

CSIRO LAND and WATER



**Stage One:**  
**A Preliminary Study to Assess the  
Potential Sources of Phosphorus in the Goulburn City  
Water Supply Catchments**

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## Acknowledgements

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# 1 Introduction

The city of Goulburn obtains its water from Pejar and Sooley dams (Figure 1). In recent years elevated levels of toxic blue green algae (cyanobacteria) have occurred in these storages that have had a detrimental impact on water quality, and also the utility of Pejar Dam for recreation. Apart from taste and odor problems associated with the blooms, the toxins produced may render the water unfit for human or animal consumption.

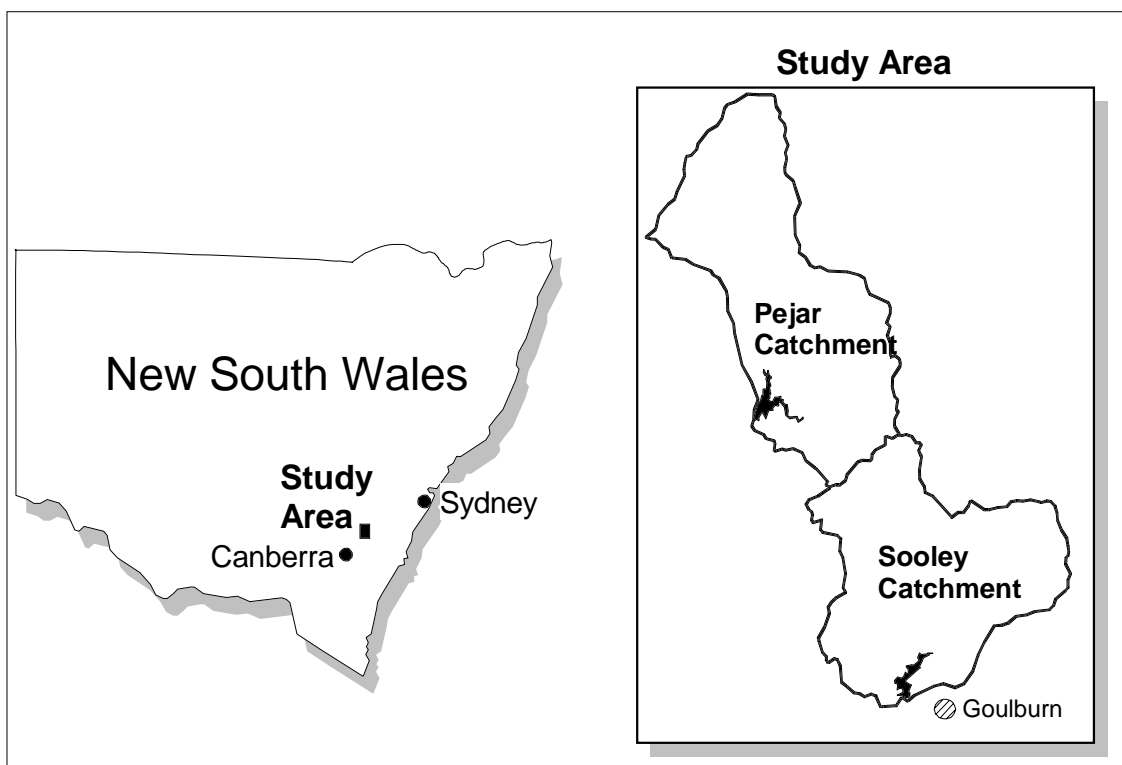
The relationship between the nutrient phosphorus, and algal blooms is well established<sup>1</sup>. Together with nitrogen, carbon, oxygen, and hydrogen, phosphorus is a principal nutrient which in many instances limits algal growth due to limited availability. In some situations the availability of nitrogen may also limit algal growth.

Previous studies have shown that phosphorus can originate from diffuse natural sources such as the natural phosphorus in soil<sup>2,3</sup>. In rural areas phosphorus can also originate from human related activity such as the application of fertiliser and excrement produced from the farming of livestock. Aquatic animals, like water birds, may also be a phosphorus source within water storages.

As part of the Goulburn City Council management strategy for its water resource, CSIRO Land and Water have been commissioned to carry out a two stage study. The Stage One study investigates the potential sources of phosphorus entering the water supply reservoirs as a precursor to Stage Two, which is a quantitative study of phosphorus delivery and storage. Included in Stage One is an assessment of the water supply catchments and reservoirs to identify the potential sediment and associated natural phosphorus sources, as well as considering what other phosphorus contributions can be made by the application of fertiliser to grazing land, contributions from livestock excrement, and other possible sources.

This report also includes a review of available data and reports, including analysis of available water quality data. A summary is also given of anecdotal information obtained from government agencies and landholders.

The third aspect of the Stage One study involves direct measurement of phosphorus and other water quality parameters in water samples from the reservoirs and inflowing streams, and measurement of sediment tracer parameters to assess the potential to determine the sources of sediment and associated phosphorus in soils eroded from the water supply catchments. Experiments were also conducted to measure the release of phosphorus from samples of reservoir bottom sediment under oxygenated (oxic) and de-oxygenated (anoxic) conditions.



**Figure 1.** Location of the Pejar and Sooley dams' catchments.

## **2 Assessment of the Water Supply Catchments**

### **2.1 General Description**

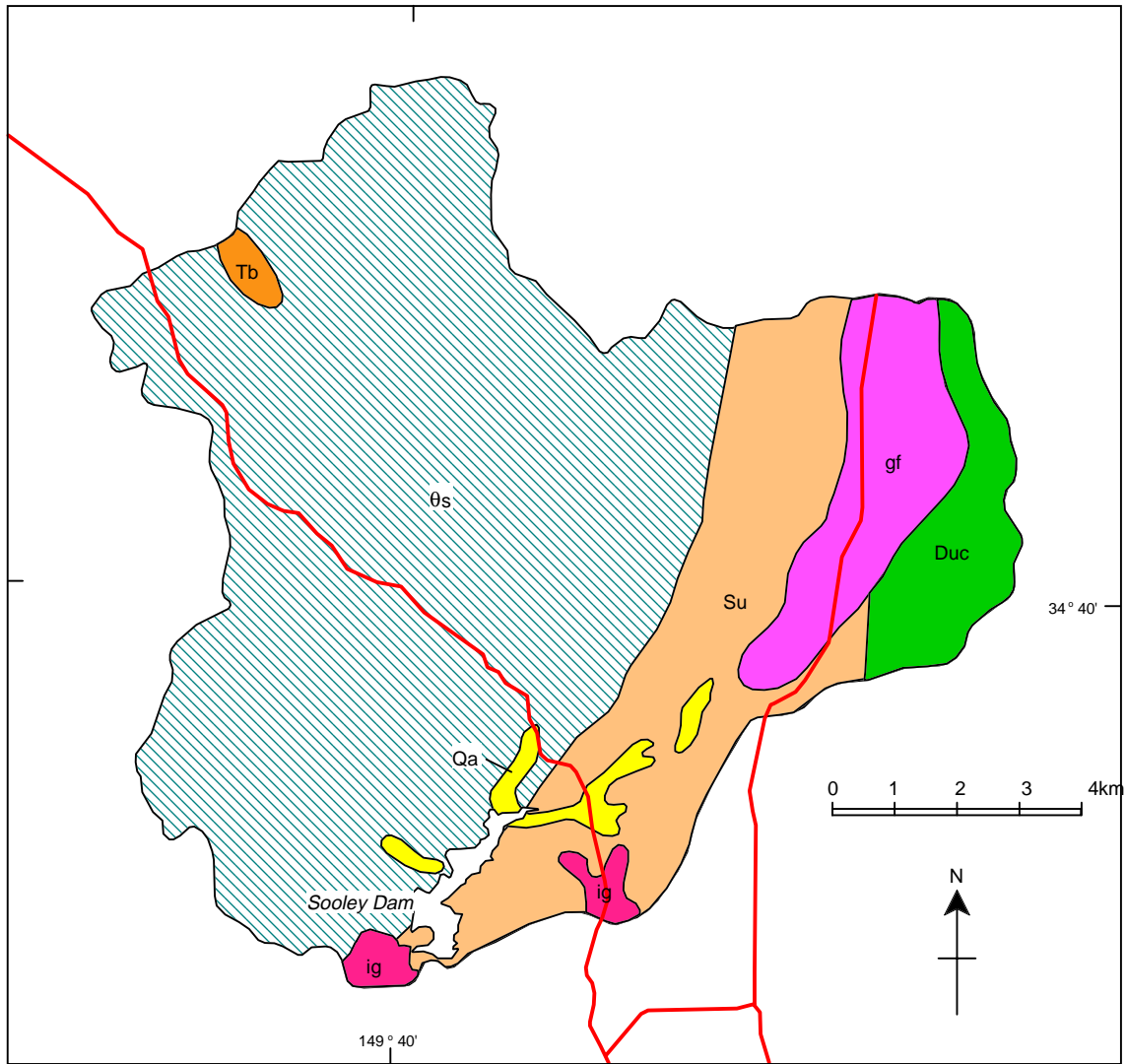
The southern limit of the Sooley Reservoir catchment is immediately north of the city of Goulburn, and the catchment extends north to a common boundary with Pejar Reservoir catchment. Sooley Dam captures flow mainly from Sooley and Bumana Creeks. Pejar Dam captures flow from the headwaters of the Wollondilly River, including Pejar Creek. Sooley catchment has an area of 13,500 ha, and Pejar is 14,200 ha. The topography of Pejar catchment is gently undulating in the north, with steeper gradients in the south. Elevation at the dam is 780 m, rising to over 1000 m in the north. The Sooley catchment is characterised by a larger area of hills located in the east, northeast, and southwest. Elevation ranges from 660 m in the south to over 800 m in the north, with Mt Wayo being the highest peak at 929 m. Rainfall is largely controlled by orographic effects, and generally rises with increasing elevation<sup>4</sup>. Mean rainfall at Goulburn is around 700 mm, and over 850 mm at Crookwell<sup>5</sup>. The steepness of slopes, and the intensity and timing of rainfall events are important influences on soil erosion, and the delivery of sediment-associated phosphorus to water storages.

### **2.2 Geology**

The geology of the two catchments can be broadly subdivided into three major rock types consisting of basalt (Tb), granite (gf, gg) and sedimentary rocks (θs, Duc, Su - Figures 2 and 3). The majority of the sedimentary rocks were deposited during the Ordovician (438-505 Ma) and Middle Devonian (380 Ma). These sedimentary rocks have undergone some metamorphic alteration due to folding, and the extensive intrusion of Silurian-Devonian (360-438 Ma) granite. Tertiary basalt (2-65 Ma) lava flows have formed an extensive capping around the Crookwell area.

Small areas of doleritic intrusives (ig) outcrop on the southern boundary of the Sooley catchment near the dam site, thought to have been implaced in the Mesozoic (65-248 Ma). Quaternary (0.01-2 Ma) alluvium (Qa) occurs as valley fills, notably in Sooley catchment<sup>6</sup>.

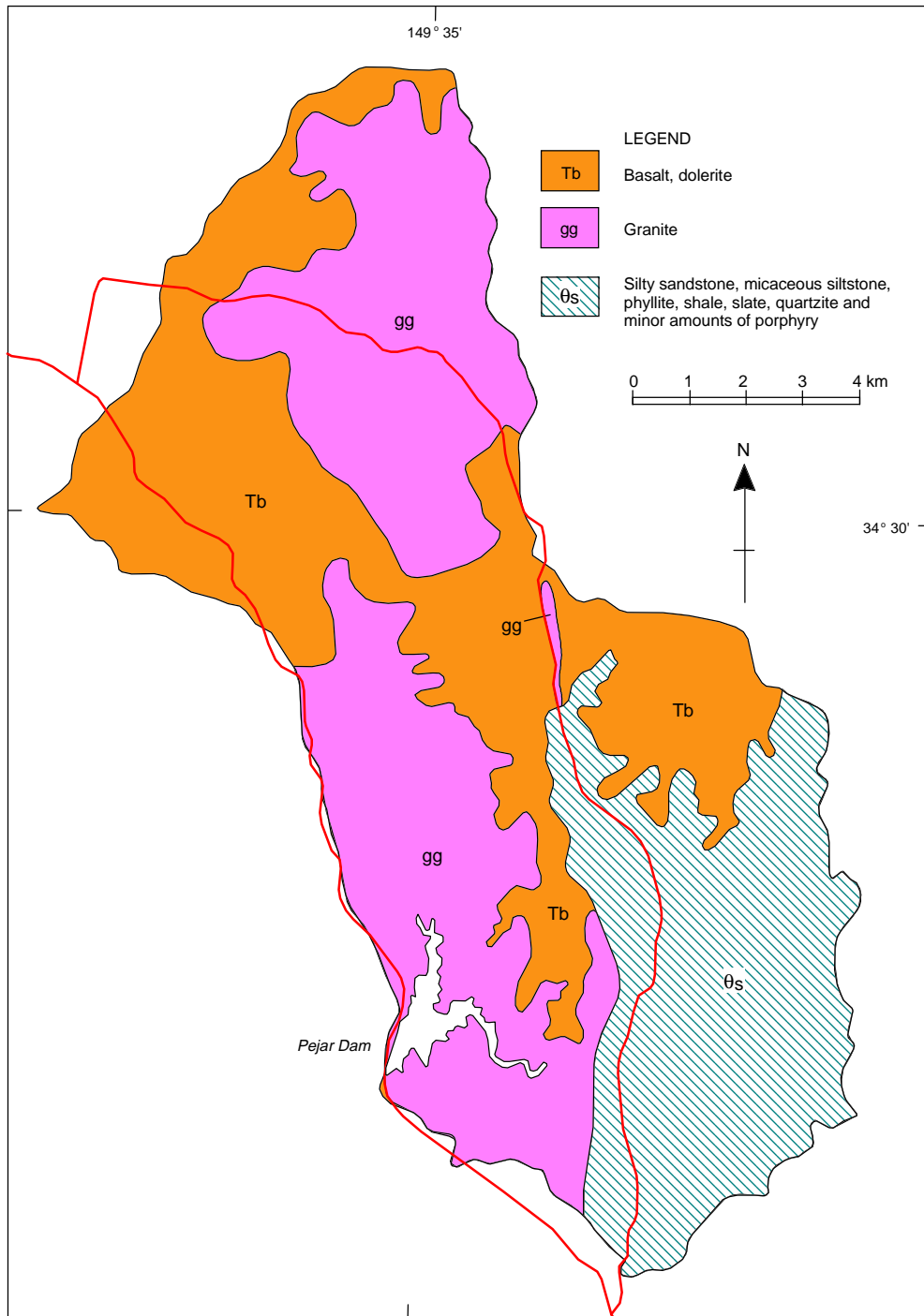
Some rocks contain phosphate minerals like apatite (e.g. some basalt rocks). Soils developed on these rocks may therefore be naturally phosphorus-rich, and a potential source of sediment-associated phosphorus delivered to water storages<sup>2</sup>.



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<table border="0"> <tr> <td style="border: 1px solid black; padding: 2px; text-align: center;">θs</td> <td>Silty sandstone, micaceous siltstone phyllite, shale, slate, quartzite and minor amounts of porphyry</td> </tr> <tr> <td style="border: 1px solid black; padding: 2px; text-align: center;">Duc</td> <td>Conglomerate, sandstone, quartzite</td> </tr> <tr> <td style="border: 1px solid black; padding: 2px; text-align: center;">Su</td> <td>Limestone, shale, chert, quartzite, tuff</td> </tr> </table>	θs	Silty sandstone, micaceous siltstone phyllite, shale, slate, quartzite and minor amounts of porphyry	Duc	Conglomerate, sandstone, quartzite	Su	Limestone, shale, chert, quartzite, tuff	<table border="0"> <tr> <td style="border: 1px solid black; padding: 2px; text-align: center;">Qa</td> <td>Sand, clay, gravel</td> </tr> <tr> <td style="border: 1px solid black; padding: 2px; text-align: center;">ig</td> <td>Dolerite</td> </tr> <tr> <td style="border: 1px solid black; padding: 2px; text-align: center;">gf</td> <td>Granite</td> </tr> <tr> <td style="border: 1px solid black; padding: 2px; text-align: center;">Tb</td> <td>Basalt, dolerite</td> </tr> </table>	Qa	Sand, clay, gravel	ig	Dolerite	gf	Granite	Tb	Basalt, dolerite
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ig	Dolerite														
gf	Granite														
Tb	Basalt, dolerite														

**Figure 2.** Geology of the Sooley catchment (source: Geological Survey of NSW, Goulburn Geological Sheet).



**Figure 3.** Geology of the Pejar catchment (source: Geological Survey of NSW, Goulburn Geological Sheet).

## 2.3 Soils

In general, the soils types in the catchments are strongly influenced by the parent rock types. The age and extent of weathering of the parent material effects the nutrient status of the soils in the region. A summary table of the soils found in the two catchments, including map code, rock type association, landform association, erosion hazard, and chemical fertility are given in Table 1. Soil distribution maps are shown in Figures 4 and 5. The natural phosphorus concentration in soil, and its erodibility, are important factors affecting phosphorus delivery to water supply reservoirs.

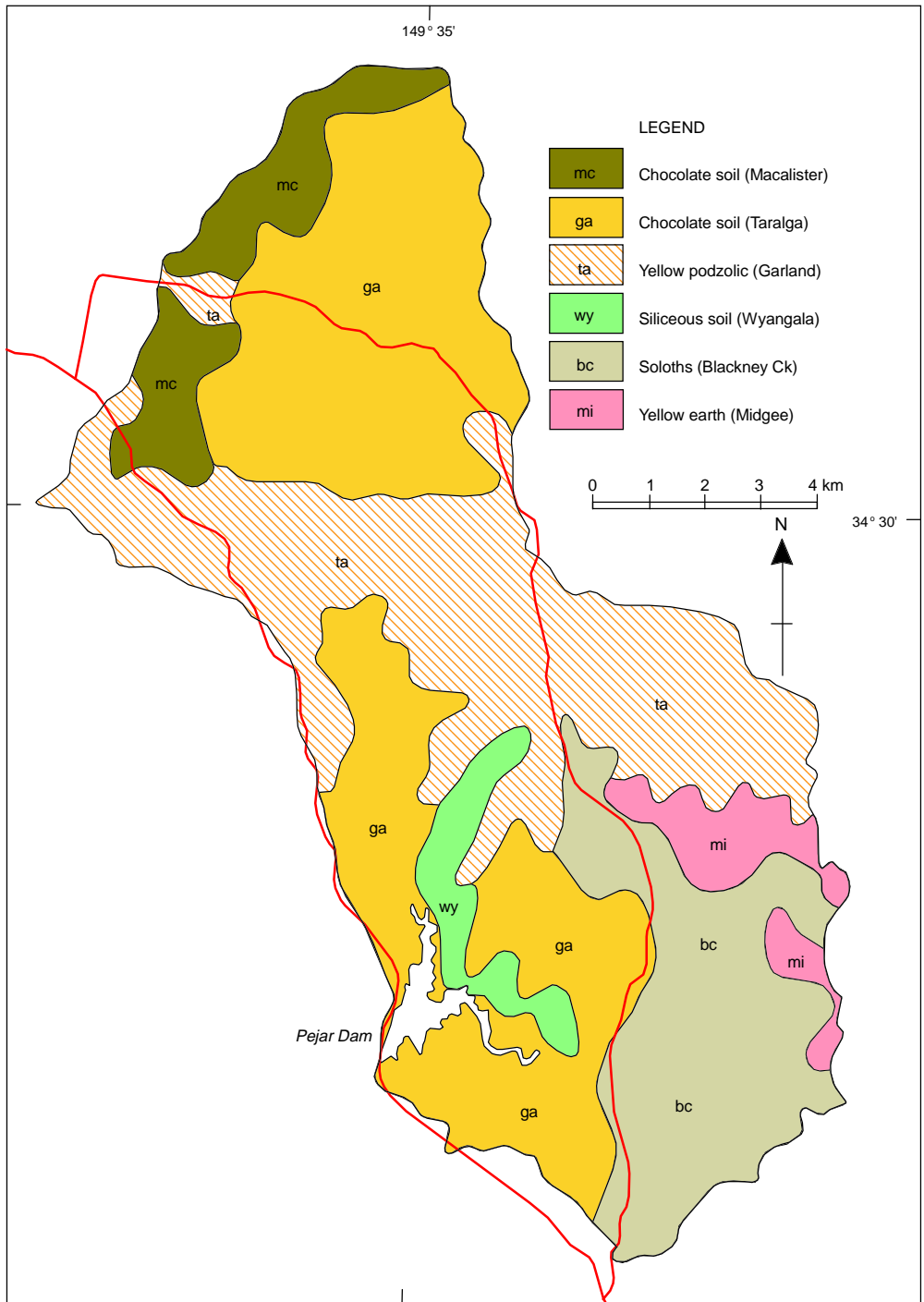
**Table 1.** Soil types in Sooley and Pejar Catchments (ref. 5, Hird, 1991).

Pejar Catchment					
Soil Type	Code	Rock Type	Landform Association	Erosion Hazard	Chemical Fertility
Chocolate Soil	ta	Basalt	Plateau or undulating	Low-Mod.	High
Chocolate Soil	mc	Basalt	Incised plateau	Low-Mod.	Moderate
Yellow Podzolic	ga	Granite	Undulating/rolling hills	Moderate	Moderate
Yellow Earth	mi	Sediments	Hills & rolling hills	Very High	Low
Silicious Sands	wy	Granite	Drainage lines	High	Low
Soloths	bc	Sediments	Undulating hills	Mod-High	Low

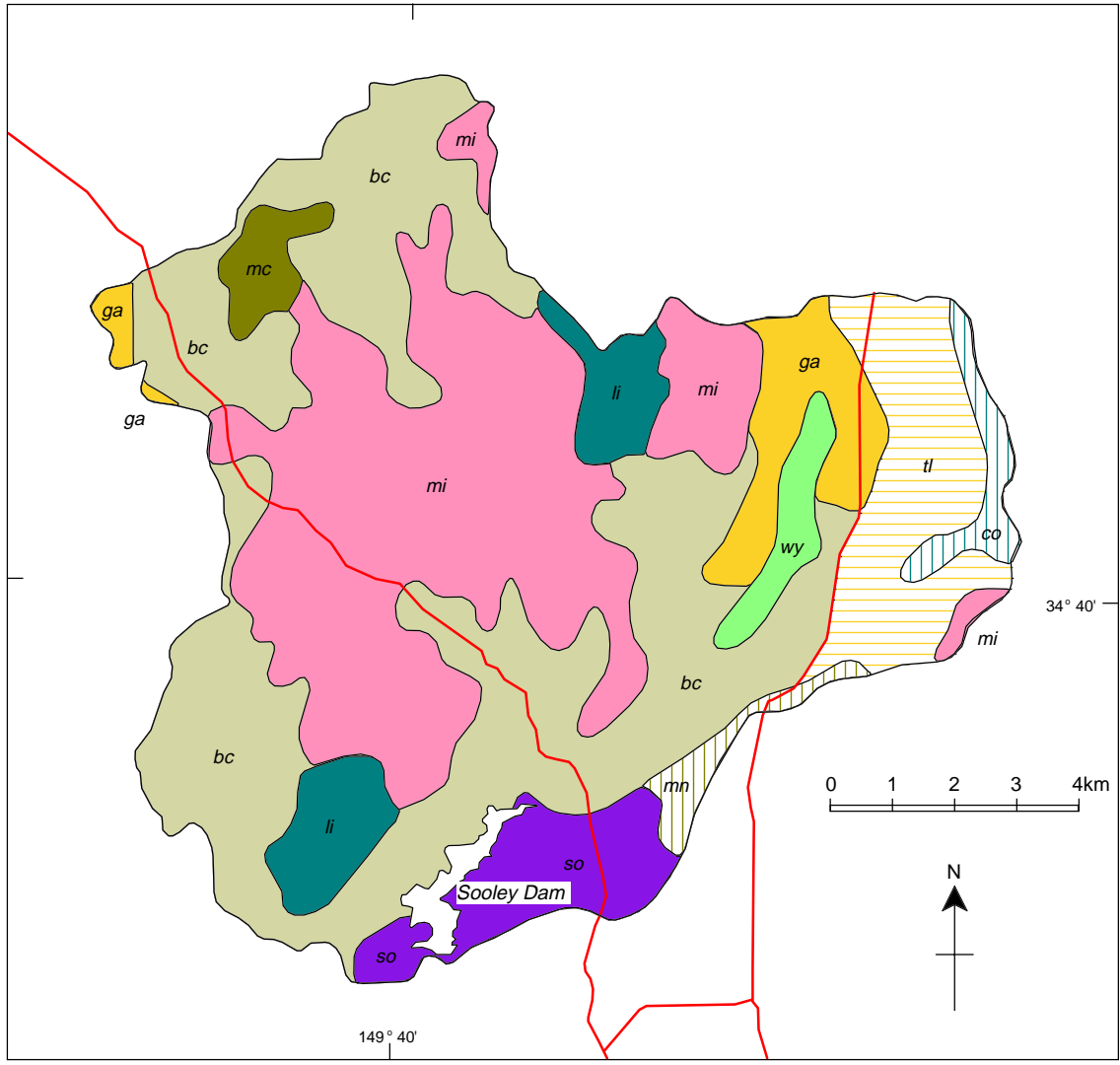
  

Sooley Catchment					
Soil Type	Code	Rock Type	Landform Association	Erosion Hazard	Chemical Fertility
Chocolate Soil	mh	Dolerite	Undulating rises	Low	Moderate
Chocolate Soil	mc	Basalt	Incised plateaux	Low-Mod	Moderate
Yellow Podzolic	ga	Granite	Undulating/rolling hills	Moderate	Moderate
Yellow Podzolic	tl	Sediments	Undulating hills	Moderate	Moderate
Yellow Earth	mi	Sediments	Hills & rolling hills	Very High	Low
Silicious Sands	wy	Granite	Drainage lines	High	Low
Soloths	bc	Sediments	Undulating hills	Mod-High	Low
Shallow Soil	li	Sediments	Steep hills	Extreme	Low
Shallow Soil	co	Sediments	Steep hills	Extreme*	Low*
Prairie Soil	so	Seds/Dol	Rolling hills	Low	High

\* No information, and will be assumed the same as Shallow Soil (li).



**Figure 4.** Pejar catchment soil types (source: Hird, 1991)



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**Figure 5.** Sooley catchment soil types (source: Hird, 1991)

## **2.4 Vegetation**

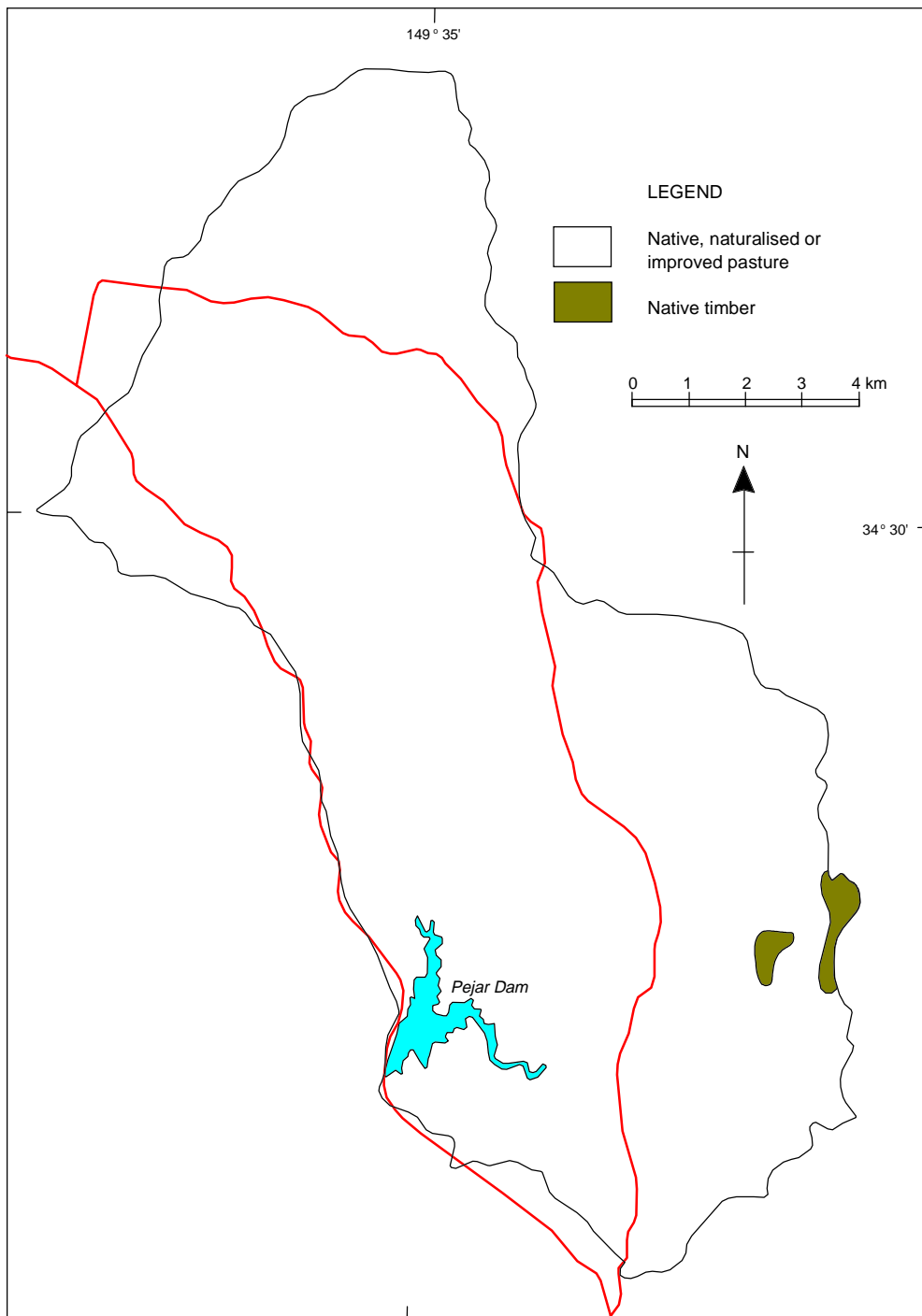
Since European settlement in the 1820's the vegetation has been drastically altered to make way for grazing. This is particularly true for Pejar catchment as only a small area of remnant vegetation remains, along with some scattered timber on farms (Figure 6). Sooley catchment has a greater area of woodland due to its steeper slopes and less fertile soils (Figure 7). Yellow Box/Blakelys Red Gum and Red Stringy Bark/Scribbly Gum communities are found in the Sooley catchment, while Brown Barrel/Ribbon Gum and Snow Gum communities are the remnant vegetation in the Pejar area<sup>4</sup>. Most of the cleared land is dominated by improved pastures. Vegetation, particularly grass cover, has a direct influence on soil erosion.

The break down products of leaf litter and other plant-derived organic matter are a source of nutrients, particularly when this organic matter is washed directly into the water storages. The break down of organic matter by bacteria in the bottom sediments of the water storages consumes oxygen, and significantly contributes to the development of anoxic conditions that facilitate the release of phosphorus from bottom sediment. Therefore the distribution and aerial extent of different vegetation types will be a contributing factor to nutrient delivery to the water storage reservoirs.

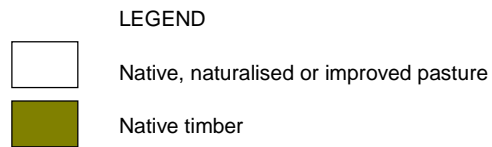
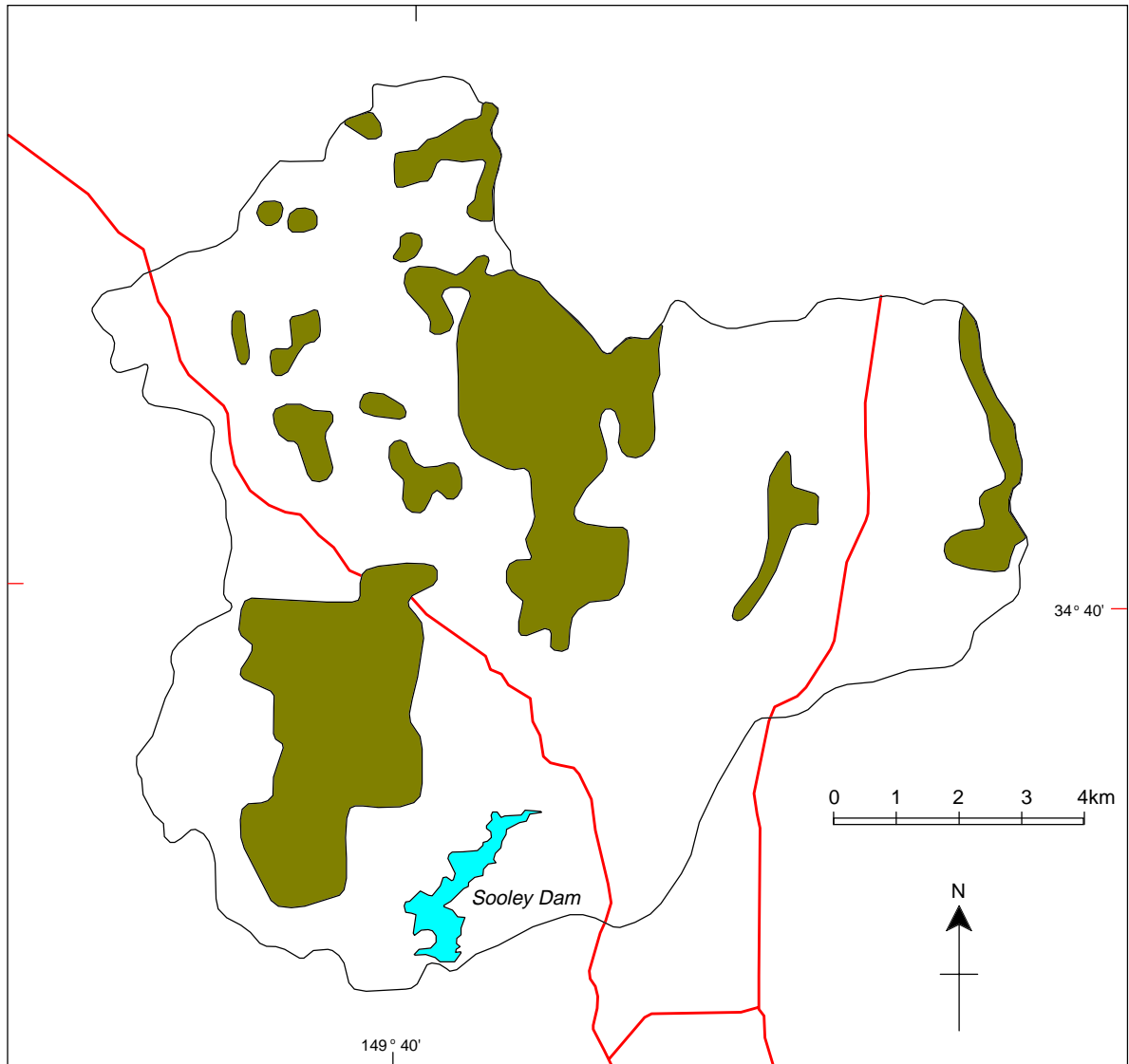
## **2.5 Land Use**

After European settlement in the area, the land was cleared for a range of farming practices. In the 1860's the region was used to grow crops including wheat, oats and barley<sup>7</sup>. It became clear that the climate was better suited to grazing and the predominant activity in the region is sheep/wool growing with some cattle grazing on improved pastures. The Pejar catchment is typified by larger land holdings, while Sooley catchment has a large number of small land holders, especially in the areas close to Goulburn.

Livestock stocking rates will impact on grass cover, which has a direct influence on soil erosion. Direct access by sheep and cattle to channel banks can also adversely affect channel bank stability leading to accelerated erosion. Stocking rates will also directly affect the production of nutrient-rich excrement that may be readily available for transport to the water storage reservoirs during flood events. For these reasons land use has a direct impact on nutrient production and delivery.



**Figure 6.** Pejar catchment vegetation (source: NSW DLWC)



**Figure 7.** Sooley catchment vegetation (source: NSW DLWC)

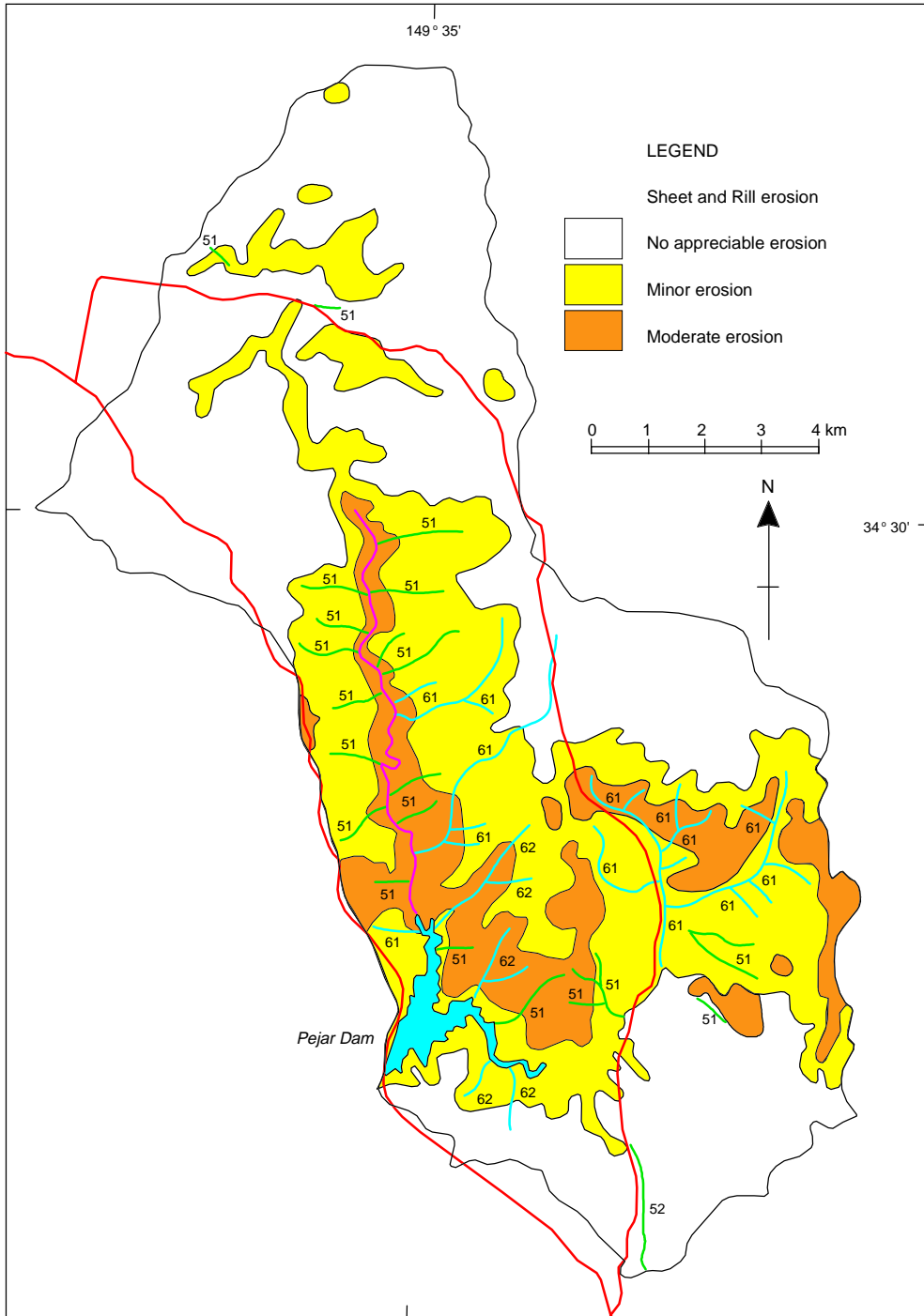
## 2.6 Erosion

Soil erodibility is a major determinant of the type and extent of erosion. In the Pejar catchment there is little identifiable erosion on the gently undulating, fertile basalt country in the north of the catchment. Fifty percent of Pejar catchment is categorised as having minor to moderate sheet erosion potential which mainly occurs in the vicinity of the stream network of the Wollondilly River and Pejar Creek. Stream bank erosion (<1.5 m) occurs along the Wollondilly River, and minor to moderate gully erosion (<1.5 m) is present in minor tributaries of the two stream systems.

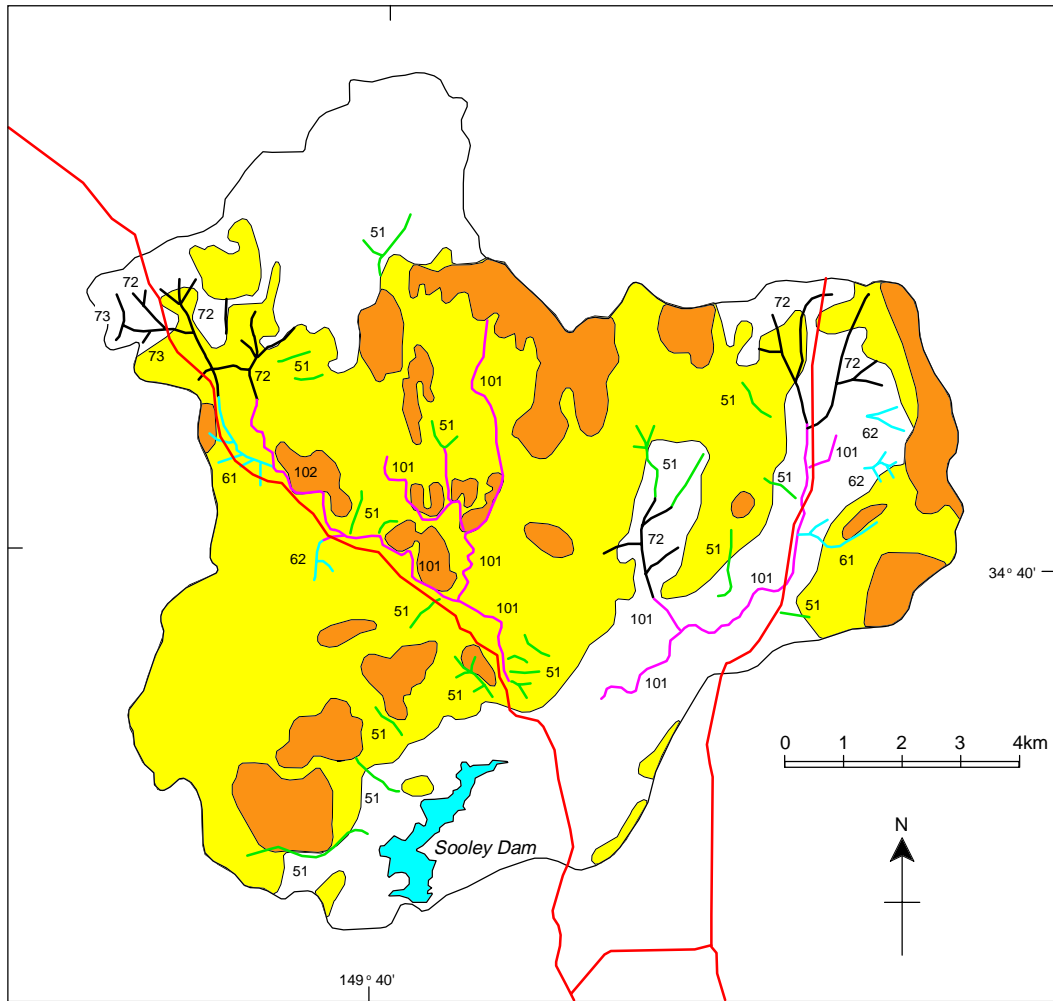
The Sooley catchment has around 60-70% of the area defined as having minor to moderate sheet erosion potential, with the higher risk categories located around the steeper country. Sooley and Bunama Creeks have stream bank erosion in the 1.5-3 m category, and gullying in their tributaries ranging from moderate to severe, reflecting the greater erodibility of the sedimentary rock derived soils.

The erosion maps shown in Figures 8 and 9 indicate the major erosion processes that present at the time when the maps were compiled. However, the maps provide no information about rates of erosion, information that could be used to determine which parts of the catchments sediment originates from.

Eroded soil that naturally contains some phosphorus is normally the principal source of sediment-associated phosphorus. In some circumstances, transported sediment may adsorb dissolved phosphorus from additional sources such as leakage from septic tanks or other sewage discharge. Eroded soil may originate from areas that have enhanced phosphorus concentrations due to the application of fertilizer, or areas that contain naturally phosphorus-rich soil. Determining where the sediment delivered to water supply storages originates from is therefore an important part of developing effective remedial management strategies.



**Figure 8.** Pejar catchment erosion. See Figure 9 for the legend (source: NSW DLWC).



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- Sheet and Rill erosion
- No appreciable erosion
- Minor erosion
- Moderate erosion

**EROSION**

		<1.5m	1.5 - 3m	3 - 6m	>6m	Salting
GULLY EROSION (51-85)	Minor	51	52	53	54	55
	Moderate	61	62	63	64	65
	Severe	71	72	73	74	75
	Extreme	81	82	83	84	85
STREAM BANK EROSION (101-104)		101	102	103	104	

**Figure 9.** Sooley catchment erosion (source: NSW DLWC)

## 2.7 Potential Sources of Phosphorus

The following external and internal sources of phosphorus have been identified as being potentially important to the eutrophication of Sooley and Pejar reservoirs. They are not listed in order of importance.

- *Diffuse Natural Sources.* The erosion of soil that naturally contains phosphorus, and its subsequent delivery to the reservoirs as sediment is a potential phosphorus source, particularly when bottom conditions in the reservoirs become anoxic and reducing. Under these conditions phosphorus will be released from bottom sediment.
- *Fertiliser.* Fertilizer applied to farm land may be washed off directly into streams, or reach the reservoirs by the erosion of fertiliser enhanced topsoil.
- *Livestock.* Phosphorus-rich excrement from sheep and cattle can be deposited directly into stream channels, or washed off catchment grazing land.
- *Aquatic Animals.* Excrement from aquatic animals is a potential source of phosphorus. The presence of a large number of aquatic birds on Sooley and Pejar reservoirs is likely to be a phosphorus source. Fish in the reservoirs may also be a source.
- *Other Possible Sources.* The excrement of wild animals (e.g. rabbits), and leakage from septic tanks are potential phosphorus sources. The break down of leaf litter and other organic matter derived from vegetation are also a source of nutrients.

All of the categories listed above identify potential sources of phosphorus that may be either delivered to, or directly deposited in Sooley and Pejar reservoirs. Stage Two of this study will quantitatively determine the relative importance of these potential sources by developing phosphorus budgets for each of the catchments that determine the size of the stores of phosphorus in the catchments and reservoirs, as well as the extent to which the various catchment stores are delivering phosphorus to the reservoirs.

### **3 Review of Available Data and Reports**

#### **3.1 Water Quality**

There is very little information available in the Goulburn area about sediment delivery and algal blooms, with the main source being the Goulburn City Council's own commissioned reports. The problem of sediment accumulation in Sooley Dam was identified in 1981, but only in terms of reduced storage, turbidity and water treatment. A sediment survey in 1980 showed that the average sediment depth was 2.5 m, reducing the water storage capacity by nearly 20%<sup>8</sup>. This indicates that sediment delivery since the dam was completed in 1928 has been significant.

The management plan for Pejar identified the possibility of algal blooms in the storage when total phosphorus exceeded 0.01-0.02 mg/l. Measurement of water samples from the dam site were 0.11-0.17 mg/l, so it was concluding that eutrophication was a concern at the time of construction<sup>9</sup>.

In 1995 the Department of Works completed a study on the control of cyanobacterial blooms in Sooley and Pejar reservoirs. The report concluded that phosphorus and nitrogen were the two major nutrients causing algal blooms, and that the main source was from free grazing cattle, with some nutrients originating from reservoir bottom sediment<sup>10</sup>. Other potential nutrient sources relevant to the two catchments (e.g. fertilizer and natural soils) were not considered, so a complete assessment of phosphorus sources could not be made. As a consequence, the conclusions reached about nutrient sources cannot be regarded as convincing.

#### **3.2 Anecdotal Information**

Anecdotal information about the catchments has been obtained from landholders and government agencies. The Pejar catchment has a large area of fertile basalt soil in the north, receives higher rainfall, and the tributaries to the dam are fed by a spring system which means that they flow for most of the year. The Sooley catchment differs in that it has a greater area under native timber, more erodible soils, and a greater number of smaller land holdings due to its proximity to Goulburn. Another feature of the Sooley catchment is that runoff occurs quickly during rainfall events (NSW DLWC).

The DLWC is constantly addressing soil erosion in both catchments on a property by property basis. In the late 1980's the Pejar Soil Conservation Project was completed to

treat sites of active erosion (except for stream bank erosion) in the Pejar catchment. Landholder funds were matched dollar for dollar to address erosion by such methods as the building of farm dams and flumes, fencing out hazard areas, and the application of fertiliser to increase ground cover.

Representatives of the NSW Department of Agriculture noted the declining use of superphosphate fertiliser in the region. At the turn of the century, the area was running around 1 dry sheep equivalent (DSE) per ha. After the advent of pasture improvement in the 1950's, fertiliser application rose to a peak in the late 1960's of a bag (50 kg) per acre. Stocking rates reflected this fertiliser usage with a range of 8-12 DSE per ha, and up to 15 DSE per ha on the more fertile basalt soils. The decline in fertiliser use followed the fall in wool prices from the early 1970's to a situation today where regular broad acre application is uncommon.

When asked about the possible sources of phosphorus entering the water storage reservoirs, all agency representatives agree that fertiliser has wrongly been identified as the principle source. They note recent work in the Chaffey Reservoir catchment where natural diffuse sources were identified as the main source of phosphorus.

The regions landholders that we spoke to confirmed the low rates of fertiliser application, and shared the government agencies view that fertilisers had been incorrectly blamed for algal blooms in the reservoirs. The primary focus of the regions farmers was profitability in a harsh economic environment, but all agreed that combating erosion was important for the long term sustainability of their enterprises.

One event that most landholders recall was the drought of the early 1980's. Some said that this ranked along with the drought of 1941 as the worst in memory. They also recalled the storms that broke the drought and the resulting erosion of bare pastures, and the washing of manure into their farm dams.

Further anecdotal information is being collected and this will be reported fully in the final Stage Two report. Where fertilizer application rates are quantitatively known, soil profile measurements will be made on different soil types to determine if phosphorus concentrations have increased in the topsoils.

## 4 Water Quality Monitoring

A water quality monitoring program at Pejar and Sooley dams was implemented as part of this study in October 1997. The monitoring will show the changes that occur to these water bodies over a summer cycle when an algal bloom may be expected to occur. Raw water and 0.2  $\mu\text{m}$  filtered samples were collected on a weekly basis. The water samples were taken from the major tributaries to the two reservoirs, the dam outlets, and close to the dam walls 1 m from the surface and bottom of the two reservoirs. Due to the prevailing drought conditions the major tributaries stopped flowing soon after monitoring began.

Measurements of total phosphorus, sulphate, suspended solids, iron, manganese, and electrical conductivity were made on the raw water samples. Filterable reactive phosphorus (FRP, approximately equivalent to bioavailable phosphorus) was measured on the 0.2  $\mu\text{m}$  filtered water samples. Dissolved oxygen and water temperature was recorded in the reservoirs with a Hydrolab.

### 4.1 Results

#### 4.1.1 Filterable Reactive Phosphorus

FRP measurements are a close approximation to the component of phosphorus that is available for algal growth, so it is a good indicator of whether this nutrient is likely to limit algal blooms. Figure 10 shows FRP measurements from the water samples collected at weekly intervals between mid-October 1997 and the end of January 1998 from Sooley and Pejar reservoirs. The few data available from the tributary streams have relatively low concentrations, averaging 3.3  $\mu\text{g/l}$  for the Sooley tributaries and 4.4  $\mu\text{g/l}$  for the Pejar tributaries. Average near-surface values (3.2  $\mu\text{g/l}$  and 2.9  $\mu\text{g/l}$  respectively) are similarly low.

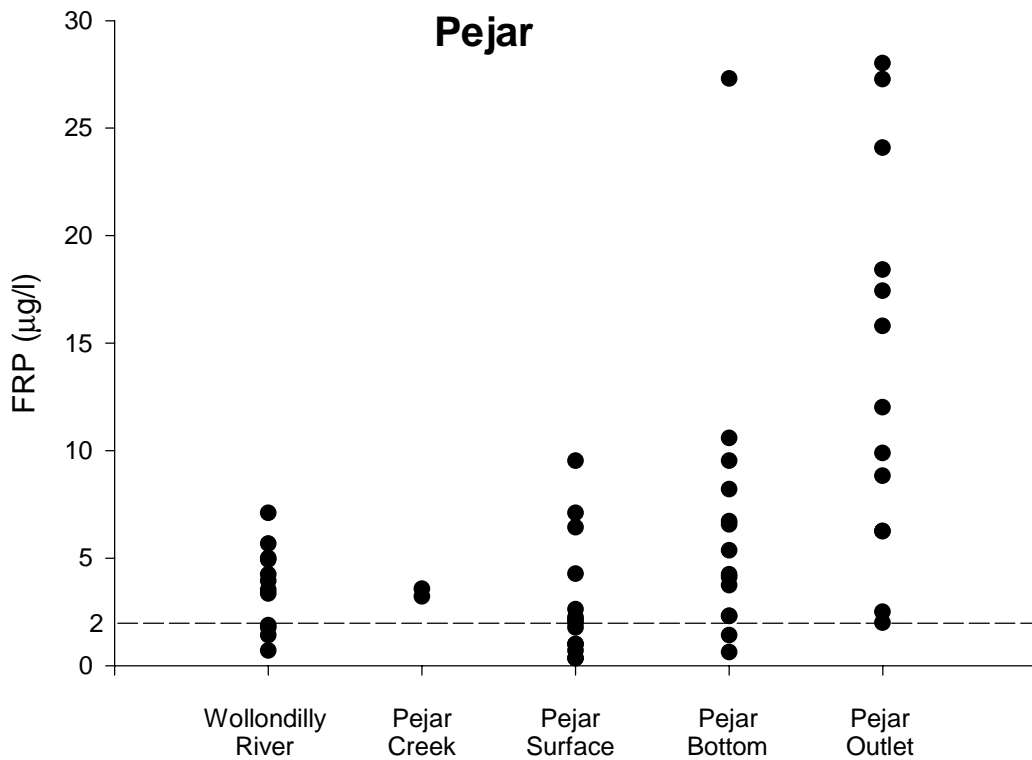
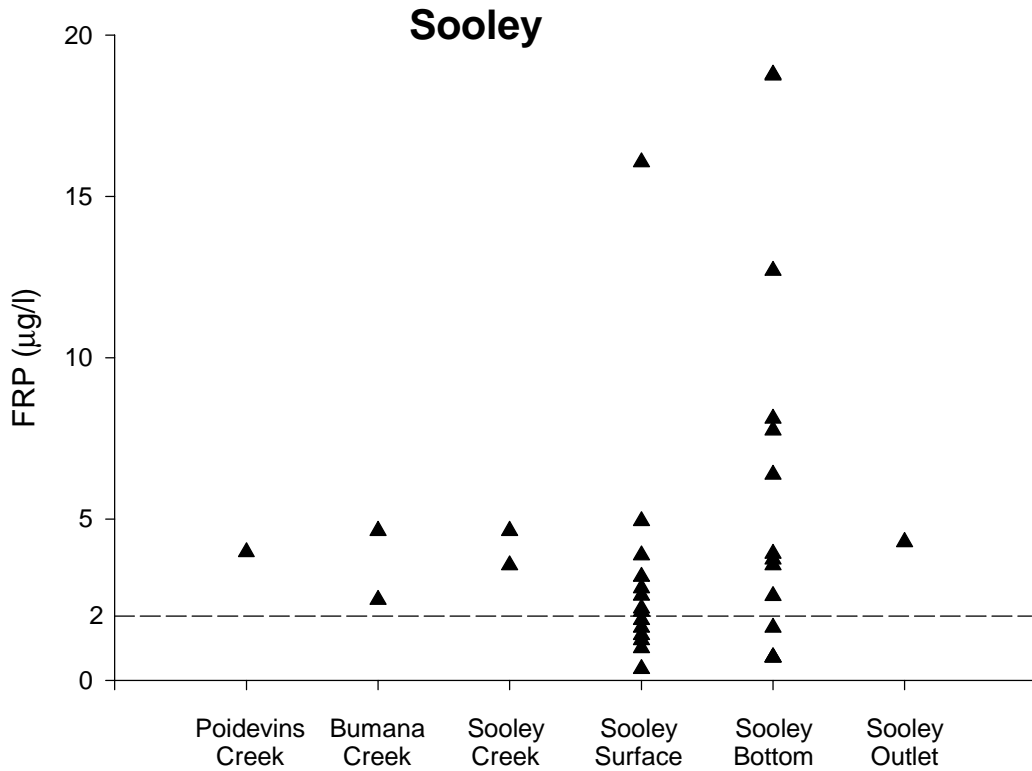
Water column measurements taken on 15 January 1998 show that Sooley Reservoir is highly stratified in terms of temperature and dissolved oxygen. FRP and total manganese values are also high in the bottom water (Figure 11). By contrast, the Pejar water column measurements show weak stratification, with FRP and total Mn values having no consistent trend with depth, and being much lower than they are at Sooley Dam. These results show that the relatively high bottom water FRP values in Sooley Reservoir during the monitoring period (mean value, 6.4  $\mu\text{g/l}$ ) are due to the release of phosphorus from the

bottom sediment. At Pejar, where the stratification is weaker, the bottom water FRP values that are still relatively high, with a mean value of 6.6 µg/l (Figure 10).

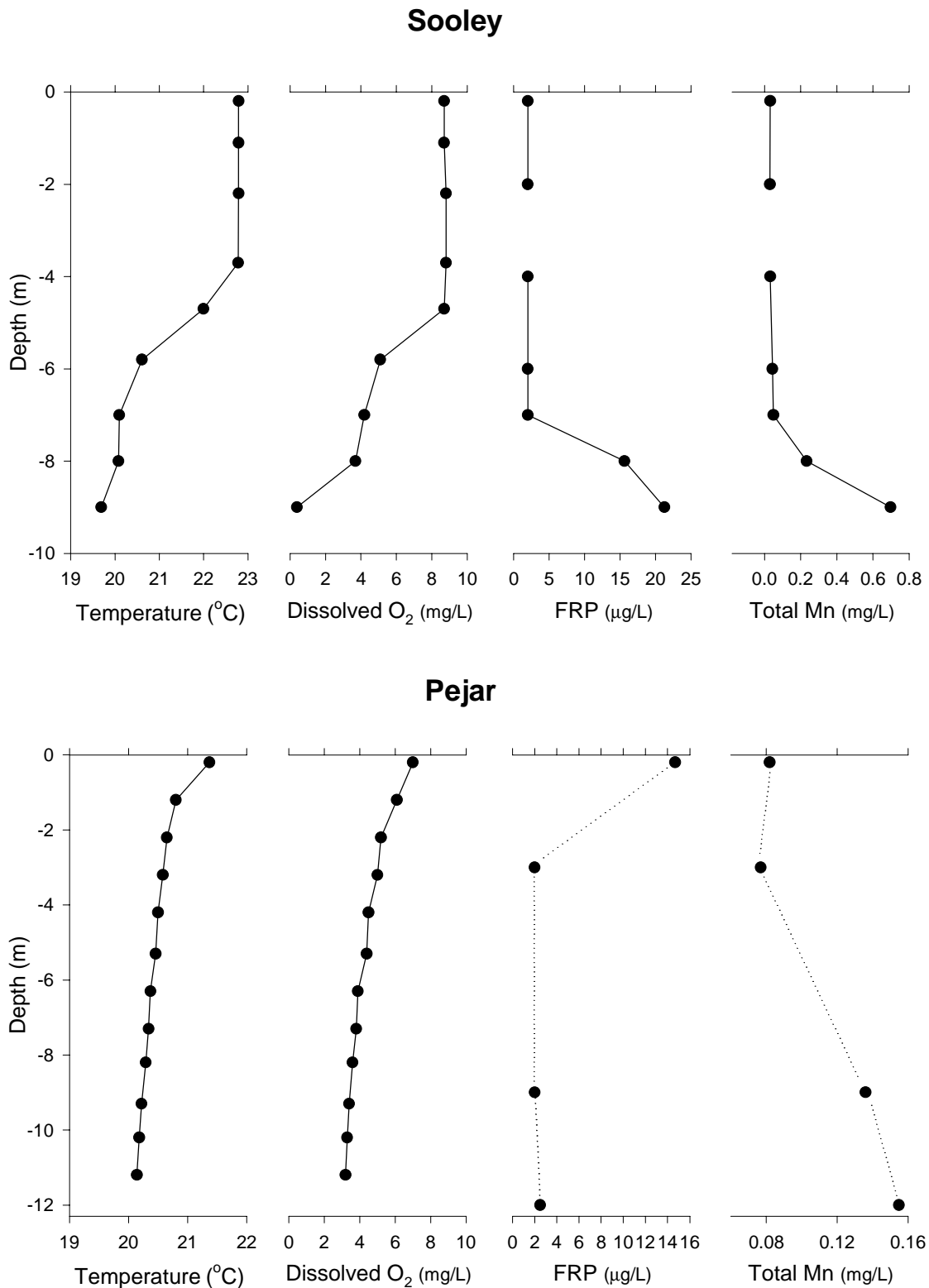
An anomaly at Pejar Dam is the relatively higher average FRP value in the outlet water (13.6 µg/l). This may be due to water being released from near the bottom of the off-take tower, however, this is also where monitoring in the reservoir is done, so it would be expected that the results from the near-bottom and outlet waters would be very similar. No explanation can be given for this anomaly at this stage.

Figure 12 shows FRP values plotted against time. The near-bottom values are consistently higher than the near-surface results, with higher peaks that probably indicate the onset of stratification in Sooley Reservoir in mid-November. The situation at Pejar is not so clear, with only one relatively elevated bottom value present.

The average near-surface and near-bottom FRP values from both reservoirs are relatively low, less than the 10 µg/l limit regarded as likely to limit excessive algal growth<sup>11</sup>. However, even at these relatively low levels there is still sufficient bio-available phosphorus present to support blue-green algae (cyanophyta) populations large enough to adversely affect potable water quality (i.e. >15,000 cells per millilitre). This is shown by the high cyanophyta counts that have occurred in both reservoirs in January and February (up to 105,000 in Sooley Reservoir, Goulburn City Council data).



**Figure 10.** Filterable reactive phosphorus data from Sooley and Pejar reservoirs sampled between mid-October 1997 and the end of January 1998. The horizontal dashed line is the limit of analytical detection, so all values below the line should be regarded as  $<2 \mu\text{g/l}$ .



**Figure 11.** Temperature, dissolved oxygen, FRP, and total manganese profiles from Sooley and Pejar reservoirs sampled on 15 January 1998. Strong thermal stratification is established in Sooley Reservoir with high FRP and total Mn values in the bottom water. Pejar Reservoir is weakly stratified with no consistent trends in the FRP and total Mn values.

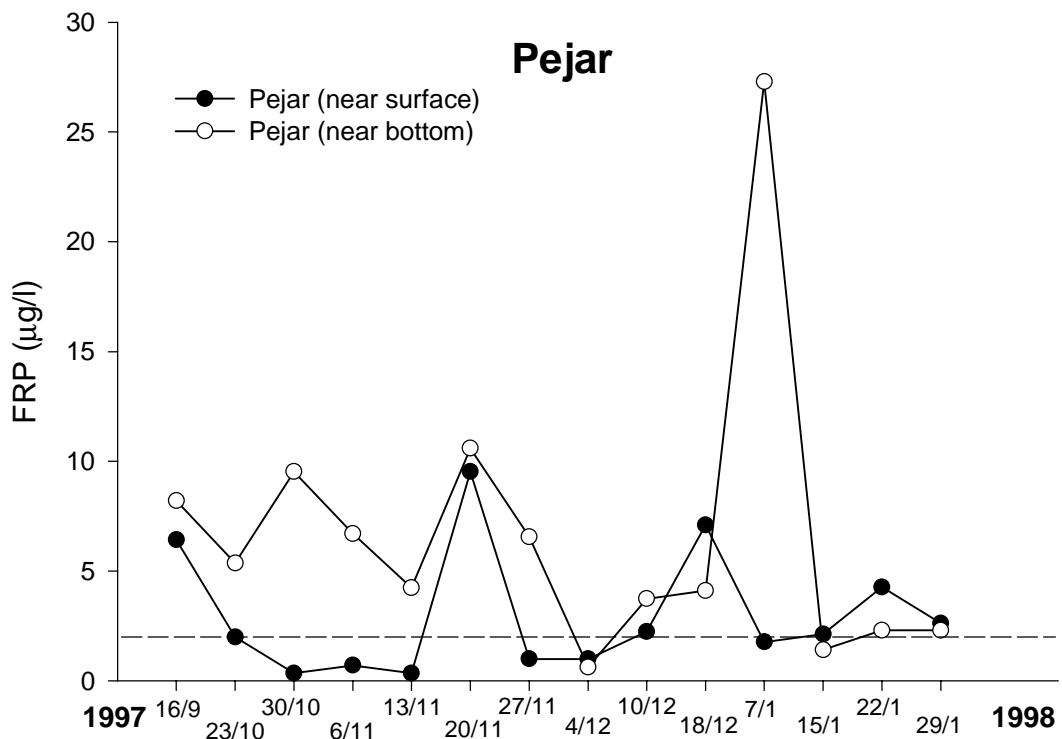
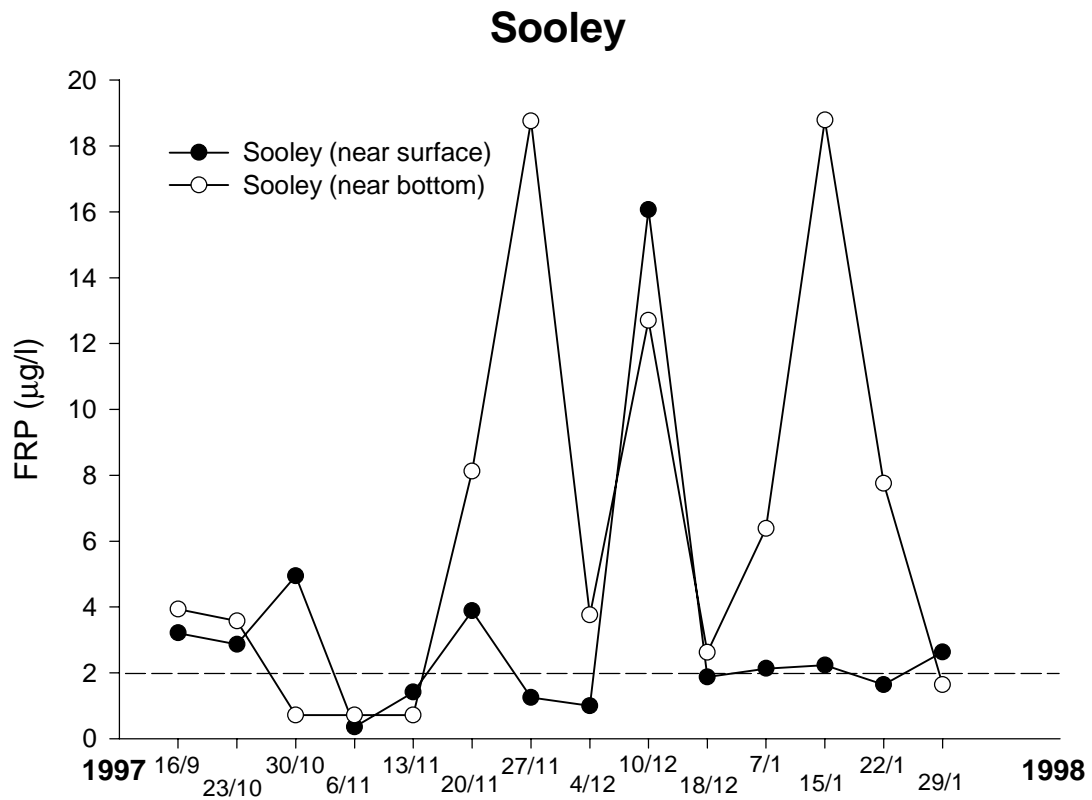
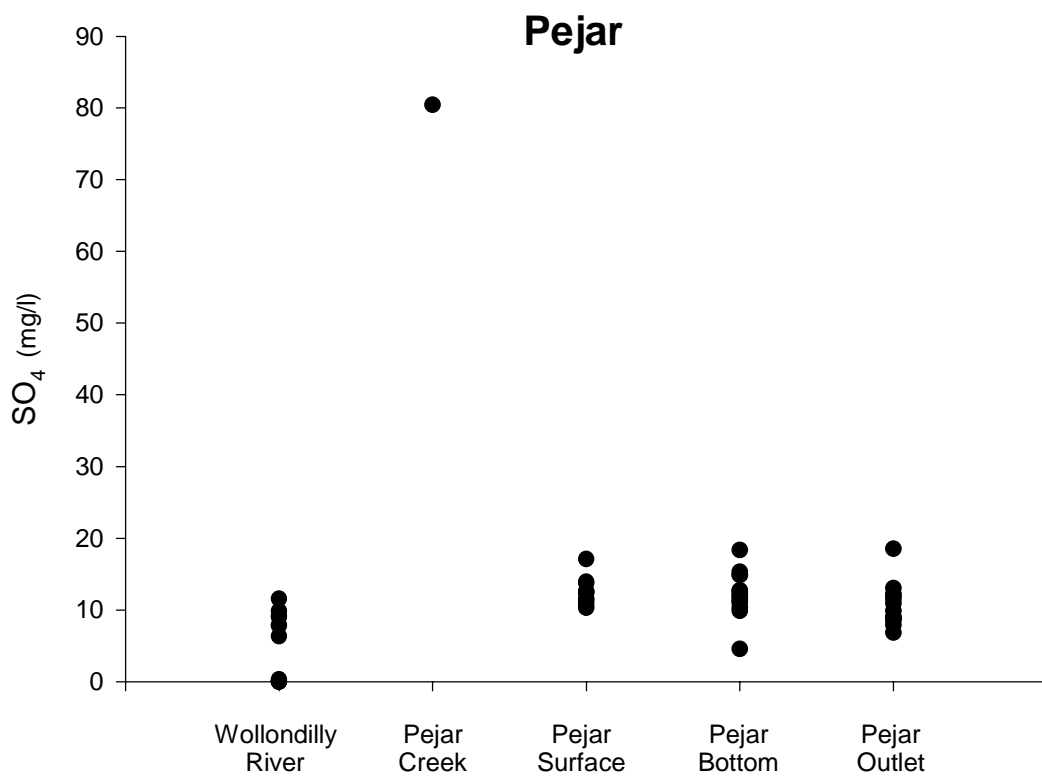
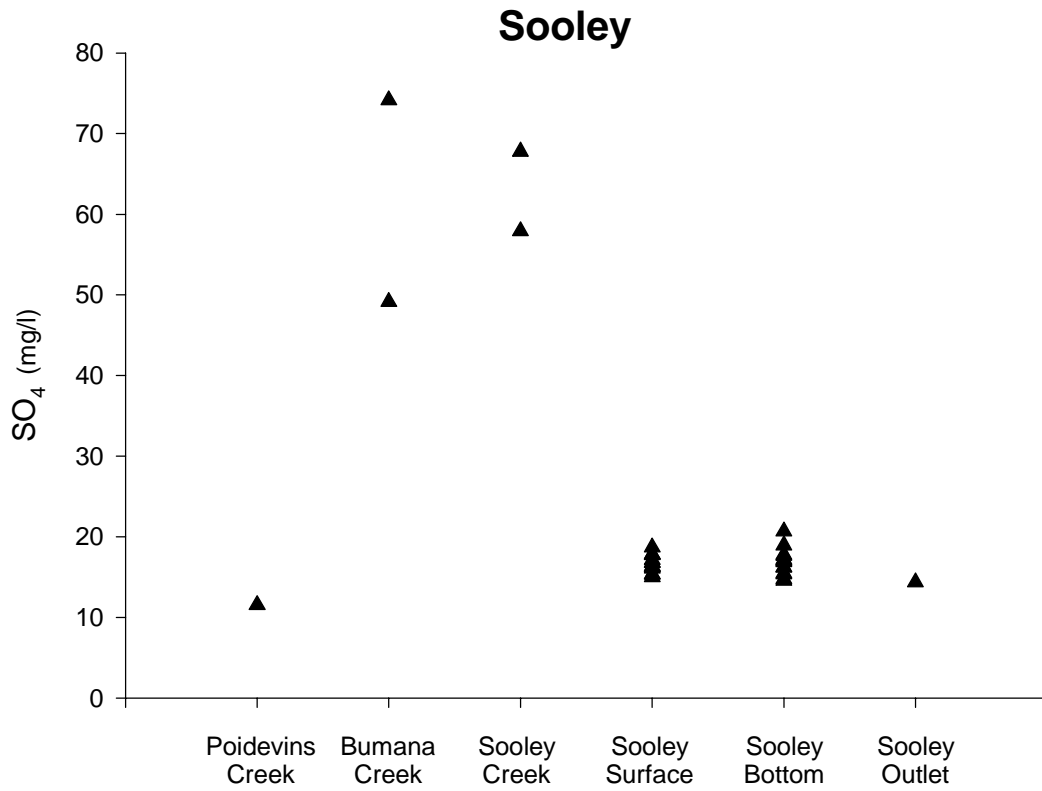


Figure 12. Near-surface (1 m depth) and near-bottom (1 m above the bottom) FRP values from Sooley and Pejar reservoirs plotted against sampling date (16 October 1997 to 29 January 1998).

#### *4.1.2 Sulfur Data*

Sulfur is not a major algae nutrient, but its role in reservoir eutrophication is important because it is required by sulfate reducing bacteria that may be active in reservoir bottom sediment. The sulfate reduction process produces sulfide that is able to chemically reduce Fe(III) oxides to Fe(II), a processes that can remove surface-bound Fe from sediment particles. This causes a concurrent release of Fe bound phosphorus into the sediment pore water. The dissolved P can then diffuse into the overlying bottom water, and so become available for algal growth.

The monitoring data (Figure 13) from both reservoirs have similar average values in the surface and bottom water (16.7 mg/l and 16.9 mg/l at Sooley, 12.3 mg/l and 12.2 mg/l at Pejar), and at the Pejar outlet (10.6 mg/l). The relatively high values in the few results available from Bumana and Sooley creeks, and one value from Pejar Creek, may indicate that a significant amount of sulfur is being delivered from these tributaries, however, there is not enough data to be certain about this. Concentrations in the Wollondilly River at Pejar are relatively low, but these results need to be converted into loads (i.e. kg) when flow data are available to determine the total amount delivered. Results from a range of flow conditions are required to get a better understanding of which tributaries are contributing sulfur to the reservoirs, and in what quantities.



**Figure 13.** Sulfate data from Sooley and Pejar reservoirs sampled between mid-October 1997 and the end of January 1998.

### 4.1.3 Nitrogen Data

Nitrogen monitoring is outside the scope of this study, however, as a nutrient nitrogen is important for algal growth, and may at times be a growth limiting nutrient if concentrations are low. Water samples have been collected by the Goulburn City Council's engineering staff on four occasions from the beginning of December 1997 at fortnightly intervals for nitrogen measurements. Despite this limited amount of data, some observations can be made.

Most of the nitrogen in Pejar and Sooley water is in organic form. However, the dissolved inorganic forms, nitrate, nitrite and ammonia, are of special interest because these forms are an available source of N for algal growth. In particular, ammonia can be used directly by blue-green algae (cyanobacteria). Ammonia is formed in the pore-water of bottom sediments by the microbiological breakdown of organic N. It can then diffuse into the water column where it is readily oxidised to nitrite and nitrate in the presence of oxygen. However, in deoxygenated water ammonia will persist, and depending on factors such as its proximity to the surface, water column mixing, and the penetration of light, it will be available for algal growth.

Elevated levels of ammonia were present in the bottom water of Sooley on January 15 and February 19, 1998, and Pejar on January 30 and February 12 and February 19. Depth profile measurements show that Sooley was thermally stratified on January 15, with low dissolved oxygen (DO) levels in the bottom water and high FRP concentrations (see Figure 11). No DO readings were taken at Pejar on January 30, but low DO concentrations were measured in bottom water in early January and February. However, high ammonia concentrations are not correlated with high FRP in Pejar. The lack of a relationship between these nutrients may be related to preferential uptake of one of these nutrients by algae, and/or the possibility of a different rate of replenishment of ammonia and FRP to the water column from bottom sediments.

In general measurements of oxidised nitrogen (nitrate and nitrite) are at, or near detection levels (0.01 mg/l). The exception is the Pejar outlet sample on 30 January, which had a nitrate concentration of 0.1 mg/l. This sample also had high ammonia and FRP concentrations. More data are required to determine possible trends and relationships in the nitrogen results.

## 5 Sediment Source Tracing

Sediment tracing methods will be applied in Stage Two of the study to determine the sources of sediment delivered to Sooley and Pejar reservoirs. An initial sampling program was carried out to determine if the spatial tracing techniques can distinguish sediment derived from the major rock types in the two catchments. The spatial tracing methods make use of the natural chemical and magnetic mineral properties of soils developed on different rock types to fingerprint the sediment produced from these areas. The results of the initial sampling program are summarised in this section.

### 5.1 Sampling and Measurements

The Sooley and Pejar catchments were sampled on the basis of the major rock types as shown in Figures 2 and 3. Sediment samples were collected from farm dams that drain sub-catchments that only contain soils developed on a major rock type. These farm dams have probably been accumulating sediment over a number of years, and so may provide some temporal representation. Farm dams were selected to ensure that they only drained an area containing one rock type based on the 1:250,000 geology map, however, it is recognised that this coarse scale mapping does not contain enough detail to be certain about the soils' parent rock type in some areas.

All of the sediment samples were fractionated to recover the <10 µm fraction (clay and fine silt). Fractionation is necessary because most of the sediment in the reservoirs is very fine, so the properties fine sediment from the catchment must also be measured so that a direct comparison can be made. Also, most sediment-associated phosphorus is likely to be associated with Fe that is chemically bound to the surface of clay and fine silt particles.

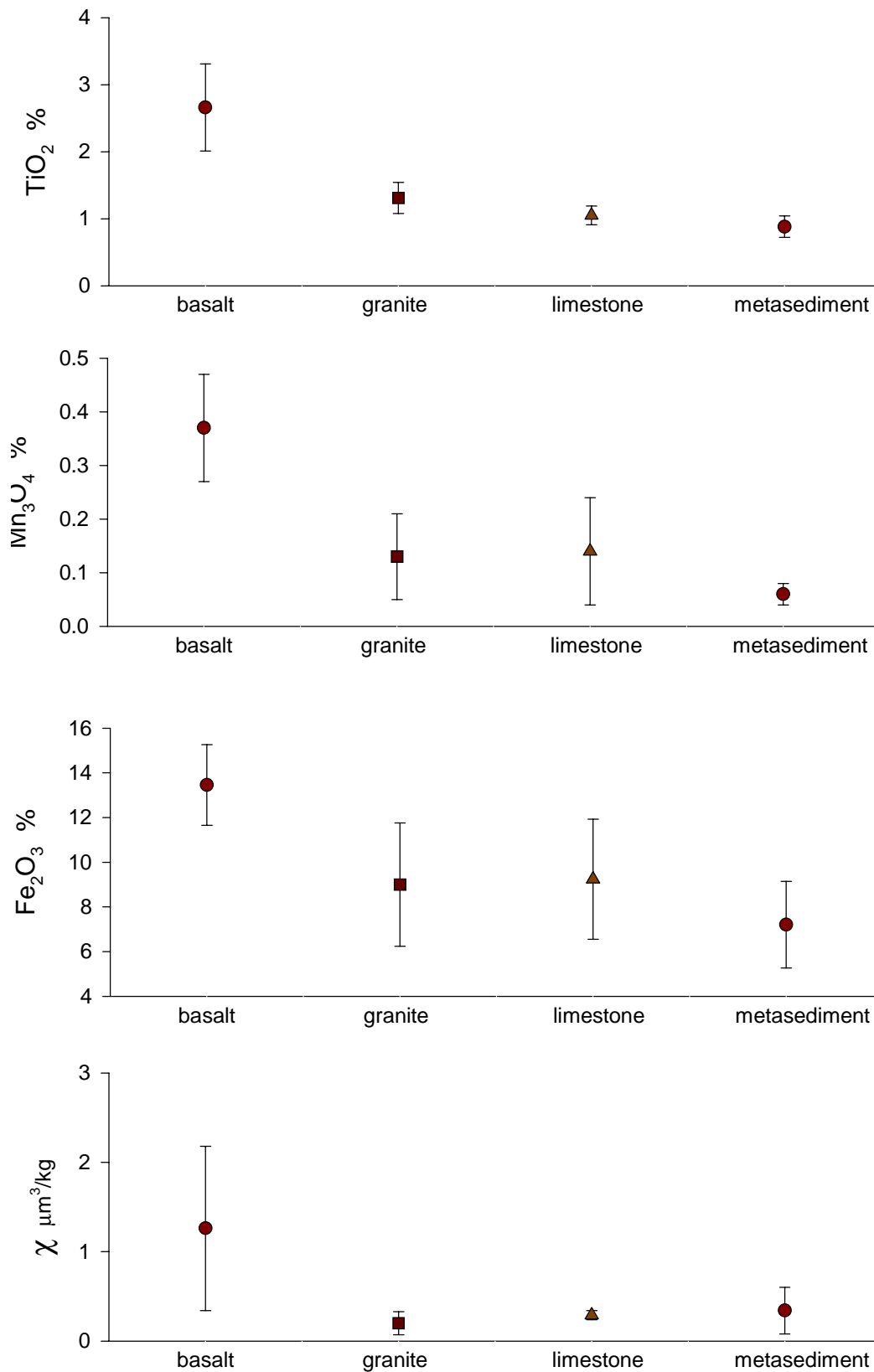
The major element concentrations of the <10µm fraction of the sediment samples were determined by X-ray fluorescence (XRF)<sup>12, 13</sup>. The properties of naturally occurring magnetic minerals were also measured<sup>14</sup>. In combination, these measurements provide the best way of fingerprinting the properties of soils developed on different rock types. These properties will be used later in the study to determine where in the catchments the sediment in the reservoirs originates from. In Stage Two of the study radionuclides that label surface soil will also be measured to find out what proportion of the reservoirs' sediment comes from surface soil (e.g. sheet and rill erosion), and subsoil (e.g. gully and channel bank) erosion.

## 5.2 Results

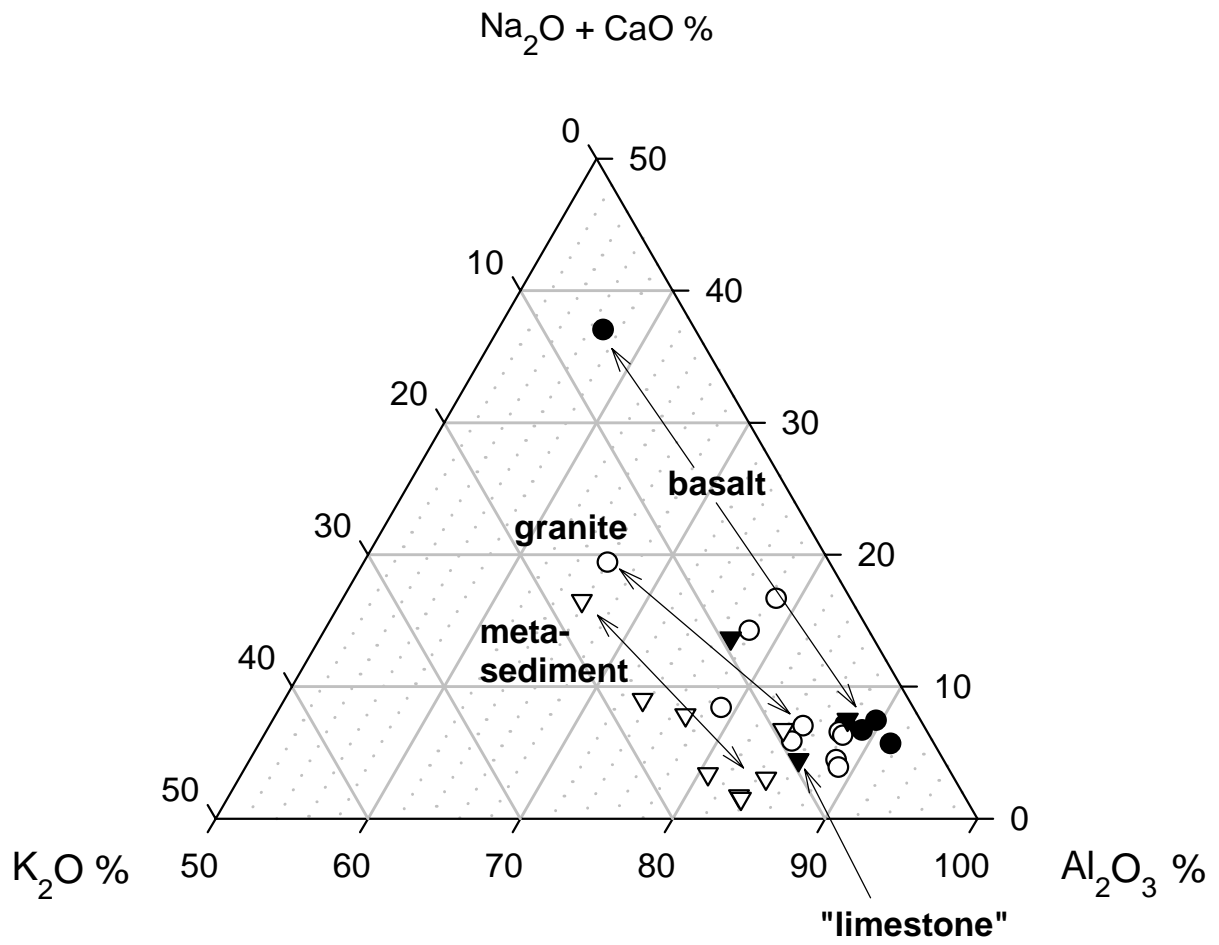
Mean values of three major elements (titanium, manganese and iron), and magnetic susceptibility ( $\chi$  is a measure of the amount of magnetic minerals present in a sample), are shown in Figure 14. Sediment derived from basalt soils have values that, on average, are higher than those derived from the other major rock types.

While the properties shown in Figure 14 are able to distinguish basalt derived sediment, they are not able to distinguish sediment originating from the other major rock types. To do this we have used combinations of major elements that reflect the chemical composition of distinctive minerals. Figure 15 is a ternary diagram that plots aluminium, potassium, and sodium plus calcium, elements primarily contained in the clay and feldspar components of sediment. The sediment data from soils derived from basalt, granite, and metasedimentary rocks plot from right to left in the diagram, indicating good discrimination. The sediments that supposedly originate from limestone areas of Sooley catchment are not well distinguished. This may be because these soils are a mix of material derived from other parts of the catchment, or that there is very little limestone derived soil in the catchment.

The results show that there is a basis for discriminating sediment derived from soil formed on different rock types. A much more detailed sampling will be undertaken in Stage Two of the study that will provide results that can be used to determine the major spatial sources of sediment delivered to Sooley and Pejar reservoirs. Radiometric data have also been obtained from the NSW Department of Mineral Resources that will enable the mapping of variation in soil types in much more detail. This will allow us to target our sampling on the basis of soil and rock type differences much more accurately.



**Figure 14.** Average titanium, manganese, iron, and magnetic susceptibility values from sediment sampled in Sooley and Pejar catchments showing relatively high basalt concentrations.



**Figure 15.** Geochemical composition of sediment derived from soils developed on different rock types in Sooley and Pejar catchments.

## 6 Phosphate Release Experiments

Bottom sediments from Sooley and Pejar reservoirs were sampled to examine the release of phosphorus under oxygenated (oxic) and de-oxygenated (anoxic) water conditions. The aim is to compare the rates of phosphorus release from bottom sediments into oxic and anoxic water columns, the latter condition occurring when thermal stratification is established during summer months when cooler bottom water is contained under a layer of warmer surface water. Under these conditions microbial activity consumes the available oxygen in the bottom water and sediment, resulting in anaerobic conditions that facilitate the diffusion of dissolved phosphorus from bottom sediment pore water.

### 6.1 Method

Bottom sediment samples were double bagged to prevent oxidation arising from the diffusion of oxygen through the walls of the bag. A plastic bag containing the sediment was placed inside another bag containing the same sediment. Sediment from the inner bag was used in the experiment. Approximately equal amounts of sediment from Sooley Reservoir was placed at the base of two 1.2 litre glass cylinders. The cylinders were carefully covered with water from the reservoir, and the cylinders stoppered. The weights of water and sediment were recorded. Air was gently bubbled through one cylinder to maintain oxic conditions and to aid mixing of the water column. Nitrogen was gently bubbled through the other cylinder for a short time each day to help purge oxygen from the water to help attain anaerobic conditions, and to aid mixing. This procedure was repeated for sediment from Pejar Dam.

Water samples were taken at regular intervals, filtered through 0.2  $\mu\text{m}$  membrane filter, and analysed for filterable reactive phosphorus (FRP). Water was replaced to keep the volume approximately constant. For the anaerobic experiments, the replacement water had been deoxygenated by boiling and bubbling with nitrogen during cooling. All cylinders were kept in a darkened room at 15° C .

### 6.2 Results and Discussion

The change in FRP concentration of Sooley and Pejar water with time is shown in Figure 16. Initial FRP concentrations in all cylinders were around 3  $\mu\text{g/l}$ . The water in the oxic cylinders of both Sooley and Pejar sediments (open symbols) shows an overall gradual increase in FRP, to 8 and 16  $\mu\text{g/l}$  respectively after 20 days. The FRP of the

anaerobic Pejar water column increases rapidly over the first 10 days to a maximum value of 66 µg/l, before decreasing slightly.

The anaerobic Sooley water column also shows a rapid initial increase of FRP to 30 µg/l, but then fluctuates between 10 µg/l and 35 µg/l. The reason for the fluctuations in the FRP concentration of the anaerobic Sooley column may be due to a leak in the cylinder cap, with the introduction of a small amount of oxygen during the removal of water samples.

The sediment added to the cylinders was initially dark grey to black in colour, indicating that it was in a chemically reduced state. However, the sediment in the oxygenated cylinders rapidly attained a light-brown coloured surface layer, about 3-4 mm thick. This layer almost certainly corresponds to a layer of oxidised sediment, containing iron and manganese oxy-hydroxides. These Fe and Mn compounds are well known for their ability to adsorb dissolved ions, and their presence at the sediment-water interface would inhibit the diffusion of nutrients into the water column, and probably accounts for the low FRP concentrations in the oxic water columns.

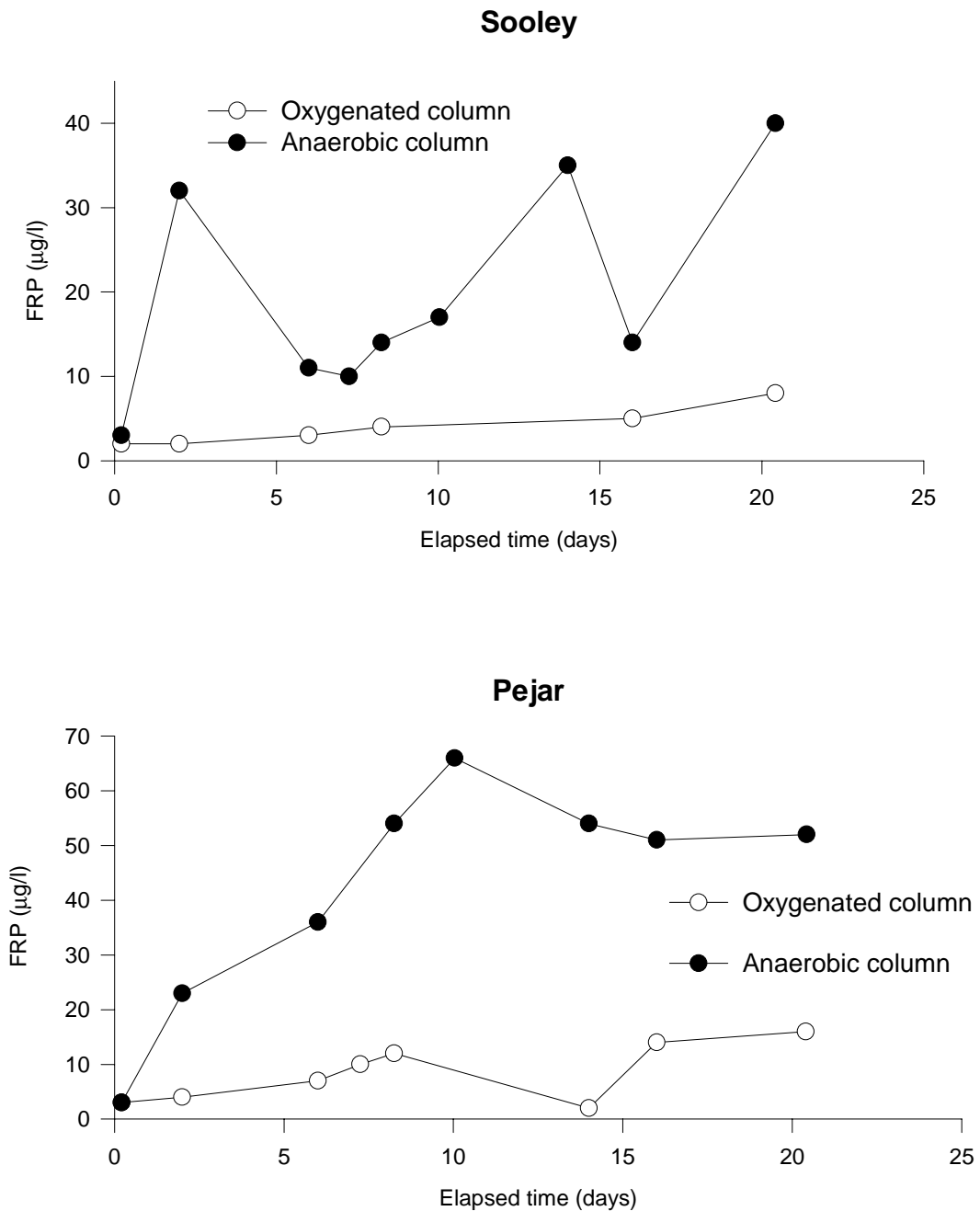
By contrast, the oxidised layer in the anaerobic cylinders was almost nonexistent, allowing phosphorus to diffuse freely from the sediment pore water into the overlying water. This is reflected in the much higher FRP concentrations in the anaerobic cylinders. The FRP content of the anaerobic Pejar sediment apparently reached an equilibrium value after about 10 days. It is also noted that the P concentration increases gradually in the oxygenated cylinders due to slow diffusion of phosphorus in the sediment pore water.

Another obvious difference between the oxygenated and anaerobic cylinders was the turbidity of the water. The anaerobic water columns both had brown turbidity, probably due to the precipitation of dissolved Fe and Mn that had accumulated in the water. The Fe and Mn probably originated from sediment-bound Fe and Mn that was released into the pore water as a result of the reducing conditions in the sediment. The dissolution of Fe and Mn in sediments is a precursor to the release of sediment-bound phosphorus into pore water.

### **6.3 Conclusion**

Anaerobic conditions at the sediment-water interface expedites the diffusion of dissolved phosphorus from sediment pore water into the water column. This process is a

pathway for the release of nutrients such as phosphorus into de-oxygenated bottom waters in a stratified water body. These nutrients may be brought to the surface when overturn occurs and the thermal stratification breaks down in Sooley and Pejar reservoirs. At this stage the nutrients become readily available for algal growth.



**Figure 16.** Phosphorus release experiment results using sediment sampled from Sooley and Pejar reservoirs.

## 7 Conclusion

In Stage One of the study to determine the sources of phosphorus in Sooley and Pejar reservoirs we have identified several possible natural and human-related sources including fertilizer, livestock, aquatic animals, natural phosphorus in soils, and other sources such as organic litter. Stage Two of the study will develop a phosphorus budget to quantify the contributions of these potential sources to the water storage reservoirs, including estimates of the rates of delivery.

As part of the first stage, an assessment has been made of the characteristics of the water supply catchments including, geology, soils, vegetation, land use, and erosion. All of these elements influence the production and delivery of phosphorus to the water storages, providing a framework of basic information necessary to carry out Stage Two of the study. Part of this information framework includes anecdotal and quantitative information obtained from landholders and government agencies, such as fertilizer use, stocking rates, erosion control, and climate data. More detail about these aspects of the catchments will be obtained in Stage Two.

Very little consistent water quality data was available prior to this study. A monitoring program was implemented in October 1997 to measure key water quality parameters through a summer season, and determine the extent of thermal and chemical stratification in the water storages. The monitoring has been successfully carried out in the reservoirs, but the prevailing drought conditions have caused the tributaries to dry up, which means that important information about phosphorus delivery to the water storages is not available.

The results of the water quality monitoring show that bio-available phosphorus is being released from bottom sediment in the reservoirs, and while concentrations are not high, there is sufficient phosphorus available to sustain high numbers of blue-green algae (cyanobacteria) in Sooley and Pejar reservoirs. The results also show that thermal stratification was probably established in Sooley Dam by the end of November, while weak stratification was present in Pejar Dam in mid-January. These conditions facilitate the release of bio-available phosphorus from bottom sediment.

The phosphorus release experiments using sediment from the two dams show that under the de-oxygenated conditions that occur in the bottom of the reservoirs due to thermal and chemical stratification, high concentrations of phosphorus can be produced, along with iron and manganese that also has a detrimental effect on water quality.

An initial sediment source tracing sampling program was carried out to determine if the spatial tracing techniques could distinguish sediment derived from the major rock types in the two catchments. These methods make use of the natural chemical and magnetic mineral properties of soils developed on different rock types to fingerprint the sediment produced from these areas. The results show that sediment derived from soils developed on basalt, granite, and meta-sedimentary rocks can be distinguished, so a much more detailed sampling can be undertaken in Stage Two of the study that will provide results that can be used to determine the major spatial sources of sediment delivered to Sooley and Pejar reservoirs.

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