PHOSPHORUS LOSSES THROUGH TRANSFER, SOIL EROSION AND RUNOFF: PROCESSES AND IMPLICATIONS

Ward, J.C. Talbot, J.M. Denne, T. and Abrahamson, M.
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Foreword

Phosphate rock is a strategic material upon which pastoral agriculture and all New Zealanders depend. Phosphate fertilizer has no close substitute, and is, therefore an important limiting factor to agricultural productivity. The future wellbeing of the country depends on its efficient acquisition, manufacture, distribution and use.

This report is part of a larger cross-disciplinary study carried out by Centre staff on the multiple dimensions of phosphate management in New Zealand. The report presents an examination of phosphorus losses from the production system and the attendant consequences on environmental quality. Special emphasis is given to hill country loss mechanism, where it is known that significant amounts of phosphate fertilizer are picked up in surface runoff and/or are displaced by grazing animals. The longer term consequences of nutrient loading on downstream water bodies are discussed, and the policy and management implications for maintaining current water quality levels are highlighted.

K.L. Leathers
Study Team Leader
1. INTRODUCTION

Phosphorus is added to New Zealand soils to increase plant growth but is lost from the pasture system by stock transfer, soil erosion and water runoff. When this nutrient reaches waterways, growth of aquatic plants is promoted; excessive growth results in changes to water quality and potential uses of the water. Phosphorus is retained by lake sediments so additions have long term consequences on lake and downstream water quality. While phosphorus losses to the farmer may be small, the costs borne by society may be large because of the long term effects and the expense of any remedial measures.

1.1 The nature and scope of the problem

The amount of phosphate fertiliser applied annually to New Zealand pastures has been approximately two million tonnes in recent years. To sustain growth of agricultural exports in coming decades, greater levels of fertiliser phosphorus may be required. Since a significant proportion of the applied fertiliser is lost to the production system, efficiency in on-farm use is becoming an important concern for farm managers and policy makers. On-farm losses raise production costs and lower farm incomes, while phosphorus enrichment of freshwater bodies has implications for environmental quality.

1.2 Specific objectives

This paper examines what is currently known about fertiliser phosphorus losses in New Zealand pastoral systems. It focuses on the potential above ground losses (and costs) to the farmer, management options for conserving phosphorus, and on the ecological effects and potential social costs of fertiliser phosphorus additions to waterways and approaches to avoiding or managing these unintended impacts. Our understanding of the issues, and factual evidence which underlines these two main theses, is explored in some detail.

2. PHOSPHORUS LOSS PROCESSES

Fertiliser phosphorus losses result from four basic mechanisms:

1. below ground phosphorus cycling processes (discussed by Scott, 1985);
2. embodied phosphorus in animal carcases and products removed from the farm;
3. 'animal transfer' or the displacement of dung phosphorus to locations on the farm which effectively removes this resource from entering into subsequent production cycles; and,
4. phosphorus lost via water runoff and soil erosion.

The relative order of magnitude of these losses is not known at present, nor are the potential savings that might be realised in their control - the value of phosphorus conservation. Because the first two mechanisms of loss are largely uncontrollable this paper considers only the nature of stock transfer, soil and runoff losses and their potential for control through improved farm management.

2.1 Stock transfer
Phosphorus cycles in ecological systems through the action of organisms at different trophic levels. Herbivores have an important role in cycling. Because of cultural practices, sheep and cattle are the dominant herbivores of New Zealand pastoral agricultural systems (although other herbivores such as horses and deer may be locally dominant), and management aims to maximise their production. Phosphorus (P) is applied to pastoral systems to increase plant production to provide food for livestock. Phosphorus is consumed with the plants; some is retained by the animal and some is returned rapidly to the soil-plant system via excretion. Although the amount returned may be quite large, phosphorus is concentrated largely in dung and deposits may be distributed in such a way that the phosphorus is unavailable to much of that system.

The distribution of cattle dung is more or less random. However, O'Connor (1981) found that the annual return of dung at 3 cows ha⁻¹ would cover only 5.5% of the grazed area. This would leave appreciable areas of the paddock without phosphate from that source for several years.
Sheep dung tends to be clumped on small areas. This is related to a behavioural characteristic of sheep in which they tend to collect together at night. Gillingham and During (1973) found a net gain of 28.6 kg P ha\(^{-1}\) on a sheep camp occupying 6.4% of a block and an average net loss of 5 kg P ha\(^{-1}\) on the other areas. Gillingham (1980) found more than 88% of the dung on campsites in two paddocks of north and south aspects, these sites occupying 20.1% and 12.2% of the total pasture respectively.

Areas grazed heavily can be depleted of phosphorus if fertiliser is not applied (Hilder, 1966). Sheep tend to camp and excrete at high points, so there is a transference of phosphorus in dung to higher areas as shown in Figure 1. However, greater movement of phosphorus in runoff means complete depletion would not occur on steep slopes.

**FIGURE 1**: Mean number of faeces > 2 cm diameter per m\(^2\) at 3 m intervals down the Woolshed Paddock, Taita, for Enclosure 1 (18 Sept 1975) and Enclosure 2 (20 Oct 1975). Faeces were counted after grazing; grass lengths were measured before grazing.

(McColl and Gibson, 1979)
Overall estimates of phosphorus loss through animal transfer are not available.

2.2 Management of transfer loss
Reduction of phosphorus loss caused by stock transfer through direct stock management (shepherding) is not presently practised in New Zealand. Current management practices such as fencing, rotational and controlled grazing may help.

Gillingham and During (1973) suggest it is possible to avoid topdressing 10% of a block (i.e. stock camps and ridges) without affecting pasture yields in high country development. However, the economic viability of this practice has not been demonstrated (Saunders et al., 1981).

In the high country, fencing steep slopes from gentle slopes would theoretically reduce transfer losses, as sheep would not be able to move to and camp on the easier slopes. In practice, the complexity of land topography limits this.

Planting trees in pasture is a potential source of phosphorus conservation. Recent experiments by M. Belton and K.F. O'Connor (in prep.) show that Olsen P levels (plant available P) in soils of different types are three times higher under exotic forest than under unimproved or improved pasture. By spacing the trees, sheep would be kept dispersed when they seek shade or shelter and slope stability would be enhanced.

Systems of management may affect the distribution of dung. While neither Gillingham (1982) nor Thorrold et al. (1985) could find discernible differences between continuous and rotational grazing on dung distribution, stocking rates may influence dung distribution. Thorrold et al. (1985) have found that a more even distribution of dung was obtained on slopes by high stocking rates. Daytime dung frequency was found to be more closely related to grazing distribution than to resting or total animal distribution. Correlations between soil Olsen P levels and dung frequency were low even when night camp areas were included, but Olsen P levels were consistently higher in paddocks with higher stocking rates. It is suggested (ibid) that at high stocking rates, pasture consumption is high and a more even distribution of phosphorus
is returned to the soil as dung, perhaps in more quickly released forms. At low stocking rates, pasture consumption is low and much of the phosphorus is retained in the herbage or in the litter from which it is released more slowly.

There are no quantitative studies on the relative turnover rates of dung and litter in New Zealand pastures. Microorganisms, earthworms, temperature and moisture are some of the factors involved in this process. Addition of earthworms is an effective and increasingly practiced method of increasing litter and dung turnover rates (Stockdill and Cossens, 1984), especially in the earthworm deficient yellow brown earths of Otago and Southland.

The economic viability of many indirect methods of stock management to reduce transfer loss of phosphorus are not known. Increased use of some methods, such as silvipastoralism and selective topdressing, appear warranted for the other benefits that accrue.

2.3 Water runoff and soil erosion
Phosphorus is present in soils in various forms which vary in solubility, and consequently in susceptibility to movement by water. Phosphorus can be lost from soil by dissolution when contact is made with water or by erosion of soil particles containing phosphorus. Erosion may occur by wind or by water. Lost phosphorus may be transported to waterways and aquatic biological systems in runoff water and attached to soil.

Phosphorus losses through soil erosion by wind and water are variable in New Zealand and are related to the land form, soil type, intensity of land use and climate. In the high country, losses through soil erosion may be high due to slope instability and heavy rainfall. In Central Otago and the Canterbury plains wind erosion causes significant phosphorus losses. The few rates of both wind and water soil erosion that have been measured point to very high soil losses by overseas standards on many New Zealand farms (Painter, 1978). Phosphorus losses through wind erosion have not been quantified but, as with runoff, may be high on cultivated or recently fertilized land.
On well-managed pastoral land phosphorus losses in runoff are usually small. Because of the reactivity of phosphorus in soils these amounts are generally regarded as insignificant from an agricultural perspective. But as phosphorus is often a limiting nutrient for aquatic biological systems, small additions of phosphorus may have a considerable effect on the biological productivity of rivers and lakes.

Runoff may be categorised as surface, subsurface or groundwater as defined by Langbein and Iseri (1960 in Ryden et al, 1973). These different types of runoff transport different forms of phosphorus. Surface runoff transports particulate and dissolved phosphorus, subsurface runoff transports dissolved and some colloidal phosphorus, and groundwater transports dissolved phosphorus (Ryden and Syers, 1973).

There have been some differences of opinion in the New Zealand literature regarding the quantitative importance of different runoff types for the transport of phosphorus. It is widely recognised that phosphorus is strongly held by most soils, and that losses in subsurface and groundwater runoff are insignificant in comparison with losses in surface runoff (Baker et al., 1975). But some workers have suggested that fluctuations in available phosphorus in subsurface runoff may often be similar and in some cases higher than those in surface flows (Ryden et al., 1973; Syers, 1974). While it can be argued that the soils tested by these authors are prone to leaching, it is still apparent that there is uncertainty regarding the importance of different runoff types to water enrichment.

Table 1 presents various data on the amount of phosphorus (loading) in different forms of runoff from pasture systems. The largest amounts of all forms of phosphorus appear to be carried in surface runoff. Particulate phosphorus (PP) incorporated in soil particles comprises the major portion of total phosphorus (TP) carried. Thus Burwell et al., (1975) found 96% of TP was transported in the form of PP over a variety of soil cover treatments. Owing to the low energy of surface runoff there tends to be preferential transportation of small sized particles (clay and silt sized colloids). Small soil particles tend
to contain higher amounts of phosphorus than large particles. Thus eroded material has higher concentrations of phosphorus than the soil from which it is derived (Stoltenberg and White, 1953).

TABLE 1: Phosphorus loadings in runoff

<table>
<thead>
<tr>
<th>Runoff Component</th>
<th>Form of P*</th>
<th>P loading kg ha(^{-1}) yr(^{-1})</th>
<th>P Fertiliser applied</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater</td>
<td>TP</td>
<td>0.1</td>
<td>+</td>
<td>Minshall et al. (1969)</td>
</tr>
<tr>
<td>Subsurface</td>
<td>TDP</td>
<td>0.01</td>
<td>-</td>
<td>Bolton et al. (1970)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.12</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Surface and subsurface</td>
<td>TP</td>
<td>0.7$</td>
<td>+</td>
<td>Witzel et al. (1969)</td>
</tr>
<tr>
<td>Surface</td>
<td>Soluble P</td>
<td>0.22</td>
<td>+</td>
<td>Schuman et al. (1973)</td>
</tr>
<tr>
<td></td>
<td>TP</td>
<td>0.28</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>Available P</td>
<td>0.2</td>
<td>+</td>
<td>Stoltenberg &amp; White (1953)</td>
</tr>
<tr>
<td>Accelerated subsurface</td>
<td>DIP</td>
<td>0.07 - 0.44</td>
<td>+</td>
<td>Sharpley and Syers (1979c)</td>
</tr>
<tr>
<td></td>
<td>TDP</td>
<td>0.10 - 0.52</td>
<td>+</td>
<td>Syers (1979c)</td>
</tr>
<tr>
<td></td>
<td>TP</td>
<td>0.18 - 0.89</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>DIP</td>
<td>0.28 - 0.50</td>
<td>-</td>
<td>Sharpley &amp; Syers (1979c)</td>
</tr>
<tr>
<td></td>
<td>TDP</td>
<td>0.31 - 0.61</td>
<td>-</td>
<td>(1979c)</td>
</tr>
<tr>
<td></td>
<td>TP</td>
<td>0.85 - 1.28</td>
<td>-</td>
<td>1.66 - 2.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.67 - 5.63</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>TP</td>
<td>0.7 - 1.0</td>
<td>+</td>
<td>Lambert et al. (1986)</td>
</tr>
</tbody>
</table>

*TP = Total Phosphorus; DIP = Dissolved Inorganic Phosphorus; TDP = Total Dissolved Phosphorus

$Based on extrapolation assuming direct relationship between runoff and nutrient loss.

As additions of phosphorus to waterways via surface runoff generally occur in large events, phosphorus concentrations in receiving waters
may be greatly increased over the short period of time. However, the immediate effects on the receiving streams may be minimal as amounts of phosphorus available may be greater than that which can be used in primary production (McColl et al., 1977). Groundwater and subsurface runoff provide a more constant supply of phosphorus to waterways. The effects of phosphorus from these sources on water quality may be greater than their smaller phosphorus loading suggests when compared to the effects of phosphorus from surface runoff.

The effects of inputs of phosphorus on receiving waters may be limited by the absorptive capacities of the sediments. Much of that arriving in runoff may quickly react or become absorbed. Conversely a very large proportion of the phosphorus concentration of waterways derives from stream-bank erosion and the release of inorganic phosphorus (IP) from suspended and in situ particulate material (Sharpley and Syers, 1979c). Sharpley and Syers (ibid.) present data which indicate that the major proportion of PP (83%) and TP (71%) transported annually in stream flow is derived from stream-bank and stream-bed material. The contribution of dissolved inorganic phosphorus (DIP) and total dissolved phosphorus (TDP) from these sources were 27% and 42% respectively. Stream sediments appear to function collectively as a slow-release pool of phosphorus. Phosphorus which is rapidly absorbed when it enters the stream is made available over time. Thus the immediate effects of additions of phosphorus to streams are reduced, but the effects extend over longer periods of time.

Absorption–desorption processes mean phosphorus loadings can be quite different at different locations in a waterway or catchment. Measurements of high phosphorus losses from small plots may not be evidence for proportionally large losses from whole catchments. For example, McColl (1978b) measured concentrations of reactive phosphorus in a stream as high as 13.4 g m$^{-3}$ after the application of fertiliser; losses of reactive phosphorus from the subcatchment were up to 1 kg ha$^{-1}$ in a single storm; however, losses of reactive phosphorus from the whole basin averaged 0.004 kg ha$^{-1}$. 
Effects of fertiliser on loading

Different types of phosphorus fertiliser probably produce different effects in terms of additions of phosphorus to waterways. Sharpley et al., (1978) conducted experiments with dicalcium phosphate (DCP) as a less soluble alternative to monocalcium phosphate (MCP, as superphosphate). Both were applied at levels of 50 kg P ha\(^{-1}\). Although in the short term greater amounts of phosphorus were transported in surface runoff from MCP applications, the annual TP loss from areas with DCP applied was 7.09 kg ha\(^{-1}\) vs. 5.63 kg ha\(^{-1}\) from MCP, equivalent to 11.5% and 8.8% of fertilizer phosphorus respectively. To our knowledge, other fertilisers have not been examined for their runoff effects.

Applications of fertiliser clearly increase the loss of phosphorus from agricultural land. But some of the dramatic increases in phosphorus concentrations are measured immediately after fertiliser applications and are the result of fertiliser falling directly into streams. The physical and biological effects of these additions depend on sorption reactions within those streams and dilution within the whole catchment.

In experiments by Sharpley and Syers (1979c) 50 kg P ha\(^{-1}\) yr\(^{-1}\) was applied to one of duplicate plots in June of three consecutive years and phosphorus losses were measured over the whole study period. Comparison of phosphorus losses in surface runoff from undrained, fertilized and unfertilized plots indicate that between 2.9 and 4.8% TDP and 5.7 and 8.8% TP was lost annually. These losses of fertilizer phosphorus were greater than observed in overseas studies (Table 2) although shorter time periods were measured in the latter. Large losses of phosphorus (6%) were also recorded in runoff from fertilized pakihi soils on the West Coast of the South Island (Lee et al., 1979). McColl (1978b) recorded fertilizer phosphorus losses from 0.02 to 1.9% (Table 2). It is suggested (ibid.) that this range in losses and the low values may be due to chemical adsorption during downstream transport and hydrological differences in the stream channel regime due to riparian vegetation. A conservative estimate of 1-2% of applied fertiliser phosphorus lost in runoff (Table 2) would represent a total of approximately 1600-3200 tonnes P y\(^{-1}\) (assuming 1-2% of 2 million tonnes superphosphate y\(^{-1}\) with 8% P).
Although the percentage of fertiliser lost in runoff (Table 2) is usually insignificant to the agricultural system (McColl, 1978b), the change in phosphorus concentrations in receiving waters may be considerable. For example, the Waingahe stream which flows into Lake Rotorua, normally has an orthophosphate concentration of around 9 mg m⁻³. Topdressing of adjacent land caused a four-week pulse of orthophosphate which peaked at 890 mg m⁻³ (Fish, 1969), one hundred times the natural level. Similar trends in change in orthophosphate concentrations were recorded by Mitchell (1971), Sharpley and Syers (1979b, 1979c) and Turner et al., (1979).

Effects of animals on loading

Animals can be responsible for large additions of phosphorus to runoff waters. They exert three major effects on the soil-grass system (Cooke, 1981): by eating the grass short the soil surface is more susceptible to erosion; closely grazed grass cannot sieve particulate matter in
the manner that long grass can; and animal trampling lowers the infiltration capacity of the soil and increases the likelihood of surface runoff. In addition, grazing animals are more directly responsible for additions of phosphorus through dung. Data relating to the increased concentration of phosphorus in runoff attributable to grazing are presented by Lambert et al., (1985) and by McColl and Gibson (1979), Sharpley and Syers (1976a, 1979a) and Turner et al., (1979).

**Sheep**

Scott (1985) has shown that the amount of P returned as sheep dung (for an 18 stock unit ha\(^{-1}\) grazing system) was about 26 kg ha\(^{-1}\) yr\(^{-1}\) or equivalent to 0.33 t of superphosphate. Transfer of some of this dung to waterways is a potential source of phosphorus loading. McColl (1978a) estimated that dung provided a greater amount of total P to Lake Tutira than any other source (Table 3).

**TABLE 3: Estimated phosphorus loading on Lake Tutira (catchment sources)**

<table>
<thead>
<tr>
<th>Input</th>
<th>Phosphorus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertiliser runoff (assuming 1% loss)</td>
<td>700 kg y(^{-1})</td>
</tr>
<tr>
<td>Dung/urine runoff</td>
<td>300-1600 kg y(^{-1})</td>
</tr>
<tr>
<td>Subsurface runoff</td>
<td>300 kg y(^{-1})</td>
</tr>
<tr>
<td>Soil erosion</td>
<td>1000 kg y(^{-1})</td>
</tr>
<tr>
<td>Other sources</td>
<td>100 kg y(^{-1})</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>2400-3700 kg y(^{-1})</strong> (14-21 kg ha(^{-1}) y(^{-1}))</td>
</tr>
</tbody>
</table>

Source: after McColl (1978a)

**Cattle**

In contrast to sheep who tend to remain on the margins of waterways and wetlands, cattle are often observed wading in bogs, ponds and
streams. In dry seasons cattle are often grazed on swamplands. This may result in stream channel widening and a change in water column structure (Skovlin, 1984) and modification of the land drainage system by interrupting stream flow (Hughes et al., 1971). The cumulative impact on the catchment of fluctuating stream levels may be considerable, particularly in downstream locations. Cattle access to these areas should be strictly controlled to maintain drainage. The advantages of an intact riparian zone in reducing nutrient losses (see p.16) and drain clearance costs need to be made clearer. Controlled grazing by livestock need not affect the ability of the riparian zone to filter nutrients (Skovlin, 1984). However, the physical conditions of this zone must be understood and matched to the grazing regime.

The grazing of cattle can have a large effect on phosphorus levels in stream flows. Sharpley and Syers (1976a) found the loss of total phosphorus (principally DIP and PP) in surface runoff due to animals alone, in the weeks following a 24 hour period of grazing by dairy cattle (25 ha⁻¹) to be 0.77 kg P ha⁻¹. (This is 27% of that lost as a result of fertilizer addition alone.) With two or three grazing events during the period when runoff occurs in the study area (June to September) a maximum of 5.1 kg P ha⁻¹ could have been lost in surface flow as a result of both cattle grazing and fertilizer addition (10% of that added). In a later study, Sharpley and Syers (1979b) found that ten hours of grazing at a pressure of 25 cattle ha⁻¹ resulted in a 100-fold increase in both PP and sediment in a nearby stream. The effect was short-lived, however, and concentrations decreased to the pre-grazing levels within two days. The observed increases could be attributed to the movement of cattle in the stream channel stirring up bottom sediments and depositing dung in the stream. Lambort et al., (1985) report runoff losses of 1.5 kg P ha⁻¹ y⁻¹ from catchments with rotationally grazed cattle as opposed to losses of 0.7 kg P ha⁻¹ y⁻¹ from sheep grazed catchments.

Earthworms

In addition to the effects of grazing animals, earthworms can exert some influence on phosphorus losses in runoff. Surface casts of earthworms contain a higher proportion of fine particles than underlying
soil and appreciably greater concentrations of inorganic and organic
P. Casts have been found to be more readily transportable in surface
runoff than soil (Sharpley and Syers, 1976b). These authors estimated
for one study area that approximately 14 kg ha\(^{-1}\) of inorganic P and
11 kg ha\(^{-1}\) of organic P were accumulated in casts during one year.
They also found that casts released considerable quantities of inorganic
and organic P to solution.

Effects of land use on loading

Different land uses produce different levels of runoff. Ryden et al. (1973)
present data relating to runoff from land under different
crops; highest nutrient losses occurred from vegetables, corn, soybeans
and wheat. Losses of phosphorus from intact forest watersheds are
generally much smaller than from agricultural land (Berg, 1980; Cooke,
1979, 1981; McColl et al., 1977; Ryden, et al., 1973; Syers and Ryden,
1973). Cooke (1981) suggests that typical exports of phosphorus from
forest catchments are approximately one tenth of those from pasture catch­
ments. Ryden et al., (1973) found runoff from unfertilised forest
land contained concentrations of P lower than that of incident rainfall.
Therefore forests conserve phosphorus. Surface runoff from forests
is also low owing to the protection provided by both canopy and forest
floor vegetation, and the high infiltration capacity usually found
at the ground surface.

Owing to the major contribution to runoff made by phosphorus carried
by eroded sediments, together with the value of vegetation in reducing
runoff and sediment movement, losses from bare ground may be consider­
able under any circumstances. Several workers cited by McColl and
Syers (1981) found significant correlations between percent bare ground
and quantities of surface runoff.

Phosphorus in urban runoff originates from sewage, stormwater, industrial
effluents and other waste discharges. Total discharges of phosphorus
in sewage effluent from urban areas in New Zealand have been estimated
at approximately 9000 tonnes y\(^{-1}\) (Syers, 1974). Polyphosphates, which
are very soluble and biologically active ingredients of many detergents
(especially in the dairy industry), are significant sources of phosphorus
to waterways (OECD, 1981). Since most urban areas in New Zealand
are coastal, total discharges of phosphates to freshwater systems are probably smaller than those to the sea. McColl (1982) estimated that 1500 tonnes y\(^{-1}\) phosphorus from sewage is discharged to freshwaters.

Preliminary estimates of phosphorus contributions to freshwater systems from various sources are reported in Table 4. Point source discharges are apparently only slightly greater than diffuse sources: 18 and 15 tonnes of phosphorus per day respectively. However, fertiliser phosphorus ranks along with the dairy industry as the highest source of phosphorus input. Diffuse source dung is next in relative importance.

**TABLE 4: Estimates of total phosphorus entering New Zealand freshwaters**

<table>
<thead>
<tr>
<th>Type of Discharge</th>
<th>Amount of P (tonnes day(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>POINT SOURCES</strong></td>
<td></td>
</tr>
<tr>
<td>Dairy industry</td>
<td>9</td>
</tr>
<tr>
<td>Meat industry</td>
<td>0.3</td>
</tr>
<tr>
<td>Human sewage</td>
<td>4</td>
</tr>
<tr>
<td>Cowsheds</td>
<td>1</td>
</tr>
<tr>
<td>Piggeries</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>18</td>
</tr>
<tr>
<td><strong>DIFFUSE SOURCES</strong></td>
<td></td>
</tr>
<tr>
<td>Dung</td>
<td>6</td>
</tr>
<tr>
<td>Fertiliser</td>
<td>9</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>15</td>
</tr>
</tbody>
</table>


Point source discharges tend to be localized in certain areas of the country, particularly in the North Island and near urban centres. Diffuse sources of phosphorus are more widespread, although they too are higher in regions of intensive land use. North Island soils receive two thirds of the applied fertiliser in New Zealand. In 1981-82 approximately 2,000,000 tonnes of phosphate fertiliser was produced.
1,347,000 tonnes (68%) was used in the North Island and 624,000 tonnes (32%) was used in the South Island (New Zealand Meat and Wool Board, 1985). Table 5 shows the breakdown of phosphatic fertiliser into upland and lowland regions during 1981-82.

**TABLE 5: Distribution of phosphatic fertiliser use in New Zealand, 1981-82**

<table>
<thead>
<tr>
<th>Location</th>
<th>Upland</th>
<th>Lowland</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Island</td>
<td>457,000</td>
<td>890,000</td>
<td>23.2</td>
</tr>
<tr>
<td>South Island</td>
<td>102,000</td>
<td>522,000</td>
<td>5.2</td>
</tr>
</tbody>
</table>


The consequence of this discrepancy between the islands is clearly seen in lake trophic levels in the North and South Islands (Figures 3a & b, p 25 & 26).

2.4 Management of losses caused by runoff and erosion

Farm management practices leading to improved water quality, by reducing fertiliser losses in runoff and erosion, can also reduce fertiliser requirements without appreciable loss in production or profit. Such practices include:

- well-engineered roads and tracks, including use of vegetated buffer strips on downhill slopes;
- the use of well-constructed shelter belts to reduce wind erosion transport of soil to water bodies;
- improvement in the application of fertiliser - applying the correct amount at the right time to the land types capable of generating the highest relative return to the farmer;
- reducing stocking rates in areas prone to significant runoff problems;
- avoiding direct application of fertiliser to stream channels, seepage zones, land adjacent to lakes and streams, stock camps and well-defined ridge tops;
- maintaining longer grass at the time of fertiliser application;
- practising conservation tillage, especially overdrilling in hill and high country development;
- utilising trees more fully, e.g. planting fast-growing thin-crowned species such as poplars in gullies and on steep hillsides to control erosion or use as cattle fodder, growing a tree crop in conjunction with pastoralism (silvipastoralism);
- improving overall grazing management, e.g. fencing or correct stock rotation; and
- improved drainage of land e.g. mole drains (Sharpley and Syers, 1976).

The relative and absolute value of each of these practices in specific situations is at present not known. More research is needed on these to enable the best choice of management options to be applied in a given situation.

2.5 Riparian zones and wetlands

Riparian zone management offers the last chance to filter out nutrients and sediment before they enter waterways (Pittmans (unpublished), 1979; McColl and Hughes, 1981; Williams and Brickell, 1983). Wetlands, and areas away from waterways but prone to surface runoff because of the poor soil infiltration capacity, may also be managed similarly (Williams and Brickell, 1983; McColl, 1983).

As water passes through the riparian zone suspended matter is filtered by the soil (McColl and Syers, 1981) or, in wetlands, the particles settle out, trapping absorbed and organically bound phosphorus in the sediment (Klopatek, 1978). Dissolved inorganic phosphorus (DIP) remaining in the water, in solution in the soil or sediment (interstitial water), or released from the sediments if conditions become anaerobic (Richardson et al., 1978) is taken up by micro-organisms and plants. For rooting plants the depth of the rooting zone and thus the species composition influences the effectiveness of interstitial
phosphorus utilization (Williams and Brickell, 1983). Species composition is also important for year-round uptake of phosphorus. Few overseas studies have looked at these two aspects (Von Oertzen, 1981), and no studies have been undertaken in New Zealand.

The efficiency of the riparian zone as a phosphorus trap is affected by the hydrological regime which may vary from year to year (Sloey et al., 1978; van de Valk et al., 1978), the biological productivity of the system and the concentration of phosphorus (Klopatek, 1978). Under conditions of high phosphorus loading the DIP uptake capacity of plants soon becomes saturated (Richardson, 1985), and although particulate phosphorus is still trapped the efficiency of the zone is reduced. Further, riparian vegetation usually has only limited possibilities for phosphorus storage unless periodic harvesting is undertaken (Richardson, 1985; Young et al., 1980). Richardson (1985) found that 35-75% of the phosphorus taken up by plants was released during winter dieback. Although this may be partly retained in the soil or sediments, net retention is dictated by precipitation events during the time of maximum senescence and nutrient release in late autumn and winter (Prentki et al., 1978).

Adequate water quality management should be able to be achieved by responsible land management. Management practices include:

- limited or lax grazing of riparian land and exclusion of stock when runoff risks are high (Yates, 1971; McColl, 1983);
- using riparian land only for meadow hay production or for growing specialised trees, especially fodder trees which are periodically harvested;
- leaving a grass border between tilled land and water (Burwell et al., 1975);
- protecting and encouraging vegetation of stream and lake sides, especially thick ground cover e.g. leaving a zone of native vegetation; and
- prevention of stock entry to streams and wetlands (permanent stock exclusion fencing would be essential only in sensitive areas).
In all cases where harvesting takes place by grazing or mechanical means, care must be taken to maintain soil permeability by avoiding compactation and pugging.

Research to test the operation of the natural water treatment process ascribed to the riparian zone is only just beginning in New Zealand (Williams and Brickell, 1983). Nevertheless, the limited evidence available indicates that riparian zones justify more care than most other parts of a catchment (McColl, 1978b).
3. IMPLICATIONS OF PHOSPHORUS IN WATER RESOURCES

Phosphorus is an essential element for plant growth. In water it is required by phytoplankton, benthic algae and rooted plants which are basic living components of aquatic ecosystems. When a large amount of phosphorus is present in the system, excessive plant growth may occur. This is acceptable in some countries and in some circumstances. For example, in China green shallow lakes are an asset for fish farming. In developed countries, eutrophic lakes (meaning those with 'good food') are often considered unacceptable because their high biological production conflicts with scenic and recreational values. Large sums of money have often been spent cleaning up eutrophic lakes.

The purpose of this section is to review the implications of phosphorus in water, and to discuss the options for managing the use of phosphate fertiliser with respect to water quality objectives.

3.1 Sources of phosphorus loading

Phosphorus enters freshwater systems in many ways. Firstly, phosphorus may be carried into rivers and lakes by way of the following:
- water from springs, streams (including transported sediment), surface runoff and ground water movements;
- air, such as from rainfall, wind-blown soil, fertiliser, leaves and dung;
- direct contact with the soil along stream and river banks and areas of swamp or flooded land;
- plant and animal biomass through natural decay and direct deposition by animals;
- direct discharge from urban and agricultural sources; and
- release from sediment during periods of anoxia or by catastrophic events.

Secondly, phosphorus loading may be considered as a point source - diffuse source continuum. Point sources include, for example, discharges from dairy and meat industries and treated sewage effluent. Diffuse sources, on the other hand, include such sources as runoff from agricultural land. Between these classifications exist cases which may
fall into either category, such as stockyard runoff or tip leachates. A similar situation applies to dung movement. Point sources are much easier to quantify than diffuse sources.

Phosphorus loading may also be viewed from its temporal aspect. Sources of phosphorus loading may be continuous or periodic. Continuous sources of phosphorus typically come from such sources as springs, while urban discharge, stream inflow and surface runoff sources may come in pulses according to human decisions or climate. Catastrophic events such as freak storms, major floods and earthquakes are hard to predict and equally hard to measure. By contrast, continuous sources are more easily quantified.

3.2 Effects of phosphorus additions on primary productivity and sediments

Primary productivity changes
Any effect that phosphorus has on a water body will depend on the form it is in when it reaches the water. If it is present as dissolved inorganic phosphorus it is immediately available for plant growth. Phytoplankton and floating plants obtain their phosphorus requirements from the water column, while submerged rooted plants obtain theirs from the sediments and the water column (Bristow and Whitcombe, 1971; Denny, 1972). Phosphorus may be locked up in plant biomass both in streams (Vincent and Downes, 1980) and lakes (Mitchell, 1975) and released again during algal and macrophyte decay. It is released more slowly from macrophytes than from phytoplankton, but the annual decay of macrophytes results in the liberation of significant amounts of phosphorus. In Lake Rotorua, 7 tonnes of phosphorus are (potentially) released from macrophytes each year (Richmond, 1978).

Where phosphorus is limiting the effect of fertiliser phosphorus on a water body is to increase primary productivity. In lakes, this increase is usually reflected in high phytoplankton numbers (Golterman, 1973; Mitchell, 1975). However, in some lakes increased phosphorus in the water results in increased biomass of macrophytes (Mitchell, 1971; Haumann and Waite, 1978) or of filamentous algae (Howard-Williams, 1981). The reasons why either phytoplankton or macrophytes show a dominant response to phosphorus additions in a given situation are
unclear but appear to be related to the availability of light and the nutrient balance in the water (Mitchell, 1971; Spence, 1982).

Patterson and Brown (1979) suggest that increased phytoplankton productivity results in more suspended material in the water. This is filtered by the macrophyte beds and accumulates as sediment with high nutrient content (Brown and Dromgoole, 1977). The sediment then stimulates further weed growth. In this way eutrophication may accelerate the growth and spread of weed by enabling suitable substrates to be formed more quickly than under low nutrient conditions.

The problems caused by increasing productivity are of several types. Algal blooms cause loss of water clarity and unsightly scums may result. Concentrations of oxygen may drop in deeper waters during plankton blooms due to increased bacterial activity resulting from sedimentation of dying plant cells. Decreased oxygen levels may in turn affect fish such as trout living in the deeper lake waters. Blue-green algae periodically become the dominant algal type under high nutrient conditions. Some of these are nitrogen fixers which may produce substances toxic to mammals. The nuisance value of excess macrophytes in lakes and reservoirs is well known both for clogging drains, streams and water filters and for interfering with boating, swimming and fishing.

Sediments
The sediments in a water body are a sink for phosphorus. They may also be a source of phosphorus under some circumstances and are an active centre for phosphorus cycling. Knowledge of whether the sediments act as a source or sink for phosphorus is essential for predicting the effects of different phosphorus loadings and for planning lake restoration (Bostrom et al., 1982).

When phosphorus enters an oligotrophic lake the sediments provide a sink for a major portion of the inflow (up to 96%, Twinch and Breen, 1978), either by direct binding by the bottom sediments or by sedimentation of suspended material. In lakes with higher nutrient levels, phosphorus may be released from the sediments and transported to the water column. This internal loading of phosphorus into lake water may exceed deposition for certain periods of the year, often increasing
the primary productivity of the lake. A detailed discussion of the phosphorus interactions between the water and sediments is given by Syers et al., (1973) and Bostrom et al., (1982). Since dissolved inorganic phosphorus is required for primary productivity, the influence of other phosphorus compartments in both sediment and water on the dissolved inorganic phosphorus is important. Figure 2 illustrates the major phosphorus compartments and the interactions between them.

FIGURE 2: Interchange between water and sediment P compartments
($P_i =$ inorganic $P$; $P_o =$ organic $P$). (Syers et al., 1973)

Nutrient exchange with the overlying water may occur from up to 20 cm deep in the sediment. This is also the zone of greatest fungal and bacterial activity. The phosphorus concentrations near the sediment surface are very variable and likely to be influenced by many factors including shape of the lake basin, water movement, water depth and trophic state. This variability suggests care should be taken when comparing lakes (McCoil, 1977). The deeper sediments may reflect
more accurately the sediment characteristics of the lake (Fish and Andrew, 1980). Sediment cores from Lake Rotorua show total phosphorus decreases from about 1.5 mg g\(^{-1}\) dry sediment at the sediment surface to an approximately constant rate of about 0.8 mg g\(^{-1}\) 20 cm below the surface (Fish and Andrew, 1980).

The interstitial water between the sediment particles contains less than 1% of the total phosphorus in the sediments but it is important because it is the phosphorus directly exchangeable with the lake water (Syers et al., 1973). The concentration of total dissolved phosphorus in the interstitial water is much higher (usually 5-20 times) than in the lake water (Bostrom et al., 1982). There is also a large difference in phosphorus concentration in interstitial water between oligo- and eutrophic lakes. Unlike the total phosphorus content of the lake sediments, the interstitial water concentration reflects the trophic state of a lake (Bostrom et al., 1982).

Once phosphorus has entered the sediments of a lake system, it becomes a major problem from the point of view of eutrophication control. Sediments release inorganic phosphorus to the overlying water during periods of anoxia. The more eutrophic the lake becomes, the more frequent and severe will be the anoxic conditions of the lake bottom, and consequently the more phosphorus will be liberated. Phosphate release from temporarily deoxygenated sediments of eutrophic Lake Rotorua during a period of summer stratification was estimated as 20-40 mg m\(^{-2}\) d\(^{-1}\). In contrast, the rate at which phosphorus returned to lake sediments during oxygenated conditions was measured at about 0.5 mg m\(^{-2}\) d\(^{-1}\) (White et al., 1978). More recent experiments (Vant, 1985) estimate that 35 tonnes of phosphorus were released from the sediments of this lake over the 1984-85 summer.

Once eutrophic, lakes will probably remain in that condition for some time even after all external sources of phosphorus are removed, because of phosphorus release from the sediments (Syers et al., 1973). Dredging the lake may reduce the problem, but equally, dredging may expose lower sediments which then become new sources of phosphorus.
Activities that stir up the sediments such as storms or harvesting of macrophytes may also promote phosphorus release. Reversal of eutrophication through control of phosphorus input is possible although a return to the oligotrophic condition would be slow and costly.

For waters that have become eutrophic, various treatment possibilities exist:
- mechanical removal of sediments from shallow lakes or bottom sealing;
- diversion of phosphorus rich waters entering lakes or reduction in input concentration;
- selective discharge of nutrient enriched bottom water;
- artificial circulation or aeration to maintain oxygenated bottom water;
- reduction of water retention time or flushing with water of low nutrient content;
- chemical treatment with Iron or Aluminium compounds to remove dissolved and particulate phosphorus and increase phosphorus retention by the sediments (Syers et al., 1973); and
- harvesting of aquatic weeds.

Most of these management techniques have been used in New Zealand. For example, dredging of sediments has been used in Tomahawk Lagoon (Mitchell, 1971). In Lake Tutira some inflow water has been diverted and the lake water has been artificially circulated by air from October to March to maintain oxygenated bottom water (Tierney, 1980).

3.3 The trophic status of New Zealand lakes

It is useful to classify lakes according to the amount of primary productivity. The productivity of a lake depends on the nutrient input, the size of the lake basin, the residence time of the water in the lake and phosphorus retention by the sediments. Oligotrophic lakes have low nutrient levels and relatively low primary productivity. Most lowland lakes in New Zealand are classified as eutrophic and most upland North Island lakes are also tending towards eutrophic status (Figure 3a & 3b). Upland South Island lakes so far have
FIGURE 3a: Trophic status of North Island lakes

Legend

○ Oligotrophic

● Mesotrophic

● Eutrophic
FIGURE 3b: Trophic status of South Island lakes
relatively low trophic status, with a few exceptions such as Lake Hayes, Lake Johnson and Lake Alexandrina (Figure 3b). Apart from a few urban catchments, the trophic state of New Zealand lakes reflects the intensity of agricultural development in the relevant catchments (White, 1982). In the South Island, further development of irrigation and concommitant increase in land use intensity in many areas is likely to promote greater movement of nutrients into water bodies. There is accumulating evidence to suggest that the trophic status of many upland South Island lakes is changing as greater development occurs in the high country (Stout 1981, Malthus 1985). In the Lake Mahinerangi catchment, 30% development over 16 years has resulted in nine times greater phytoplankton production along with increased total nitrogen and total phosphorus (Table 7) (Malthus, 1985).

TABLE 7: The relationship between catchment development and phytoplankton production in Lake Mahinerangi and inflow stream nutrient concentration

<table>
<thead>
<tr>
<th>% lake catchment development</th>
<th>Phytoplankton production mg C m⁻³ d⁻¹</th>
<th>% stream catchment development</th>
<th>Inflow stream Total N mg m⁻³</th>
<th>Inflow stream Total P mg m⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964-66 0</td>
<td>76</td>
<td>0</td>
<td>132</td>
<td>13</td>
</tr>
<tr>
<td>1968-70 3</td>
<td>210</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1976-78 30</td>
<td>630</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1980-82 100</td>
<td>451</td>
<td>86</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Phosphorus concentration in water is a commonly measured indicator of trophic status. However, other factors can also be used to distinguish one trophic state from another. These include water transparency, chlorophyll a, oxygen and total nitrogen (McColl, 1972, 1977; White, 1983). It is now generally agreed that no single quantitative parameter can be used to distinguish between trophic states. Table 8 shows the average total phosphorus concentration in lakes of different trophic
status in New Zealand. Data obtained from the OECD programme for eutrophication research is also reported (White, 1982). The large range for each category clearly illustrates that total phosphorus alone is not sufficient to categorise each lake.

Several nutrient loading models have been developed in the USA and Europe (as part of the OECD programme on eutrophication) to describe the relationships between nutrient load and trophic condition. Phosphorus loading curves have been used to estimate the specific phosphorus loading on a lake necessary to produce a particular trophic state (Vollenweider and Dillon, 1975). However, some New Zealand lakes do not fit well on these curves, such as Lake Taupo (White, 1982). This is because New Zealand lakes exhibit low levels of nitrogen, compared with lakes sampled in the OECD study, and may be nitrogen limited at times. Caution is therefore necessary in the use of OECD predictive equations (White, 1983).

### TABLE 8: Average total phosphorus concentration in lakes of different trophic status

<table>
<thead>
<tr>
<th>OLIGOTROPHIC</th>
<th>MESOTROPHIC</th>
<th>EUTROPHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg m⁻³</td>
<td></td>
</tr>
<tr>
<td>Taupo</td>
<td>5.5</td>
<td>13.7</td>
</tr>
<tr>
<td>Aratiatia</td>
<td>11.5</td>
<td>14.1</td>
</tr>
<tr>
<td>Tikitapu</td>
<td>6.4</td>
<td>21.1</td>
</tr>
<tr>
<td>Rotorua</td>
<td>11.0</td>
<td>23.8</td>
</tr>
<tr>
<td>Okataina</td>
<td>17.6</td>
<td></td>
</tr>
<tr>
<td>Waikaremoana</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Ahaura</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>Brunner</td>
<td>16.5</td>
<td></td>
</tr>
<tr>
<td>Haupiri</td>
<td>21.5</td>
<td></td>
</tr>
<tr>
<td>Hochstetter</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>Kangaroo</td>
<td>14.0</td>
<td></td>
</tr>
<tr>
<td>Kaniere</td>
<td>13.0</td>
<td></td>
</tr>
<tr>
<td>Lady</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td>Poerua</td>
<td>14.0</td>
<td></td>
</tr>
</tbody>
</table>

N.Z. lakes 11.7 mean 20.8 mean 115

4.2-21.5 range 13.7-31.3 range 15.9-501

OECD study 8.6 mean 25.1 mean 113

3.0-16.1 range 5.6-80.0 range 8.1-386

Source: after White (1982)
Another approach to assessing primary productivity assumes a direct relationship between phosphorus and chlorophyll concentration in the water. However, lakes with high levels of phosphorus do not fit this relationship (Stans, 1983). Studies by Vant and Pridmore (1981) suggest that ATP (adenosine triphosphate) concentration may be a more useful indicator of algal biomass. This is because when phytoplankton numbers are high, chlorophyll increases faster than ATP in order to compensate for increasing light limitation by self shading.

The phosphorus content of water is a function of inflow concentration, residence time and loss to sediments. Estimates of phosphorus transfer between Lake Taupo and the Waikato River suggest that 80-90% of phosphorus inputs to the lake are retained in the lake (White and Downes, 1977). Hoare (1982) has related the nutrient concentration in a lake to both the nutrient concentration of the inflow and the 'retention coefficient' of the lake. He has applied these concepts to lakes Rotorua, Tutira and Alexandrina (Hoare, 1980; 1982; 1983). His results indicate that mass balance phosphorus models can be very useful in predicting the results of changes in nutrient loading or water retention time. Potential sources of nutrients can be compared using simple calculations before decisions on the treatment of eutrophication problems are made (e.g. McColl, 1978a).

4. CONCLUSIONS AND POLICY IMPLICATIONS

The New Zealand agricultural industry is based to a considerable extent on a ryegrass-clover system which requires substantial inputs of phosphate to maintain productivity. Each year large quantities of phosphate are applied to agricultural land in the form of superphosphate and each year a proportion of this is lost via stock transfer, soil erosion and water runoff.

Available data suggest that on farmland in many parts of New Zealand losses through runoff and soil erosion can reach over 10% of the maintenance fertiliser phosphorus additions. The total value of phosphorus lost from agricultural land in runoff waters alone is conservatively estimated as being $3-$6 million per year, while loss of phosphorus
through erosion of the topsoil by wind is likely to be equally significant where farming practices expose dry silty and sandy soils such as on the Canterbury plains and in Central Otago. Furthermore, although overall estimates of phosphorus losses through animal transfer are not known the few studies suggest that in hill country at least an additional 5% per year can be lost in this way. Losses of this kind are agriculturally very significant, costing in the order of 15-25% of annual fertiliser expenditure. However, they may, with appropriate management techniques, be partly avoidable.

Even when loss of phosphorus from agricultural land is less than 5% of maintenance phosphorus additions, a level insignificant to farmers, the effects of phosphorus on water quality of the receiving rivers and lakes may be considerable. Water is the common property of the people of New Zealand and hence adverse effects on water quality result in losses that are shared by the community as a whole.

4.1 Future risks

Increased use of fertilizer in the future also implies increased losses to the farmer via stock transfer, wind erosion and water runoff if improved fertilizer management is not practised. If a 'do-nothing' policy is adopted, the water quality of many New Zealand waterways will continue to decrease from increased phosphorus loading. Currently unaffected water bodies could also change in the future. For lakes in agriculturally developed catchments, the expense and effort of lowering trophic levels may be too great for society to bear. However, lakes and their catchments can be managed to maintain the present water quality so that they may continue to be used for recreation and/or as a wildlife habitat. Prevention is almost always less costly than rehabilitation. It is therefore important to identify the potential lake management problems in terms of the aspirations of people and the technical and economic feasibility of fulfilling these aspirations. The future risks and management needs are poorly understood in New Zealand at the present time.
4.2 Management needs and approaches
If the surface runoff and wind erosion losses of fertiliser phosphate could be controlled, using one or more of the methods put forward in this paper, a significant reduction in the social costs associated with water quality degradation could be achieved. For animal transfer losses however, alternative grazing management approaches at present are limited to significantly reducing overall fertiliser phosphorus waste (inefficient use). Successful and economic fertiliser phosphorus conservation methods would appear to involve increased diversification rather than extremely intensive management currently precluded by very high costs. Management options based on economic criteria from the viewpoint of the individual farmer include "targeting" fertiliser applications to those areas of hill country where stock transfer of phosphorus is relatively less severe; silvipastoralism, which has the added advantages, if well planned, of reducing runoff and erosion and enhancing soil nutrient levels; and diversification e.g. running goats or deer with, or rather than, sheep. However, while the techniques for control of phosphorus losses listed in the second section of this paper are all viable options few, if any, have been tested and evaluated technically or economically in New Zealand and their relative usefulness is unknown. This applies equally to the catchment development phase (prevention) and the developed catchment phase (rehabilitation).

The economic benefit to the individual farmer of controlling losses may not by themselves be sufficient to encourage farm phosphorus conservation practices. But farm management may be the most efficient way to avoid the social costs associated with reduced water quality. Clearly, then, there is the important question of how to encourage individuals to behave in such a way that contributes to the larger interests of society. To achieve this end, the main task will be to demonstrate to the farmer that wider land and water management objectives are important and that various management options are available to achieve them.
The environmental costs of farming are not generally appreciated, particularly in the case of riparian wetlands. But it is certain that a positive, constructive response would eventuate from the farming community, given encouragement and advice from local authorities, water boards, and agricultural advisors. Regional and local government and the Ministry of Agriculture and Fisheries have especially important responsibilities in this respect.

Williams and Brickell, 1983.

Studies of the options from the viewpoints of efficient nutrient control and agricultural management need to be undertaken by research organisations so that authorities will have a basis on which to base their recommendations to farmers.
ACKNOWLEDGEMENTS

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