

Phosphorus in the Landscape: Diffuse Sources to Surface Waters

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by the National Eutrophication Management Program²
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Contents

<i>Executive Summary</i>	1
<i>Section One: Introduction</i>	5
<i>Section Two: Defining the context of diffuse phosphorus transport</i>	6
<i>Section Three: Dominant processes of phosphorus mobilisation</i>	8
Transport of dissolved phosphorus	9
Transport of particulate phosphorus by surface erosion	10
Transport of particulate phosphorus by gully and bank erosion	13
Run-off from saturation zones	14
<i>Section Four: Examples of phosphorus exports from catchments</i>	15
Heterogeneous soils, low relief catchments in Western Australia	15
Zones of heavy reactive soils in Eastern Australia	17
Irrigated agriculture in the Goulburn–Broken Catchment	19
Gross phosphorus exports from tropical river basins	21
<i>Section Five: Interpreting phosphorus exports</i>	24
<i>Section Six: Conclusion</i>	26
<i>References</i>	27
<i>Invited specialists to the workshop</i>	28

Figures and Tables

Figure 1	
Processes involved in the transport of N and P from agricultural land	8
Table 1	
A list of some common factors that influence phosphorus loss and concentration in streams	12
Table 2	
Median bicarbonate extractable P in relation to soil reactive Fe content and time at which fertiliser additions began	16
Table 3	
Estimated annual sediment export from North Queensland	20
Table 4	
Area, annual flow, sediment and phosphorus export in North Queensland catchments	22
Table 5	
Area, Annual flow, Sediment and Phosphorus Export in North Queensland Catchments	22

Executive Summary

The National Eutrophication Management Program (NEMP) and Environment Australia convened a workshop to develop a coherent overview of the sources and transport of diffuse phosphorus in Australian catchments based on the latest knowledge. The Land and Water Resources Research and Development Corporation (LWRRDC) and the Murray–Darling Basin Commission (MDBC) jointly fund NEMP. A select group of scientists attended the workshop and developed a coherent statement about phosphorus sources and transport in Australian catchments. The group did not extend this statement to include recommended management practices. This paper reports the findings from the workshop.

State governments have developed algal and nutrient management strategies in response to concerns about the frequency and severity of algal blooms, including cyanobacterial blooms, in Australian rivers and estuaries. There is an emphasis on phosphorus management, particularly in rural environments, now that nutrients are recognised as fundamental drivers of algal growth.

Best management practices (BMPs) were developed for these strategies on the basis of the limited scientific evidence that was available at the time. The absence of a significant body of Australian information meant that there was a reliance on overseas research findings to develop such BMPs. A number of research projects have been completed in recent years on the sources and transport of nutrients in Australian catchments that challenge the Northern Hemisphere model of nutrient behaviour and will have implications for future development of BMPs.

Principal conclusions

1. The studies presented in the workshop demonstrate that control of phosphorus entering surface waters must start with land management that minimises accelerated erosion and overland flow of water potentially rich in phosphorus. Heavily grazed lands, irrigation areas and intensive animal and horticultural industries are at risk, especially at the onset of rainy seasons and during periods of high rain intensity.
2. The transport of phosphorus from diffuse sources in landscapes can occur in both dissolved and particulate form. This can be due to different mobilisation and delivery mechanisms operating in different environments.

Phosphorus mobilisation and delivery

1. Diffuse sources of phosphorus are the dominant component in most Australian catchments. Episodic rainfall is responsible for the bulk of phosphorus loss from the landscape. The mechanisms vary with each catchment.
2. Particulate phosphorus is carried by overland flow, resulting from run-off and erosion. In high to medium rainfall environments most is carried as filterable reactive phosphorus of less than 0.45 microns. Although most of the coarser materials from high parts of the landscape are deposited before they reach a watercourse, the particles ultimately carried into drainage lines are phosphorus-enriched by processes of sorting and filtration.
3. In river systems studied in the Murray–Darling Basin river sediments that originate from gully erosion and stream-bank collapse of readily dispersible soils carry most of the diffuse-source phosphorus. It is very likely that most of the phosphorus on these sediments is ‘native’ phosphorus coming from subsoils.

Although the major episodes of gully formation occurred several decades ago, inputs of sediments and phosphorus from these sources continue at a high rate. Reduced input rates can best be achieved by targeting the gullies themselves and stabilising them by conservation works—particularly in small headwater catchments.

4. In larger dry-land catchments, fertiliser phosphorus is generally not an important component of phosphorus loss/export, although it may be locally significant.
5. Local soil, vegetation, terrain and climate conditions dictate whether surface erosion is the dominant source of phosphorus into a watercourse. To describe phosphorus exports from a specific landscape by surface erosion requires local studies. However, guidelines can be developed for management purposes to identify and minimise sources of phosphorus carried by overland flow.
6. Potential sources of diffuse phosphorus run-off occur wherever fertilisers are applied to soils that are already wet at the surface, or that may become wet by seasonally emerging groundwater. The magnitude of the loss will be greater if the application occurs on bare soils, or if it is next to a waterbody.
7. Dissolved phosphorus (from fertilisers and other sources) is readily mobilised and transported directly where the soil has both little ability to bind the phosphorus and a high leaching rate, as occurs in sandy regions of high rainfall around the continent. Phosphorus-laden water then travels via overland or shallow sub-surface flow to surface waterbodies quite quickly, unless other processes impede the movement. If the dissolved phosphorus moves via deep groundwater the time scales for its reappearance in surface water are generally large.
8. Dissolved phosphorus may also enter tributary waterbodies in headwater catchments via short-circuit pathways, such as macropores, but this is only likely to be important over distances of hundreds of metres. However, these sub-surface pathways may reduce the effectiveness of local management practices that do not take them into account.
9. Large amounts of dissolved phosphorus are also being produced from irrigated dairy pastures (and possibly from other irrigation enterprises also). There is little or no sub-surface movement because soils are generally high in clay and flat. Phosphorus-laden water is pumped or drained across the land surface to channels. The time scale of dissolved phosphorus movement is comparable with the time with which the water itself moves. Once within drainage channels and streambeds the dissolved phosphorus fraction may be partially re-adsorbed onto particulates.
10. Large quantities of dissolved phosphorus are found in surface waters next to areas where animal excreta or over-fertilised market gardens give rise to phosphorus in surface wastewater that flows directly into waterways. These situations are most likely to arise in catchments that contain mixtures of horticultural, dairying, hobby-farming and similar land uses. Where farm dams are abundant a significant fraction of this phosphorus will not enter streams but will be retarded or retained in the landscape.

Case studies of phosphorus exports

Confirmation for the workshop summary findings comes from detailed studies of particular environments.

1. Catchments in South-West Western Australia exhibit phosphorus run-off into estuaries by leaching through sandy soils, as saturated overland flow and from surface erosion. Sandy soils of low phosphorus retention are able to retain only small amounts of phosphorus. Other significant sources of diffuse phosphorus run-off in that area are associated with local waterlogging and the tendency for soils to become seasonally water repellent. The Mediterranean climate predisposes the soils to erosion after long dry summers when the ground has often become bare from grazing.
2. Intensive studies in a few catchments with dispersive duplex soils in the Murray–Darling Basin have demonstrated that most of the sediments carried by rivers draining terrain with these soils comes from eroded gullies. This sediment carried in the river is the main vehicle for transporting phosphorus. Phosphorus is most likely also derived from the same sub-soil sources as the sediments.
3. In the headwaters of the Namoi basin, where well-structured iron-rich soils occur, the use of rare-earth isotope methods have shown that fertiliser phosphorus in reservoir sediments is negligible when compared with phosphorus derived from natural sources. The same methods can be used to resolve issues of phosphorus sources in terrain with other soil types, particularly in dispersive duplex soils.
4. Well-structured iron-rich soils normally produce high quality water because the soils retain phosphorus. Even on such soils local wash-off of nutrient-rich soil into drainage lines can occur from compacted, steep or cultivated slopes in high rainfall areas. Buffer strips and farm dams, both of which act to slow run-off and trap sediments, can reduce the net delivery of phosphorus to streams significantly.
5. Poorly managed intensive animal industries and some high-input fertiliser systems are threatening the ecological health of adjacent rivers, as occurs in tributaries to East coast rivers. Phosphorus contamination from dairy pastures, animal waste ponds and fertiliser washoff can be high and will increase in the near future as more animal rearing units and irrigation drains are constructed—unless water and fertiliser application methods are changed. The key principles for reducing phosphorus exports are known and rely on improving farm water and fertiliser management, while establishing district soil infiltration and sorption limits.
6. High intensity storms on catchments in tropical regions cause discharge of sediment at rates orders of magnitude higher than in temperate regions. The interplay of drought, groundcover and cyclonic storms results in fewer but higher impact storms. Sheet and gully erosion are the major contributors of sediment inputs to streams and waterbodies during storms. Firm linkages between the sources of phosphorus and the sources of sediments have yet to be established.

There is a relative paucity of studies in the tropics and subtropics in general, where the risk of phosphorus related pollution may be much greater than hitherto appreciated. The studies reported at the workshop showed that many Australian catchments behave differently to those in the Northern Hemisphere. It is conventional wisdom in more densely settled parts of the world that point sources (particularly urban sewage effluent) are a major contributors of phosphorus to waterways and that fertiliser is a major component of diffuse source phosphorus. However, for much of the Australian continent the evidence indicates that phosphorus in waterways arises from natural soil sources. Surface and sub-surface erosion, much of which arises from land clearance and subsequent agricultural practices, liberate this ‘native’ phosphorus.

Where population densities and the intensity of agricultural enterprises reach the intensities found in Europe and parts of North America, we see evidence of anthropogenic phosphorus from sewage, fertiliser and animal wastes. This occurs in some coastal catchments (experiments in a small sub-catchment of the Hawkesbury–Nepean catchment were described at the workshop) and in limited areas of intensive irrigation for animal production (results from experiments in the dairying areas of the Goulburn Valley were also described). High rainfall sandy soils, such as are found on the coastal plains of WA, are also prone to fertiliser phosphorus losses. Phosphorus sourced from fertilisers, irrigation effluent and sewage are more bio-available than sediment bound P, and hence may attain higher local importance.

Australia's climate is characterised by highly episodic rainfall. Phosphorus is transported as particulate phosphorus overland and along creeks and rivers during these infrequent but intense events. Although there is only limited evidence from the North of Australia, it seems that this pattern of episodic movement of phosphorus also applies in tropical systems, even in rivers that flow all year round.

It is now clear that the management practices adopted for phosphorus control in the Northern Hemisphere will have only limited success in Australia. The next steps are to develop a national picture of which processes control the sources and transport of phosphorus in each part of Australia, and to bring together scientists, managers and community groups to decide on the best management practices for each region.

Introduction

Phosphorus is one of the critical factors leading to the development of algal blooms in surface waters. Massive, toxic, algal blooms in particular have a degenerative effect on aquatic ecosystems, causing widespread loss of species, long-term alteration in composition and abundance, and reduce the ability of such ecosystems to repair themselves and adjust to normal cycles of seasonal fluctuation in flow regime.

Phosphorus is derived from both point sources and diffuse areas in the landscape. Diffuse sources were the focus of the workshop, because they are much more difficult to identify, monitor and control than such sources as effluent from sewage plants, intensive animal units, and rural processing industries.

The National Eutrophication Management Program (NEMP) and Environment Australia co-sponsored a workshop for scientists currently active in investigating the sources and movement of phosphorus in the landscape. The aim was to resolve areas of uncertainty and to establish the processes now believed to control the sources and movement of phosphorus.

Environment Australia is responsible for protecting Australia's environments for the national good and to report on the state of the Australian environment. Reporting against a modified 'pressure-condition-response' framework allows the effects of human interventions on ecosystem function to be evaluated. NEMP has the task of elucidating the causes and effects of algal blooms and investigating how best to minimise them, for the needs of managers who focus on the public health aspect of algal blooms, as well as for the purpose of environmental health. Both organisations have the same need to understand the types, range and variation in the processes involved in phosphorus movements through the landscape and into rivers, reservoirs, wetlands and estuaries across Australia, so that we may manage our environments safely for the long term.

Other workshops and industry gatherings are planned to take this information further through the environmental cycle and management options available to land and water managers. This workshop's objective was to provide the most informed current view of scientists on the sources of diffuse phosphorus into different water systems.

Defining the context of diffuse phosphorus transport

By the time phosphorus becomes assimilated into algal cells in a waterbody, it will have experienced a history of mobilisation and transport from its point of origin in the landscape. Mobilisation is either by physical displacement of particles containing phosphorus into flowing water, or by dissolution of soluble compounds of phosphorus into water. A flux of phosphorus moves towards a waterbody as long as water moves through the landscape. However, the flux varies enormously across the terrain, and is not continuous either in space or in time, and depends on a large number of factors.

Both the water and the transported phosphorus pass through phases that include immobilisation and re-release from dry and wet storage sites, chemical and biological changes through interactions with soil minerals, microorganisms and plants. These affect the transit time of mobilised phosphorus and the quantity and rate of phosphorus that enters a waterbody. Once in the waterbody, further physical and biochemical changes occur, making it difficult to identify the original source of phosphorus, the processes involved in its mobilisation, its phase changes, the transit time and the contorted pathways it experienced during its interrupted journey.

It is not generally possible, therefore, to interpret whether a postulated source of phosphorus is implicated in a particular water quality issue simply by observing the phosphorus status in the waterbody at the location where algal blooms actually develop. To the manager who needs to control the input of phosphorus to the waterbody, it is the presence of phosphorus in suitable forms and concentrations in the water (together with other essential nutrient and environmental factors) sufficient to allow bloom formation, no matter what its source, that is significant.

Scale considerations

To some extent, we can assess the net phosphorus inputs to streams in specific situations—provided we know some key attributes of the system being considered. Traditionally, research has emphasised processes and properties that determine phosphorus mobility at a small plot in the landscape. But these do not indicate how much of that material is delivered to the stream. The quantity delivered is affected by transport mechanisms that change as we move up from the smaller to a larger scale, and by the different pathways taken by various forms of phosphorus during its transit. This point has not always been appreciated or made clear by specialists communicating their results to managers.

The concepts of scale and pathway provide a framework to interpret the relative importance of phosphorus sources in the landscape. This is the approach taken in this report. In essence, it is necessary to understand the importance of a few water and phosphorus pathways that may dominate, infer from these the magnitude of phosphorus fluxes, and determine whether or not this material is delivered into a waterbody.

A second factor that affects phosphorus transport is the time-scale of the process involved. The natural time-scale of the system reflects how quickly a pulse of phosphorus moves through the ecosystem. If changes are made to a landscape that alters flow pathways and residence times (for example by urbanisation, or reservoir construction) then the natural time-scale also changes. Another time-scale relates to the time elapsed since a more or less continuous disturbance was imposed. In the case of fertiliser application, this time is a few years to several decades. Where land use has changed from forest to agriculture, it could be a century or more.

The interplay of pathways, storages and scales influences how a system responds to phosphorus input. By focussing on the key processes that dominate system behaviour, at the appropriate space and time scales, it should be possible to identify the relevant phosphorus sources in most situations.

Dominant processes of phosphorus mobilisation

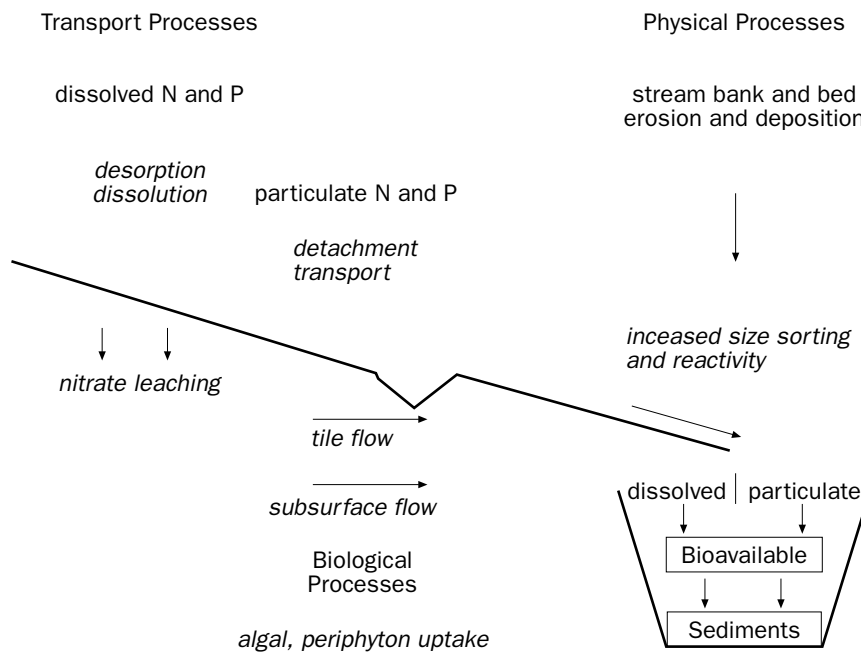
Phosphorus is a natural constituent of the rocks that comprise the earth’s crust. The weathering products that contribute to soil formation contain phosphorus in varying amounts. The quantities of phosphorus and the relative proportions of its forms varies among different soils, and together with soil characteristics and hydrological conditions affect the flux of phosphorus that is moved by infiltrating water or surface run-off.

We have added to the stores of naturally occurring phosphorus by applying fertilisers in several forms—as organic matter (primarily from manures and improved pasture organic matter build up), and as artificial fertilisers (rock phosphate, superphosphates, and compound fertilisers such as di-ammonium phosphate (DAP) which have become standard in cropping regions in the past two decades)—as well as by adding materials that change the availability (and mobility) of phosphorus in the soil. The history of soil management is therefore an important factor in whether or not a particular soil is a potential phosphorus source.

We now consider the dominant mechanisms that mobilise and transport phosphorus to the waterbody, as outlined in Figure 1.

Figure 1
Processes involved in the transport of N and P from agricultural land

(modified from Sharpley, A. N. Daniel T. C. and Edwards D. R. 1993, J. Prod. Agric. 6, 492–500).



Transport of dissolved phosphorus

The consensus of scientific evidence is that dissolved phosphorus can move through porewater in the soil as well as via the more usual route of surface run-off. The rate of transport along either route increases when excess soil water is present. Flow through the soil depends on the drainage characteristics of the soil. Sandy soils drain much better than heavy clay loams; well-structured soils, even though high in clay, also drain well. If the soil becomes saturated, the rate of movement can increase dramatically, especially if larger macropores are present and become filled with water. Under high intensity rainfall conditions, for land prone to waterlogging and in irrigation grazing systems, the predominant movement is by overland flow.

When water moves through the soil, exchange takes place between the dissolved and suspended phosphorus in the water and the 'pools' of phosphorus in the soil matrix. By this mechanism, phosphorus in the soil water may be either enriched or depleted. The reactions of this mechanism are complex, and depend on the chemical environment in the soil, and on the abundance of very small reactive particles. In sandy, low phosphorus sorbing soils, phosphorus effectively moves straight through the soil column without experiencing these exchange reactions.

The effluent phosphorus at the base of a sandy soil profile is likely to have the same concentration as the water moving through the top few centimetres of soil. If phosphorus is added to the low phosphorus sorbing soil as fertiliser, and subsequently dissolved into the soil water, only a tiny proportion of the phosphorus can be retained on the surfaces of the coarse and non-reactive soil particles. The applied fertiliser is therefore readily mobilised by rainwater moving through the soil (Neller, 1945). There is, however, a range of phosphorus sorption capacities in sandy soils. Often phosphorus rich water will encounter iron rich soil layers at the groundwater interface. These layers serve to delay the movement of phosphorus until the retention capacity is overwhelmed.

Phosphorus in water moving through crumb-structured soil comes into contact with clay particles having a very high surface area that can adsorb phosphorus. The high iron (indicated by red, orange and yellow colours in the soil) and aluminium content of these soils adds to their ability to bind phosphorus, effectively immobilising it. Although these soils are comparatively rich in phosphorus (derived from phosphorus-rich minerals in the parent rocks, usually basalt), experience shows that phosphorus is not transported with percolating water beyond a depth of about 500 mm, even after decades of fertiliser applications at high rates.

Some soils have developed internal passageways that provide rapid transit conduits for water movement. These passageways can arise from plant roots, soil cracks, ants, and so on. Water and dissolved materials move freely through these pathways without significant contact with the soil matrix, and usually emerge as springs close to drainage lines. Soils that contain these preferred pathways (macropores) can be transparent as far as dissolved phosphorus is concerned, and can provide the dominant input of phosphorus to streams from adjacent hillsides. Swelling soils with big cracks that close when the soil is saturated do not conduct dissolved phosphorus, but may be a pathway for phosphorus movement to depth in such soils.

Thus, coarse-grained soils (such as sands) or soils with macropores can readily transmit phosphorus in dissolved form. High clay, well-structured iron-rich soils are effectively impervious to the leaching of dissolved phosphorus, although heavily fertilised market garden soils formed into raised beds may transmit phosphorus through surface soil into the furrows between the beds and out into the drainage system.

When dissolved material intercepts a watertable or a stratum of low conductivity, the direction of water flow changes from being vertical to lateral, towards drainage lines or zones of surface seepage. The transit time in these pathways depends directly on a few parameters that are easily measured (flow gradient, path length, hydraulic conductivity), and therefore can be readily calculated. Fluxes of phosphorus that enter the stream can also be calculated.

Dissolved phosphorus in surface run-off is a major component when average rainfall occurs in high rainfall and irrigated areas of mixed farming, especially where there is intensive animal production, storage of animal manures, and a large proportion of the water balance moves through the landscape in surface streams, channels and other water bodies.

In summary, dissolved phosphorus is easily mobilised and transported through a soil profile if the soil medium has a small exchange capacity (as in sands with low P sorption capacity or in soils where the P sorption capacity has been exhausted), or if it passes into a waterbody by overland flow or via short-circuit pathways. Usually, phosphorus transported in this manner travels via groundwater or shallow subsurface flow until it emerges into a drainage line that connects with a waterbody. The typical path length for this process is the natural hillslope length, but in irrigated areas it is determined by the low infiltration rates of the predominantly finer textured soils, shallow slopes and by constructed features such as contour banks and drain spacing.

When dissolved phosphorus travels via overland flow or shallow subsurface flow the time-scale of movement is short, and is comparable to the time that water itself takes to move through the soil, unless other physical, chemical or biological processes along the transport pathway retard its movement. Dissolved phosphorus exports that depend on these scales will change rapidly if the input of phosphorus to the system changes. The time-scale of dissolved phosphorus transport via deep groundwater is usually long.

Transport of particulate phosphorus by surface erosion

Overland flow has a capacity to transport significant quantities of phosphorus in various forms. While some of this is dissolved phosphorus moving directly with the water, in many sub-humid to semi-arid environments a much larger flux of phosphorus can occur via eroded particulate material. The particles are a mixture of mineral fragments that contain crystalline inorganic phosphorus compounds, organic detritus, and particles that have phosphorus adsorbed to their surfaces. The different forms of phosphorus are not equally available for uptake by biota, so the relative proportions of phosphorus in various forms have an important bearing on algal bloom development. However, algal blooms may take place months or years after an erosion event when conditions enable the phosphorus to become bio-available. This may occur when the sediments become anoxic during, for example, periods of drought, thus resulting in release of bio-available phosphorus into the overlying water column.

Phosphorus transport by overland flow occurs only where overland flow is generated on the land surface. If land is irrigated, the action of flood irrigation itself causes overland flow within an irrigation bay.

Material mobilised by overland flow is derived from surface layers of the soil and loose overlying material such as dung, decomposing plant remains, litter, stubble, organic matter, much of which releases soluble phosphorus. Soils that have, or have had, surface-applied fertilisers are potentially sources of high phosphorus concentrations in run-off while the fertiliser remains on the surface. Exposed soils with less than 30% attached plant cover are most vulnerable. This is common where animal grazing causes bare ground in dry seasons, where cropland is left exposed at seeding, and at the beginning of the growing season if annual pastures are dominant. However, it can be shown that, once applied, fertilisers are distributed through the top few centimetres of the soil profile through ploughing, and the average soil concentration of phosphorus is little different to that of unfertilised soils. However, the applied phosphorus is more bio-available than native phosphorus and, until this bio-available fraction is either taken up by plants or bound to soil particles, the fertiliser phosphorus can increase the overall soil bio-available phosphorus significantly.

The quantity of particulate material that can be transported depends on the land slope and overland flow velocity as well as soil texture and other characteristics. The fractions that are preferentially carried in the flow are proportional to their size and density. If the local flow rate diminishes (by lateral spreading for example), or if the land slope decreases, the same quantity of material can not remain suspended in the flow, and preferential deposition of the larger, denser particles occurs.

Preferential deposition has two important consequences for phosphorus exports. First, only a fraction of material eroded from upslope locations actually reaches the watercourse. The delivery ratio of eroded material passing over natural terrain (cultivated or otherwise) is usually quite small. The net result is that much of the material carrying phosphorus is simply re-located in the landscape, where it may become stabilised by vegetation growth. However, the delivery ratio is closely related to catchment size and drainage density. In small sub-catchments, on dissected landscapes, and where highly polluting land uses (heavily fertilised pasture, market gardens, land-based sewage disposal) are close to receiving waters, the delivery ratio can be very high. That is, little assimilation may occur, and the plot scale estimates of nutrient run-off may approximate the loads that reach the receiving waters.

The second consequence of preferential deposition is that the materials remaining suspended in the flow are often those most enriched in phosphorus compared with the material originally eroded. This is because the quantity of phosphorus adsorbed to soil particles is proportional to their total surface area and composition. In the small particles and organic fragments, this surface area can be very large, and provide most of the sorption sites. For example, Olley (Pers. Comm.) estimates that 80% of all phosphorus transport is associated with particles smaller than 25 microns; in contrast, the median size of suspended sediments is about 40 microns or larger. This process can enrich the phosphorus concentration by up to 10 times. In irrigation drains in the Shepparton Irrigation Region, 40% of the phosphorus that drains from pastures is filterable reactive; ie. it is either dissolved P or attached to colloidal material. However, some distance along the drain, this amount drops by half as phosphorus is sorbed to suspended sediments entrained in the drainage flow.

We can list the factors that are known to affect phosphorus exports. An example has been given by Weaver and Summers (1998), based on an understanding of conditions in Western Australia and is summarised in Table 1.

Table 1

A list of some factors that influence phosphorus loss and concentration in streams (modified from Weaver and Summers 1998).

Factor	Risk of P loss
Years of fertiliser application	Increases with time
Time since fertiliser application	Decreases since application
Fertiliser rate	Increases with amount
Streamflow	Increases with flow rate
Surface run-off v. subsurface flow	Increases with run-off
Seasonality	Increase in wet season
Catchment size	Unit area loss decreases as catchment size increases
Travel time in stream	Decreases with increase in stream travel time
Streambank vegetation	Decreases as vegetation status improves
Stream order	Unit area loss decreases with increasing stream order
Soil P retention capacity	High loss decreases if leaching/subsoil flow dominate
Soil fertility	Increases with high P status
Grazing pressure	Increases with stocking rate
Rainfall intensity	Increases if erosion dominates
Amount of previous rainfall	Decreases as previous rain increase
Land use	Increases with increasing intensity
Land management	Decreases when soil conservation increases
Drainage	Decreases with subsurface or tile drainage Increases with increasing surface drainage

The picture given above can be confounded by a large number of complexities and moderating effects. Soils are not homogeneous across landscapes, and local soil conditions (and erodability) change seasonally and are strongly influenced by cover and cultivation. Hydrological conditions change drastically as we move between a hillcrest and a footslope. Longer hillslopes behave differently from shorter slopes, and terrain shape can play an important role in run-off during storms.

This type of information provides guidelines that can be used by land managers to minimise phosphorus exports. However, it gives no absolute means for identifying the relative magnitude of phosphorus sources, or how net phosphorus exports are likely to change, as we move from one landscape scale to another, or how phosphorus exports vary through time.

In summary, phosphorus can be carried by overland flow in forms that have varying bio-availability. Most is carried as eroded mineral, organic particulate material or adsorbed to fine grained soil particles. The important factors that affect the quantity of mobilised material are land cover and terrain slope. Most of the coarser materials from higher landscape positions are deposited before they reach a watercourse. Consequently, the particles ultimately carried into drainage lines are fine-grained and phosphorus-enriched. Local soil, surface cover and climate conditions dictate whether surface erosion is a dominant source of phosphorus into a watercourse. To describe phosphorus exports from a specific landscape by surface erosion requires an analysis that takes account of local conditions. While generalisations have limited use, guidelines that account for the dominant factors can be used for management purposes to identify and minimise sources of phosphorus carried by overland flow using appropriate BMPs.

Transport of particulate phosphorus by gully and bank erosion

Studies by CSIRO and ANU in large catchments of the Murray–Darling Basin show that most of the total sediment carried with river flows has been derived from subsoils in the small headwater catchments. It is hypothesised that the subsoil sediments carried by the flow originate from incised gullies and collapsed stream banks. A range of methods using radioisotopes and rare earths has been used in these studies (Martin and McCulloch 1998). If the phosphorus content of the subsoils accounts for the phosphorus carried by river sediments, there are important implications for the sources of phosphorus and management methods that should be targeted by land and water managers.

Sediment yield has changed greatly in South-Eastern Australia over the 150 years. Hairsine and Prosser presented data to show that channel sediment sources peaked at nearly $1,000 \text{ m}^3 \text{ km}^{-2} \text{ yr}^{-1}$ in the late nineteenth century, whereas yields are now less than one hundredth of that (averaging $8 \text{ m}^3 \text{ km}^{-2} \text{ yr}^{-1}$) (Prosser and Winchester, 1995). Hillslope and stream bank (including gully) erosion now contribute near-equal amounts of sediment (Neil and Fogarty, 1991, and Wallbrink *et al.*, 1996). One hundred years ago stream bank erosion was the dominant component as gully networks went through a major phase of expansion. While much of the gullying in upper reaches was initiated and most active decades ago, the process is still currently active in some river basins. Poor land management practices in the past have set up conditions that favour gully formation. Once gullies were initiated, sediment export rates increased one thousand-fold, and persisted at that rate for some years. Export rates diminish slowly towards a new equilibrium—this may take centuries. At present, export rates from these gullied catchments remain at levels much higher than in the pristine environment. There is little that can be done on the land surface to reduce sediment export rates after gullies have formed other than by stabilising and revegetating the gullies.

The scale at which gully erosion occurs is important. Although they are commonly observed along watercourses in larger catchments, by far the greater number occur in drainage lines where flow is ephemeral. In terms of total gully length in a catchment, about 85% are in first or second order catchments that feed these drainage lines. Gully initiation and extension are therefore associated with hillslopes in small headwater catchments (10–100 ha). Most of the sediments and exported phosphorus in tributaries of the Murrumbidgee are derived from subsoil gullying. Measures to control gully erosion must address landuses and processes that operate at the hillslope and small catchment scale. It should also be recognised that gullies at this scale are inactive most of the time, and active erosion is highly episodic—perhaps at average intervals of a few years. Management of gullies should therefore be based on coping with flow events of this magnitude.

The delivery ratio for the gully-wall material is high (close to 100%). It also undergoes some phosphorus-enrichment through abrasion and particle size reduction as the particles are transported with the flow. Some weathering of mineral particles may also occur, liberating phosphorus from the crystalline state. The gradual transformation into smaller size fractions provides adsorption sites for phosphorus that might have entered the flow from other sources.

In summary, there is evidence that in the catchments of the Murray–Darling Basin studied so far, most of the diffuse-source phosphorus carried by river sediments originates from gully erosion and stream-bank collapse. Although the major episodes of gully formation occurred several decades ago, inputs of sediments and phosphorus from these sources continue at a high rate. Reduced input rates can be achieved best by targeting the gullies themselves, and stabilising them by conservation works (eg. revegetation, stock exclusion and fencing) particularly in small headwater catchments.

Run-off from saturation zones

In all the situations described above, irrespective of soil characteristics, it is possible that soil in low-lying parts of the terrain can become saturated. In these areas, the soil surface can remain wetted for long periods, depending on season and plant cover. They are potential sources for run-off and erosion, because material applied to the surface on these saturated areas does not enter the soil profile, but is washed towards the drainage line either by steady upwelling flow, or by rainfall. Because these saturation areas are usually next to streamlines, flushing of surface-applied fertilisers can be very effective in terms of delivery, and is essentially instantaneous. The saturated soil predisposes the area to run-off, which will also enhance erosion.

In summary, potential sources of diffuse phosphorus run-off occur wherever soils are already wet at the surface or that may become wetted by seasonally emerging groundwater, and is exacerbated where fertilisers are, or have been applied to the soil.

Examples of phosphorus exports from catchments

Workshop participants described some specific instances of phosphorus exports from catchments. These cover a range of climates, soil types, and agricultural practices. They illustrate how the various processes of mobilisation and transport described above differ from one situation to another.

Heterogeneous soils, low relief catchments in Western Australia

Several catchments in the South-West corner of Western Australia, partly cleared for agriculture over the last several decades, are now exhibiting signs of eutrophication and excessive growth of benthic algae. The best known of these is the Peel Inlet and Harvey Estuary on the West coast of WA. Other catchments being intensively studied include Oyster Harbour and the Wilson Inlet Catchments (Weaver and Reed, 1998). The Peel–Harvey catchment has a large proportion of deep sandy soils, the catchments are highly dissected by constructed watercourses, and surface gradients are generally flat. The landscape in the Oyster Harbour and Wilson Inlet catchments consist mainly of undulating plains developed predominantly on tertiary sediments with occasional granitic hills. Soils are commonly duplex with shallow grey acidic siliceous sands overlying laterite and clay in the higher landscape, and sands and sandy gravels at lower elevations. Valleys are often deep sands.

Some attributes of the sandy components of these soils in these catchments are their high permeability characteristics and their low capacity to retain phosphorus. When wetted, the soils are quite permeable and water drains freely from higher positions in the landscape through the soil to the watertable. Because of the flat terrain, waterlogging at lower slope positions is widespread in wet years, and often drains have been constructed to alleviate that problem. When the surface soil dries, a water-repellent layer often develops preventing water entry. During light to moderate rainfall, the soils exhibit leaching or surface run-off due to water repellancy and waterlogging, but the dominant mechanism in light to moderate rainfall is thought to be by vertical leaching. Loam, gravel and clay soils in these catchments can exhibit limited leaching behaviour because of their greater capacity to retain phosphorus, however, they can contribute significant amounts in episodic run-off events that cause erosion.

The soil's ability to retain phosphorus can be described by its PRI (Phosphorus Retention Index, a single point phosphorus sorption measure), which is related to the quantity of iron and aluminium oxides in the soil matrix (Allen and Jeffery, 1990). A related quantity is the phosphorus sorption capacity, which is a function of soil mineralogy and past phosphorus additions, and as such, both the PRI and the phosphorus sorption capacity are dynamic characters. Soils that have a low PRI and a history of significant fertiliser application may have a phosphorus-sorbing capacity that approaches zero, so additional applied fertiliser may be easily leached by rainfall (Behrendt and Boekhold, 1994). This situation has already occurred in parts of these catchments. Table 2 shows that the (bicarbonate extractable) phosphorus content of soils with low PRI has peaked within a decade or so after clearing, while soils of high phosphorus retention (indicated by high reactive iron contents) have continued to accumulate phosphorus over a 40-year period. In time, we can expect that more of these soils will cease to accumulate phosphorus, except through plant detritus, and release rates via leaching will increase.

Table 2
Median Bicarbonate extractable P in relation to soil reactive Fe content and time at which fertiliser additions began (modified from Weaver and Reed, 1998)

Ammonium oxalate extractable iron (mg kg ⁻¹)	<100 (low P sorption)	400–800 (moderate P sorption)	>1,600 (high P sorption)
Uncleared	1	4	9
1979–1989	7	17	25
1959–1979	10	26	32
Prior to 1959	9	31	42

The Western Australia data also illustrate how phosphorus accumulates in the soil profile of a fertilised pasture compared with an uncleared area. Mean storage of total phosphorus in a one-metre profile increased from an average of 450 kg ha⁻¹ to 930 kg ha⁻¹ from native bush soils to paddocks, with sediments in river pools showing much higher storages (3,200 kg ha⁻¹). Both fertilised paddocks and river pools showed considerable enrichment in the top 5 cm. In the case of river pools, it is not known whether surface erosion or gully and bank erosion contributed. Water quality monitoring in the Kalgan River suggests that when high phosphorus export is measured, seventy percent of the measured export can be associated with particulate materials during intense periods of rainfall and run-off. When lower phosphorus export is measured, only 40% of it is particulate. To some extent this difference can be explained by changes in contributing area and the dominant hydrologic process during the differing rainfall regimes (Weaver et al. 1994). When the distribution of phosphorus in the soil profile of fertilised pasture is examined it can be seen that comparatively high phosphorus storages occurs in the top few centimetres, which is most vulnerable to surface washoff if the soil becomes water repellent or intense rainfall and erosion occurs.

Summers et al. (1997) gives analyses of the correlations between soil and landscape factors and phosphorus exports in the Peel–Harvey catchment. The types of factors are similar to those shown in Table 1. In those parts of the catchment where sandy soils occurred, there were strong correlations between phosphorus-export rates and the soil PRI, as well as with the occurrence of waterlogging close to drains or watercourses. In the Peel–Harvey catchment, Summers et al. (1997) have made similar observations, but go on to conclude that the appropriate scale for correct interpretation of these data (and comparison of management solutions) is preferably on a small scale (below 50 ha). This is because information about phosphorus mobilisation and transport becomes smeared or lost as we move up in scale, and the linkages between observed effects and their causes become increasingly tenuous.

In summary, catchments in South-Western Western Australia exhibit phosphorus run-off into estuaries by leaching through sandy soils, overland flow and by surface erosion. Sandy soils of low phosphorus retention are able to accumulate only small amounts of phosphorus and an increasing proportion of agricultural land is contributing to the phosphorus-loading of estuaries as the soils become enriched to their limit. Soils with high phosphorus retention and long fertiliser history accumulate significant amounts of phosphorus and can contribute to movement if surface erosion occurs. Other significant sources of diffuse phosphorus run-off in that area are associated with local waterlogging and the tendency for soils to develop water repellancy.

Zones of heavy reactive soils in Eastern Australia

Dispersive duplex soils

Extensive tracts of grazing and cropping land on the continent have a mantle of soil material derived from in-situ weathering of the parent rock material. These soils are dense, have high clay content, are low in total and available phosphorus and other nutrients, and have low water conduction properties. If the ground is fully protected by standing perennial vegetation soil stability is fairly high, but many of the soils are highly dispersive, that is, subject to structural breakdown, when wetted, because of the significant amounts of exchangeable sodium on the clay surfaces. To achieve adequate agricultural biomass productivity on these soils requires the addition of fertiliser, and stabilisation with gypsum as a source of soluble calcium to replace the exchangeable sodium.

Water and phosphorus move through this terrain by overland flow, or shallow subsurface flow through macropores in localised situations. Soil erosion (carrying phosphorus) therefore dominates at the paddock scale, but this is overwhelmed by much greater subsoil losses from eroding gullies if these are present. Indeed the evidence is essentially irrefutable that most of the sediments carried by the Murrumbidgee and Namoi Rivers comes from soil lost through gully erosion. It is likely that the same conclusion can be made in other landscapes of this type where active gully erosion is significant.

This evidence is based on the use of soil radionuclide tracers ^{210}Pb and ^{137}Cs that are concentrated in the top few centimetres of soil. If the concentration of these substances seen in river sediments is diluted by unlabelled subsoil material, then the amounts coming from surface versus subsurface sources can be calculated (Wallbrink and Murray, 1993).

Phosphorus is carried on these river sediments. If most of the sediments come from eroding gullies, does most of the phosphorus also come from the same source, or from some other source? This question needs to be answered to properly identify the important sources of phosphorus, rather than the major sources of sediment.

Independent methods have been applied to interpret the origin of phosphorus in the sediments of Chaffey Reservoir. The methods are based on isotope tracing of Sr and the element Nd. The parent rock and fertiliser both contain traces of the same elements but in isotopic ratios which give them a different signature. At Chaffey, they provide evidence that no more than 2% of the total phosphorus in sediments suspended in the water of the inflowing river is derived from fertiliser; the remainder comes from basalt-derived surface soils. This reservoir does, however, have a significant proportion (~30%) of its P delivered in dissolved form, the sources of which have not been clearly identified. Further downstream in the Namoi River, the source of the suspended sediment (and total phosphorus) changes significantly with a larger contribution from subsoils. Not surprisingly, this reflects the progressive contributions from eroding gullies and riverbank collapse below Chaffey Reservoir.

However, it does not follow that the readily exchangeable phosphorus adsorbed to sediment particles also originates in the subsoils. Indeed, Olley (1995) has shown that phosphorus discharged from a sewage outfall adsorbs to sediments and becomes indistinguishable from other sources of exchangeable phosphorus within a river travel distance of 40 km (in this case, the Murrumbidgee River). It seems that the history and fate of phosphorus in its more reactive forms still needs to be clarified, especially when it comprises only a small fraction of the total phosphorus load.

Irrespective of these considerations, the volume of sediment transported by both overland flow and gully erosion is an important factor, being controlled by the land use, and more particularly the amount of land cover. Studies between paired tributary catchments that compare the effects of tree-clearing and grazing with native forestry or conservation reserve can best supply the definitive answers needed as to where in the landscape phosphorus is originating in these parts of the Murray–Darling Basin.

Well structured krasnozems (oxisols)

Unlike the duplex soils described above, krasnozems (oxisols) are freely draining, and tend to retain their structure well. They have high levels of phosphorus-sorbing substances such as iron and aluminium oxides, as well as moderate to large clay contents, giving them a high Phosphorus Retention Index. Because of their fertility and usually deep profile, they are highly valued for intensive agricultural crops, such as potatoes and bananas. Krasnozems are widespread but patchy, occurring as residual soils weathered from basalts. They seldom produce surface run-off except in high intensity storms, or where surface layers have been compacted by trampling or road construction. In the forested water supply catchments near Melbourne, they produce high quality water carrying very little sediment, because most water infiltrates through the deep soil column.

Under repeated cultivation and fertiliser application, especially on steep slopes, sediment and hence phosphorus losses can occur. In cases where soil next to a watercourse is disturbed, high loads of clay and colloids rich in phosphorus can be exported in heavy storms, leading to severe water quality degradation to the extent that it could require treatment.

Since krasnozems have a high phosphorus sorption capacity, leaching of applied phosphorus beyond the root zone is unlikely if fertiliser is applied at a rate that matches the average nutrient demand of the crop or pasture. For example, in Southern Queensland, it has been observed that no free phosphorus is detected at a depth of 500 mm in a banana plantation on a krasnozem soil that had been fertilised at a rate of 150 kg phosphorus per hectare each year for 10 years. (However, phosphorus may well have been exported from the site with overland flow.)

It can be seen that the appropriate scale for considering phosphorus losses from well-structured, phosphorus-retentive soils is the hillslope itself. The dominant mechanism is overland flow during heavy storms, but actual phosphorus exports are strongly modified by the delivery ratio, which can be dramatically reduced by re-deposition in an effective buffer strip.

In summary, a few intensive studies in catchments with dispersive duplex soils in the Murray–Darling Basin have demonstrated that most of the sediments carried by rivers draining terrain with these soils comes from eroded gullies. This sediment carried in the river is the main vehicle for transporting phosphorus. But it is not clear whether the phosphorus is derived from the same source as the sediments. The issue must be resolved before the dominant sources of diffuse phosphorus and management strategies can be correctly identified.

In the headwaters of the Namoi basin where well-structured iron-rich soils occur, methods using rare-earth isotopes have shown that the input of fertiliser phosphorus to reservoir sediments is negligible compared with natural sources. The same methods can be used to resolve issues of phosphorus sources in terrain with other soil types, particularly in dispersive duplex soils, where clay dispersion, flocculation, retention and adsorption-desorption processes all occur simultaneously within soil profiles and waterbodies. Well-structured iron-rich soils normally produce high quality water, because the soils retain phosphorus and surface run-off rarely occurs. But compacted, steep or cultivated slopes on these soils in high rainfall areas allow local washoff of nutrient-rich soil into drainage lines. Buffer strips can reduce the net delivery of phosphorus to streams significantly.

Irrigated agriculture in the Goulburn–Broken Catchment

The area of the Goulburn–Broken catchment in Northern Victoria is 2% of the Murray–Darling Basin, but contributes 11% of the Basin’s streamflow. It contains 280,000 ha of irrigated land, of which 88% is heavily fertilised irrigated pasture. Currently, drainage from the irrigated area contributes 169 tonnes of phosphorus to the Murray River, or 19% of the load measured in the Murray at Torrumbarry. For comparison, point sources contribute only 2% of the Murray’s total phosphorus load (HydroTechnology, 1995).

Continued expansion of drainage works planned for the irrigated area will increase the estimated phosphorus export to 203 tonnes of phosphorus to the river annually. The phosphorus dynamics of drains are poorly understood. While over 90% of the phosphorus from pastures is in dissolved reactive form (acid molybdate reactive following 0.45 micron filtration) (Austin et al. 1996), transformations occur in irrigation drains, so that only 25–50% of the phosphorus in drainage water is in dissolved form (Hydrotechnology 1994). In addition, the ratio of estimated phosphorus input to measured phosphorus outfall from drains varies from 22:1 to 1.5:1 (HydroTechnology 1995). Good options for managing phosphorus could arise if we could gain a better understanding of the in-drain dynamics of phosphorus.

On intensively fertilised, irrigated pastures the main mechanism of phosphorus loss is by surface washoff of fertiliser, with up to half the annual export occurring during the first irrigation after fertiliser is applied. There is an exponential decay in phosphorus concentration in run-off from consecutive irrigations following fertiliser application. By the third irrigation, concentrations have returned to levels typical of these pastures without recent fertilisation (Bush and Austin, 1998).

Typical phosphorus concentrations from irrigated pastures average greater than 1.0 mg l⁻¹ (ten times higher than the ANZECC classification for ‘degraded’ waters), with phosphorus moving primarily in a soluble reactive form. These high concentrations translate to an estimated 5.4 kg ha⁻¹yr⁻¹ not including the contribution following fertiliser applications.

Current investigations are directed at measures to reduce phosphorus inputs to the drainage system by, for example, incorporating unfertilised buffer zones into the lower parts of irrigation bays. So far, these measures have demonstrated that dramatic reductions in phosphorus washoff rates can be achieved (down to one fifth). Translating these results into improved water and fertiliser application practices requires only a few technological changes based on knowledge of local soil properties.

Heterogeneous catchments with multiple land-use and high rainfall

Similar high amounts of dissolved phosphorus are entering the environment from mixed farming, horticulture and intensive livestock activities in tributary catchments of the Hawkesbury and Nepean catchments in Eastern coastal Australia and the Adelaide Hills, SA. Intensive horticulture is also associated with very high exports of particulate phosphorus. In such dissected, hilly terrains close to large urban populations, phosphorus may enter surface waters through a combination of erosion, fertiliser and animal manure washoff and overland flow, or by throughflow in the upper steeper parts of catchments that have duplex soil profiles, of sandy surface texture and less pervious subsoils. In these tributary catchments, subsurface flow may be the dominant process high in the landscape, but overland flow is responsible for the majority of phosphorus reaching the creeks attached to particulate material. The composition of this material invariably contains organic matter in association with phosphorus and other metalo-clay complexes.

Attenuation of the phosphorus transported into surface streams has been related to the number of farm dams and water storage dams, and their salinity level as well as the other factors mentioned in Table 1. The role of organic matter in association with phosphorus has been undervalued in the past. Dissolved organic matter both adds other nutrients (particularly nitrogen) and depletes oxygen from the waterbodies into which these phosphorus-rich materials are transported.

Cornish (1997) sampled an unnamed tributary in the Currency Creek sub-catchment of the Hawkesbury–Nepean catchment over 30 months, and a dairy farm at Camden, South-West Sydney. The tributary's catchment contained 44 ha of intensive dairy pasture, 16 ha market garden, 165 ha semi- or unimproved pasture including several hobby farms, and a large intensive poultry establishment. Run-off was measured from three market gardens, two dairies, and semi-improved pasture (mostly hobby farms). In addition, monitoring stations were located so that the value of farm dams as sediment traps could be assessed, as well as the role of wetlands in removing sediment and nutrients from run-off water.

For the whole of the Currency Creek sub-catchment, the estimated long-term exports of N and P were found to be very high at 19.3 and 3.3 kg/ha/yr, respectively. Nutrient generation rates were particularly high for market gardens and intensive dairies with high stocking rates (Table 3).

Table 3
Nutrient export rates from Currency Creek

Land use	N (kg/ha)	P (kg/ha)
market garden*	200	15.3
dairy (intensive)*	5.8	6.4
dairy (extensive)	4.1	1.9–2.5**
semi-improved pasture/hobby	7.0	0.8
unimproved	2.4***	0.3****

* Tributary, Currency Ck,

** Camden data, few run-off events, (range depended on farm area sampled),

*** derived from Camden data,

**** published data for the Nepean–Hawkesbury (Cullen 1991).

The form in which nutrients (particularly phosphorus) occur varies with land use and to some extent management. The total phosphorus concentration in run-off from market gardens was very high (2–80 mg/L), and mainly in the particulate form. Particulate P is associated with high rates of erosion, calculated to be about 20 tonnes/ha/yr. Particulate P can be effectively removed from run-off water in farm dams. However, old market gardens with long fertiliser histories and very high soil phosphorus had increased exports of soluble P (up to 2 mg/L), which is much harder to remove from run-off water than particulate phosphorus. Run-off water from the intensive dairy (approx. stocking rate five cows/ha) was surprisingly high in total P (up to 5 mg/L), considering the very low erosion rate on these properties. Most of this P was in the soluble reactive form that does not settle out in dams and will only be removed in wetlands when water moves slowly.

Dams are an important trap for phosphorus. Although total nutrient export from the catchment from Currency Creek was high, it was clear that much of the nutrient generated on the farms was intercepted before it reached the creek. Sediment sampling of dams and flowlines showed that more than 7,000 kg of phosphorus had accumulated since intensive use of the catchment began, about 20 years ago. One dam about 15 years old held a staggering 4,632 kg phosphorus. A dam completed at the beginning of the study contained 758 kg of P in sediments at the end of the study, just 30 months later.

Land management had significant effects on nutrient export. Bare or recently disturbed soil greatly increased erosion and nutrient export from market gardens, with implications for best practice. Over fertilisation of one market garden over a relatively long period, has led to extreme phosphorus concentrations in soil and to elevated concentrations of soluble P in run-off. This makes the retention of P on-farm much more difficult. High stocking rate of dairy pasture, combined with irrigation effluent, has led to high run-off of soluble P, also presenting a difficult management problem.

In summary, the ecological health of rivers is threatened where there is run-off either from intensively fertilised irrigation areas or from mixed farming, horticulture and dairying in areas of dissected hillslope terrain with high rainfall. While phosphorus contamination by fertiliser washoff is unacceptably high, all washoff from irrigated pastures contains sufficient phosphorus to be environmentally deleterious. Many of the key principles for reducing phosphorus exports are known. Further work is required to translate this process knowledge into management practices that confine fertilisers within irrigation bays, or into recycling systems, and develop adequate practices for treatment of animal wastes which also minimise off-site loading.

Gross phosphorus exports from tropical river basins

The annual sediment exports from areas under differing land uses in 12 river basins and regions in North Queensland are shown in Table 4. The phosphorus exports from the same catchments are shown in Table 5. Most of the sediment is discharged from the Fitzroy, Burdekin–Haughton and North-East Cape York basins, but the real rates from these basins are comparatively low. Some catchments where higher real export rates are associated with areas of pastoral activity and intensive plantation cropping (such as bananas and sugarcane), but others have a large proportion of their area in a pristine state.

Large volumes of soil and phosphorus are being lost from these catchments, and they are being delivered to downstream waterbodies that are both landlocked and maritime. The impact on those waterbodies depends on the size of the contaminant pulse in relation to the size of the waterbody itself. In the case of the Great Barrier Reef, the impact of these contaminants is still speculative, in both the short and long term. The relative amount of sediment and phosphorus delivered to offshore areas from these major rivers, compared with local near-coastal sources is also uncertain.

In tropical regions, most sediment and phosphorus exports occur in only a few storms. For example, the Herbert River discharged over 100,000 tonnes of suspended sediments and 64 tonnes of total phosphorus during cyclone Sadie in 1994. Most of this load probably originated from severe gully and sheet erosion in grazing land. Sheet erosion is more likely to have a high delivery ratio to streams during high intensity rainfall, as in cyclones, and therefore be more significant than in temperate regions. The point is illustrated by data of erosion rates from grazing lands in the Burdekin catchment, classified according to the severity of sheet and gully erosion, which show a range from 1.0 to 35 t ha⁻¹yr⁻¹ across different sub catchments.

Table 4
Estimated Annual Sediment Export from North Queensland ('000 tonnes) after Moss et al. 1992.

Catchment	Pristine	Grazing	Cropping	Urban	Total
Mary	53	351	80	2	486
Burnett–Kolan	32	599	65	2	698
Fitzroy	41	1,589	229	2	1,861
Pioneer–O’Connell	32	464	233	1	720
Burdekin–Haughton	12	2,741	73	2	2,829
Herbert	23	462	64	1	550
Tully–Murray	113	196	9	0	401
Johnstone	60	271	235	1	567
Mulgrave–Russell	66	192	212	1	471
Barron	15	75	20	4	114
Mossman–Daintree	104	111	52	1	268
North-East Cape York	130	1,963	3	0	2,096

Table 5
Area, Annual flow, Sediment and Phosphorus Export in North Queensland Catchments

Catchment	Area (km ²)	% Pristine	Mean Annual Flow: '000ML	Sediment export (kg/ha)	P export (kgP/ha)
Mary	9,595	35	300	506	0.38
Burnett–Kolan	39,470	17	2,900	177	0.13
Fitzroy	142,646	9	7,100	130	0.10
Pioneer–O’Connell	3,925	19	2,650	1,838	1.47
Burdekin–Haughton	133,510	2	10,850	212	0.15
Herbert	10,130	16	5,000	543	0.04
Tully–Murray	2,825	66	5,300	1,422	1.10
Johnstone	2,300	39	4,700	2,436	1.98
Mulgrave–Russell	2,020	49	4,200	2,328	2.04
Barron	2,175	76	4,000	1,150	0.41
Mossman–Daintree	2,615	76	4,250	1,024	0.78
North-East Cape York	43,300	21	19,100	484	0.34

Little can be said about how phosphorus moves in these river basins, except that overland flow is probably important because rainfall intensities are high. As well, poor groundcover during drought can result in massive exports of sediments and applied phosphorus in isolated events. The same conditions favour episodic erosion from dormant gullies. The result is that delivery ratios and total phosphorus exports in these regions are higher than in temperate regions with similar soils and land use.

The scales relevant to phosphorus sources in tropical landscapes are the same as in temperate areas, providing we are dealing with similar climatic events that is, storms of moderate intensity. In large storms, especially if they coincide with poor groundcover, the scale then extends to the size of the storm, which could cover a substantial part of the river basin. The mobility, transport and storages of sediment within the major river network should then be considered as factors that have a significant role in material delivery through the system.

In summary, high intensity storms on catchments in tropical regions cause discharge of sediment at rates much higher than in temperate regions. The interplay of drought, groundcover and cyclonic storms results in fewer but higher impact storm events when soil erosion events occur. Sheet and gully erosion is the major contributor of sediment inputs to streams and waterbodies. Exports of phosphorus from the same sources are likely to follow the same pattern, but firm linkages between phosphorus and sediments have yet to be established. The effect of fertilisers and localised animal manure sources of phosphorus is comparatively less than in Southern Australia, whereas the influence of groundcover is paramount.

Interpreting phosphorus exports

The descriptions of how phosphorus can be mobilised for various soil, terrain and climatic conditions have shown that each system can be complex and variable and that it is difficult to compare different systems except in an anecdotal way. It is also difficult to make generalisations based on gross observations.

In this section, we suggest that this confused picture can be clarified. We have already indicated that understanding the dominant processes that determine phosphorus mobilisation and delivery can be simplified by recognising the space and time-scales of these processes. In the suggested framework, five groups of attributes are necessary. These are:

- Soil
- Terrain
- Hydrological state
- Land cover
- Soil nutrient state.

Soil and terrain are fixed in any situation. The others are dynamic, because they change seasonally, or with land management practices. To use them, an understanding of the basic mobilisation and transport mechanisms for sediment and phosphorus is needed, and this must be applied at the appropriate time and space scales.

In general, the appropriate scale is the distance that water can carry phosphorus on its way to a watercourse. Much of the landscape may not be hydraulically connected to a watercourse, especially in a semi-arid zone, except during exceptional rain events. The scale then becomes quite localised to the contributing areas close to a watercourse. But where leaching of material into groundwater occurs, flow pathways can be long, and exhibit a correspondingly long time-scale.

If the scale of the field data is not well matched to the processes that dominate phosphorus exports, (and field data are usually collected at too large a scale) then the information content of field data becomes indecipherable, making it impossible to interpret or generalise. In catchments where several processes operate simultaneously, we can isolate the dominant phosphorus export mechanisms only if we analyse the problem at the correct scales. Sometimes this will indicate that local phenomena can be ignored, such as sheet erosion in comparison to gully erosion. At other times, the vital part played by riparian filter strips will become evident in comparison with flow pathways for leaching through the soil.

Much of the knowledge we have about phosphorus sources and transport rates is inferred from a variety of observation techniques that do not measure the same things. The various forms of phosphorus are often lumped into a single quantity. Many publications report only on a single form, and almost none give sufficient information to link phosphorus in waterbodies with the factors that dictate how phosphorus is mobilised and transported. Information is generally vague so that it serves little purpose other than to prolong debate between scientists with different viewpoints or between land managers and resource agencies.

Those responsible for setting land management and water quality policy objectives need to be aware of the gaps between the available data and its information content, and whether generalisations are warranted. The problem will persist unless it is specifically addressed. It does not arise from a major knowledge gap, but from the need to bring existing field data together so that they can be interpreted holistically.

There is also, at the technical level, a basic uncertainty about whether turbidity (which is easily measured) or even sediment export rate (which is much more difficult to measure) is a suitable surrogate for phosphorus export rate. Again, it is not possible or wise to make a general statement, because the factors that determine water quality depend on many aspects of phosphorus availability to biota. This availability can change across different time and space scales. The consensus is that, if we wish to characterise phosphorus exports by using turbidity as a surrogate, then the relationship between the two quantities must be established in each situation. While this adds a significant complexity to any experimental program, it vastly assists its utility for interpretation, reduces the need for follow-up investigations, and accelerates the process of correct diagnosis of phosphorus sources and their importance.

Conclusion

This report has described how phosphorus mobilisation and transport occurs in different Australian environments. It is now clear that the Australian climate, land use, soils and terrain impose conditions that result in many of our catchments and waterbodies responding differently from those in other continents. Some results—the transport of dissolved phosphorus through macropores in some soils, the dominance of sub-soil phosphorus in gullied catchments—run counter to the understanding developed in other countries. Whether similar or different to other countries, the solutions for current or emerging water quality problems in Australia can only be based on information and understanding that is appropriate to these landscapes.

Except in the most general terms, we have not attempted, in this report, to develop management recommendations. However, it is clear that the last 10 years of research into phosphorus sources and transport has provided enough information to allow us to develop best management practices for Australian conditions. The next step is to assemble a group of scientists, managers and community representatives to translate these research findings into management recommendations and to propagate these recommendations to those concerned with nutrient management.

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