Water and Phosphorus Transport Processes in Permeable Grey Sands at Talbot's site near Harvey Western Australia

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WATER AND PHOSPHORUS TRANSPORT PROCESSES IN PERMEABLE GREY SANDS AT TALBOT'S SITE NEAR HARVEY, W. AUSTRALIA

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1. INTRODUCTION

Eutrophication of the Peel-Harvey Estuarine System in Western Australia has been strongly associated with the leaching of phosphorus from the catchment soils into the rivers and drains entering the system (Birch, 1982). High phosphorus loads in drainage water are due primarily to extensive agricultural development of permeable sandy soils, with low phosphorus adsorption capacity, in areas of high winter rainfall; and to the long term application of fertilizer in which a high proportion of the phosphate is in a water soluble form.

One means of contributing to the control of the eutrophication problem is to significantly reduce the amount of phosphorus leaching from soils into drainage. A reduction in the flow-weighted mean concentration of phosphorus in drainage would reduce the frequency and magnitude of algal blooms currently occurring in the Estuary provided the phosphorus released from estuarine sediments is not excessive.

Research into methods of reducing phosphorus leaching has focused primarily in two areas:

(1) the development of alternative fertilizer sources containing a lower portion of water soluble phosphorus in association with a comprehensive fertilizer management programme on the coastal plain;

(2) an intensive investigation of phosphorus transport processes within the soils of the Estuary catchment.

This report concentrates on the second area of research and describes progress made at one field research site. The site is situated on Mr Talbot's property, near Harvey, W.A. (hereafter called 'Talbot's site'). Talbot's site is located on permeable grey sands of the Bassendean soil association which occupy some 22% of the coastal plain catchment of the Harvey Estuary, but contributes about 35% of the total phosphorus load to the Harvey River and drains. These grey sands not only exhibit a greater than average phosphorus loss to drainage but also, because of their low phosphorus adsorption capacity, are more amenable to change of fertilizer practice than other soils of the coastal plain. These two facts have attracted intensive research to this site. The results of the first year of research (1983) are presented in this report.

2. RESEARCH OBJECTIVES AND METHODOLOGY

The Talbot's experiment attempts to fulfill multiple objectives, ranging from relatively straightforward management questions to much more detailed research problems. In this section three levels of objective are described along with the appropriate research methodology and the expectations of results.

Objective 1 : To determine the potential reduction in phosphorus leaching to drainage by nil application of fertilizer on non-responsive grey sands, as compared to 'normal' superphosphate application, whilst maintaining full pasture growth.

This is a 'black box' management problem requiring a direct answer to a direct question. The approach has been to establish a pair of similar catchments at the management scale and directly compare the two treatments over several winters. The measurements required are the amount of phosphorus applied as fertilizer and the amount lost to drainage.

The results expected from this experiment are a quantification of the reduction in phosphorus leaching to drainage over a period of time, and the effect of nil application on pasture growth during the time when the soils change from non-responsive to responsive to phosphorus application as measured by soil testing.

Objective 2 : To quantify the water and phosphorus budgets for each catchment.

This objective requires considerably more measurement. In respect of the water budget, measurements of rainfall, evaporation, runoff, unsaturated soil water content and groundwater are required. The components of the phosphorus budget to be measured are phosphorus applied as fertilizer, phosphorus loss in drainage, phosphorus loss to agricultural export, and phosphorus change in the soil and soil water reservoirs.

The information from this experiment should be quite significant. Firstly it would give a quantitative understanding of the seasonal water and phosphorus components. It should then be possible to identify where most of the phosphorus changes are occurring in the system and this will influence future fertilizer practices and research.

Objective 3 : To gain an understanding of phosphorus transport processes in permeable grey sands.

This last objective requires more intensive field measurements, monitoring and laboratory analyses, and relies heavily on computer modelling. Three types of computer model are being developed. The first is essentially a groundwater model that aims to describe water movement through the catchments and predict runoff. An intensive network of groundwater observation bores are monitored as part of this work. The second model has been developed from laboratory phosphorus column leaching trials which simulate field conditions of wetting, drying and heating and can predict some of the main features of phosphorus drainage loss observed in the field (see Ritchie and Deeley, 1984). The third model is an ambitious, complex, hydrological-phosphorus transport, deterministic model which is in a very early stage of development. The expectations of this objective are high and may only be partially fulfilled. It has the potential to give a very good conceptual understanding of the system which should be applicable elsewhere; to describe the dynamic behaviour of the system; to identify those parts of the system most appropriate to treat; to predict phosphorus 'rundown' times; and to predict the effect of a range of different treatments.

3. SITE SELECTION AND DESCRIPTION

3.1 Sources of Phosphorus

Over a number of years monitoring of rivers and drains converging on the Peel-Harvey Estuarine system, both regular sampling at gauged sites and opportunistic sampling at other sites, has indicated large differences in phosphorus concentrations. Although the greatest part of the surface catchment of this system lies to the east of the Darling Scarp, in the catchment of the Murray-Hotham river system, and by far the greatest application of phosphate - largely as superphosphate - is made in this area, the major input of phosphorus to the Estuary comes from coastal plain drains and rivers (Fig. 1). Some 52% of phosphorus inputs to the Peel-Harvey system arrive via the Harvey River Drain (1978 budget : Department of Conservation and Environment, 1984).

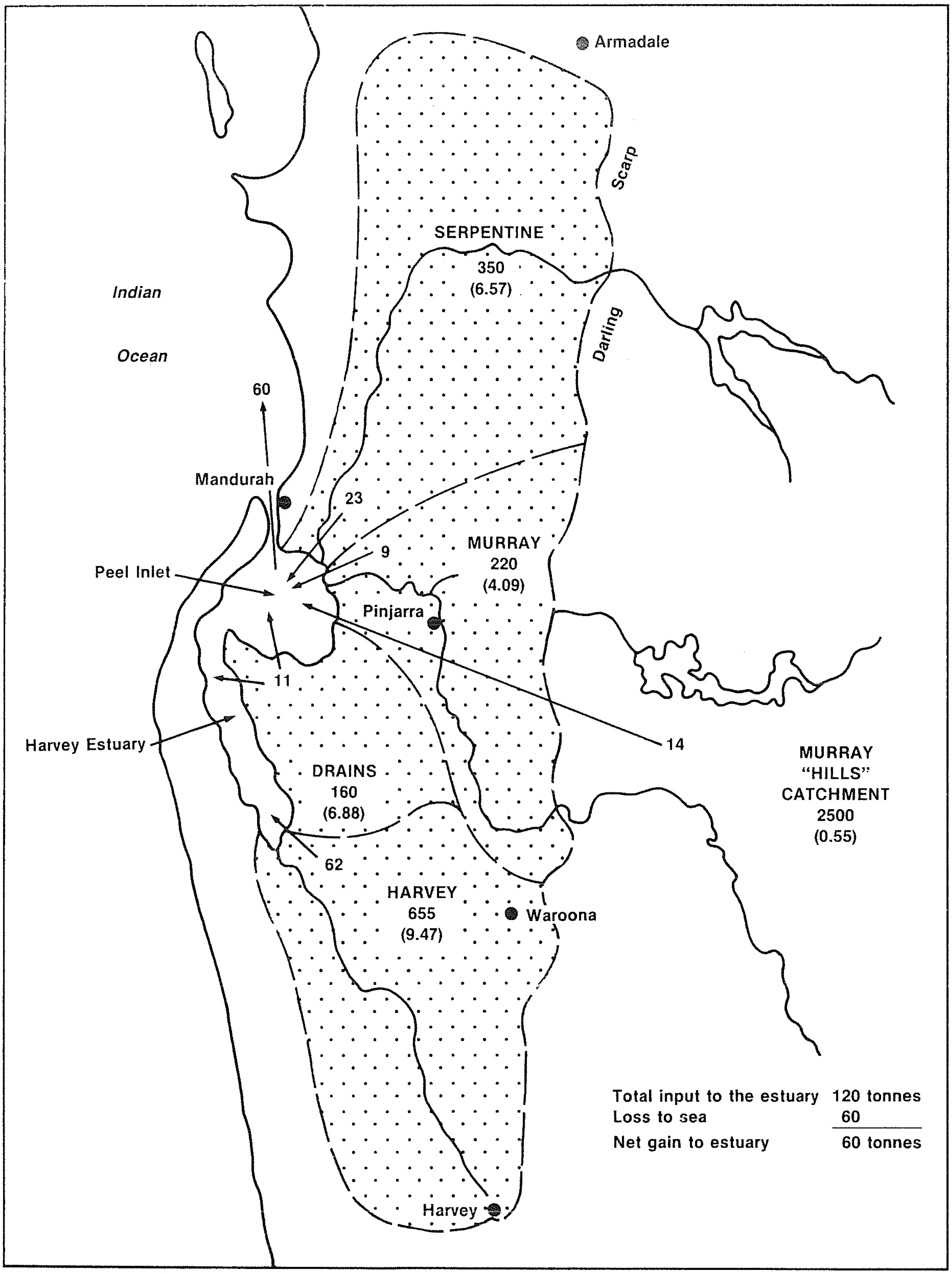
3.2 The Swan Coastal Plain Catchments

The catchment area of the Peel-Harvey Estuary is thought to be bounded to the west by the topographic high of the Spearwood dune system (further information on this is being sought through unpublished data of the Mines Department). To the north there is a low divide to the drainage of the Canning and Southern River Systems, while to the east the divide is marked by the Darling Scarp and to the south by a low divide to drains which discharge into the Harvey River Diversion Drain. Over much of the area both surface and groundwater gradients are very low (about 1:1000) and the boundaries between catchments are indefinite and frequently controlled by man made drains installed largely to reduce winter waterlogging.

3.3 The Swan Coastal Plain Soils

Soils of the Swan Coastal Plain (Fig. 2) vary widely in their chemical and physical properties, and this affects both their hydrological behaviour and their patterns of phosphorus export. Despite long continued, and high, phosphorus applications to irrigated areas, these loamy soils (largely Dardanup association) have not been found to export excessive quantities of phosphorus. This appears to be largely attributable to their very high capacity to adsorb phosphorus. More clayey soils of the Serpentine River association also have a strong capacity to adsorb phosphorus, and the surface runoff generated from these areas, when the winter rainfall rates exceed infiltration capacity, has low phosphorus concentrations. Samson Brook North drain, which largely drains such loam and clay soils, has a flow-weighted mean phosphorus concentration about 0.36 mg/L (Schofield et al., 1984).

Duplex soils (sandy surfaced soils with sandy clay subsoils) of the Guildford association have relatively permeable top soils,



Total input to the estuary	120 tonnes
Loss to sea	60
Net gain to estuary	60 tonnes

Figure 1 Locality map and sources of phosphorus to the Peel-Harvey Estuary.

but infiltration is restricted by the subsoil and perched water tables develop in winter. Drainflow is generated by both surface and soil water flow and has intermediate phosphorus concentrations. Mayfields Sub-G drain, which drains soils of this type, has a flow-weighted mean phosphorus concentration about 0.52 mg/L. However, because of the large area of such soils under agriculture, they are very important in terms of total inputs to the estuary and are the subject of a separate detailed study.

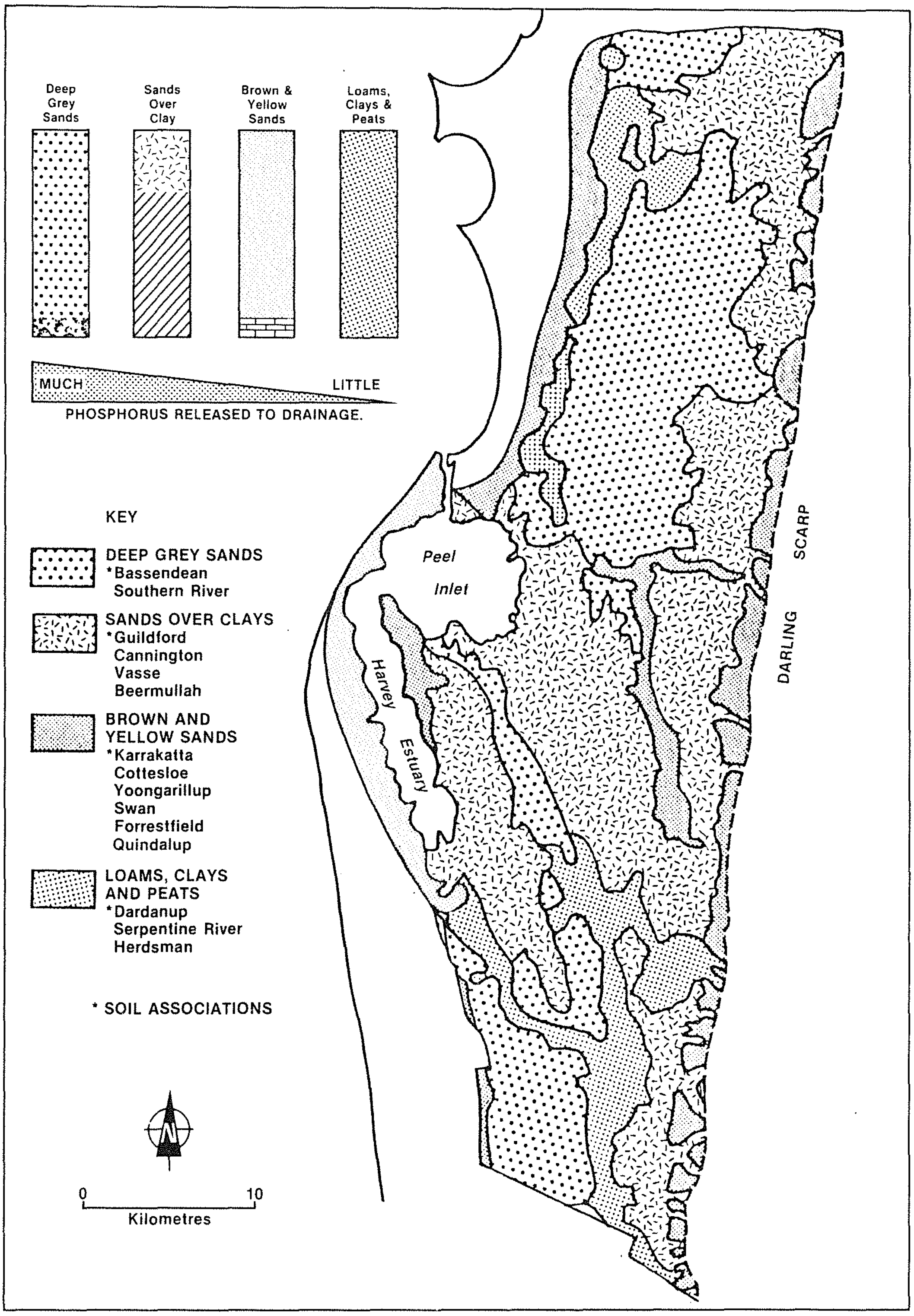


Figure 2 Peel-Harvey catchment soil map.

Sandy soils of the Bassendean association are characterised by low sandy rises, with intervening flats and swamps which also have largely sandy soils. There is an extensive aquifer system at depth and seasonal and permanent swamps represent areas where groundwater intersects the surface at various times of the year. In areas of such soils developed for agriculture, groundwater with phosphorus concentrations > 30 mg/L have been detected. Meredith drain (Fig. 3) which includes areas of native vegetation, as well as areas developed for agriculture, has a flow-weighted mean phosphorus concentration about 1.7 mg/L. Because of these high concentrations, and the permanent flow in drains feeding from such areas, they have been the subject of detailed field investigation.

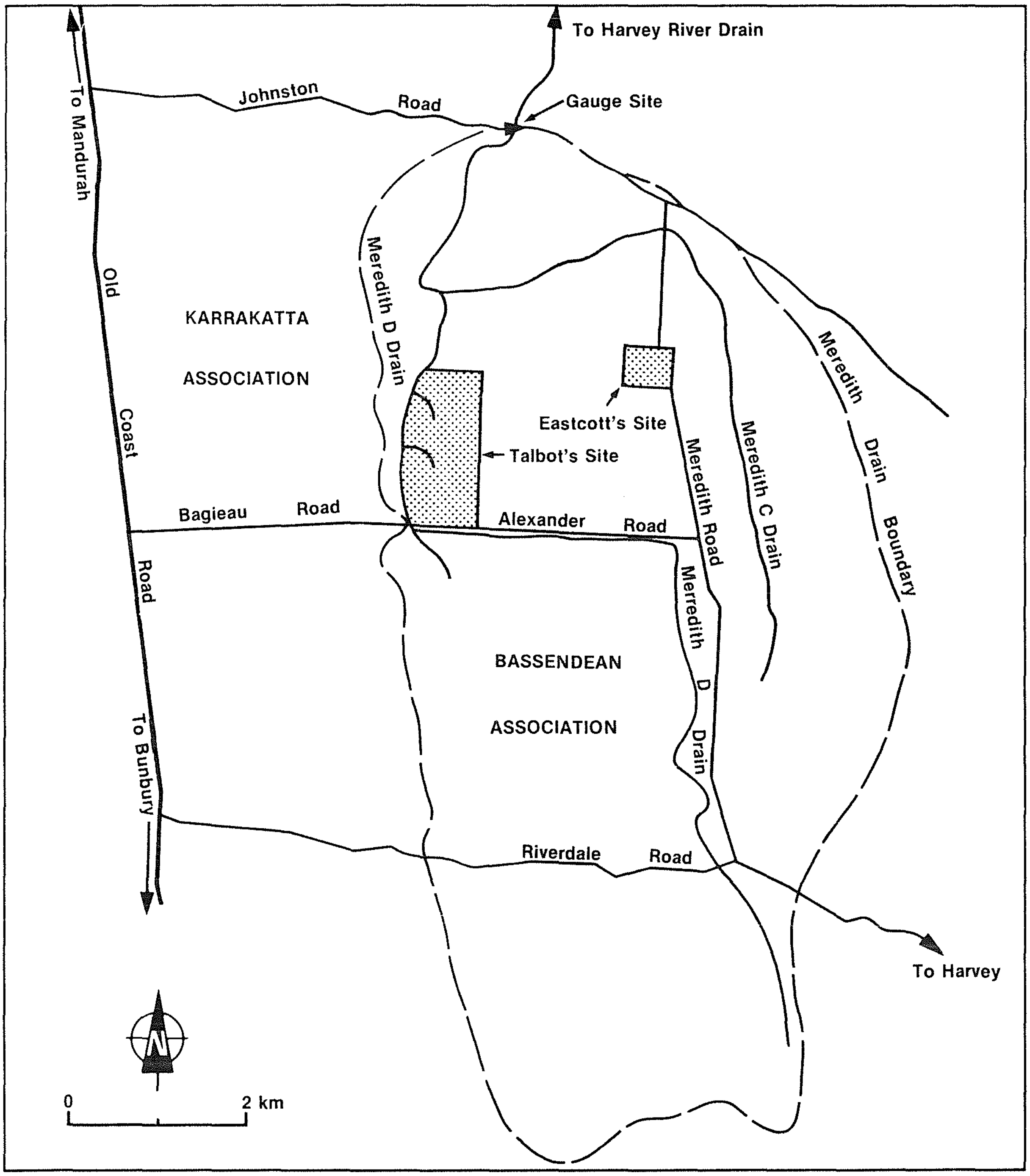


Figure 3 Location map of experimental sites.

3.4 Talbot's Site

3.4.1 Location and climate

Talbot's farm (Karinga Downs) with a total area of 200 ha lies to the north of the Bagieau Rd - Alexander Rd alignment, and straddles the boundary of the Karrakatta and Bassendean soil associations (see Fig.3). Meredith D drain flows from south to north approximately along this boundary. A major stream gauging station and sampling site is situated on Meredith drain on the south side of Johnston Rd. Approximately 70 ha of Karinga Downs, together with a part of the property adjoining to the east, has been instrumented for a detailed hydrological study. This area was chosen particularly because it is considered to be representative of normally farmed Bassendean association for the district, and because of the presence of two farm drains which made possible separate gauging and experimentation within the Talbot's site.

From a comparison of both published and unpublished data (Commonwealth Bureau of Meteorology; Water Resources Branch, Public Works Department, Western Australia), climatic conditions at Talbot's would be expected to be intermediate between Mandurah and Harvey. Average annual rainfall is estimated at 825 mm with a strong winter incidence, some 810 mm, or 88%, falling in the winter months May to October inclusive. Average maximum temperatures would exceed 25°C for November to April inclusive, rising to above 40°C on some occasions. Lowest maximum temperatures occur in winter and would be about 17°C in July, with the temperature occasionally falling as low as 0°C. Annual potential evaporation is estimated to be approximately 1300 mm.

3.4.2 Soils and topography

The soils to the east of Meredith drain are typical of the Bassendean association developed on an approximately north-south set of dunes and swales with a relief of about 5 m. This compares to survey information (Department of Administrative Services) giving an altitude range from 34 m, on the sandy rises, to 12 m AHD, in the swamps, within the Meredith drain area generally. Data collected at the same time on swamp heights, extending from the divide south of Riverdale Rd to Johnston Rd, indicate a gentle gradient of ~ 1:1500 to the north-west. This approximates the gradient along Meredith drain. Soils of the dunes range from Jandakot sand, with a yellow-brown weakly cemented B horizon, on the crests, to Gavin sand with a thick and strongly bleached A2 horizon overlying a brown to black organic, or iron organic (coffee rock) hardpan B horizon. Joel sand, sandy loam and loam profiles occupy the swales. These have more organic matter in the A1 horizon, and an A2 with a patchy bleach overlying the coffee rock B horizon. There are seasonal swamps containing sandy and peaty soils in which the coffee rock pan is at best weakly developed. A low lying flat area adjoining Meredith drain has a variety of swamp soil profiles in which clay size materials are present at or near to the surface, and in which coffee rock is generally absent. Soils have been mapped (Fig. 4), and ground-surface contours generated from levels at bore sites. Soils have been mapped on general morphological properties, organic matter content, presence and depth of coffee rock, texture and colour etc. Contours were generated by computer using surveyed ground heights at each of the bore sites, while catchment boundaries above the gauge sites were drawn from stereoscopic interpretation of paired photographs.

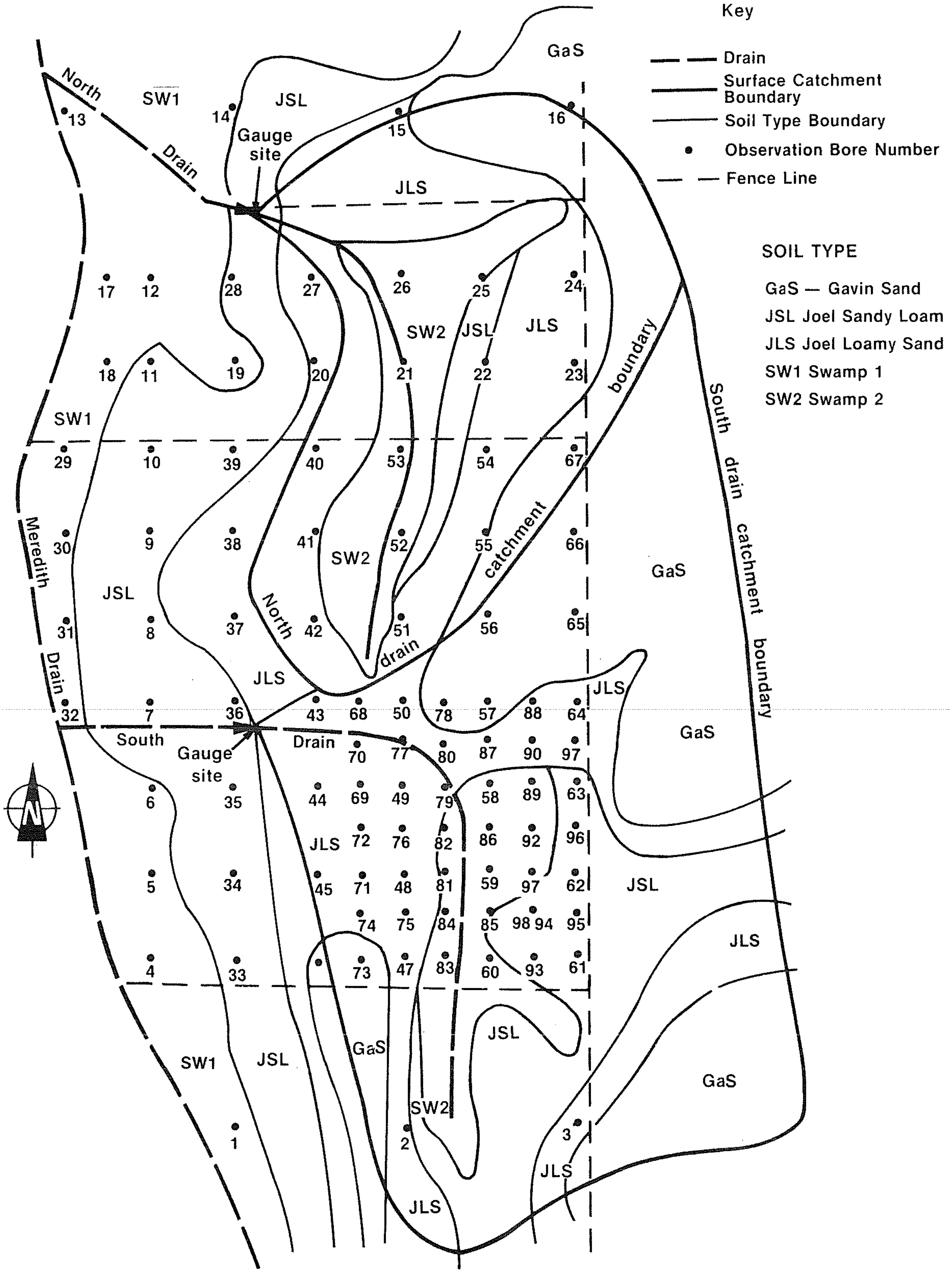


Figure 4 Talbot's site soil map and monitoring installations.

3.4.3 Development of agriculture and drainage

These sandy and loamy areas are drained to Meredith D drain by a number of shallow drains which flow during most of the winter and spring period, but are dry in summer and autumn. Meredith drain intersects the permanent groundwater, at least in some sections, and has a perennial flow. Talbot's site has been cleared of native vegetation and farmed since 1968. Pastures range from sparse sub-clover and volunteer grasses on the dunes, to thick stands of sub-clover in the swales. Perennial white clover and seradella, together with thick stands of rushes, occur on some of the swamp soils. Pastures are grazed, and/or cut for hay.

The area to the east (Bellairs' property) was largely uncleared at the start of the investigation. Native vegetation consists of a Jarrah-Banksia woodland, with a groundcover including some legumes, on the dunes, with trees and shrubs of *Melaleuca* and *Leptospermum* on the swales, and with rushes and sedges in the swamps.

4. EXPERIMENTAL METHODS

Talbot's site has been instrumented with the object of determining water and phosphorus budgets and describing phosphorus transport processes. Different fertiliser treatments have been applied to the North and South paired drain catchment areas to determine run-down time to reduce the soil phosphorus store to a point where pasture growth is affected.

Instrumentation and sampling procedures are described briefly below. These, together with results to date, will be elaborated on in the sections which follow. The main sample sites are shown in Fig. 4.

- Gauging station and sample sites on North and South drains, as well as the main gauging site on Meredith drain.

- Partially slotted bores at 200 and 100 m intervals extending to, or into, the coffee rock: 100 m intervals were chosen as the main spacing, since the general direction of movement of the groundwater body and the low gradients had been determined by the broader scale survey mentioned earlier. Because spatial variability of phosphorus concentrations is great, part of the grid has subsequently (1984) been closed to a 50 m interval and vertical and spatial variability at some wells determined by sampling by spear.

- Nests of bores slotted over a single interval have been installed to determine phosphorus concentrations with depth.

- Pump and observation wells have been installed for hydrological testing (K_s, and specific yield) of the aquifer.

- Rain gauges have been installed to measure both total rainfall and intensity.

- Evaporation from a Class A pan is being measured.

- Soil samples have been collected to measure total phosphorus (total P) and bicarbonate extractable phosphorus (bic. P).

- Fertilizer (superphosphate) has been applied to that portion of the South drain that lies on Karinga Downs. Some fertiliser was applied by the farmer to Bellairs' property.

5. FIELD RESULTS

5.1 Comparison of Treatments

The first objective of the paired catchment study is to make a direct measure of the reduction in phosphorus losses to drainage when no fertilizer is applied to a non-responsive site, as compared to the normal rate of application of superphosphate. The experiment will be continued over a period necessary to determine any progressive decrease in phosphorus losses to drainage as a result of the nil application. The other key factor is pasture growth, since the management objective is to run down the soil phosphorus store to the point where pasture growth is affected; at this time a maintenance dressing of low solubility fertilizer would be applied. Such a run down of the soil phosphorus store would be applicable to all areas where soil phosphorus is above the level required to give maximum or optimum pasture yield as based on soil testing. According to current soil tests, this applies to 62% of the grey sands of the coastal plain Peel-Harvey catchment (Fig. 5).

The selection of paired test catchments is not an easy task and often relies on good luck as much as good judgement. However a number of catchment selection criteria were established, as follows:

- catchments to be of a management (paddock) scale and of similar size;

- catchment drainage patterns and topography to be similar;

- soil formations to be similar, in this case to represent a cross section of Gavin dunes, Joel flats and swamps;

- soil phosphorus (i.e. plant available phosphorus) to be slightly above the non-responsive limit (i.e. > 8 ppm bic. P);

- catchments to have very similar clearing, land use and fertilizer application histories.

The catchments selected are shown in Fig. 4 and their relevant properties are given in Table 1. Both of the catchment drains run into Meredith D drain and were installed primarily to drain the extensive swamp areas during winter. Although the South catchment is somewhat larger than the North catchment, they both have very similar slopes, drainage densities and distribution of soils. Soil phosphorus tests to 10 cm indicate that both catchments are slightly in excess of the non-responsive limit (~8 ppm bicarbonate-extractable phosphorus for grey sands) and of similar magnitude (Fig. 5). The fact that the North catchment has a slightly higher soil phosphorus store means that it will take longer to observe an effect on pasture yield than if the treatments had been reversed. Both catchments have been cleared and fertilized with superphosphate for 15 years and have undergone the same agricultural land use, primarily sheep grazing pasture.

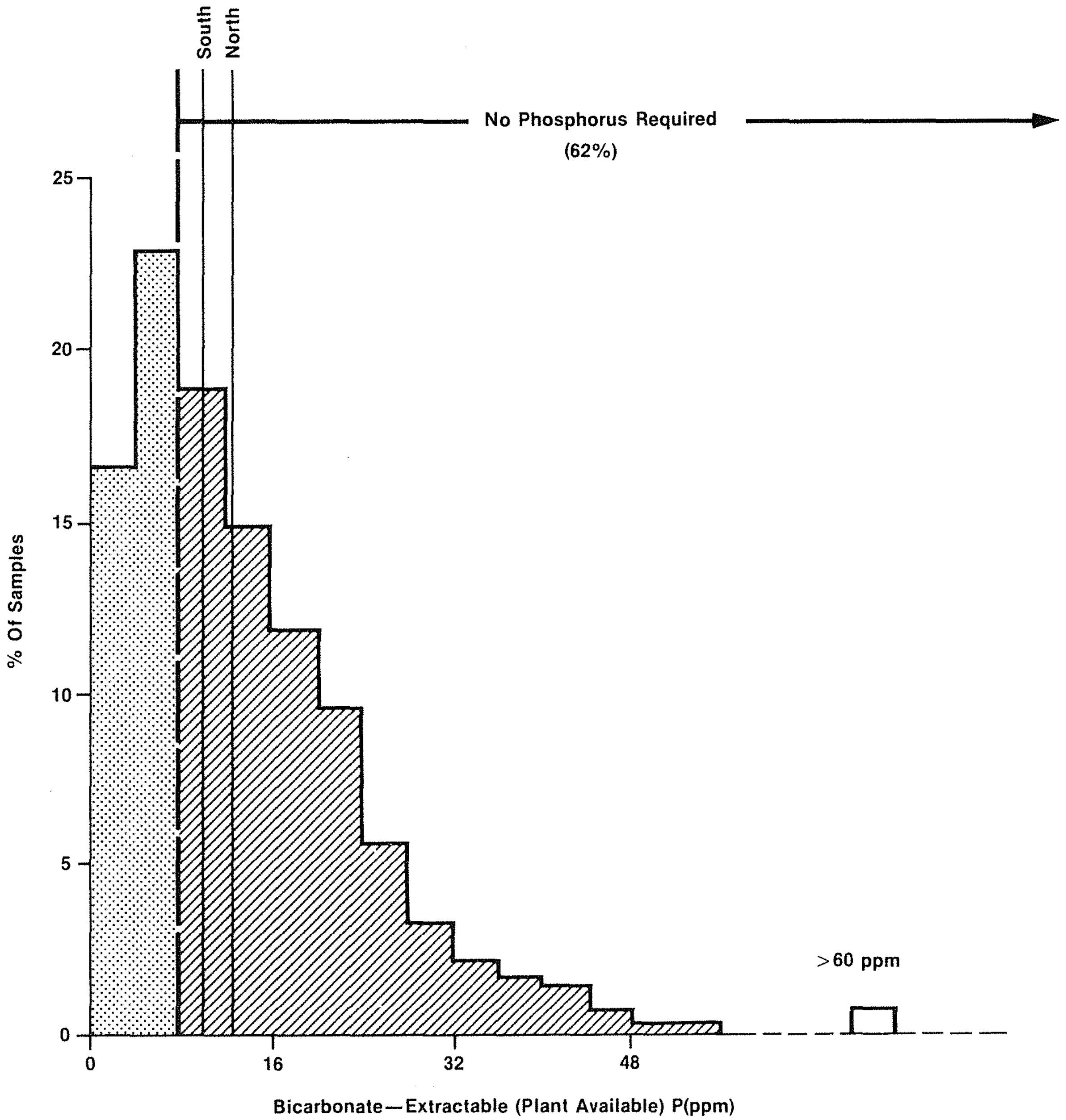


Figure 5 Phosphorus soil test levels for permeable grey sands of coastal plain catchments of the Peel-Harvey Estuary (1983-84).

Table 1 : Comparison of Talbot's paired catchment properties

		North drain		South drain	
total area (ha)		22.7		39.6	
		ha	%	ha	%
soil types : areas	SW1	0.0	0.0	0.0	0.0
	SW2	4.9	21.6	4.1	10.3
	JLS	11.8	52.0	11.6	29.3
	JSL	1.2	5.3	7.6	19.2
	GaS	4.8	21.1	16.3	41.2
mean slope		0.515°		0.383°	
drainage length (km)		0.6		1.05	
drainage density (km/km^2)		2.7		2.8	
		total P	bic. P	total P	bic. P
soil phosphorus tests (ppm)		68.8	12.3	54.2	9.7
(kg/ha/10cm depth)		103.2	18.5	78.6	14.6
fertiliser history		15 years		16 years	
land-use		sheep grazing pasture		sheep grazing pasture	

<u>Legend</u> :

SW1	swamp soils - clay loam surfaces
SW2	swamp soils - sandy surfaces
JLS	Joel loamy sand
JSL	Joel sandy loam
GaS	Gavin sand (with minor areas of Jandakot sand)

Ideally an extensive pre-treatment period of monitoring would have been desirable but the pressing need to obtain results allowed only a limited period into the winter (until July 21st). The pre-treatment data, however, indicated a very close hydrological similarity between the two catchments (Table 2) with runoff to rainfall ratios of 0.17 and 0.19 and flow-weighted mean phosphorus concentrations of 2.54 and 2.63 mg/L for the North and South drains respectively.

In May the farmer fertilized 5.4 ha of the South drain (at a rate of 20.7 kg P ha^{-1}) and, as a result, the South drain was chosen to be the fertilized catchment. On 21st July superphosphate was applied to the remainder of the catchment (25.2 ha) at the rate of 18.2 kg P/ha. Substantial rainfall ocurred 3 days later and a high concentration 'spike' (~ 15 mg/L) was observed during this rainfall event in the South drain. For the 4-day period following application of fertilizer the flow-weighted mean concentration of phosphorus in the South drain was 8.3 mg/L and then decreased to 3.8 mg/L for the next 3 weeks (Fig. 6). After this time the concentration decreased to a similar value to the unfertilized North drain.

A summary of the results for the two catchments is given in Table 2. The runoff coefficients following treatment were comparable for the two catchments and much higher than pre-treatment values. However, of most significance is the 34% difference in flow-weighted mean phosphorus concentration between the two catchments following fertiliser application.

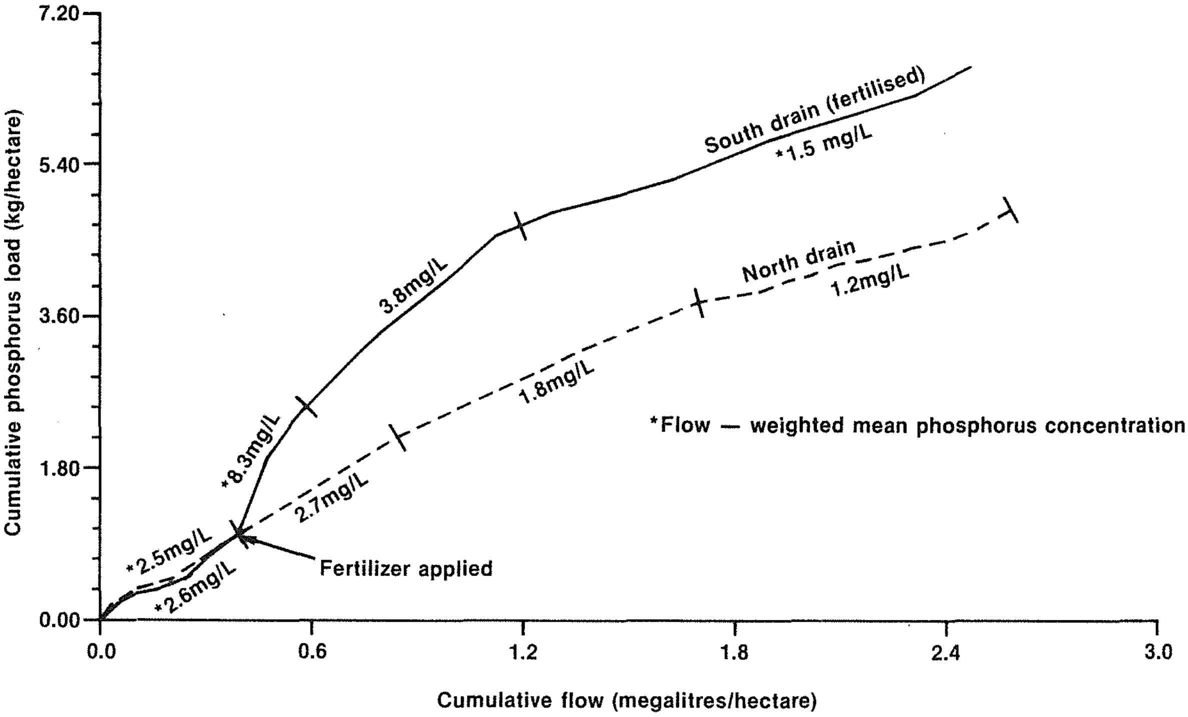


Figure 6 Cumulative phosphorus load v flow from superphosphate and nil treatments on permeable sands at Talbot's (winter 1983)

Since the pre-treatment difference between the two catchments was only 3%, the result indicates that there was a net reduction in mean phosphorus concentration of about 30% in one year due to not applying fertiliser.

The values of the pasture yield showed that the North catchment (nil treatment) had slightly higher yield than the South catchment. Thus pasture yield was considered to be unaffected by not applying fertilizer.

5.2 Water and Phosphorus Budgets

5.2.1 Water budget

The main components of the water budget are rainfall, evaporation, runoff, and change in unsaturated water and groundwater content. Only the first three of these components have been measured. Rainfall was measured by a single pluviometer and two storage rain gauges. Evaporation was measured weekly by a Class A pan evaporimeter. Runoff was measured in the field drains by a broad crested v-shaped weir. The drains have a mean depth of about 0.5 m and intercept both overland flow and near surface groundwater flow. Since the area is generally very flat, the topographical boundaries of the catchments (Fig. 4) are not distinct. All contour maps presented in this report are drawn by computer, and are based on the point source data from the 100 m grid intersects. As such they may not accurately reflect the situation. As an example the catchment divides shown in Fig. 4 which are drawn from stereoscopic interpretation of paired photographs is not identical to catchment divides interpreted from the contour data.

Table 2 : Paired catchments results summary (1983)

	North catchment	South catchment
pre-treatment		
total rainfall (mm)	218	218
total runoff (10^6L)	8.2	15.8
runoff/rainfall	0.17	0.19
P load (kg)	20.8	41.6
P conc. (flow-weighted mean) mg/L	2.54	2.63
treatment	nil	5.4 ha at 20.7 kg P/ha 25.2 ha at 18.2 kg P/ha
post-treatment		
total rainfall (mm)	357	357
total runoff (10^6L)	50.3	82.1
runoff/rainfall	0.64	0.61
P load (kg)	89.1	219
P conc. (flow-weighted mean) mg/L	1.77	2.67
total period (18.6.83-30.9.83)		
total rainfall (mm)	575	575
total runoff (10^6L)	58.5	97.9
runoff/rainfall	0.46	0.45
P load (kg)	109.9	260.6
P conc. (flow-weighted mean) mg/L	1.86	2.67
yield (tonnes/ha) of pasture	5.72	5.12

The water budget for the full flow period 18.6.83 - 30.9.83 is given in Table 3. The rainfall recorded for this period is estimated to be about 8% higher than that of the long term average. The values for change in soil water and groundwater are obtained by subtracting pan evaporation and runoff from rainfall. Net rises in the groundwater level of 0.23 m and 0.43 m for the North and South catchments respectively were observed over this period (see Table 12). If a soil water content change from 'field capacity' to saturation of 10-15% is assumed, then the values cited in Table 3 are of the correct order of magnitude.

5.2.2 Phosphorus budget

The main components of the phosphorus budget are phosphorus applied as fertilizer, phosphorus loss to drainage, phosphorus exported in agricultural produce and phosphorus changes in soil and soil water stores. In addition to the above components, phosphorus is recycled through plants and animals but these do not contribute a loss or gain to the system.

The phosphorus applied as fertilizer is measured directly. The measurement of phosphorus loss to drainage is also relatively straightforward, although it should be noted that errors compound in this measurement, with errors in flow measurement, phosphorus concentration measurement and errors resulting from limited sampling intervals for phosphorus analysis.

Table 3 Water budgets for Talbot's paired catchments (18.6.83 - 30.9.83)

Component	North catchment	South catchment
rainfall (mm)	575	575
pan evaporation (mm)	259	259
runoff (mm)	264	258
change in soil water and groundwater storage (mm)	52	58

The phosphorus budgets for each catchment are given in Table 4.

Table 4 : Phosphorus budgets for North and South catchments (1983)

Component	North catchment		South catchment	
	total area	per hectare	total area	per hectare
P applied (kg)	0	0	570.4	14.40
P drainage (kg)	109.9	4.84	260.6	6.58
P ag. export (kg)	38.0	1.67	81.3	2.05
P ground store* (kg)	-147.9	-6.51	+228.5	+5.77

* ground store refers to sum of soil and soil water phosphorus stores

The budget shows that, under normal fertilizer practice (i.e. 1 bag of superphosphate to the acre, equivalent to 18.2 kg P/ha), the system is accumulating phosphorus. About 40% of the phosphorus applied is retained in the ground store. When no fertilizer is applied, there is a net loss to the system, but this is only a small proportion of the total phosphorus stored (c/f Table 1).

5.2.3 Breakdown of phosphorus budget components

The phosphorus in soil and soil water stores has, in itself, several components, namely phosphorus adsorbed to soil particles, organic phosphorus, phosphorus in soil water solution, both in the saturated and unsaturated zones, and fertilizer applied inorganic phosphorus and its products.

These phosphorus stores are continually interacting with each other in response to wetting, drying, heating, plant extraction, leaching etc. The complex dynamic behaviour of these stores makes measurement more difficult.

To date two measurements of the ground phosphorus store have been attempted. Firstly the concentration of phosphorus in groundwater has been measured in space and time as described in section 5.4.3.

The second measurement of the ground phosphorus store was total P and bic. P within the top 10 cm of the soil profile. These measurements have been made for bush, pasture and combined areas and are given for the two catchments in Table 5. The values were determined from transects of 80 and 120 samples in the North and South catchments respectively. This method permits the calculation of soil phosphorus variation and the values quoted are means with standard deviations of ± 10% at the 95% confidence limit. The analysis represents only one date and does not allow for variation throughout the year. A study of spatial and temporal variations in soil phosphorus is discussed in section 5.4.4.

Table 5 Measurements of total and bicarbonate extractable soil phosphorus for North and South catchments

Component (kg/ha/10cm depth)		North Catchment	South Catchment
bush	Total P	25.5	48.8
	bic. P	3	6.8
pasture	Total P	129	93.5
	bic. P	23.6	18.5
combined	Total P	103.3	78.6
	bic. P	18.5	14.6

The final measurements of interest are the amounts of phosphorus extracted by plants and exported by hay and sheep (Table 6). Plant extracted phosphorus was measured by harvesting a single enclosure (6m x 6m) on each catchment during winter and spring. The harvesting regime attempted to simulate sheep grazing. The method of sampling pasture has now improved, with the use of portable cages randomly relocated within the catchment at appropriate time intervals. The amount of phosphorus in plant tops was slightly higher for the fertilized South catchment although the plant yield for this catchment was slightly less (Table 2). The amount of phosphorus taken up by plants is relatively high and provides an easy means of extracting phosphorus from the soil store. In the normal course of events, however, most of this phosphorus is returned to the soil by sheep grazing. The amount exported as hay was minimal due to only 5 hectares being cut for hay in the North catchment (this amount has been averaged over the whole catchment to produce the value in Table 6). The amount of phosphorus exported as sheep and sheep products was estimated from average figures per sheep supplied by the Department of Agriculture.

Table 6 Agricultural phosphorus components

Component (kg/ha)	North catchment	South catchment
phosphorus in plant tops	15.6	16.7
phosphorus exported as hay	0.3	0
phosphorus exported by sheep	1.41	2.14

5.2.4 Agricultural accumulation of phosphorus in the soil profile

This section presents the results of a study to quantify the amount of phosphorus that has accumulated in the soil profile since fertilizer application began. To do this it was necessary to measure the soil phosphorus stores on both fertilized and virgin sites. The fertilized site was Talbot's South catchment and the virgin site was on adjacent bush (Bellairs' property) which runs along the eastern boundary of Talbot's property. Both sites were in the South catchment. The sampling was carried out in the 1983/84 summer period when the groundwater level was low.

Methods

Four 50 mm diameter auger holes were drilled in close proximity down into the organic hard pan of a fertilized Joel soil. The surface to 20 cm depth was sampled at 5 cm depth intervals, as was the hardpan and the 10 cm above the hardpan. The remaining profile was sampled in 10 cm intervals. Samples of equivalent depth from the four holes were composited. This was then repeated on a nearby virgin Joel soil of similar composition and depth. All samples were analysed for bic. P, inorganic phosphorus (inorg. P), organic phosphorus (org. P), total P and a phosphorus retention index (P.R.I.). P.R.I. can be used to indicate how strongly a soil can adsorb phosphate, with higher numbers indicating a higher capacity to adsorb.

In order to calculate accumulated phosphorus in the profile, it was assumed that phosphorus concentration down the virgin profile represents the virgin condition of the agricultural soil 15 years ago. This was reasonable as virgin coastal plain soils tend to be low in phosphorus concentration, therefore spatial variability should not alter the quantity of phosphorus down the profile to any great extent. An attempt to reduce variability has been made by compositing four auger samples.

Accumulated phosphorus then, is the difference between phosphorus stored in the virgin soil and phosphorus stored in the agricultural soil profile.

Results

Agriculturally accumulated phosphorus was calculated down the profile for each of the inorganic, organic and total phosphorus analyses (Table 7) and Figs. 7 and 8.

The graph of accumulated total phosphorus (Fig. 7) shows an almost hyperbolic relationship with depth, the greatest accumulation being found in the top 15 cm. Coffee rock was encountered at about 110-120 cm. However, no phosphorus accumulation was measured at this depth using the total P analyses.

When total phosphorus is divided into organic and inorganic fractions, a clearer picture is obtained (Figs. 8 a,b). The majority of the surface (0-15 cm) phosphorus accumulation is organic, due to pasture uptake, conversion to organic form then subsequent return to soil via decomposition. The small amount of organic accumulation seen between 50 and 110 cm may be due to spatial variability of organic phosphorus in the soil. This was probably caused by bush species with deeper root systems when the soil was in its virgin state. The organic phosphorus seen in the organic hard pan in Fig. 8a probably represents natural variability of organic phosphorus in this material rather than an actual depletion in the agricultural paddock relative to the virgin site.

Inorganic phosphorus also shows some preferential accumulation in the surface 15 cm. However, it is also found to accumulate in low concentrations below this depth continuing into the organic hard pan. The concentrations are low in comparison with the surface, but the quantity is large due to the greater depth range (Table 8).

The total agricultural phosphorus accumulation down the profile is calculated to be approximately 112 kg P/ha. Using this value a crude phosphorus budget can be produced for the pastured Joel soils on Talbot's property.

The farm history, as supplied by the previous owners of Talbot's property, was used to calculate total phosphorus applied as fertilizer and total phosphorus exported as agricultural produce. These were calculated on an average per hectare basis for the whole farm. Export rates used in calculations are as follows (Cornforth and Sinclair 1982, Russell pers. comm.):

0.5 kg P/ha/yr/sheep
2.7 kg P/ha/yr/steer
0.3 %P in hay

Table 7 Phosphorus concentrations (kg P/ha) through fertilized and virgin soil profiles

DEPTH	INORGANIC P.		ORGANIC P.		TOTAL P.		P.R.I.	
(cm)	1	2	1	2	1	2	1	2
0-5	13.50	3.00	35.25	19.50	53.25	26.25	0.2	0.2
5-10	8.25	3.00	23.25	12.00	35.25	18.00	1.2	1.4
10-15	6.00	2.25	12.00	7.50	21.75	13.50	1.3	0.7
15-20	3.75	1.50	5.25	5.25	12.75	10.50	6.8	3.0
20-25	3.00	1.50	3.00	3.00	9.75	6.00	3.8	1.9
25-30	3.00	1.50	3.00	3.00	9.75	6.00	3.8	1.9
30-35	3.00	0.75	2.25	2.25	8.25	5.25	3.2	2.0
35-40	3.00	0.75	2.25	2.25	8.25	5.25	3.2	2.0
40-45	2.25	0.75	2.25	2.25	8.25	5.25	3.5	1.4
45-50	2.25	0.75	2.25	2.25	8.25	5.25	3.5	1.4
50-55	2.25	0.75	2.25	1.50	7.50	5.25	2.6	1.4
55-60	2.25	0.75	2.25	1.50	7.50	5.25	2.6	1.4
60-65	3.00	0.75	2.25	1.50	9.75	5.25	3.6	1.1
65-70	3.00	0.75	2.25	1.50	9.75	5.25	3.6	1.1
70-75	3.00	0.75	2.25	1.50	10.50	6.00	2.8	1.6
75-80	3.00	0.75	2.25	1.50	10.50	6.00	2.8	1.6
80-85	3.00	1.50	2.25	0.75	8.25	6.00	4.9	1.2
85-90	3.00	1.50	2.25	0.75	8.25	6.00	4.9	1.2
90-95	3.00	0.75	2.25	2.25	7.50	6.00	4.0	1.7
95-100	3.00	0.75	2.25	2.25	7.50	6.00	4.0	1.7
100-105	4.50	3.75	3.75	2.25	9.75	8.25	5.1	7.6
105-110	4.50	3.75	3.75	2.25	9.75	8.25	5.1	7.6
110-115	3.00	1.50	4.50	5.25	9.75	11.25	18.0	10.0
115-120	3.00	0.75	4.50	6.00	9.75	9.75	18.0	11.0
120-125	3.00	1.50	3.00	6.75	7.50	11.25	8.1	44.0
125-130	3.00	1.50	3.00	7.50	7.50	12.75	8.1	160.0
130-135	3.00	2.25	3.75	8.25	9.75	14.25	13.0	460.0
135-140	2.25		4.50		8.25		20.0	
140-145	3.00		6.00		11.25		49.0	
TOTAL	105.75	39.75	150.00	112.50	345.75	234.00		

1 = profile down an agricultural soil
2 = profile down a virgin soil

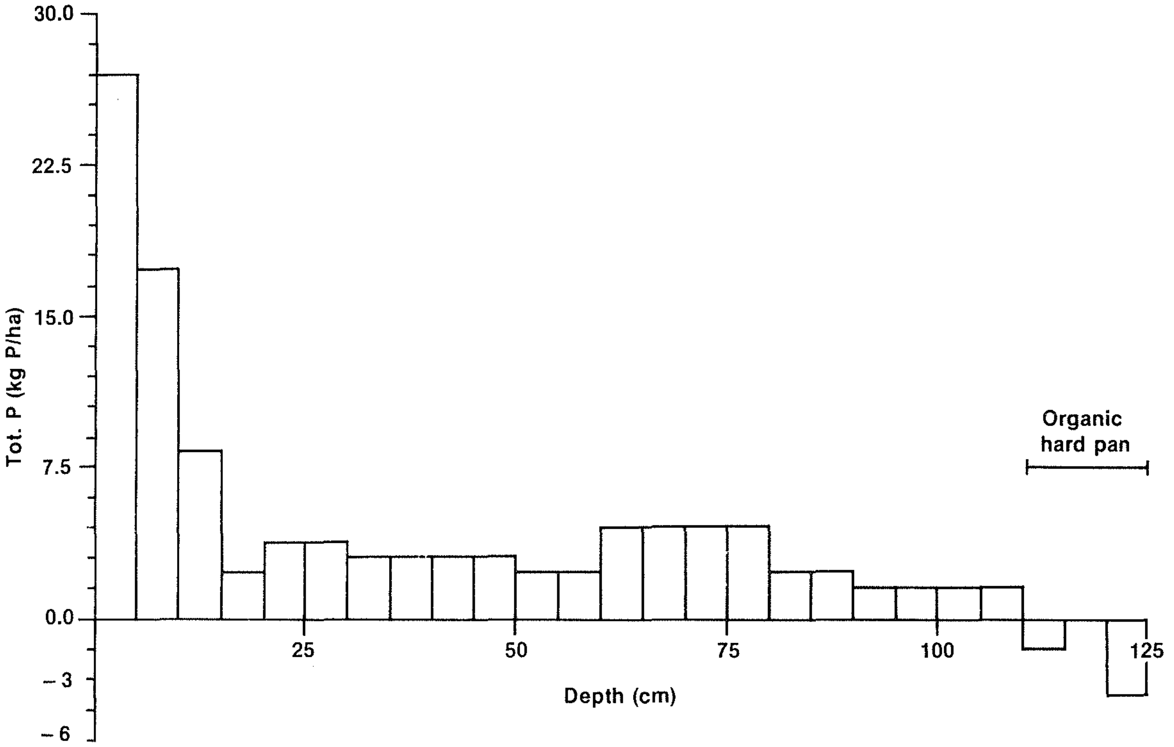


Figure 7 Accumulation of total phosphorus in a Joel soil of the Bassendean association, farmed for 15 years

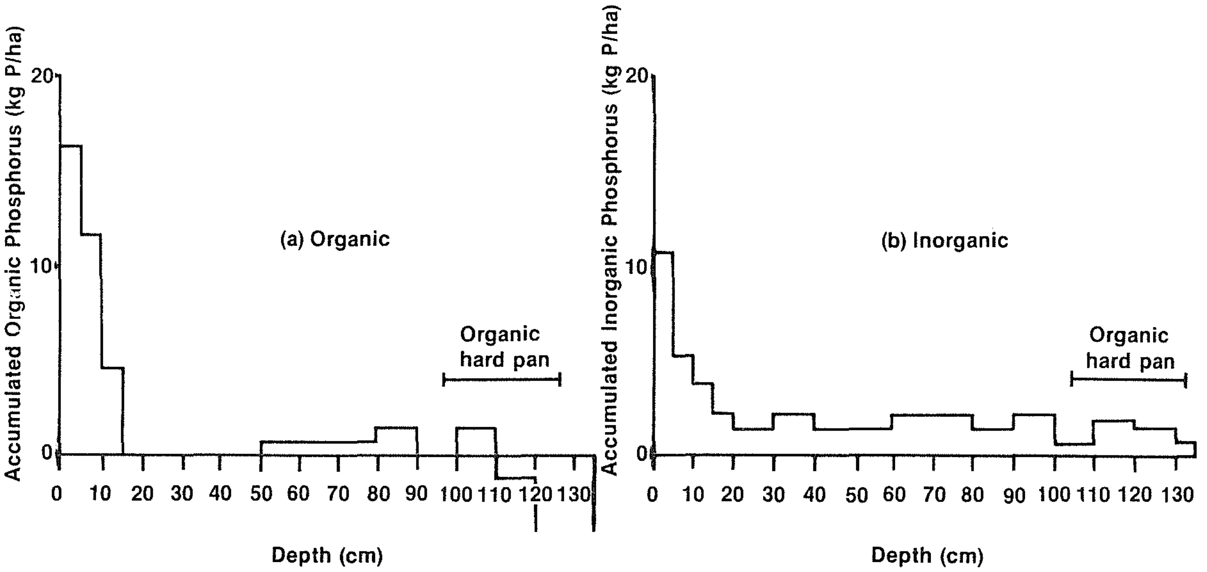


Figure 8 Accumulation of organic and inorganic phosphorus in a Joel soil, farmed for 15 years

Values for phosphorus applied and agriculturally exported are combined with those for soil accumulated phosphorus to give a long term phosphorus budget (Table 9). The phosphorus lost to the system may be accounted for in the following way.

In 1983 Talbot's South catchment lost 261 kg of phosphorus to drainage from 31 hectares of fertilized land. This corresponds to 8.4 kg P per fertilized hectare, which is 46% of phosphorus applied that year, or 41% of the average yearly phosphorus application since cultivation began. Given that 1983 was a near average rainfall/runoff year, this suggests that the 126 kg/ha of unaccounted phosphorus could have been lost to drainage over the 15 years of cultivation.

Table 8 Accumulated phosphorus above and below 15 cm

Phosphorus fraction	Depth (cm)	Phosphorus store (kg/ha)	%
Inorganic	0-15	19.50	30
	> 15	46.50	70
Organic	0-15	31.50	84
	> 15	6.00	16
TOTAL	0-15	52.50	47
	> 15	59.25	53
		111.75	

Table 9 Long term phosphorus budget

Total phosphorus applied as fertilizer	304 kg/ha
Agriculturally exported phosphorus	-66 kg/ha
Soil accumulated phosphorus	-112 kg/ha
Phosphorus lost to the system	126 kg/ha

Discussion

It appears that the fertilized profile is not yet saturated with phosphorus down to the hard pan, although phosphorus has actually accumulated at this depth. The capacity of the soil to adsorb phosphate, as indicated by PRI, increases dramatically when coffee rock is reached (Table 7). However, only a small amount of inorganic phosphorus accumulation is found at this level. This indicates that agricultrual phosphorus has barely leached to coffee rock depth and is unlikely to be found any deeper in the profile. PRI results down the profile indicate a capacity for phosphate adsorption at all levels although further phosphorus accumulation at the surface will be predominantly organic in form. Although agricultural phosphorus does leach to the deeper parts of the profile, nearly 50% of the accumulated phosphorus is in the top 15 cm of soil and potentially may be leached to drainage (Table 8).

The potential for the more deeply leached phosphorus to be lost to drainage is very low. However, if the profile should eventually saturate its phosphate adsorbing capacity, the deeper groundwater could become contaminated.

The results indicate a need for more profile studies to be carried out at Talbot's for an improved understanding of phosphorus accumulation characteristics, e.g. phosphorus may have leached more deeply under Gavin ridges. It should be emphasised that the crude phosphorus budget for Talbot's (Table 9) is based on only a single set of profile data for a Joel soil; as such it should be considered only as a preliminary result.

5.3 Water Movement

5.3.1 Conceptualisation of processes

The Bassendean sand system (Fig. 9) comprises a sand or sandy loam overlying (in lower landscape areas) a layer of organic coffee rock of thickness ranging from less than 1 metre to more than 3 metres. Beneath the higher dunes the coffee rock may be absent but there is a ferruginous sandy B horizon. Beneath the coffee rock there is a deep (order 20 metres), highly permeable sand aquifer which overlies basal silts, clays and calcareous materials.

Recharge to the deep aquifer probably takes place through the highest points in the landscape where coffee rock is absent. Elsewhere water continuity with the perched surficial aquifers is thought to be minimal due to the confining nature of the coffee rock layer. This is borne out by results from a hydraulic testing study.

Water movement in Bassendean sands can be conceptualised from considering both the hydrological system itself and the annual water cycle.

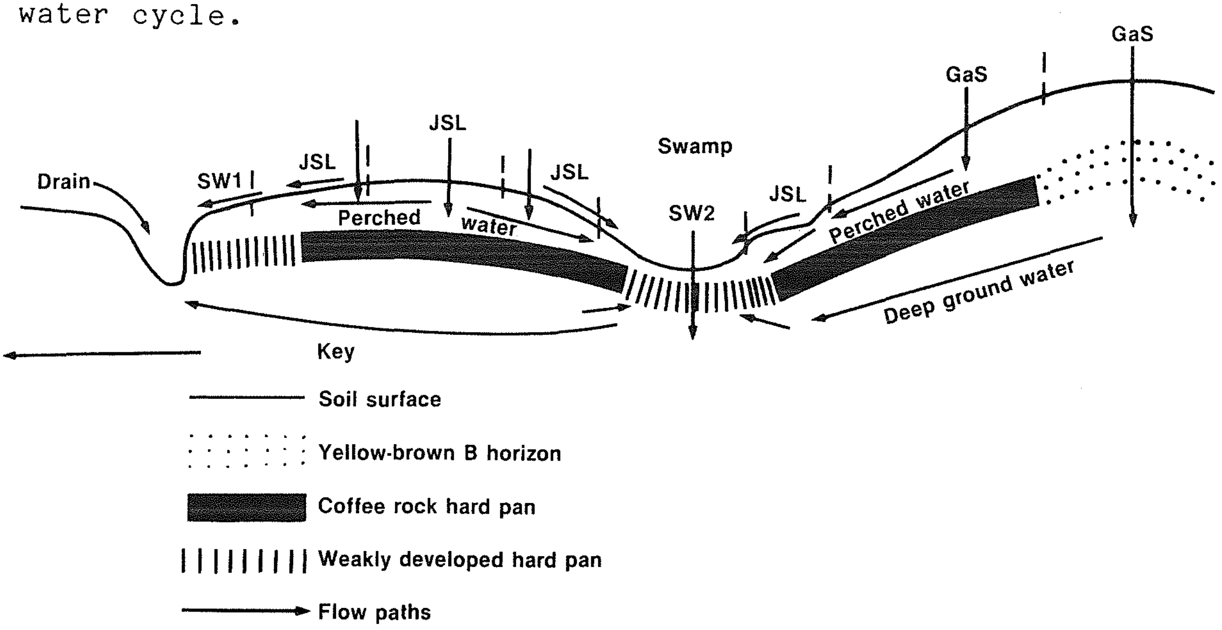


Figure 9 Conceptual water movement — Bassendean association

Hydrological system

In the lowest parts of the landscape in the Meredith catchment the groundwater table intersects the surface to form permanent swamps. On the Joel flats the perched water table generally lies within 1 m of the surface whereas under the Gavin dunes the water table may be 3 m or so below the surface. In the Meredith catchment there are two main mechanisms of runoff generation, groundwater discharge and overland flow. Groundwater discharges directly into Meredith drain and provides a baseflow through the summer. On the Talbot's paired catchments, however, the drains are shallower and groundwater discharge to them ceases in spring. Overland flow to drains occurs when the watertable has risen to the land surface, rendering the soil impervious.

Annual cycle

Starting from the beginning of winter, the groundwater is at its minimum level due to drainage and summer evapotranspiration. At this time groundwater discharges only to deep drains (> 1 m depth). The unsaturated zone of the Joel flats maintains a soil water flux to the surface from the shallow water table under the summer drying regime. On the Gavin dunes, the surface of the unsaturated zone would be air dry during summer.

At the onset of winter rain, water infiltrates the soil rapidly, except where non-wetting conditions occur, and initially wets up the unsaturated zone to 'field capacity'. Once field capacity is reached, further rain causes the watertable to rise. As this happens, groundwater discharge to drains increases, which has the simultaneous effect of lowering the watertable. In the study area, however, the high saturated hydraulic conductivity of the soil (> 30 m/day) is offset by the small groundwater gradient (< 1%). Thus groundwater movement is not rapid, and once the watertable has risen to near the surface of the Joel flats, rainfall recharge is sufficient to keep the watertable high throughout the winter. Winter drain flow, therefore, is characterised by a fairly constant groundwater discharge with superimposed events of overland flow. On the Gavin dunes infiltrating water takes much longer to reach the water table due to the wetting of the greater depth of soil.

Towards the end of winter (September) rainfall decreases and evapotranspiration increases. As a result, runoff decreases to zero, the water table lowers, and the soil begins to dry out. This continues through the summer months. On rare occasions (approximately 1 in 10 years) there is a summer storm of sufficient magnitude to wet up the soil profile and produce significant runoff. Usually, however, the unsaturated zone merely undergoes a series of wetting and drying events in response to summer rains.

5.3.2 Analysis of runoff data

Runoff coefficients

The runoff coefficients or proportion of drain flow to rainfall are shown for the North and South catchments in Table 2. Two interesting observations can be made from the results. First, the runoff coefficients for the two catchments, both pre-treatment and post-treatment, are nearly identical.

The second observation is that the magnitudes of the runoff coefficients are high, averaging 0.45 over the winter and 0.6 post-treatment. This runoff coefficient is higher than that for the Meredith catchment as a whole (0.13), and may be attributed to such factors as the higher proportion of the Meredith catchment under native vegetation, the higher drainage densities and the direct drainage of swamps of the paired catchments.

Hydrographic analysis

The drain flow hydrographs for the two catchments are shown in Fig. 10. and their cumulative flows in Fig. 11. The hydrographs for both catchments indicate two distinct types of flow, namely fast response flow accounting for most of the runoff, and baseflow. For the North drain a high proportion (73%) is fast response flow, lasting typically 1-2 days after a rainfall event and then returning to the baseflow level. In contrast, only 53% of the South drain runoff appears as fast response flow. The South catchment hydrographs are broader, with runoff often lasting a week or more following the rainfall event, and baseflow generally remaining somewhat higher than that of the North drain. The runoff peaks of the North drain are much greater than those of the South drain for rainfall events greater than 30 mm, but not for lower rainfall events.

The different hydrographic behaviours of the two catchments have not yet been fully explained. Some of the factors likely to be involved are:

(i) the area of the North catchment is smaller, and smaller catchments tend to be 'flashier';

(ii) the mean slope of the North catchment is greater, implying that overland flow will move to the drain more quickly;

(iii) the swamp area of the South catchment is proportionally greater, providing a larger store and possibly slowing the discharge rate;

(iv) the hydraulics of the South catchment (e.g. slope, dimensions, etc.) may tend to impede drain flow in comparison with the North drain;

(v) above a critical storm rainfall (in this case ≃ 30 mm) and after the catchments have undergone initial winter wetting, a larger proportion of the North catchment becomes saturated and acts as a saturated source area;

(vi) the large swamp area of the South drain provides a significantly greater groundwater seepage area than the North drain.

Inspection of the cumulative flow per unit area graphs (Fig. 11) indicates that, over a period of time, the average runoff from the two catchments is similar.

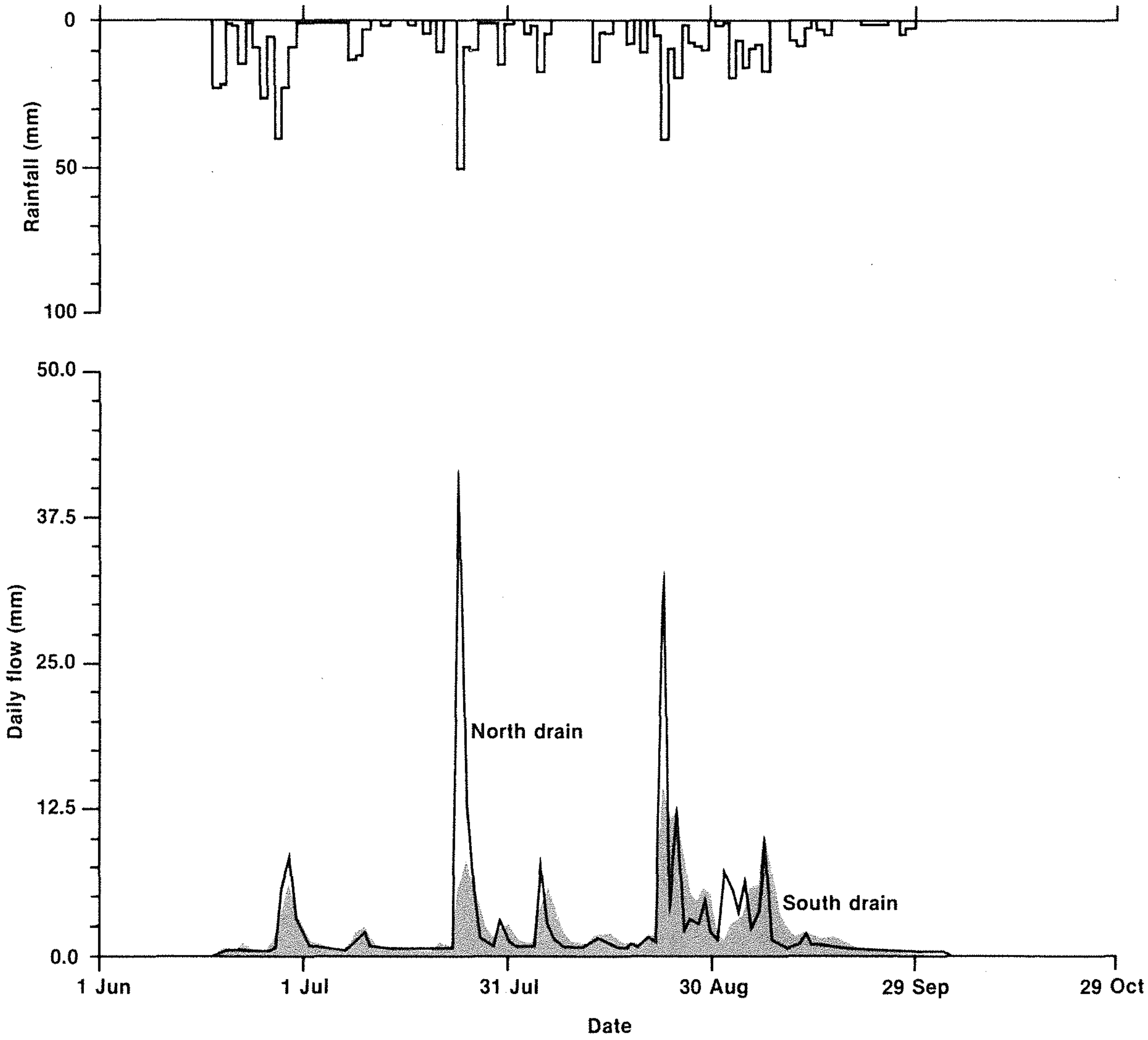


Figure 10 Daily flow for North and South catchments for whole flow period (1983)

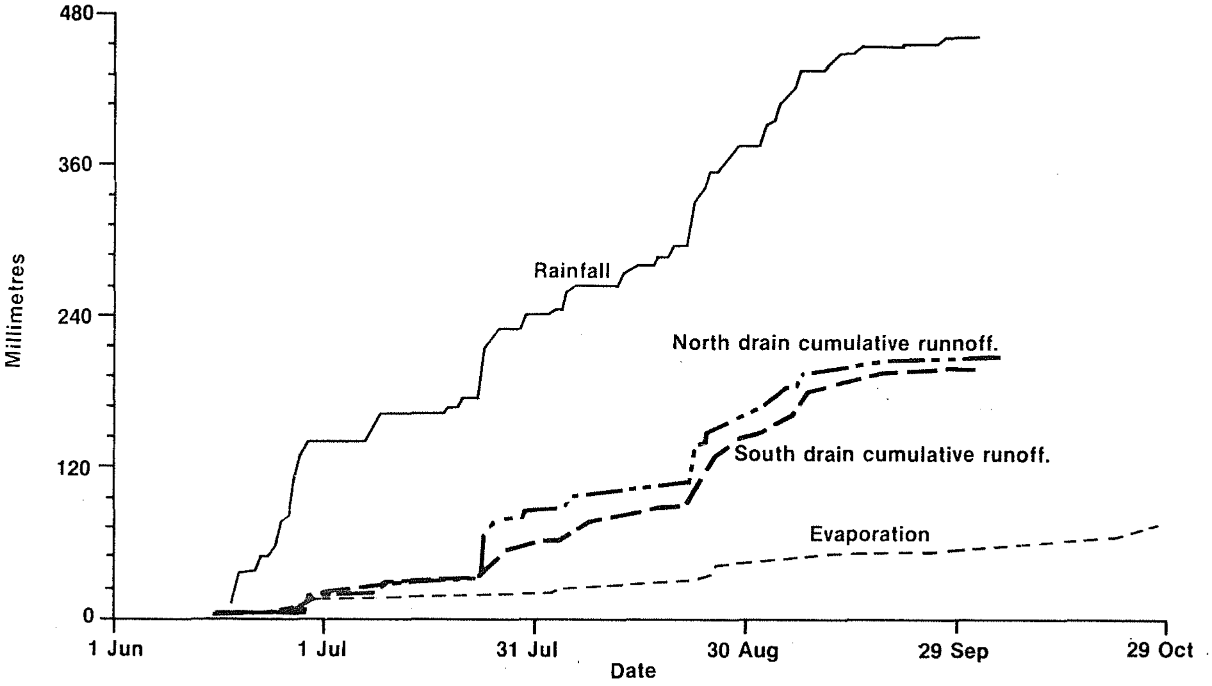


Figure 11 Cumulative flow, rainfall and pan evaporation for North and South catchments (1983)

Division of overland flow and groundwater flow

A question frequently asked is how much water flows overland to drains and how much is groundwater discharge. This is not always easy to determine but several techniques are available, including hydrographic separation, a water balance calculation, mathematical estimation of the groundwater component, and by computer simulation modelling. The first three methods are considered here.

Hydrographic separation essentially involves the differentiation of fast response flow from baseflow in the drain hydrographs. The results of this exercise are given in Table 10. As indicated previously, the South drain appears to have significantly more baseflow than the North drain, although total runoff per unit area is similar.

The second method is to derive groundwater discharge as the residual in a water balance equation. This, however, requires accurate measurements of the other water balance components which, as indicated in section 5.2.1, are not available to sufficient accuracy in this study.

Table 10 Hydrographic baseflow separations for North and South drains

	North drain	South drain
Total runoff (mm)	258	247
Baseflow (mm)	70	116
Fast response (overland) flow (mm)	188	131

The third approach is simply the use of Darcy's Law which states that groundwater discharge (Q) is proportional to the groundwater gradient (S) and the area of discharge (A), i.e.

$$Q = K A S$$

where K is the hydraulic conductivity of the soil. Values of groundwater discharge estimated by this method are given in Table 11. Hydraulic conductivity values are taken from laboratory analyses of Cameron and Ho (1984) on Gavin soils and the groundwater gradients are determined from piezometer head measurements. Substitution into the Darcy equation shows values for groundwater discharge of similar magnitude to the baseflow separation method.

Table 11 Groundwater discharge estimated by Darcy's law for North and South catchments

	North catchment	South catchment
hydraulic conductivity	30 m/d	30 m/d
area of drain discharge (including perimeter of adjoining swamp)	573 m^2	1693 m^2
groundwater gradient	0.01	0.008
groundwater discharge over monitoring period	76 mm	103 mm

5.3.3 Analysis of Groundwater Data

The monitoring programme

During the 1983 winter period (May-October, 1983), approximately 70 shallow observation bores were monitored weekly. These bores were located on a 100 metre square grid covering both the North and South catchments, as well as the area between the western boundaries of the catchments and the

Meredith drain (see Fig. 12). These bores were installed to the depth of the top of the hardpan and were slotted to within 0.25 metres of the soil surface. Bores were monitored for depth to groundwater to determine water table level, and groundwater samples were collected for analysis to determine ortho-phosphate concentrations. This section concentrates on the discussion of groundwater responses. Groundwater phosphorus observations are described in section 5.4.3.

Aquifer responses

Prior to significant rainfall in 1983, depths to groundwater were seen to vary according to landscape position, ranging from about 0.8 metres in the lower-lying swampy areas to more than 4 metres beneath the highest Gavin dunes. Fig. 12 shows a contour map of the depth to groundwater on May 25th 1983.

All levels shown on the contour maps are the levels above an arbitrary datum. Generally, groundwater levels reflected ground surface elevations, relative levels of groundwater varying from more than 3.7 metres above datum under the Gavin dunes on the southern catchment, to less than 1 metre on the northern edge of the North catchment. This shows an average gradient of about 3×10^{-3} m/m. The relative levels of groundwater above datum on 25th May 1983 are shown in Fig. 13.

Groundwater responses to winter rainfall were seen to be relatively uniform across the study area, except where groundwater levels were near to the ground surface. In lower swampy areas levels rose to ground surface, or slightly above, early in winter and remained near those levels over winter. Fig. 14 shows observed groundwater responses under the Gavin sands (bore 56), Joel sandy loams (bore 45), and the swamp soils (bore 59) on the South catchment. Apart from the initial slower response to rainfall under the Gavin dune (bore 56), which may be due to storage of infiltration in the unsaturated profile, the responses are similar for the remainder of the season.

The storage of groundwater at the times of measurement have been estimated for the North and South catchments and for the adjacent areas between the western boundaries of the catchments and Meredith drain. This was achieved by determining water stored in the profile between the top of the hardpan and the groundwater surface. Where the hardpan was not detected during bore installation, the hardpan surface was interpolated from adjacent hardpan elevations. An average porosity of 0.3 m^3/m^3 was determined using an estimate of soil dry bulk density of 1.9 tonne/m^3 and a soil particle density of 2.65 tonne/m^3.

Table 12 lists average depth of groundwater above hardpan and average storage of groundwater above hardpan on selected sampling dates. Total groundwater storage on the Talbot's site was seen to increase from about 0.07 metres on May 25 to about 0.38 metres on September 7 after which time groundwater storage began to decline. Fig. 15 shows a comparison of changes in storage for the North and South catchments during 1983.

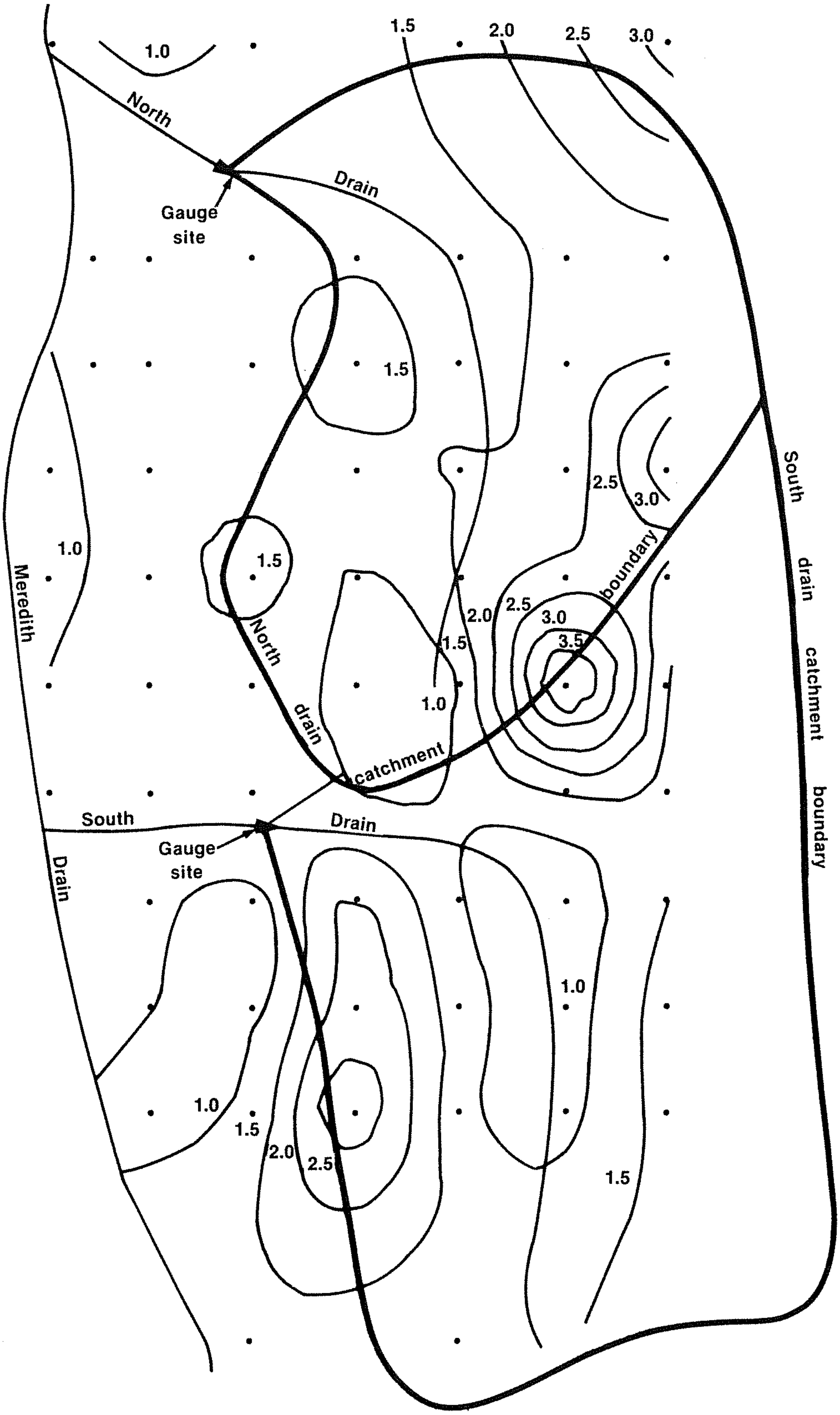


Figure 12 Contour map of depth to groundwater on 25.5.83 at Talbot's site

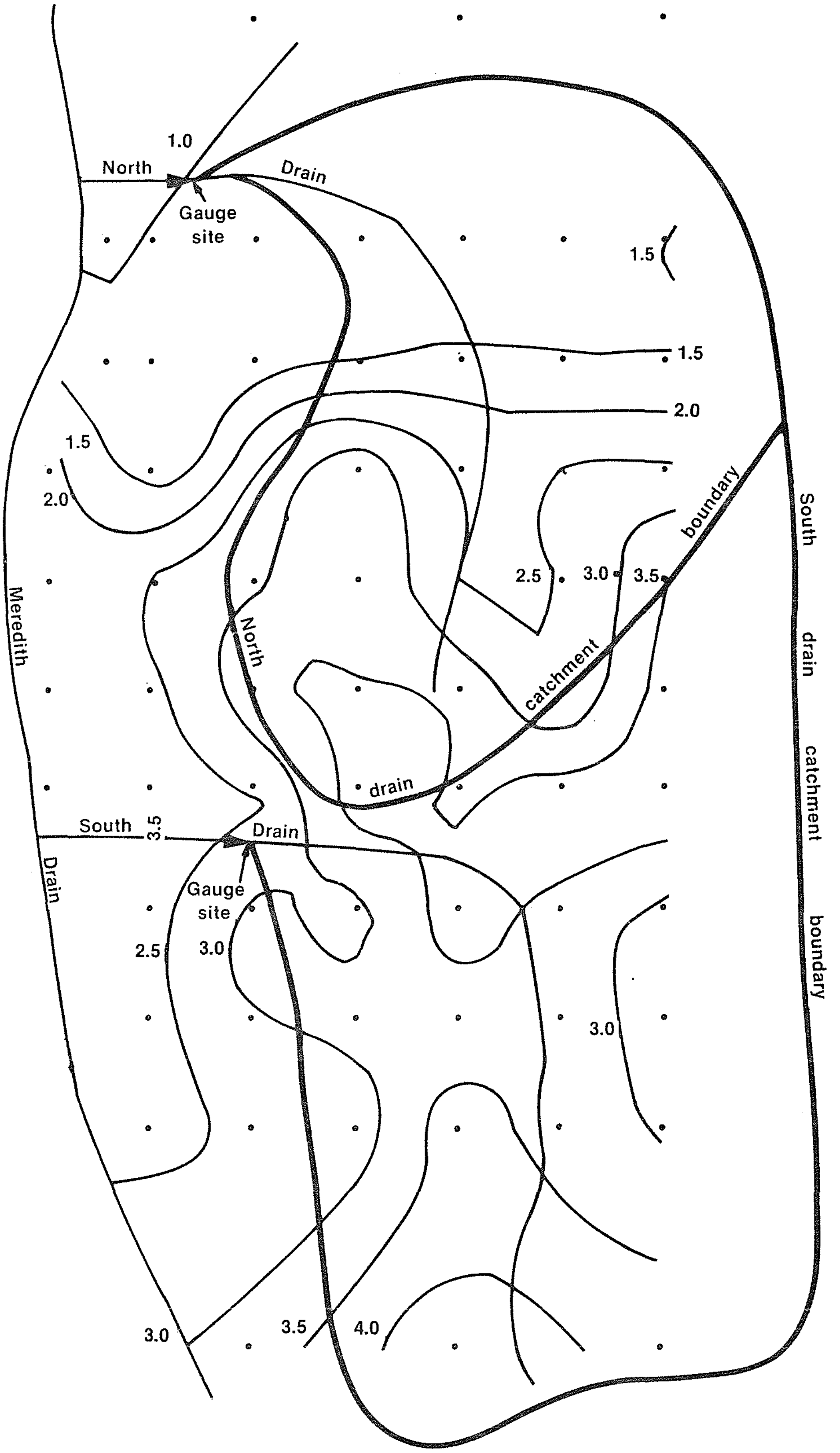


Figure 13 Contour map of relative groundwater level (m) above datum on 25.5.83 at Talbot's site.

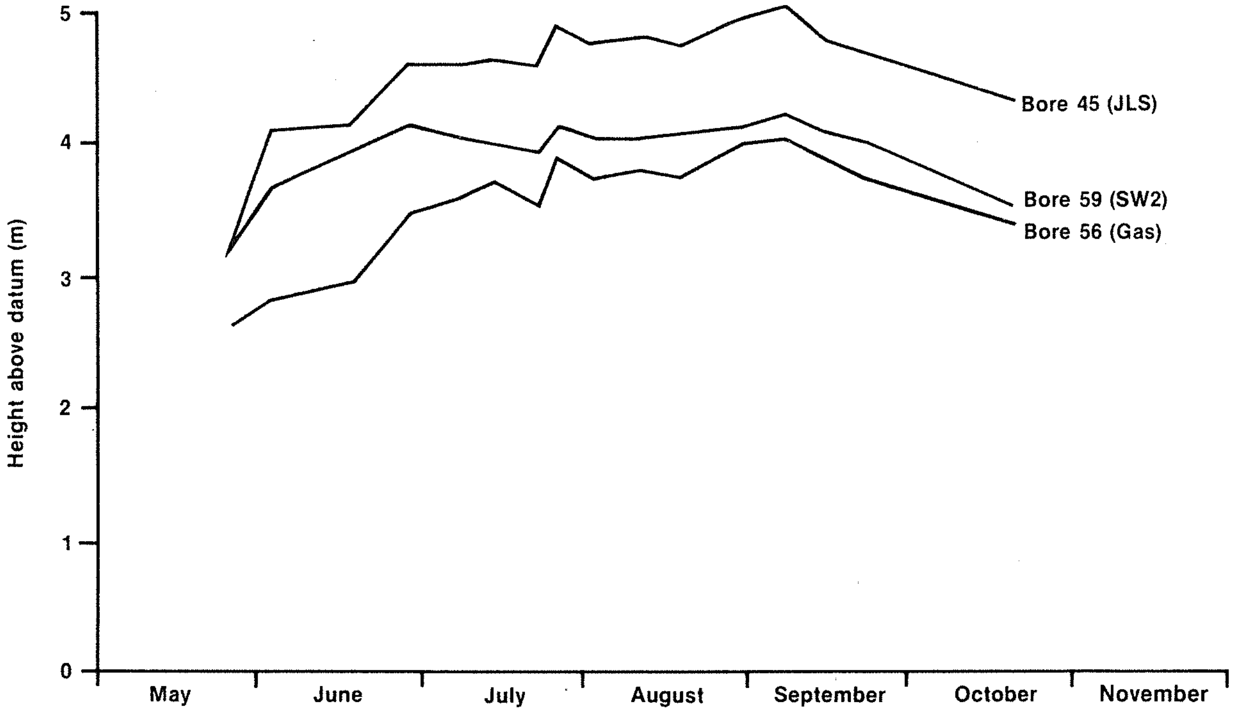


Figure 14 Observed groundwater response of different soil types of Talbot's South catchment during 1983

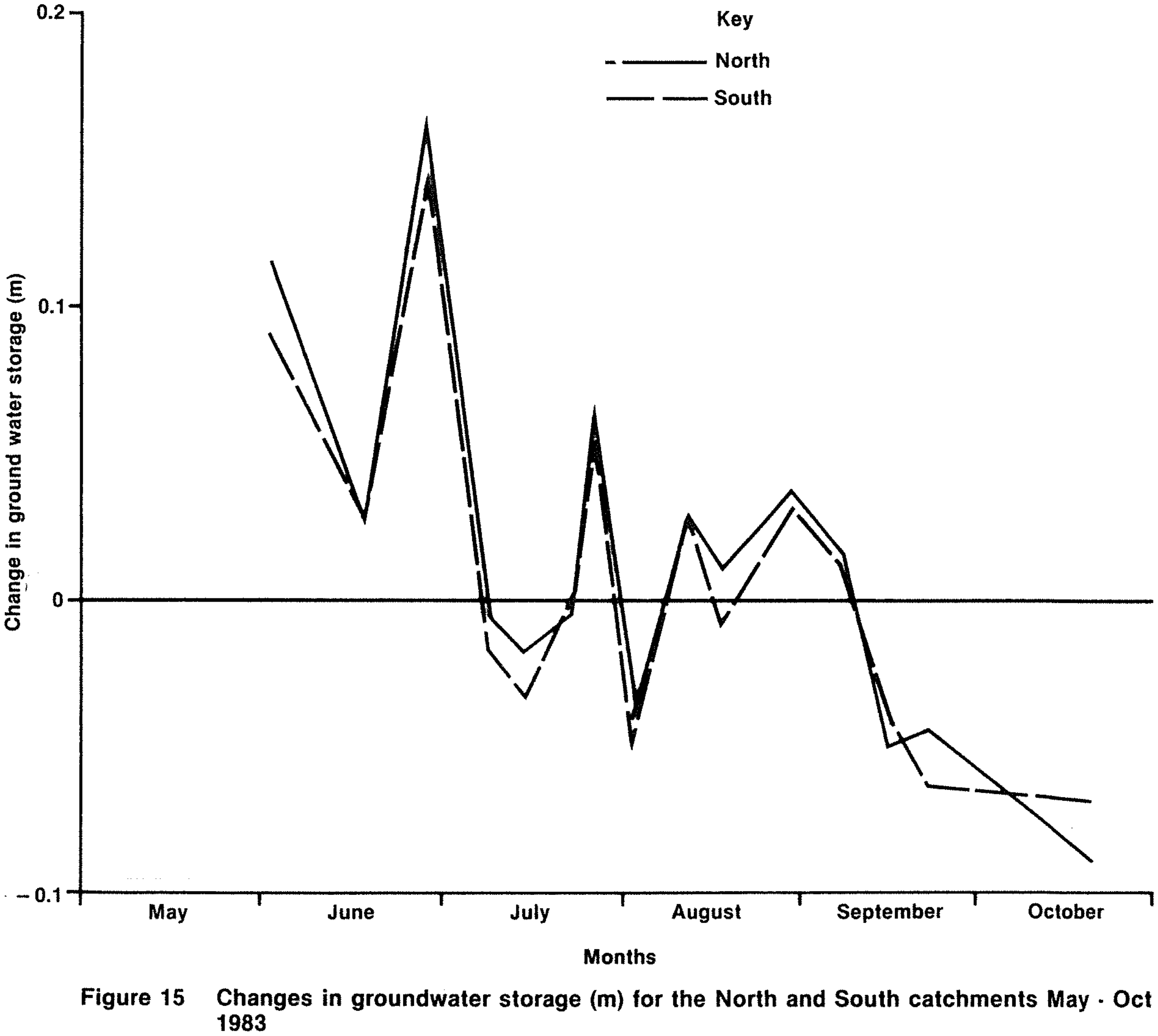


Figure 15 Changes in groundwater storage (m) for the North and South catchments May - Oct 1983

Table 12 Average depths and storage of groundwater above the hardpan for North and South catchments and the total site (May-Oct 1983)

AVERAGE DEPTH OF GROUNDWATER ABOVE HARDPAN (METRES)

	25/5	2/6	17/6	28/6	8/7	14/7	22/7	26/7	2/8	12/8	18/8	30/8	7/9	15/9	22/9	21/10
TOTAL	.228	.547	.61	1.16	1.07	.972	.96	1.19	1.03	1.13	1.08	1.21	1.25	1.10	0.88	0.62
SOUTH	.42	.799	.886	1.43	1.41	1.35	1.33	1.54	1.41	1.5	1.47	1.59	1.64	1.47	1.32	1.02
NORTH	.255	.557	.644	1.13	1.07	.96	.97	1.16	1.0	1.1	1.07	1.17	1.21	1.08	0.87	0.64
OUTSIDE	.101	.398	.431	1.02	0.89	.77	.74	1.01	0.82	0.93	0.87	1.03	1.07	0.90	0.64	0.39

AVERAGE STORAGE OF GROUNDWATER ABOVE HARDPAN (METRES)

	25/5	2/6	17/6	28/6	8/7	14/7	22/7	26/7	2/8	12/8	18/8	30/8	7/9	15/9	22/9	21/10
TOTAL	.068	.164	.183	.348	.321	.292	.288	.357	.309	.339	.324	.363	.375	.330	.264	.186
SOUTH	.126	.240	.266	.429	.423	.405	.399	.462	.423	.450	.441	.477	.492	.441	.396	.306
NORTH	.077	.167	.193	.339	.321	.288	.291	.348	.300	.330	.321	.351	.363	.324	.261	.192
OUTSIDE	.030	.119	.129	.306	.267	.231	.222	.303	.246	.279	.261	.309	.321	.270	.192	.117

An average storage change over the period May 25 to September 7 of 310 mm does not take into account any change in unsaturated water content, but compares favourably with rainfall over that period of 650 mm and other components of the site's water budget. Table 13 lists the period changes in groundwater storage for each of the areas examined.

Table 13 Changes in groundwater storage above hardpan (metres)

	25/5-2/6	2/6-17/6	17/6-28/6	28/6-8/7	8/7-14/7
TOTAL	0.096	0.019	0.165	-0.027	-0.029
SOUTH	0.114	0.026	0.163	-0.006	-0.018
NORTH	0.090	0.026	0.146	-0.018	-0.033
OUTSIDE	0.089	0.010	0.177	-0.039	-0.036

	14/7-22/7	22/7-26/7	26/7-2/8	2/8-12/8	12/8-18/8
TOTAL	-0.004	0.069	-0.048	0.030	-0.015
SOUTH	-0.006	0.062	-0.039	0.027	0.009
NORTH	0.003	0.057	-0.048	0.03	-0.009
OUTSIDE	-0.009	0.081	-0.057	0.033	-0.018

	18/8-30/8	30/8-7/9	7/9-15/9	15/9-22/9	22/9-21/10
TOTAL	0.039	0.012	-0.045	-0.066	-0.078
SOUTH	0.036	0.015	-0.051	-0.045	-0.090
NORTH	0.030	0.012	-0.039	-0.063	-0.069
OUTSIDE	0.048	0.012	-0.051	-0.078	-0.075

Further field monitoring

Since 1983, the piezometer network has had 30 additional bores added to the southern swamp area, reducing the grid spacing to 50 metres. This has been done to attempt to define the smaller scale variation in hydraulic heads and more particularly the very high ortho-phosphate concentrations measured in bore 59.

Additionally a deep production bore with observation piezometers has been installed. This was tested in order to provide estimates of horizontal and vertical permeabilities and to quantify the potential for water leakage to/from deeper aquifers (Bettenay et *al*., 1985).

Further analysis of groundwater responses

Comprehensive statistical analysis of the groundwater storage estimates is presently being undertaken to quantify the associated errors.

5.4 Phosphorus movement

5.4.1 Conceptualisation of processes

An understanding of the process of phosphorus transport in soils is an important key to the estimation of phosphorus rundown times, and to modelling phosphorus losses under different environmental conditions and management practices. An appreciation of the relative importance of different processes often only develops after testing a model against field observations.

Phosphorus movement in soils consists not only of transport with the soil solution but also involves movement between the many phosphorus pools within the soil. The solid forms of phosphorus may be broadly divided into two groups, a slowly leachable pool (slp) and a readily leachable pool (rlp) (Fig. 16). The pools differ in their capacity to supply phosphorus and the rate at which they can maintain that supply. The level of phosphorus in each pool is not constant but continually changing in response to inputs from fertilizers, and outputs such as leaching and plant uptake.

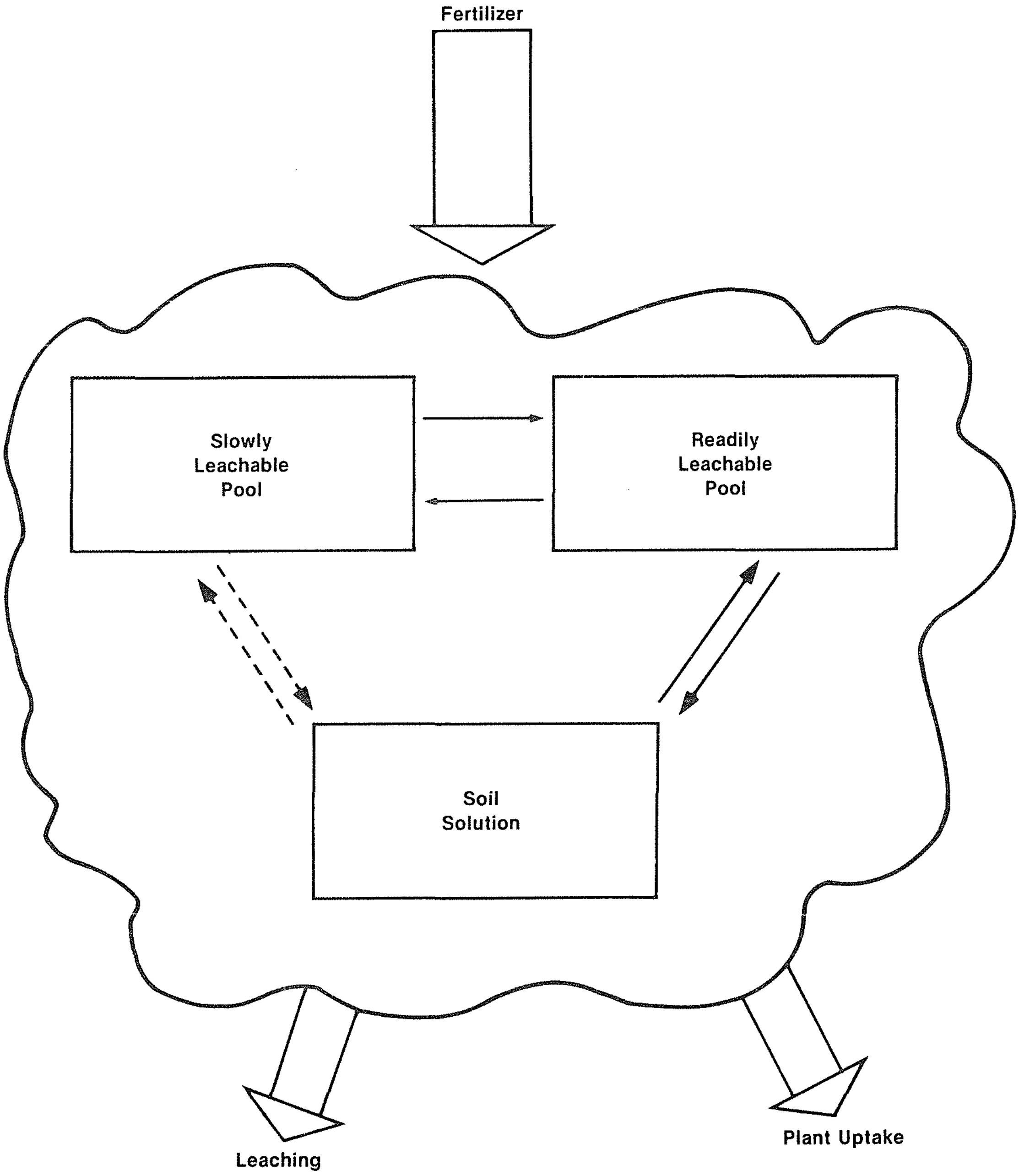


Figure 16 Soil phosphorus pools

Different methods of measuring the phosphorus status of a soil will not necessarily be equally sensitive for detecting changes due to fluxing. For example if a method measures phosphorus from both the rlp and the soil solution, then it may not be consistently useful at measuring phosphorus fluxing between these two pools. Also, the detection of phosphorus movement between pools depends on the difference in the rates of loss and replenishment. No change in the phosphorus level of a pool may be observed simply because the input and output fluxes are approximately equal and therefore the net change is zero. Consequently, the interpretation and usefulness of field data is limited if the dynamic behaviour of phosphorus is not recognised. Apart from the problems associated with soil variability between and within soil types which can occur across one experimental field site, a long term picture of phosphorus movement cannot be achieved from isolated, short term measurements of the current status of soil phosphorus.

This section considers the fluxing of phosphorus under the conditions of high winter rainfall, dry, hot summers and the application of phosphorus as superphosphate. The interpretation of phosphorus data will then be discussed in relation to its usefulness in understanding phosphorus rundown times and development of models for predicting phosphorus losses.

Phosphorus movement in sandy soils

In high rainfall areas, leaching is a major output mechanism of phosphorus from sandy soils. Environmental conditions and management practices control the actual loss of phosphorus within the constraints of the potential loss defined by soil properties such as the size of the rlp.

Movement between pools

Seasonal changes of phosphorus levels in soil pools are illustrated in Fig. 17. During winter, the rainfall pattern and fertilizer applications are the main determinants controlling the magnitude of losses by leaching and plant uptake. The flux between the slp and the rlp is quite slow, and remains fairly uniform throughout the wet season. The flux between the rlp and soil solution is more rapid and is therefore much more sensitive to changes in phosphorus levels in both pools. After the initial rains have saturated the soil at the beginning of winter, there is a large amount of phosphorus in the soil solution (a in Fig. 17). Soluble phosphorus is lost by leaching and runoff following rain (b in Fig. 17). This disturbs the overall equilibrium between the pools and so phosphorus moves from the rlp to the soil solution to balance the loss. However, the rate of replenishment is not as fast as the rate of leaching and therefore the solution pool becomes more and more depleted and losses decrease as the season progresses. The movement between pools continues during any pauses in rainfall even though water movement temporarily ceases. Consequently, when leaching and runoff recommence with the next rainstorm, more phosphorus is lost than would be the case with continuous rain because of the build up of the solution pool during the pause (c in Fig. 17). At the end of winter, the readily leachable pool and the soil solution are both depleted of phosphorus because of the continual leaching and plant uptake (d in Fig. 17). During the following summer, the movement between the slp and rlp continues at an enhanced rate due to higher soil temperatures and occasional summer storms that wet the soil but not sufficiently to cause leaching. The flux between the rlp and the soil solution is limited by low phosphorus levels and lack of water. Also, the death of annual pasture and the application of phosphorus fertilizers in late autumn add phosphorus to the soil. Consequently at the beginning of the next wet season, the phosphorus in the readily leachable phosphorus pool has built up again and is available to supply the solution pool once the first rains begin.

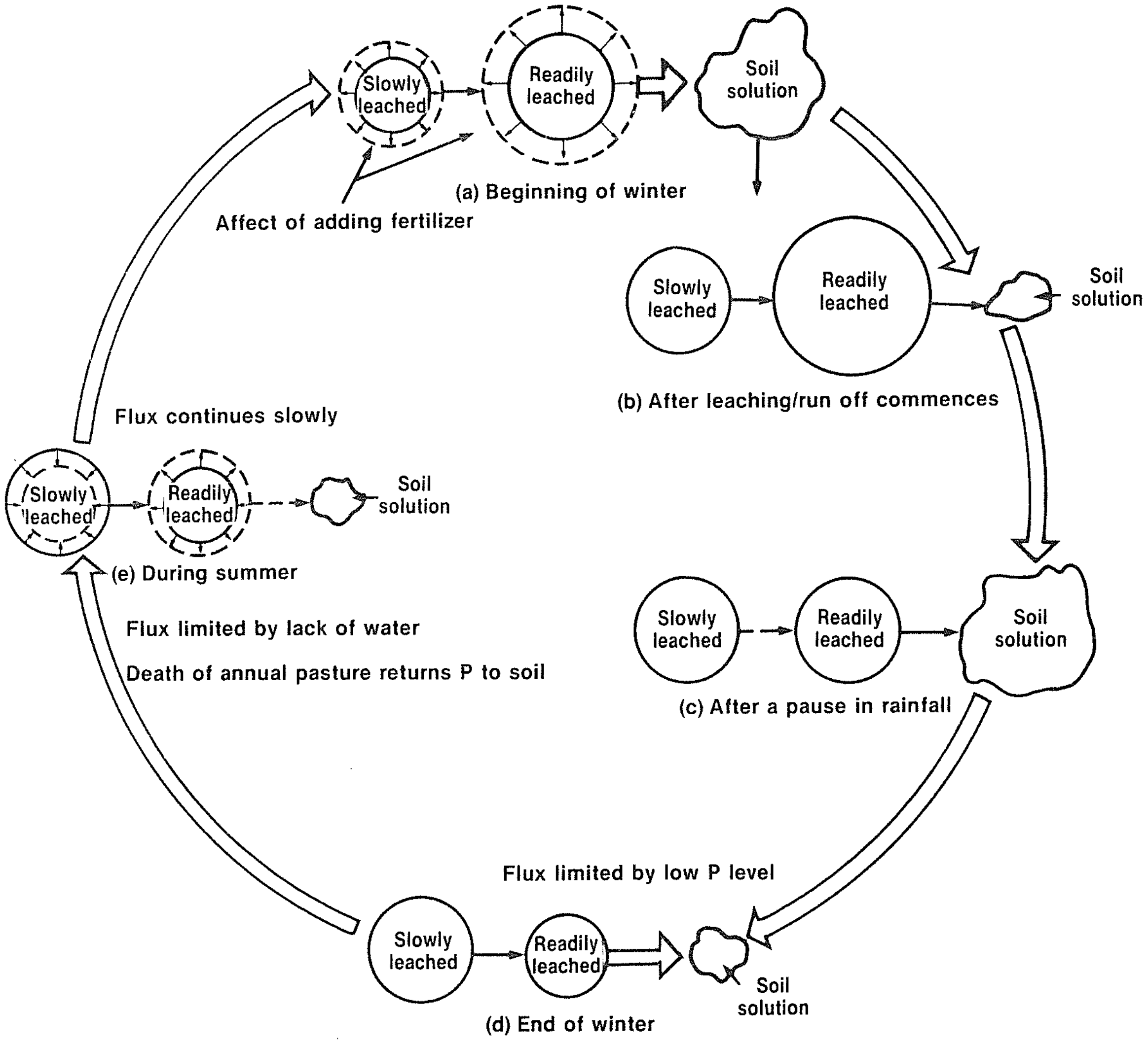


Figure 17 Seasonal changes of phosphorus levels in soil pools

Movement with the soil solution

The amount of phosphorus lost from sandy soils will also depend on the flowpath of the soil solution once it becomes mobile. This is particularly important for assessing phosphorus residence times in soils and calculating net losses. Also, it controls the distribution of phosphorus throughout the soil profile. Some flowpaths (e.g. overland flow) can lead to marked changes in phosphorus levels over a 2 cm depth and therefore real changes in phosphorus levels can be overlooked if soils are sampled over a greater depth range.

The dominant flow path will depend on several factors such as degree of saturation of soil, soil permeability, topography and rainfall intensity and amount.

The use of models to predict phosphorus losses is dependent upon knowledge of the proportion of total water (and therefore phosphorus) travelling through the soil by different routes as shown in Fig. 9.

Conclusions

The dynamic behaviour of phosphorus is of fundamental importance in understanding its movement in soils. Field observations are a necessary and important part of determining transport processes, but are hampered by soil variability and phosphorus fluxing. Consequently, phosphorus data should be interpreted in relation to soil variability, the analytical method used, depth range of sampling, most recent rainfall pattern, plant growth stage, fertilizer management, soil water flow path and the stage of the season.

5.4.2 Phosphorus in drain flow

Phosphorus concentrations

Phosphorus concentrations for the North and South drains over the runoff period are shown in Fig. 18 and Fig. 19. In the unfertilised North drain, the concentration is high at the outset of winter (~ 6 mg/L) but tends to decline gradually through the high rainfall weeks. At the end of winter, the phosphorus concentration begins to 'recover' to higher levels. This seasonal trend relates to the depletion of the readily leachable phosphorus during the high rainfall part of the winter. Towards the end of winter, once rainfall decreases, the readily leachable phosphorus tends to be restored, causing the upward trend in concentration. Superimposed on the seasonal trend are shorter term variations in response to storm events. On unfertilized areas, during a rainfall event, the phosphorus concentration decreases, but then recovers during the inter-rainfall period to the higher general level.

The South drain is seen to start at a lower concentration but rise to a slightly higher value than the North drain after the first main winter rainfall event. Then, shortly after fertiliser application, the phosphorus concentration rises rapidly to peak at 15 mg/L. This very high concentration, however, is only maintained for a relatively short period of time (less than one week) and appears as a large 'spike' on the graph. For a month following the application of fertilizer,

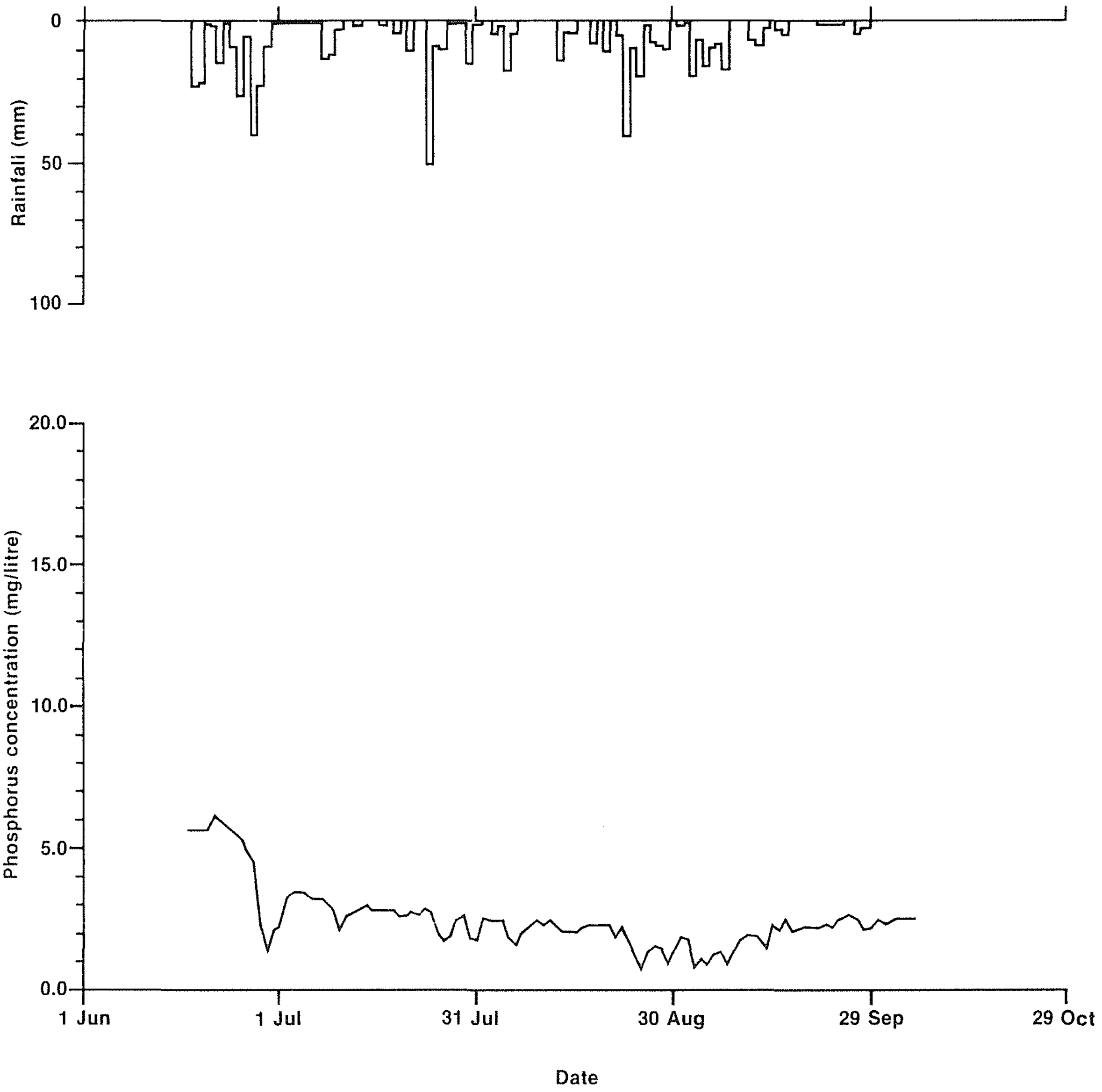


Figure 18 Phosphorus concentration of the North drain for the 1983 winter

the concentration remains significantly higher than that of the North drain, but towards the end of August drops and recovers to a similar value.

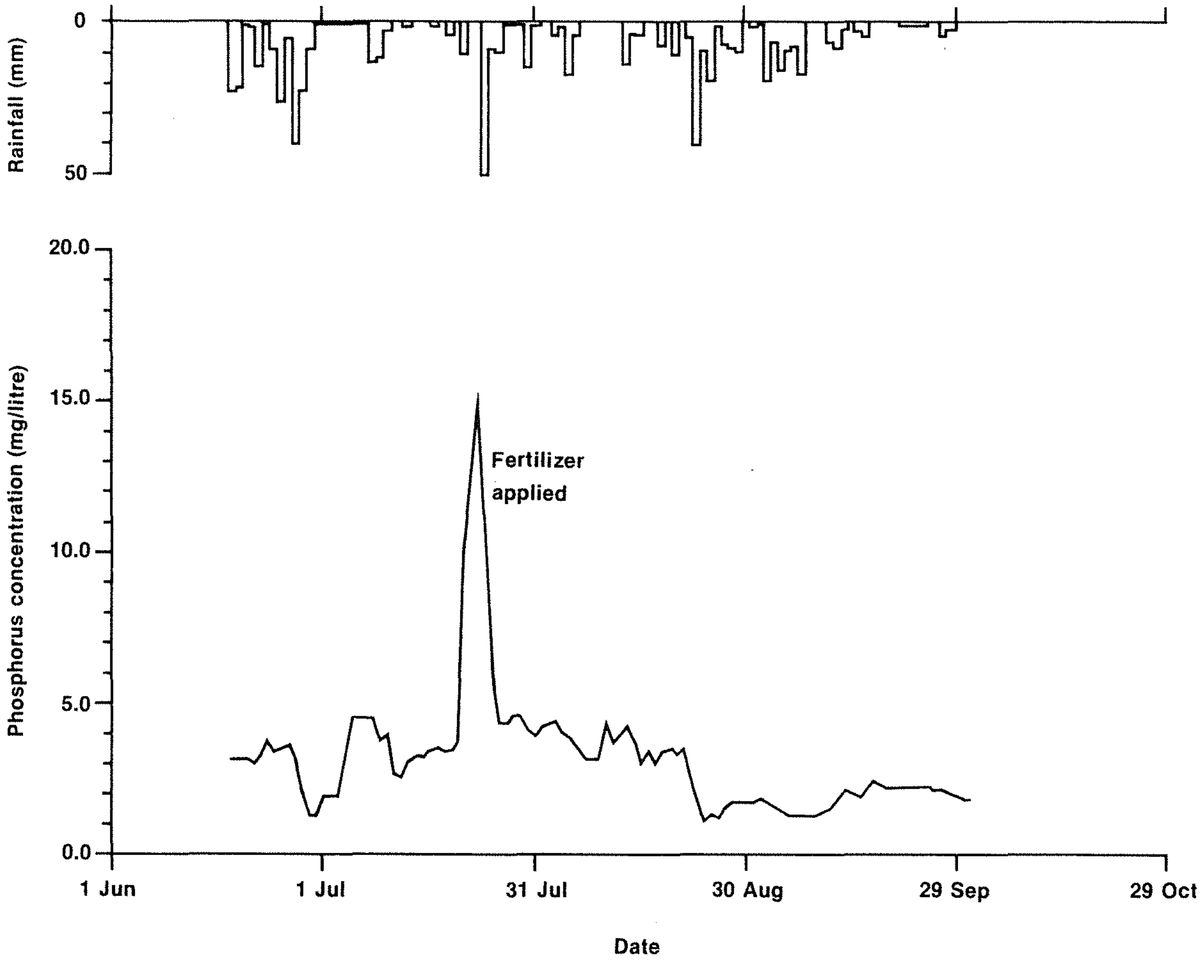


Figure 19 Phosphorus concentration of the South drain for the 1983 winter

Phosphorus loads

Phosphorus loads for the North and South drains are shown in Fig. 20. The loads naturally reflect the simultaneous variations in flow and concentration. Generally, it is worth noting that major storm events can yield high phosphorus loads. This implies that the dilution of phosphorus concentration by rainfall is not nearly sufficient to compensate for the higher flow.

Cumulative load-flow graphs

Cumulative load-flow graphs (see Fig. 6) seem particularly instructive in distinguishing the effect of fertiliser application. The graphs have been divided into their main linear sections to which flow-weighted mean phosphorus concentrations have been assigned. Prior to fertiliser application, it is apparent that the phosphorus export in drainage per unit area is very similar for the two catchments. Immediately after fertiliser application the South drain mean concentration rose to 8.3 mg/L whilst that of the North drain remained the same. Flow-weighted mean concentrations for both catchments then decrease during the remainder of the winter, with the South drain value approaching but not reaching that of the North drain. It is not clear at this stage whether the 20% lower phosphorus concentration for the North catchment at the end of winter is a true reflection of the run-down of phosphorus due to witholding fertilizer.

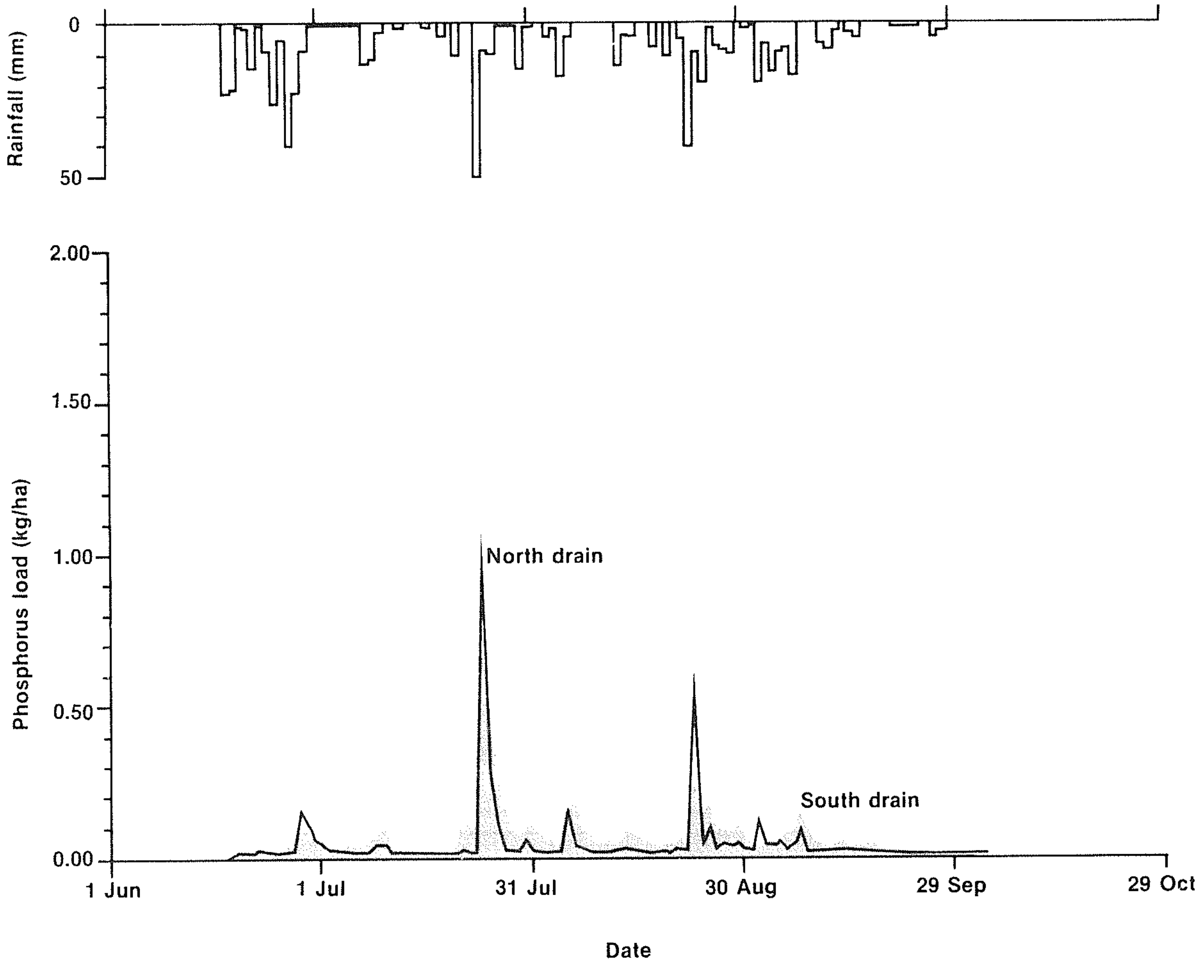


Figure 20 Phosphorus load in North and South drains for the 1983 winter

5.4.3 Groundwater Phosphorus Observations

Monitoring and analysis

Water samples taken routinely from each observation bore were analysed for ortho-phosphate using the Murphy and Riley method. Samples were taken after the bores had been bailed and allowed to recover, and phosphorus concentrations represent an averaging over the total slotted interval. Results obtained were processed and displayed in graphical format as :

- concentration versus time for each bore
- contour plots of phosphorus concentrations over the monitored areas at each sampling time.

Statistical analysis was undertaken to attempt to quantify total areal storages in the profile between the top of the hardpan and the groundwater surface.

Groundwater phosphorus responses

Groundwater phosphorus concentrations measured prior to any significant rainfall in May were examined in relation to the detailed soil map of the study area (see Fig. 4).

In the areas adjacent to the Meredith drain, designated as soil type SW1, concentrations are generally low (<1 mg/L). Similarly under the Gavin dunes, low concentrations are observed.

Within the Joel soils, concentrations are generally higher, and within the Joel series, the sandy loams have higher concentrations than the loamy sands. These concentrations may exceed 4 mg/L.

The swamp soils SW2 were observed to contain groundwaters of variable, but high phosphorus concentration. Within the swamp on the South drain, phosphorus concentrations have been recorded as high as 16 mg/L.

Variations of phosphorus concentrations in observation bores throughout the winter are shown in Fig. 21 for locations under the Gavin sands (bore 56), Joel sands (bore 45) and in the high concentration swamp area (bore 59), of the South catchment.

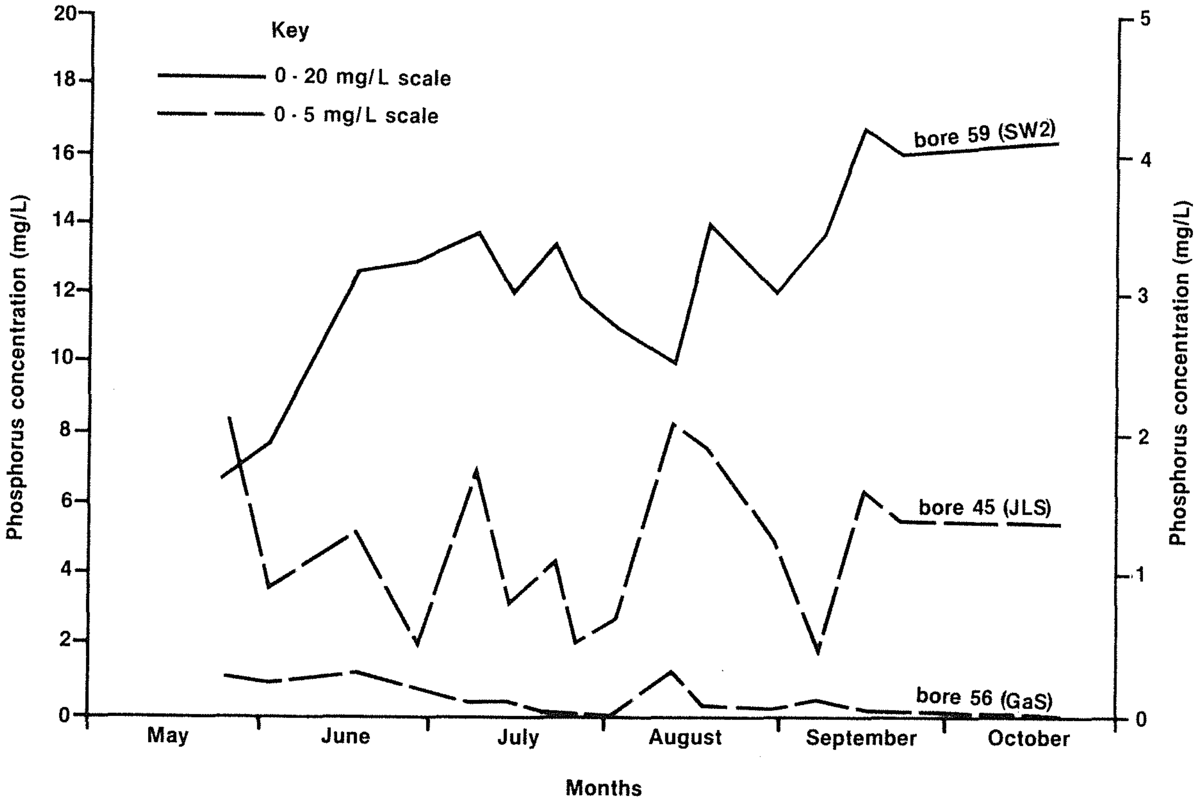


Figure 21 Variation of ortho-phosphate concentration in selected bores (1983)

The areal distribution of concentration is shown for 14th July, 1983 and 30th August, 1983 in Figs. 22 and 23 respectively. These two contour maps represent the groundwater concentrations before and after the application of phosphatic fertilizer on the southern catchment for the period 18th July - 21st July,

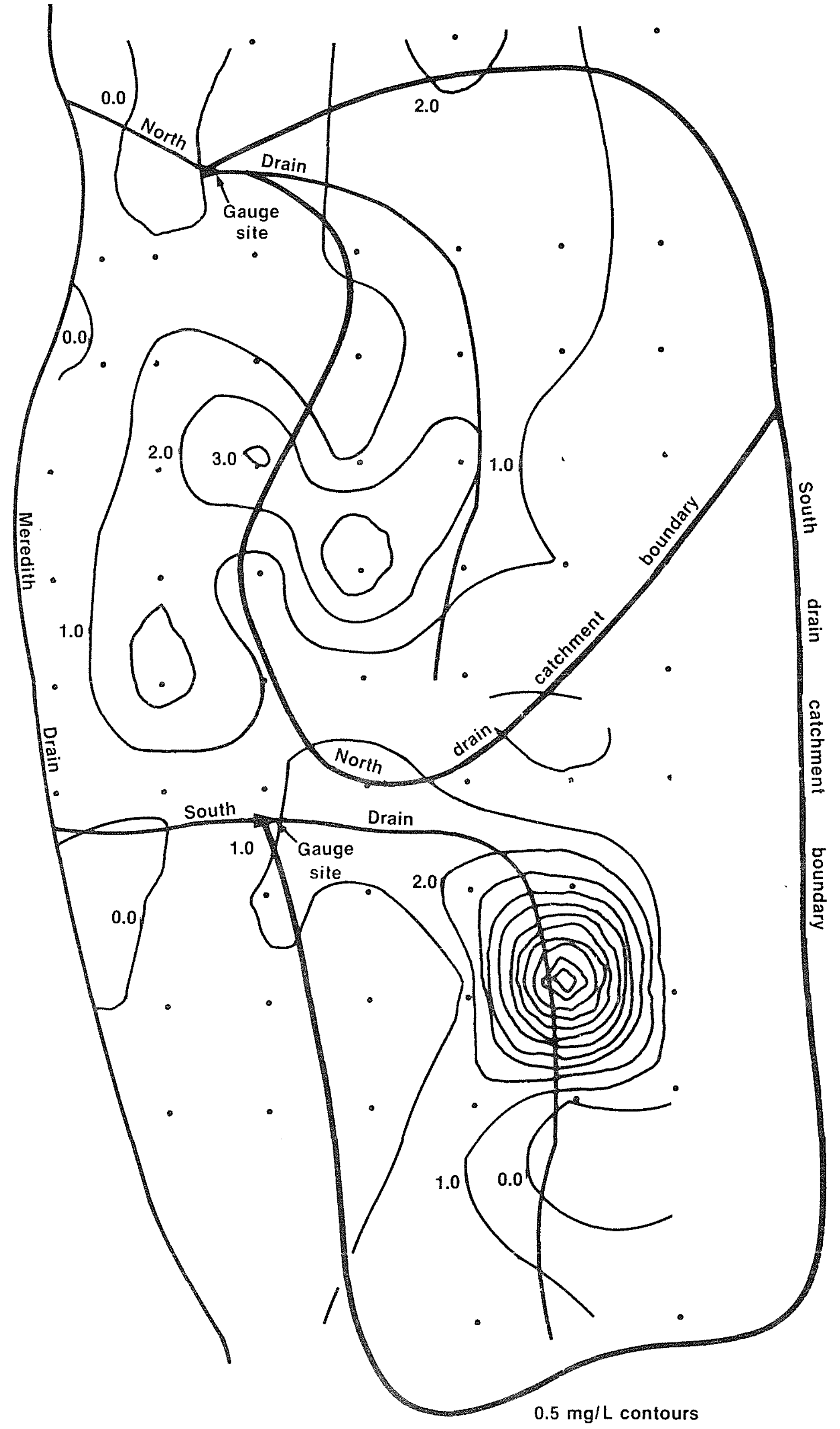


Figure 22 Areal distribution of ortho-phosphate concentration on 14th July 1983

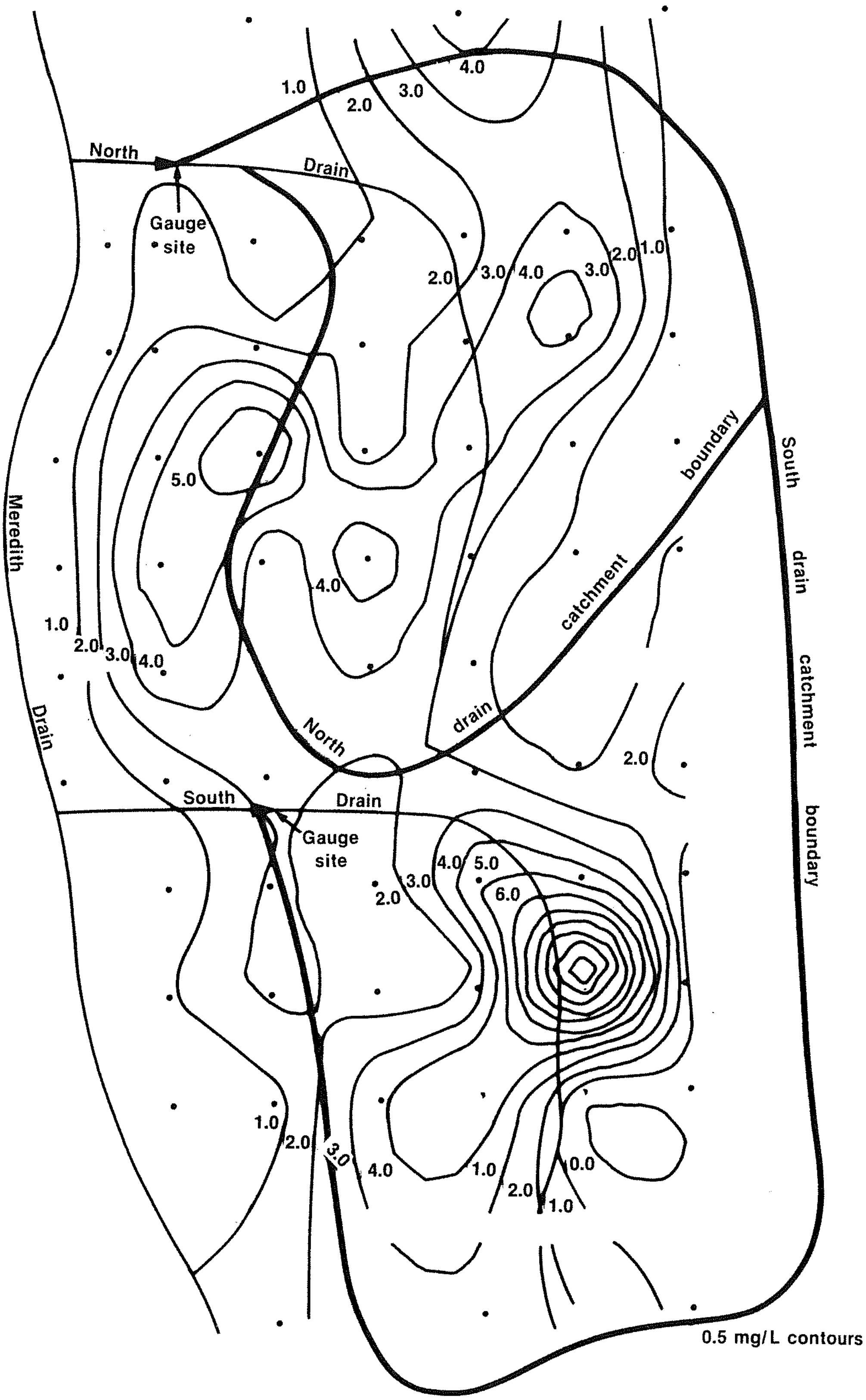


Figure 23 Areal distribution of ortho-phosphate concentration on 30th August 1983

1983. Examination of these figures shows that while the concentrations at individual bores change with time, the general pattern of highs and lows remains fairly static.

Although there are strong indications that the individual concentrations for each bore are log-normally distributed, the catchment mean concentrations are normally distributed. Hence the standard errors of the mean concentrations for each catchment at each sampling date can be calculated (see Table 14). Examination of the results shows that changes in the mean concentration for the South catchment after the application of fertilizer were not statistically significant.

Table 14 Mean and standard error groundwater phosphorus concentrations for North and South catchments and outside bores (1983)

CATCHMENTS

DATE	SOUTH Mean	(17 bores) S. Error	NORTH Mean	(20 bores) S. Error	OUTSIDE Mean	(30 bores) S. Error
25/5	1317	389	963	264	627	92
2/6	1356	434	1491	285	745	130
17/6	1729	730	1577	296	730	188
28/6	1394	758	875	222	1010	247
8/7	1730	815	1260	277	1075	264
14/7	1501	708	1065	231	682	153
22/7	1843	803	1558	304	1301	321
26/7	1919	703	999	239	1012	249
2/8	1731	658	1142	263	1124	270
12/8	2401	598	1712	278	1833	269
18/8	2228	819	1693	336	1666	327
30/8	2494	714	1831	327	1797	298
7/9	2518	805	1320	297	1409	245
15/9	2567	956	1447	292	1499	275
22/9	2458	919	1600	307	1380	299
21/10	2405	960	1495	282	1181	244

It is evident that while catchment mean phosphorus concentrations are at similar levels during the early rain period, the levels in the South catchment rise, with time, to be 60% higher than those in the North catchment towards the end of October. This may in part account for the higher flow weighted mean phosphorus concentration in the South drain experienced in the latter part of the year as shown in Fig. 6.

Over the entire area monitored, in 38 bores groundwater levels intersected the ground surface at some time of the year. All phosphorus concentrations exceeding 4 mg/L with the exception of one, were located in such areas of flooding. The seasonal trend of mean phosphorus concentrations on each catchment, and for adjacent areas to the west, is shown in Fig. 24. The variability of the concentration data is so high that it tends to mask any spatial correlation structure.

Results from groundwater phosphorus analyses, when integrated with the estimates of water storage, enable changes in groundwater phosphorus storage to be made for North and South

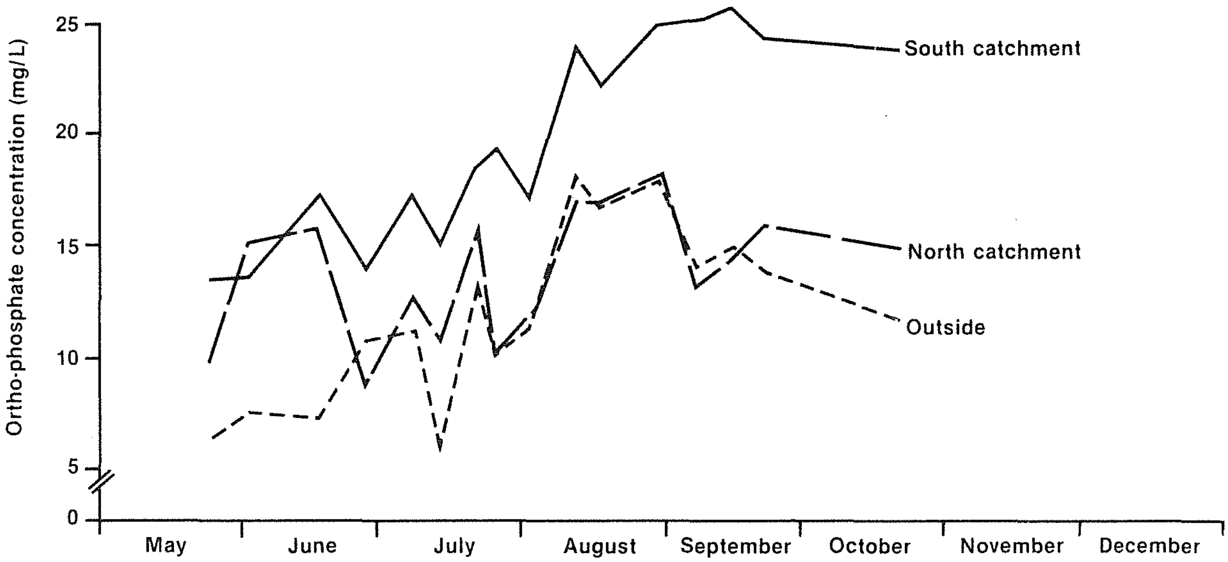


Figure 24 Seasonal trend of mean groundwater ortho-phosphate concentration for North and South catchments and outside bores (1983)

catchments and the monitored area outside of these catchments. The seasonal variation of phosphorus storage in the saturated profile above the hard pan is shown in Fig. 25. The mean phosphorus storages for each sampling date are listed in Table 15. The larger phosphorus storages on the southern catchment are due to both higher mean concentrations and greater depth of saturated profile above the hardpan (see Table 12). The marked change between 2nd and 12th of August is due to change in phosphorus concentrations in all catchments.

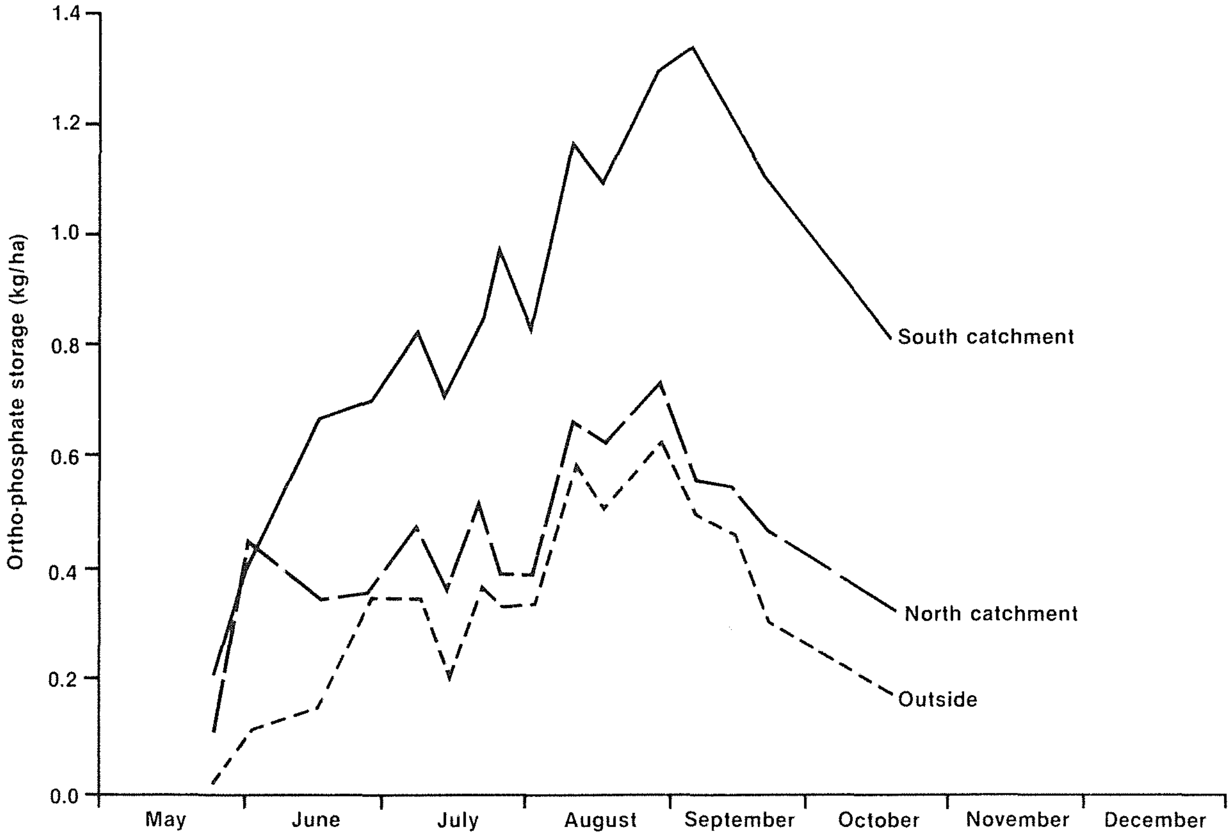


Figure 25 Changes in groundwater ortho-phosphate storage above hardpan for North and South catchments and outside bores (1983)

Table 15 Mean and standard error groundwater phosphorus storages (kg/ha) above the hardpan for North and South catchments and outside bores (1983)

	CATCHMENTS					
DATE	SOUTH Mean	(17 bores) S. Error	NORTH Mean	(20 bores) S. Error	OUTSIDE Mean	(30 bores) S. Error
25/5	2.2	1.0	1.1	0.6	0.2	0.1
2/6	4.2	1.7	2.9	1.0	1.1	0.3
17/6	6.6	3.4	3.4	1.1	1.5	0.5
28/6	7.0	3.9	3.6	1.2	3.5	1.0
8/7	8.2	4.0	4.8	1.3	3.5	1.0
14/7	7.1	3.4	3.6	1.1	2.0	0.6
22/7	8.4	3.8	5.2	1.3	3.7	1.1
26/7	9.8	3.7	3.9	1.1	3.3	0.9
2/8	8.3	3.2	3.9	1.1	3.4	0.9
12/8	11.7	3.0	6.6	1.4	5.8	1.1
18/8	10.9	4.1	6.2	1.3	5.1	1.2
30/8	12.9	3.8	7.3	1.5	6.3	1.2
7/9	13.4	4.5	5.6	1.5	5.0	1.0
15/9	12.3	4.8	5.5	1.4	4.7	1.1
22/9	11.0	4.4	4.8	1.2	3.1	0.8
21/10	8.0	3.2	3.2	0.9	1.7	0.4

Further analysis of groundwater phosphorus responses

The accuracy of the statistical estimates of phosphorus storage in the groundwater can be improved by stratifying the concentration data according to soil type. This is presently being done using the soil map shown in Fig. 4 section 5.3.3.

In addition the phosphorus concentration data for 1984 for the 50 metre grid area in the southern swamp can be used to improve the estimate of phosphorus storage for the southern catchment.

5.4.4 Spatial variability of soil phosphorus

Phosphorus concentrations of the coastal plain soils are not uniform over areas of similar agricultural history (e.g. the same paddock). The top soil (<10 cm) tends to show variation within small areas of similar soil, which may be caused by small scale variations in topography, clumping of pasture species, distribution and decomposition of faecies etc. It is important to quantify this variation as the sampling technique is dependent on the degree of variability.

Methods

To estimate the scale of spatial variability in the Joel series of the Bassendean association, a grid sampling system was established. The layout consisted of two 6 m x 11 m grids spaced approximately 40 m apart on the North catchment. Within each grid six 1 m^2 plots spaced at 5 m intervals were marked. Nine cores of 10 cm depth were taken from each plot, i.e. 54

samples per grid and 108 samples total. Sampling was carried out in April before the heavy winter rains arrived to ensure that soluble phosphorus fractions were only slightly leached by summer rain in March. The soil samples were analysed for total phosphorus and bicarbonate-extractable phosphorus concentrations. Spatial variability was estimated by a comparison of means and standard deviations between grids and plots. As the number of samples taken was large, it was also possible to calculate the sub-sample size required to provide a reasonable estimate of the sample mean.

Spatial variation was tested by using a one-way analysis of variance (ANOVA) between grids and between the plots within the grids. If by this method there is a significant difference between the mean and variance of each data set ($p<0.05$ using F Tables) then the null hypothesis (data sets are the same) is rejected and variation is said to occur.

Large scale variation

The possibility of variation over a 40-50 m radius was investigated by ANOVA between the two sets of grid data. Both bic. P and total P were found to be significantly different even at the 0.01 level (Tables 16 and 17).

Table 16 Grid mean ($\bar{x}$), standard deviation (s) and coefficient of variation (V) of bic. P and total P

	Grid 1		Grid 2	
	bic. P	total P	bic. P	total P
$\bar{x}$	9.7	48.3	7.9	41.0
s	2.9	9.1	2.3	12.8
V	0.30	0.19	0.29	0.31

Table 17 ANOVA F values for large scale variation (40m)

Comparison	bic. P	total P	significance
Between grids	11.5	11.9	$P(F>3.94)=0.05$ $P(F>6.90)=0.01$

Small scale variation

There were large differences in the means and standard deviations of the soil phosphorus concentrations over the small distances (5 m) which separate the individual plots (Tables 18 and 19). As a significant difference was found in the phosphorus concentration data between each grid, an ANOVA between plots must be done separately for each grid (Table 20). This analysis shows a significant differences ($p<0.05$) between plots in both grids for the two phosphorus extractions. Variation is therefore also occuring at these small scale distances.

Table 18 Plot means, standard deviations and coefficient of variations for bic. P

		Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6
Grid 1	$\bar{x}$	11.1	9.9	8.9	9.9	10.3	8.6
	s	3.8	2.8	2.3	3.1	3.4	1.3
	V	0.34	0.28	0.26	0.31	0.33	0.15
Grid 1	$\bar{x}$	10.4	8.0	8.1	7.6	6.7	7.7
	s	2.8	1.4	2.5	1.5	1.4	2.3
	V	0.27	0.18	0.31	0.20	0.21	0.30

Table 19 Plot means, standard deviations and coefficient of variations for total P

		Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6
Grid 1	$\bar{x}$	50.6	43.4	38.1	57.3	52.7	47.9
	s	5.7	7.6	3.9	10.2	8.4	4.1
	V	0.11	0.18	0.10	0.18	0.16	0.09
Grid 1	$\bar{x}$	42.4	41.7	37.4	42.9	38.7	42.9
	s	7.9	7.2	11.4	13.8	19.1	16.5
	V	0.19	0.17	0.30	0.32	0.49	0.38

Table 20 ANOVA F values for small scale variation (5m)

Comparison	bic. P	total P	significance
Between plots within grid 1	57.2	264.6	$P(F>2.41)=0.05$ $P(F>3.42)=0.01$
Between plots within grid 2	158.6	96.7	$P(F>2.41)=0.05$ $P(F>3.42)=0.01$

Microscale variation

The coefficients of variation (or relative variability, V) for bic. P and total P analyses on each m^2 plot (Tables 18 and 19) are large, in many cases larger than their respective grid coefficients of variation (Table 16). This indicates that most of the measured variability is occurring between sample points within each m^2 plot. Sampling points were regularly spaced at 30 cm intervals.

Sample size

Using the large number of soil samples taken in this investigation, the sample size necessary for a given confidence interval of concentration estimate can be calculated. The following assumptions can be made with a large sample:

i) normal distribution (by central limit theorem);
ii) sample standard deviation = population standard deviation

Table 21 Total sample mean, standard deviation and coefficient of variation of bic. P and total P

	bic. P	total P
$\bar{x}$	8.8	44.7
s	2.8	11.6
V	0.32	0.26

Using the equation below, sample sizes were calculated and the results obtained are shown in Table 21.

$$n = \left(Z \times \frac{s}{\bar{x} - \mu}\right)^2$$

where n = sample number
Z = 1.64 for 90% confidence
Z = 1.96 for 95% confidence
Z = 2.57 for 99% confidence
$(\bar{x}-\mu)$ = error of estimate (confidence interval)
μ = population mean

Table 22 Sample size calculations for soil P determination with varied confidence intervals and confidence levels

	bic. P confidence level			T.P. confidence level		
confidence interval	90	95	99	90	95	99
$\mu \pm 5\%$	109*	156	267	72	103	178
$\mu \pm 10\%$	27	39	67	18	26	44
$\mu \pm 15\%$	12	17	30	8	11	20

* i.e. to be 90% certain that the sample mean is within 5% of the actual soil P concentration, 109 soil cores must be taken.

Discussion

The results clearly show that soil phosphorus is not uniformly distributed throughout a Joel soil. There is significant variability at all three scales investigated, however the majority of the variability appears to be at the microscale. This is probably caused by such factors as remnants of faecal matter, clumped distribution of pasture, scouring of the soil surface with subsequent puddling or filling in, etc. The variation in phosphorus concentration occurring at the larger scale within the Joel series is not as great, and is probably a result of soil type change (JSL, JLS) associated with small changes in topography.

The large sample variation of phosphorus concentration in this Joel series means that a large number of samples are necessary to accurately estimate concentration. Since time in the field is usually limited, a reasonable compromise of approximately 20 cores per plot is therefore recommended. This provides one with 90% confidence of being ± 10% of the population mean soil phosphorus concentration.

5.4.5 Seasonal variation of soil phosphorus

As well as spatial variation, there is a seasonal change in concentrations of the more available and potentially leachable pools of phosphorus as described in section 5.4.1. In the winter these pools are readily leached by rainfall and also readily taken up by pasture. In the summer microbial activity, and the effect of sunbaking on the surface, replenish these depleted soluble phosphorus fractions from the less soluble inorganic and organic fractions.

Obviously this seasonal variation must be considered when comparisons of soil phosphorus are being made between sites or plots. The same is true for any comparisons between soil phosphorus and leached phosphorus in the drains. It is necessary therefore to both qualify and quantify this seasonal trend, not only for our experimental work, but also to determine the optimum time of year to sample for farmer fertilizer recommendations. On Talbot's site this was done on a soil of the Joel series that was known to be unresponsive to phosphorus addition.

Methods

Two 6 m x 6 m plots were enclosed by fence for pasture and soil monitoring. Each plot was situated on a Joel soil in each of the North and South drain catchments. The South catchment was treated with 200 kg/ha of superphosphate (18.2 kg P/ha) while the North drain had no phosphorus application. Both catchments received a basal dressing of potassium and sulphur.

Twenty 0-10 cm samples were composited monthly from each plot. These samples were then analysed for bicarbonate extractable phosphorus, total bicarbonate extractable phosphorus, inorganic phosphorus, organic phosphorus and total phosphorus by Government Chemical Laboratories.

Results

The results of these five analyses over one year have been plotted (Figs. 26-30). The bars on the bic. P and total P plots represent the 90% confidence intervals as calculated in the previous section.

In the three weaker extractants (bic. P, total bic. P and inorganic phosphorus) (Figs. 26-28), a rise in phosphorus concentration is seen from September to February as rainfall decreases. Over the same period pasture dies off and temperature increases. Just prior to sampling in March, 47 mm of rain fell on Talbot's property. The leaching effect of this rain has shown up as a depression of the phosphorus concentrations in the graphs of the three phosphorus fractions, especially in the more soluble bic. P pool (Fig. 26). The leached fraction quickly equilibrated with the less soluble pools of phosphorus and had recovered by May. In May the winter rains began and pasture germinated, resulting in greatly reduced soil phosphorus concentrations in the same three fractions.

The expected increase in soluble phosphorus after superphosphate addition (July 4) on the South catchment was not noticeable in the analyses. Sampling was done two weeks after superphosphate addition so it is probable that the very soluble phosphate had already been leached.

Organic phosphorus (Fig. 29) appears to show a very slight decrease in concentration at both sites from September through to May-June. This is followed by a rise in concentration in June-July, probably associated with pasture growth. However, it is difficult to form any strong conclusions because of the weakness of the trends.

Total phosphorus (Fig. 30) should remain constant throughout the year. Any change due to fertilizer addition would be too small to show up conclusively in the analysis. The changes seen in the total phosphorus graph are uncontrolled sampling variations. Most of the points are actually within the 90% confidence limits.

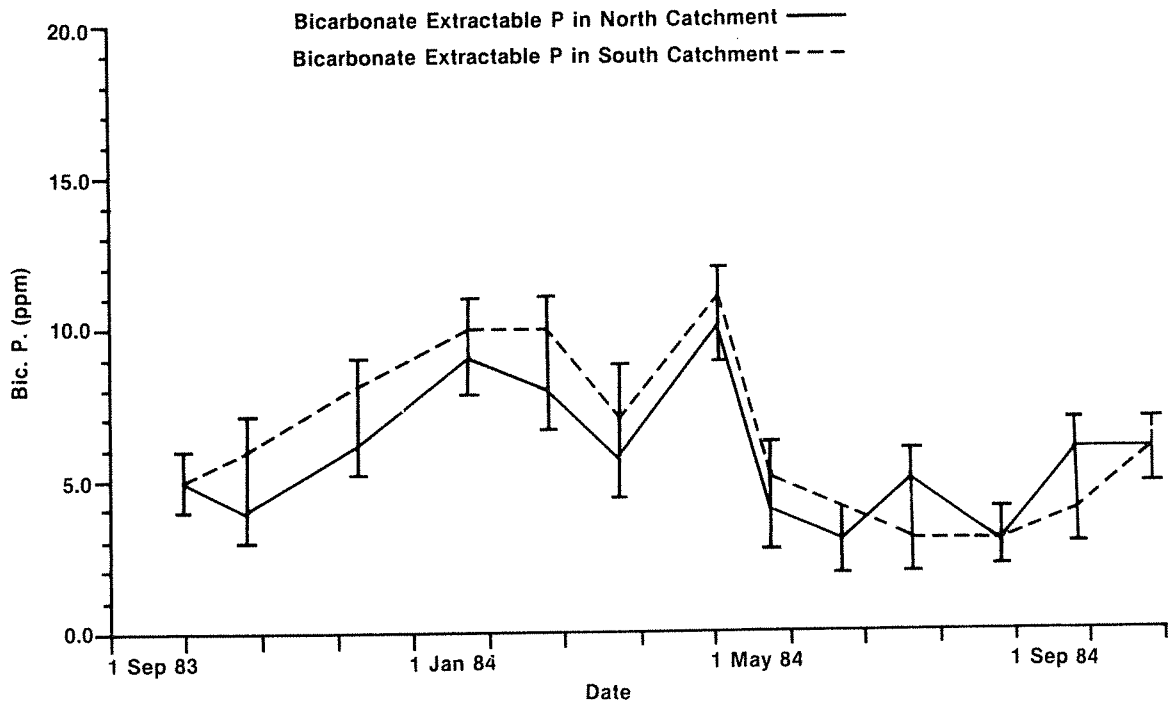


Figure 26 Time variation of soil bic. P for North and South catchments (1983-84)

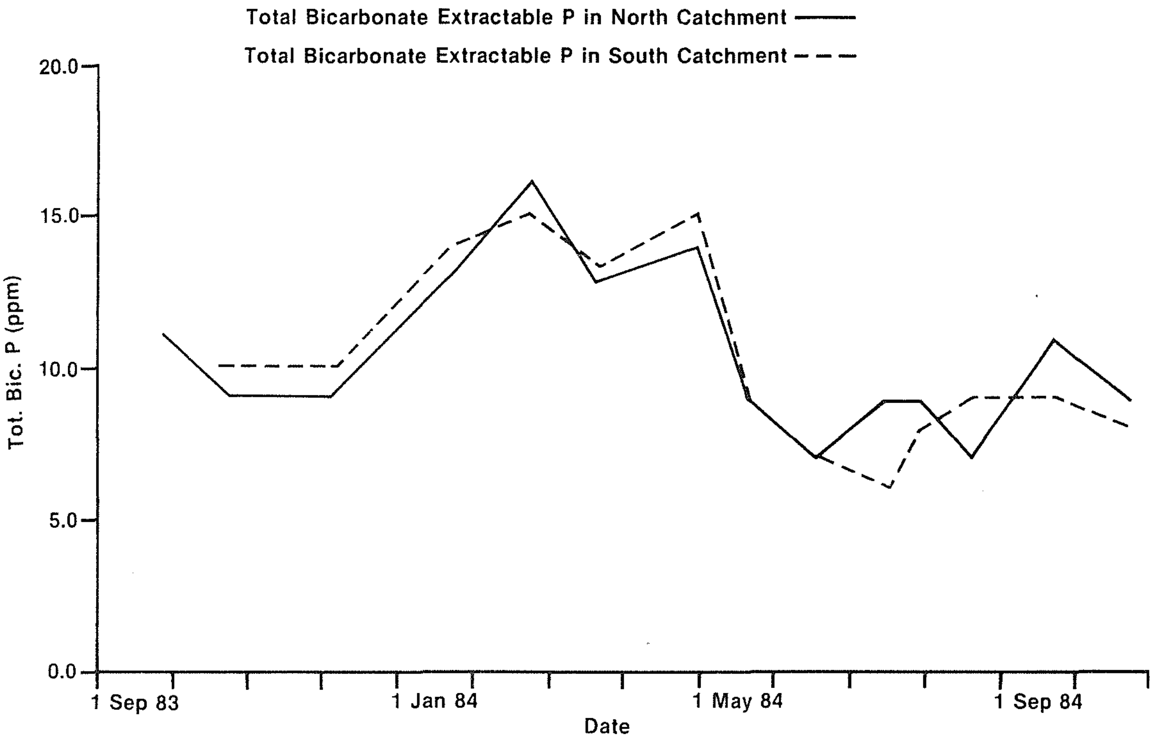


Figure 27 Time variation of total bic. P in soils for North and South catchments (1983-84)

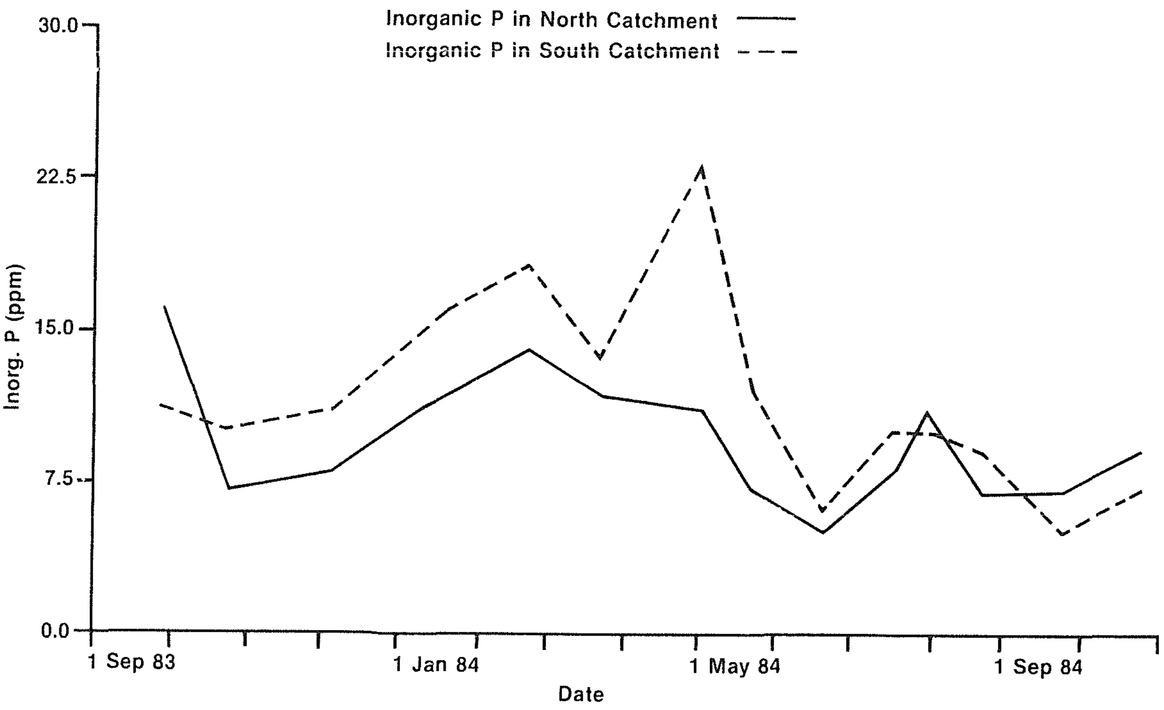


Figure 28 Time variation of inorganic P in soils for North and South catchments (1983-84)

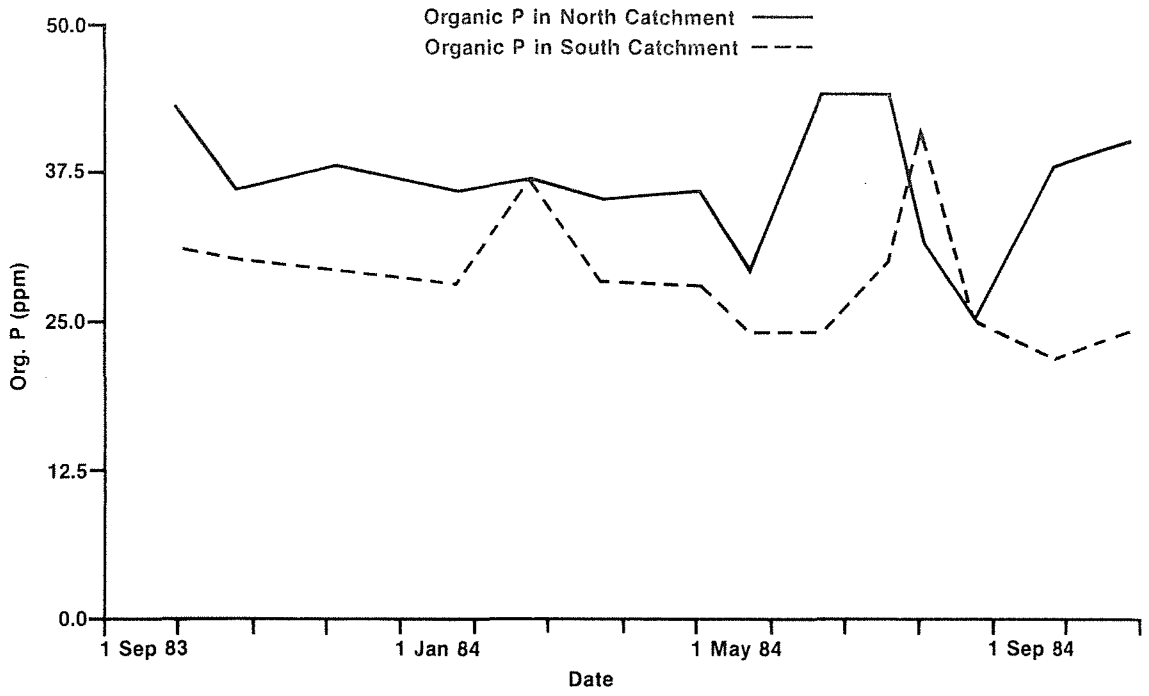


Figure 29 Time variation of organic P in soils for North and South catchments (1983-84)

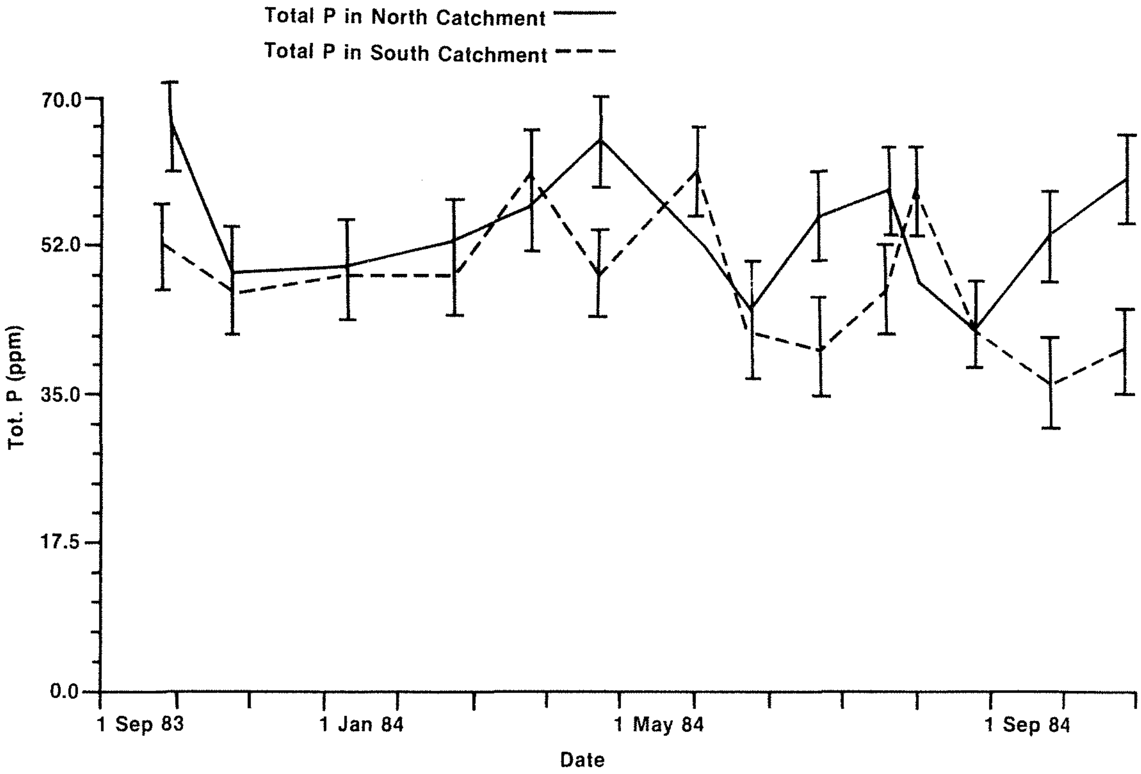


Figure 30 Time variation of total P in soils for North and South catchments (1983-84)

Discussion

Seasonal changes of similar magnitude are found in the soluble phosphorus pools of other coastal plain soils but the relative change between seasons is larger in the Bassendean association soils (approx. 70% drop in bic. P). This is because of the lower readily soluble phosphorus concentration in these cultivated soils due to a lesser ability to adsorb phosphorus. The bic. P graph shows the importance of sampling in summer for fertilizer recommendations but preferably not after a heavy rainfall. This enables maximum bic. P concentrations to be measured consistently for comparisons on a yearly basis.

In the period following the first winter of treatment (i.e. Sept. '83 - Aug '84) the North catchment (nil P) shows marginally less available phosphorus in the soil relative to the South catchment (see Fig. 26). After another year or two a rundown effect should become obvious. Therefore sampling will continue on these plots.

In future monitorings the 10 cm cores should be divided into 0-2 cm and 2-10 cm as the highest phosphorus concentrations have accumulated in the top 2 cm. Seasonal effects on the soil phosphorus such as sunbaking and microbial activity will also be greatest near the surface. Thus the 10 cm integrated samples may have diluted these seasonal changes.

6. GROUNDWATER MODELLING

Objectives

Conventional groundwater modelling techniques have been applied to subsurface water flow in the shallow aquifers associated with the Bassendean sands. The model has been developed in order to match predicted hydrological responses with those observed on the intensively monitored experimental farms. Results of these simulations are to increase our understanding of the subsurface water budgets, and to lead to prediction of the groundwater transport contribution to catchment phosphorus rundown under different management practices.

Methods

The groundwater model has been developed in order to represent areas of the experimental site consistent with the scale over which the monitoring data can be interpolated. A finite difference grid of variable spatial dimensions is overlaid on the area to be modelled, and to each cell is assigned the various parameters associated with the area it represents. These parameters include:

- ground surface elevation above datum
- elevation of hardpan layer above datum
- elevation of groundwater above datum

and hydraulic properties such as :

- hydraulic conductivity
- storage coefficient
- leakage to/from deeper aquifers.

A grid layout has been applied to Talbot's farm site so that cells can be assigned to each of the areas they represent, namely :

- South catchment
- North catchment
- area outside the catchment boundaries.

A variable grid size has been defined in order to represent the catchment drains, as well as the Meredith main drain to the west of the experimental sites.

Numerical procedures

The numerical simulation of groundwater redistribution requires firstly a discretisation of the general equation of groundwater flow in both space (as function of the numerical grid) and in time by using a finite interval time step.

A description of this process is given by consideration of water balance applied to a representative model cell.

The components of water flow that may be applicable to any representative cell are given as (see Fig. 31) :

- groundwater flow to/from the cell across its boundaries described by Darcy's law

- accretion/depletion attributed to recharge/discharge

- leakage to/from deeper aquifers.

The vertical forcing associated with recharge/discharge is the main component producing groundwater level changes. Consequently, a large component of this work is aimed at developing relationships between groundwater recharge and measured rainfall, evaporation, depth to groundwater, soil type and other site specific variables.

Groundwater discharge to drain flow is calculated in two ways.

First, following prediction of the distribution of heads during the simulation, hydraulic gradients are used to calculate rates of groundwater flow to the catchment drains as well as to the Meredith D drain. This is achieved using Darcy's law.

Second, prediction of groundwater intersection of the ground surface yields an area in which additional groundwater accretion results in overland flow. Numerically, this flow is routed directly to drain flow.

Predictions by the model consist of the major components of catchment water balance (although these may be listed for each cell). These components are given for each simulation time step, and consist of :

- change in aquifer storage
- total recharge by rainfall
- total discharge by evaporation
- total drainflow.

These water balance components are listed for each of the catchments as well as the entire area modelled.

It is also possible to list out maps of the spatial distribution of :

- hydraulic head
- changes in hydraulic head
- depth to groundwater
- rates of predicted recharge/ discharge.

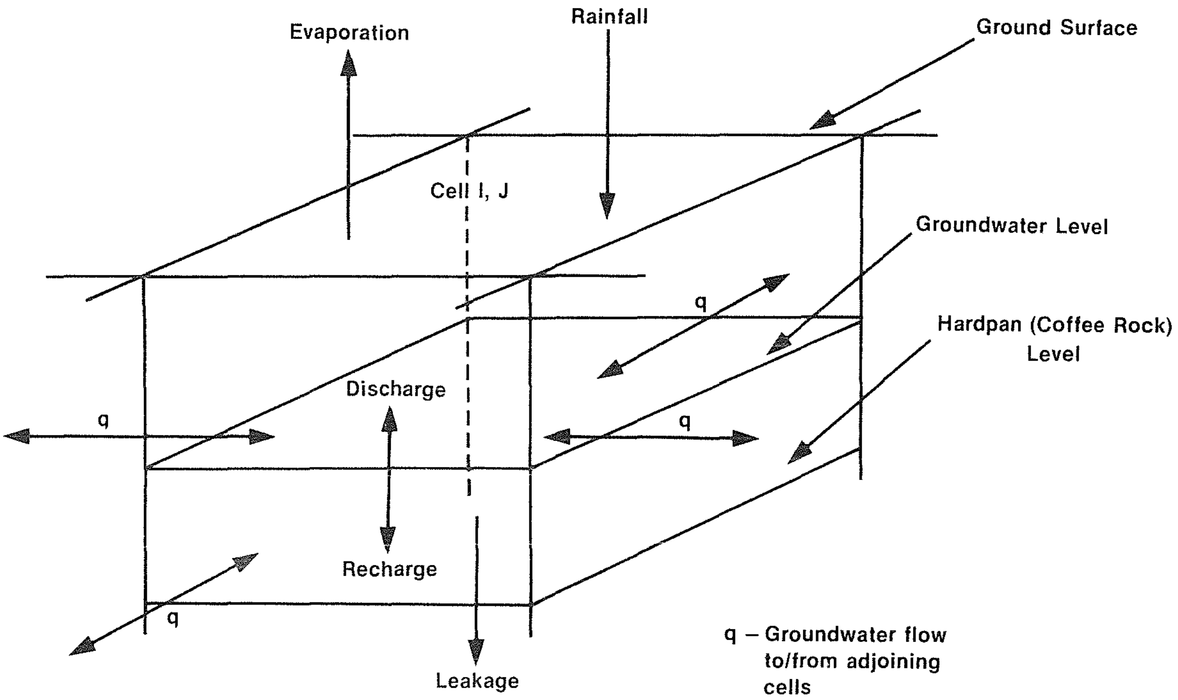


Figure 31 Schematic diagram of cell water flow components

Simulation of responses at Talbots

Following development of the model code on microcomputer, the software was transferred to the Cyber main frame so that the larger array of cells that needed to be applied to Talbots could be run without storage limitations. Preliminary testing and simulation has been directed towards :

- matching observed groundwater level changes for winter 1983
- predicting drainflows in both the southern and northern catchments.

Computer matching of these observed data is expected to be achieved by :

- defining a recharge/discharge algorithm dependent on meteorological and site specific data
- adjustment of the hydraulic parameter distribution in accordance with soil mapping.

Initially, a simplified recharge/discharge algorithm was used. Measured rainfall and pan evaporation were used to estimate both recharge to the groundwater and discharge by evaporation as follows :

i) The amount of rainfall recharged to the groundwater was assumed to dependent on the soil water storage in the unsaturated zone above the water table. Initially the unsaturated zone is set to a minimum water content (WCMIN). Rainfall is added to this storage until the water content exceeds another preset value (WCMAX). On reaching this upper level water content, excess rainfall is added to the groundwater as recharge.

ii) Similarly, the amount of measured pan evaporation that is extracted from the groundwater is also dependent on the storage in the unsaturated zone. When the groundwater is at the ground surface 100 percent of the pan evaporation is removed as discharge. When the groundwater is between the ground surface and 0.1 metres below the ground surface, it is assumed that discharge is removed at a rate of 75 percent of pan evaporation. When the groundwater level is greater than 0.1 metres below ground surface, discharge is assumed to decline linearly from 75 percent of pan evaporation at a depth of 0.1 metres, to zero percent at a depth of 1.0 metres. These extraction rates are used to adjust the water content of the unsaturated zone. This discharge is extracted from the unsaturated zone storage until the lower storage limit (WCMIN) is reached. Excess discharge is then removed from the groundwater.

Simulation results

The early model runs were undertaken to simulate observed responses over the winter 'wet-up' period. Since meteorological data is recorded daily a constant simulation time step of 1 day was used. Comparison of observed and predicted heads were made on monitoring dates, but drain-flow predictions by the model were integrated over seven day periods to compare with the recorded rain hydrographs. This was necessary since numerical surface routing procedures were not incorporated into the model, and this resulted in faster response times in predicted surface flows. In this way, the model is used to predict the total catchment water budget, as well as a water budget for each area represented by a numerical cell.

For these early simulations, spatially constant values of permeability and specific yield were assumed. These values were 1.0 metres/day and 0.15 respectively. The unsaturated storages were assumed to vary between 0.15 m/m (WCMIN) and 0.25 m/m (WCMAX) yielding a potential storage capacity for the unsaturated zone of 0.1 m/m.

Comparison between the observed and predicted heads at the bores showed a reasonable match overall, although adjustment to the spatial distribution of hydraulic parameters will enable a closer simulation to be achieved. This will be done by consideration of the recently described soil mapping on the catchment. Table 23 lists the observed/predicted heads at each observation bore over the simulation period.

TABLE 23

COMPARISON OF PREDICTED AND OBSERVED GROUNDWATER LEVELS IN OBSERVATION BORES

	NORTH CATCHMENT MEAN LEVELS IN 19 BORES (m)		SOUTH CATCHMENT MEAN LEVELS IN 15 BORES (m)		OUTSIDE CATCHMENT MEAN LEVELS IN 27 BORES (m)	
DATE	PREDICTED	OBSERVED	PREDICTED	OBSERVED	PREDICTED	OBSERVED
28.6.83	3.58	3.62	4.67	4.64	3.11	3.16
8.7.83	3.59	3.62	4.60	4.61	3.03	3.01
14.7.83	3.64	3.51	4.60	4.53	3.02	2.88
22.7.83	3.66	3.50	4.59	4.52	3.00	2.86
26.7.83	3.85	3.74	4.79	4.74	3.14	3.13
2.8.83	3.78	3.59	4.65	4.59	3.01	2.94
12.8.83	3.80	3.70	4.61	4.70	2.98	3.05
18.8.83	3.85	3.63	4.65	4.65	3.01	2.99
30.8.83	3.94	3.78	4.76	4.77	3.09	3.15
7.9.83	3.98	3.83	4.81	4.82	3.12	3.19

Cumulative drain flow hydrographs were compared for both the North and South catchments. On the South catchment drain flows were matched to within 10% over the first 21 days of flow using the parameter values defined. The predictions for the North catchment tended to over-estimate the observed flows. This may be due to reduced groundwater outflow from the catchment in a northerly direction imposed by the model boundaries. This would result in there being more groundwater available for surface water runoff than really occurs. Parameter adjustment and the use of constant flow cells to the north will rectify this overestimate in northern drain flow. Figs. 32 and 33 show the comparison between observed and predicted drain flows for the North and South catchments.

Discussion

Preliminary results from the study indicate that the observed hydrological response of Talbot's experimental site can be simulated using a physical process based model. Further updating to improve matching of observed and predicted responses will be undertaken to more clearly define and quantify the flow processes. This will provide a basis for

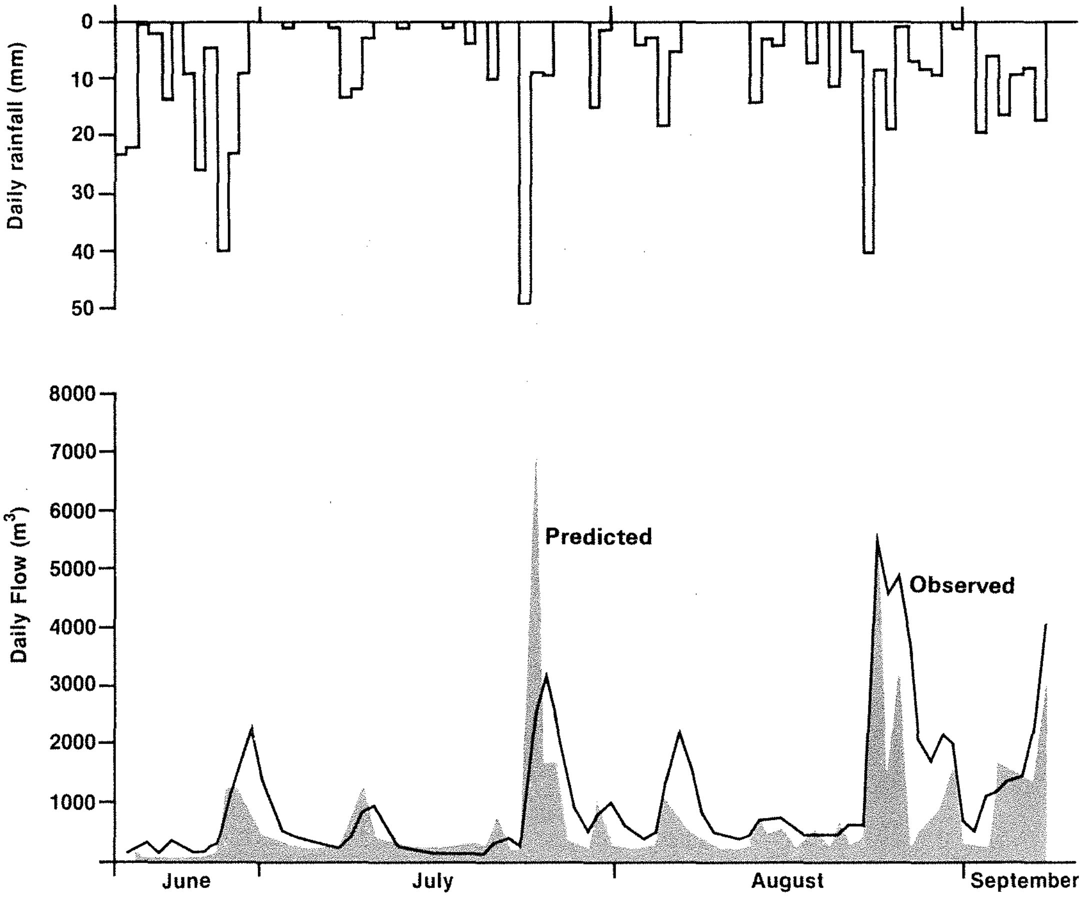


Figure 33 Observed and predicted drain flows for South catchment

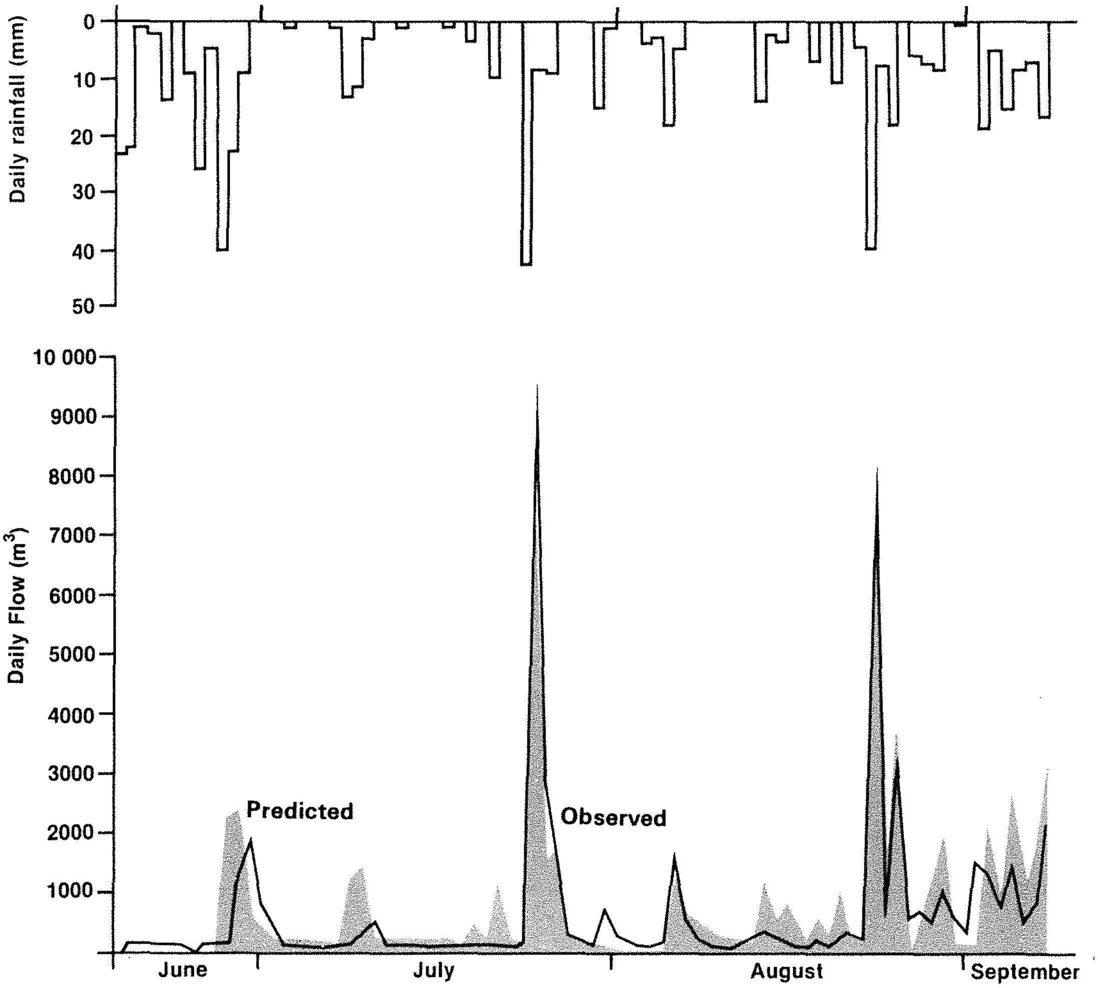


Figure 32 Observed and predicted drain flows for North catchment

predicting catchment phosphorus transport on a farm scale. In preparation for this it is convenient to introduce a conceptual model of phosphorus transport in order to identify the hydrological and soil chemical processes that will need to be defined. Superphosphate application can be thought to result in the addition of phsophorus to two surface stores. The active surface zone store which can be readily dissolved, and an inactive surface zone store which is less readily leached and includes plant phosphorus. (These correspond to the rlp and slp in section 5.4.1).

The readily dissolved phosphorus will become mobile following rainfall and may be transported directly in overland flow to drains, or may be leached downwards into the soil profile.

It is convenient to consider two zones within the soil profile, namely the unsaturated and fully saturated zones. Within these zones phosphorus can be thought to be stored in two phases :

- an 'active' phosphorus store which can be readily transported within and between zones by convection/diffusion

- an 'inactive' phosphorus store which can be released by desorption, and microbial breakdown of organic P.

Phosphorus may be removed from the active zone stores by adsorption. Within the soil profile, following leaching from the surface, the phosphorus may be redistributed by convection/diffusion within the unsaturated profile, and may be transported to/from the groundwater as a result of the recharge/discharge processes.

Phosphorus storage within the groundwater may be transported areally by convection/diffusion or may be discharged to the ground surface following saturation of the soil profile, or directly to drains which intersect the water table.

The water transport components of this conceptual model are compatible with the groundwater modelling described above, and it is envisaged that the two models will be integrated such that phosphorus movement can be simulated.

7. SUMMARY AND CONCLUSIONS

Measurements to date suggest that Talbot's paired catchments are well matched in physical and chemical properties. The landform is typical of the extensive grey sands of the Harvey and Serpentine catchments with the characteristic features of dunes, flats and swamps well represented. The drainage characteristics and soil phosphorus availability of the two catchments are similar.

In comparing nil and superphosphate treatments, the parameter 'flow-weighted mean phosphorus concentration' (Pconc) was used to indicate the effect of the treatments on phosphorus export in drainage. Prior to treatment Pconc was nearly identical for both catchments, but following treatment Pconc was 30% greater on the superphosphate fertilized catchment. There was no effect of the treatment on pasture yield. It is tentatively concluded that not applying a phosphatic fertilizer may lead to a reduction in phosphorus export in drainage by up to 30% in one year. This occurs with no decrease of pasture yield for non-responsive sites. The results are tentative to the extent that little pre-treatment data was available to establish the 'natural variability' of phosphorus discharge under normal superphosphate use.

Measurement of the major water budget components indicated that over the runoff period (18.6.83 - 30.9-83), there was little change in the soil water storage, with rainfall input being divided almost equally between evaporation and runoff.

The runoff coefficients for the two catchments were similar but high (~.45). Of the runoff, about 27% was baseflow in the North drain and 47% was baseflow in the South drain.

At the beginning of winter the depth to groundwater ranges from 0.8m in the low-lying swamps to more than 4m on the highest Gavin dunes. The response of the groundwater to winter rain in terms of the timing and rise of the water table was similar over the whole site. On the Joel flats the water table rises close to the surface, and intersects the surface following storm events. On the Gavin dunes the water table response is similar in magnitude but occurs slightly later.

Comparisons between the two catchments show that under normal superphosphate application and farming practice of the area, there is a net accumulation of phosphorus in the ground of about 6 kg/ha/yr. However, when no superphosphate is applied, there is a net loss to the system, mostly in drainage, of a similar magnitude. Neither quantity, however, is large compared to the total soil phosphorus store. The amount of phosphorus taken up in plants is high but this does not generally have a significant impact on the budget, since most is returned to the soil surface by grazing animals, unless plants are removed as hay. Phosphorus exported by sheep from the site was about 30% of that exported in drainage.

The accumulation of soil phosphorus resulting from fertilizer use is well demonstrated by comparing farmed and virgin sites.

The fertilized site shows a near 50% greater total phosphorus store. The higher storage is more evident in the inorganic fraction (2.7 times greater) than the organic fraction (1.3 times greater). In both profiles approximately 50% of total phosphorus is stored above 15 cm depth. Organic phosphorus is more strongly distributed towards the surface (84% above 15 cm) than inorganic phosphorus, the majority of which is distributed through the profile. At the location studied, the organic hardpan (coffee rock) is not a site of large accumulation of phosphorus despite its high adsorption capacity. This indicates that the profile above the hardpan is still accumulating phosphorus, or that water with high phosphorus concentration is not coming into contact with the hardpan.

On the North catchment, with no superphosphate application, phosphorus concentration in drain flow gradually decreased through the winter due to the leaching of the readily leachable phosphorus pool. In spring the phosphorus concentration increased slightly as rainfall leaching decreased. Superimposed upon this trend, there were responses to rainfall events which decreased the phosphorus concentration in the drain by dilution. In contrast, on the fertilized catchment the phosphorus concentration increased dramatically after superphosphate application. This probably indicates the importance of surface washing of areally broadcast fertilizer.

Examination of the phosphorus load in drainage over the winter period indicated that major storm events could export large amounts of phosphorus. The cumulative load-flow diagrams are also particularly useful for identifying the effects of fertilizer application.

The groundwater phosphorus concentration throughout the area was highly variable, ranging from <0.5 mg/L to >16 mg/L. There is, however, a clear relationship between phosphorus concentration and soil type. In the swamp soils close to the Meredith drain the concentrations were generally less than 1 mg/L, on Joel soils the concentration could exceed 4 mg/L and in the swamp soils concentration reached 16 mg/L. Higher phosphorus concentrations were also associated with areas subject to flooding.

The change in the mean groundwater phosphorus concentration of the South catchment following superphosphate application was not significant. The mean phosphorus storage in groundwater, however, did change significantly over the year (e.g. ranging 2-13 kg/ha in the South catchment above the hard pan). In both catchments there was a peak in groundwater storage at the end of August.

A test of the spatial variability of soil phosphorus in a Joel soil clearly shows significant variability at all scales from $1m^2$ to 500 m^2. The greatest variability occurs at the smallest scale, probably being caused by such factors as remnants of faecal matter, clumped distribution of pasture, scouring of soil surface etc. At the large scale the variability probably relates to different soil and landscape features. In a test for soil sampling frequency, it was found that 20 samples per plot provides 90% confidence of being ± 10% of the population mean.

As regards seasonal changes in soil phosphorus, relatively large changes were observed in the solute phosphorus pool (e.g. 70% variation in bic. P over the year). Thus it is important that sampling for fertilizer recommendations takes place in summer and not after heavy rain.

Groundwater modelling has been initiated and some early results are described. Further details are given by Bettenay *et al.* (1985).

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