and the coffee rock, creating limited potential for stripping of P. The role of coffee rock in fixing P requires closer investigation.

Native bushland appears to have little effect on reducing P concentrations in shallow, laterally flowing groundwater. Many native species have a low P requirement and their feeder roots are predominantly in the top few centimetres of soil (A. Reid, Floricultural Development Officer, pers. com.). Consequently, these plants would have limited ability to remove P from the watertable.

Nitrogen

Nitrate-nitrogen concentrations in shallow groundwater beneath horticultural properties

All the sandy soils of the Swan Coastal Plain have a poor ability to hold nitrate. On these soils, often only about a third of the nitrogen fertiliser that horticulturalists apply is taken up by the plant, leaving a large amount of residual nitrogen in the soil (Appendix 3). Heavy rainfall and irrigation readily leaches nitrates from the root zone and into the shallow groundwater.

This study found high to very high NO_3-N concentrations in the shallow groundwater beneath all of the properties monitored (Table 5). Concentrations were above the World Health Limit for drinking water of 10 mg/L NO_3-N on all but one property. Pionke *et al.* (1991) and McPharlin and Pritchard (unpublished) found similar results when they surveyed the NO_3-N concentrations in horticulturalists' production bores.

NO_3-N concentrations in the shallow groundwater increased rapidly following the development of horticulture. Within five months NO_3-N concentrations had increased to over 5 mg/L on both Properties 4 and 9 (Figures 7 and 23 respectively).

Nitrate-nitrogen concentrations in the deep groundwater

Only two of the properties monitored had high NO_3-N concentrations in the deep bores which monitor from the base of the superficial aquifer (Properties 6 and 7). The difference in NO_3-N content from the top to the bottom of the aquifer appears to be due to three factors:

- in some cases the underlying coffee rock is largely impermeable and prevents nutrient rich water from moving down the aquifer;
- significant denitrification may be occurring within the upper part of the aquifer; and

- nitrate rich water is being greatly diluted by water coming in from outside the production area.

The continuous and cemented coffee rock which occurs below areas of Property 5 appears to be preventing nitrate from moving deeper into the aquifer. On Properties 4 and 8 where the coffee rock layer is not present or does not significantly restrict downward movement of water, it is likely that denitrification and dilution are significant processes. The aquifer beneath the Bassendean Dune System exhibits characteristics conducive to denitrification (Gerritse *et al.* 1990). It has low redox potentials and high dissolved organic carbon.

Nitrate-nitrogen concentrations in the shallow groundwater down-gradient from the cropped area

Significant denitrification appeared to have taken place in the groundwater below areas of Joel sands. On the two properties with Joel sands NO_3-N levels fell rapidly with increasing distance from the production area. On Property 8, NO_3-N concentrations fell from levels of 10 mg/L to 0.5 mg/L within 50 m (Table 6). Phosphorus concentrations did not fall over the same distance. On Property 5, NO_3-N concentrations fell from 110 mg/L to 11 mg/L within 100 m of the garden (Table 6). The shallow groundwater beneath both these areas on the two properties contains large amounts of organic matter.

A different scenario occurs under the properties located on Gavin, Jandakot and Spearwood sands. High NO_3-N concentrations were detected in the down-gradient bores on Properties 4, 5 (Bore 10, Transect A), 6 and 7. The groundwater beneath these properties is lower in organic matter and the coffee rock is less developed or absent. Significant denitrification does not appear to have occurred.

Recycling of nutrients via irrigation

The abstraction of groundwater for irrigation from dams and bores in the superficial aquifer may create a situation where nutrient rich water is recycled back onto the property. During the warmer months, when abstraction is greater and rainfall is minimal, the amount of nutrient leaving the property may be greatly reduced. Recycling of nutrients may explain the relatively low amounts of phosphorus and nitrogen leaving the old section of Property 5 (Transect B). This transect of monitoring bores was located close to a groundwater-fed dam which is used for irrigation. Sharma *et al.* (1991) found negligible export of water and nutrients from one of the properties they studied because pumping for irrigation drew water in from surrounding areas.

Placement of shallow production bores or irrigation dams on the down-gradient edge of the cropped area may reduce nutrient loss from the property and, because of recycling of nutrients, allow lower rates of fertiliser to be used. However, recycling of fertiliser salts will increase the salinity of the water and may not be sustainable. The use of this method to reduce nutrient loss from sandy soils on the Swan Coastal Plain requires further investigation.

Rate of fertiliser application

Horticultural activities on the Swan Coastal Plain can be classified according to their relative phosphorus and nitrogen use and the amount of residual nutrient remaining in the soil after harvest. Table 7 shows the relative phosphorus and nitrogen pollution risk of different horticultural activities.

Table 7a. Relative phosphorus pollution risk of different horticultural activities

High	Market gardens, greenhouse flowers
Moderate	Orchards, vineyards, turf
Low	Native flowers, nurseries

Table 7b. Relative nitrogen pollution risk of different horticultural activities

High	Market gardens, greenhouse flowers
Moderate	Orchards, vineyards, turf, native flowers, nurseries
Low	–

The amount of residual nutrient remaining in the soil and associated potential for nutrient pollution varies greatly among different horticultural activities. (Appendices 2 and 3).

Market gardens and greenhouse flower growers apply the highest rates of phosphorus and nitrogen fertilisers while nurseries and native flower growers the least. On nurseries and native flower farms, the residual phosphorus remaining in the soil after crop removal may be similar to or less than that from grazing properties (Appendix 2).

Horticulturalists growing the same crop also apply considerably different amounts of nutrients, with the rate depending on factors such as soil type, cropping history, length of rotation, irrigation uniformity and method of fertiliser application. Growing techniques such as applying water and nutrients through trickle irrigation and the use of plastic mulch allow considerably lower rates of fertiliser to be applied.

It is imperative that the relative nutrient pollution risk of different horticultural activities is taken into account when assessing the environmental acceptability of new horticultural developments.

In many cases horticulturalists can reduce the rate of fertiliser application without loss of yield. Soil testing should be used to determine the nutrient content of the soil and tissue analysis to determine nutrient status of the plant.

Bassendean sands hold P more poorly than most other soils, making the nutrient more available for both plant growth and leaching. Traditionally phosphorus fertiliser rates on Bassendean sands have been derived from those used on higher fixing soils of the Spearwood Dune System. Recent trial work (Lantzke and McPharlin 1997) has shown that the total phosphorus fertiliser application can be greatly reduced for vegetable production on Bassendean sands provided it is applied in small, regular doses. It is likely that phosphorus fertiliser rates can also be reduced for other horticultural crops on these soils without affecting yield. By doing so the residual P remaining in the soil after harvest can be reduced, lowering the risk of P enrichment of the groundwater.

Applying nitrogen fertilisers in small regular doses reduces the chance of nitrate leaching by heavy rainfall events, as well as increasing production. Applying large pre-plant applications of poultry manure is an inefficient method of fertilising as a considerable proportion of the nitrogen is leached before the crop can use it. Horticulturalists should have their irrigation water analysed for its nutrient content and take account of this in their fertiliser program.

Education of horticulturalists in plant nutrition, advice on how to refine fertiliser programs and dissemination of information on improved growing techniques are essential to reduce nutrient leaching.

Planning guidelines for new horticultural developments

The monitoring results in this report provide information useful for assessing the nutrient pollution risk for different horticultural activities on Bassendean sands. This information is useful for the development of regional, strategic land capability maps. These maps identify areas suitable for horticulture, areas where there is some environmental risk and areas where the risk of nutrient pollution is high.

Van Gool and Runge (unpublished) have produced broadscale land capability maps of the Swan Coastal Plain to assist planning the future location of horticulture so as to minimise environmental risk.

The land capability maps can assist in the environmental assessment of proposals for new horticultural developments. However, in some cases, assessments of proposals for new horticultural developments need to be carried out on an individual basis. This is particularly so for areas of Bassendean sands within environmentally sensitive areas such as the Ellenbrook and Peel–Harvey catchments.

Assessing the environmental acceptability of proposals for new horticultural developments is often difficult and complex. High nutrient concentrations below horticultural properties do not necessarily equate to high nutrient concentrations in adjacent water bodies which are hundreds of metres or kilometres away.

Nutrient concentrations in the shallow groundwater may significantly decrease with increasing distance from the area where fertiliser was applied due to processes such as fixation, dilution, denitrification and plant uptake. In many cases the groundwater leaving horticultural properties may flow through areas of high P fixing soil or areas where denitrification is significant, reducing nutrient concentrations to acceptable levels before the water reaches environmentally important water bodies. A well documented example of where nutrient concentrations were greatly reduced is the Spectacles wetland at Mandogalup (Heady *et al.* 1991).

As a general principle, the addition of nutrients to the groundwater is poor practice. The reality of whether this causes adverse off-site environmental effects depends not only on the assimilative capacity of the saturated zone but on factors such as the total amount of nutrient applied and direction of groundwater flow at different times of the year.

Setting appropriate buffer widths which separate horticulture from water bodies, drains and wetlands is difficult. The widths of these buffers need to vary to take account of the environmental significance of water bodies in the catchment. Lantzke (unpublished) lists suggested buffer widths for different types of horticulture for different soil/landscape units on the Swan Coastal Plain. The buffer width is varied to take into account the phosphorus holding ability of the soil, the likely rate of fertiliser application and the potential for surface run-off.

Conclusions

- Very high phosphorus concentrations often occur in the shallow groundwater beneath high (market gardens and flower greenhouses) and moderate (orchards and turf farms) phosphorus-use horticultural properties on Bassendean sands.
- Low P concentrations were generally found in the shallow groundwater beneath low phosphorus-use horticulture such as native flower production and nurseries on Bassendean sands. The phosphorus pollution risk for low phosphorus-use horticulture on Bassendean sands is generally low.
- Soil type is critical in determining phosphorus loss. Small areas of high phosphate fixing soil near a drain can greatly reduce phosphorus loss into the drain. The phosphorus pollution risk of horticulture on the soils Spearwood Dune System is almost always low, with P breakthrough times being considerably longer than the life of horticultural activity on most properties.
- Iron organic pans or coffee rock have a major impact on nutrient movement down the aquifer. The role of coffee rock in stripping phosphorus needs further investigation.
- Phosphorus concentrations in the shallow groundwater beneath Bassendean sands decrease with increasing distance from the production area. However, high phosphorus concentrations were often detected 100 m down-gradient of the horticultural production areas. Buffer widths need to be considerably greater than 100 m to allow phosphorus concentrations to be reduced to acceptable levels. In some situations it may not be possible to find ways for some horticultural activities to have acceptable levels of impact.

- The native vegetation on Bassendean sands has little ability to remove phosphorus from the shallow watertable.
- On some properties pumping for irrigation at certain times of the year may create a situation where little or no nutrient rich water leaves areas of the property but is recycled and put back on the crop. Placement of production bores or groundwater-fed irrigation dams on the down-gradient edge of the cropped area, may reduce nutrient loss from the property and allow lower rates of fertiliser to be used. The use of this method to reduce nutrient loss requires further investigation.
- High to very high nitrate concentrations commonly occur in the shallow groundwater beneath horticultural properties on the sandy soils of the Swan Coastal Plain. These levels are often in excess of the World Health Limit for drinking water (10 mg/L NO_3-N).
- Significant denitrification is likely to occur in the watertable under areas of Joel sands. NO_3-N concentrations at the bottom of the superficial aquifer and down-gradient of horticultural properties on these areas are likely to be greatly reduced.
- NO_3-N concentrations in the shallow groundwater are still likely to be high 100 m down-gradient of the production area for high nitrogen use horticulture located on soils such as Spearwood, Karrakatta, Jandakot and Gavin sands where denitrification is not significant.
- Procedures for the approval of new horticultural developments (and expansions to existing developments) need to be reviewed. This particularly applies to proposals on Bassendean sands and similar soil types with low nutrient retention capacity. Guidelines that determine the environmental acceptability of proposed, new horticultural properties and which set development restrictions, such as buffer widths need to be developed for different horticultural activities on the Swan Coastal Plain.
- Continuing education of horticulturalists on the problems caused by nutrient leaching and advice on how they can minimise their impact is critical in reducing nutrient enrichment of surface and groundwaters. Local government authorities and the Health Department may need to provide advice to landowners on potential problems associated with the use of shallow groundwater in horticultural areas for drinking purposes.

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Appendices

Appendix 1 – Methods of chemical analysis

	Description
Cl	Chloride, colorimetric using segmented flow auto analyser.
E.C.	Electrical conductivity, electronic using meter.
K	Potassium direct reading using inductively coupled plasma spectroscopy (ICP).
$N\text{-}NH_3$	Nitrogen, ammonia, colorimetric using segmented flow auto analyser.
$N\text{-}NO_3$	Nitrogen, nitrate, colorimetric using segmented flow auto analyser.
N_{total}	Nitrogen, persulphate total, persulphate digestion followed by colorimetric determination using segmented flow auto analyser.
P_{tot}	Phosphorus, total, persulphate digestion followed by colorimetric determination using spectrometry.
$SO_4\text{-}S$	Sulphate, sulphur expressed as sulphate, direct reading using inductively coupled plasma spectrometry (ICP).

Conducted by Chemistry Centre of Western Australia.

Appendix 2

Recommended upper phosphorus application rate, crop removal and residual phosphorus for different types of horticulture on a Karrakatta sand

Phosphorus

Type of horticulture	Yield (t/ha/crop)	kg/crop			kg/year		
		Application rate (kg P/ha/crop)*	Crop removal (kg P/ha/crop)	Residual P (kg/ha/crop)	Application rate (kg P/ha/year)*	Crop removal (kg P/ha/year)	Residual P (kg/ha/year)
Market gardens		**123**	**25**	**98**	**307**	**66**	**241**
Carrots	60	100	24	76	250	60	190
Cauliflower	30	100	25	75	250	63	187
Celery	100	130	31	99	325	78	247
Lettuce	50	100	30	70	250	75	175
Onions	60	170	27	143	425	68	357
Potatoes	55	100	23	77	250	58	192
Tomatoes	100	160	16	134	400	60	340
Orchards					**46**	**7**	**39**
Citrus	30				45	12	33
Avocados	12				19	2	17
Peaches	30				50	6	44
Grapevines	20				70	8	62
Greenhouse flowers							
Roses					686	215	471
Carnations					150	59	91
Native flowers							
Waxflower	10				15	10	5
Banksia	5				15	2	13
Kangaroo paws	5				20	10	10
Nurseries					25	25?	< 5?
Turf production					80		
Golf courses					24	12	12
Pasture hay**	5				20	16	4
Beef cattle**	1.25 (live weight)				20	9	11

* It is likely that the phosphorus application rates in this table can be reduced for many crops without yield decline.
** The data for pasture hay and beef cattle refer to production on the soils of the Pinjarra plain.

Appendix 3

Recommended upper nitrogen application rate, crop removal and residual nitrogen for different types of horticulture on a Karrakatta sand

Nitrogen

Type of horticulture	Yield (t/ha/crop)	kg/crop			kg/year		
		Application rate (kg N/ha/crop) *	Crop removal (kg N/ha/crop)	Residual N (kg/ha/crop)	Application rate (kg N/ha/crop) *	Crop removal (kg N/ha/crop)	Residual N (kg/ha/crop)
Market gardens		**486**	**135**	**351**	**1214**	**364**	**849**
Carrots	60	350	86	264	875	215	660
Cauliflower	30	500	109	391	1250	273	977
Celery	100	550	151	399	1375	378	997
Lettuce	50	400	120	280	1000	300	700
Onions	60	400	147	253	1000	368	632
Potatoes	55	550	184	366	1375	468	915
Tomatoes	100	650	148	502	1625	560	1065
Orchards					**151**	**52**	**99**
Citrus	30				140	87	53
Avocados	12				160	14	146
Peaches	30				125	69	56
Grapevines	20				180	38	142
Greenhouse flowers							
Roses					2340	1300	1040
Carnations					624	322	302
Native flowers							
Waxflower	10				175	29	146
Banksia	5				75	20	55
Kangaroo paws	5				130	10	120
Nurseries					**336**		**< 100?**
Turf production					**513**		
Golf courses					144	80	64
Pasture hay **	5				0	130	low
Beef cattle **	1.25 (live weight)				0	34	low

* It is likely that with improved management practices the nitrogen application rates in this table can be reduced without yield decline.

** The data for pasture hay and beef cattle refer to production on the soils of the Pinjarra plain. Nitrogen fertiliser is not applied but significant input occurs due to nitrogen fixation by legumes.

Source of data and assumptions made in Appendices 2 and 3

Application rates

Application rates for market gardens, orchards, flowers, pasture hay and beef cattle grazing are based on Agriculture Western Australia recommendations.

Application rates for nurseries were taken from the 1992 Nursery Fertiliser Survey (Horticulture Industry Newsletter No. 26, Western Australian Department of Agriculture, and unpublished data).

Application rates for turf are based on a survey of four properties. Agriculture Western Australia (unpublished data).

Application rates for golf courses come from turf consultant Ken Johnston (pers. com.).

Yearly application rates for vegetable crops were calculated assuming 2.5 crops per year.

Crop removal

Crop removal figures are approximations and will vary according to species, variety and yield. Crop removal does not include crop residues or prunings that remain in the field or greenhouse. Nutrients in this material are available for recycling.

Crop removal figures for market gardens were based on empirical data from Lorenz and Maynard (1988).

Crop removal figures for orchard crops were taken from Clarke *et al.* (1986).

Crop removal figures for greenhouse flowers and native flowers were calculated from samples collected and analysed by Agriculture Western Australia.

Crop removal figures for golf courses come from turf consultant Ken Johnston (pers. com.). They assume grass clippings are removed from the site.

Crop removal figures for pasture hay and beef cattle were obtained from G. Parlevliet (unpublished data).

Appendix 4

Typical phosphorus retention indices (PRI) of soil types found on the Swan Coastal Plain

System	Spearwood Dune System			Bassendean Dune System			Herdsman Association	Pinjarra Plain		Ridge Hill Shelf
Depth (cm)	Cottesloe sand (Spearwood sand)	Cottesloe sand (Spearwood sand+)	Karrakatta sand (yellow phase)	Jandakot sand and Karrakatta sand (grey phase)	Gavin sand	Joel sand	Herdsman peaty loam	Boyanup clay loam	Coolup sand	Forrestfield soil
0	7	4	3	< 1	0	0	200	> 100	3	20
50		25					300	> 100	> 100	> 100
100	8	27	5	< 1	0	0	Watertable**	> 100	> 100	> 100
150	14	Limestone		3		18–390		Watertable	Watertable	
						(Coffee rock)				
200	Limestone	Limestone	6	3	0	Watertable^{x}				
250	Limestone	Limestone	22	4						
300	Limestone	Watertable		5	Watertable					
> 800	Watertable		Watertable	Watertable						Watertable

+ Flats with grey sand over limestone at shallow depth. Adjacent areas seasonally inundated.

x In winter the watertable rises above the coffee rock layer.

** The watertable occurs near or close to the surface during the winter months.

Note: This table gives typical PRI values for each of the major soil types. Considerable variation may occur from site to site. For example in some cases coffee rock with a PRI greater than 30 may occur in the subsoil of the Jandakot and Gavin sands.

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