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Nitrogen and phosphorus budgets for the sub-tropical Richmond River catchment, Australia

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Abstract. Nitrogen and phosphorus budgets were developed for four sub-catchments in the Richmond River catchment for two study years. The catchment is used for a variety of farming pursuits including dairying, beef, cropping, fruit, nuts, forestry, and sugar cane. Each sub-catchment varies in hydrology, the proportion of each land use, and the population density which enabled a unique opportunity to study fluxes and storage associated with a variety of environmental factors. Total loadings entering each sub-catchment varied from 12 to 57 kg $ha^{-1}yr^{-1}$ for nitrogen and 0.25 to 6.6 kg $ha^{-1}yr^{-1}$ for phosphorus with little inter-annual variation. Averaged across the whole catchment, nitrogen fixation (47%) dominated the inputs; fertiliser (26%) and rainfall (21%) made up the next largest inputs. Fertiliser inputs dominated the phosphorus budget (65.5%); rainfall and manures making up 13% and 12% respectively. Produce dominated the outputs of both nitrogen and phosphorus from the four sub-catchments being greater than the riverine export. The delivery of nitrogen to catchment streams ranged from <1 to 24% of the total inputs and the delivery of phosphorus to catchment streams ranged from <1 to 39%. Storage of phosphorus in catchment soils varied between –0.32 and 4.46 kg $ha^{-1}yr^{-1}$. When denitrification and volatilisation were estimated using data from other studies, storage of nitrogen ranged from 1 to 24 kg $ha^{-1}yr^{-1}$. Despite the episodic nature of runoff in the sub-tropical Richmond River catchment, the magnitude of nutrient fluxes and storage appear similar to other catchments of the world which have mixed land use and relatively low catchment nutrient loadings.

Introduction

Nutrient loss from catchments appears to be closely related to the magnitude of human disturbance. For example, 53% of the variation in nitrogen export and 47% of the variation in phosphate export from catchments may be accounted for by population density (Cole et al. 1993; Caraco 1995). There are also positive correlations between fertiliser nitrogen and fertiliser phosphorus inputs and riverine export (Frissel 1978). Few studies have attempted to estimate catchment scale losses associated with denitrification and volatilisation and atmospheric losses are often incorporated in to a term either called "unknown" or "storage" (e.g. Jaworski et al. 1992; Hoyas et al. 1997; McMahan & Woodside 1997). However, atmospheric losses are significant (Keeney 1979; Denmead 1990; Freifelder et al. 1998) and typically large atmospheric losses of nitrogen occur following application of ammonium based fertilisers and organic manures to agricultural lands.

Catchments are hydrologically linked to downstream estuaries and therefore an understanding of the effects of land use and soil management on nutrient fluxes in the landscape are important for improved understanding and management of nutrient loads on estuaries (Correll et al. 1992). For example, following massive blooms of algae in the Peel-Harvey estuarine system in Western Australia, a management strategy was developed to reduce diffuse phosphorus loads (McComb & Humphries 1992). Farm soil testing and improved information about crop yield-fertiliser response resulted in a reduction of recommended fertiliser application rates and a new fertiliser formulation which was less water soluble. There were also bans on further clearing of native vegetation and the promotion of tree crops. These management recommendations have resulted in a 30% reduction in phosphorus fertiliser use and a reduction in nutrient exports from the catchment to its estuary (McComb & Humphries 1992). The Richmond River estuary is closely linked in both space and time to its catchment; nutrients exported of catchment surfaces during the wet season usually arrive in the estuary within hours.

There have been few terrestrial nutrient budgets constructed in Australia (Campbell 1978; Feller 1981; Dillon 1989; Denmead 1990; Ford 1991; Eyre 1995; Kohn et al. 1997) yet clearly there is an economic and environmental advantage associated with improved understanding of farm nutrient management (Kohn et al. 1997). Further, Murtagh (1980), in a study in the Richmond River catchment, found that increased rainfall during wet years increased runoff rather than improving the plant response to increased fertiliser applications. This study is important for two reasons. Firstly, accept for the studies by Dillon (1989) and Eyre (1995) there appears to have been no nutrient budgets constructed on a catchment scale for an agricultural catchment in Australia and secondly, no such sub-tropical catchment scale budgets have been found in the literature either for a single year or that consider inter-annual variations.

The objectives of this study were (1) to collate an inventory of all nitrogen (TN) and phosphorus (TP) inputs, outputs and storage in four sub-catchments in the Richmond River catchment, (2) to develop nitrogen and phosphorus budgets for each sub-catchment, and (3) to compare broad scale nutrient processes in the Richmond River catchment to catchments in other parts of the world. In general, agricultural intensity is low in Australia relative to many other countries (Ford 1991). The Richmond River catchment currently produces about seven times more produce (on a nutrient mass basis) than is consumed by residents.

Methods and data sources

Study area

The area defined for the catchment nutrient budget is that which drains to the seasonally saline estuary occupying the lower 50 km of the Richmond River. The total area considered makes up 99% of the Richmond catchment (6,861 km^2). There are three distinct sub-catchments in the Richmond River catchment (Bungawalbin, Richmond, and Wilsons) (Figure 1). A further sub-area for the purpose of the nutrient budget consists of three small drainage basins that enter the estuary at Broadwater (Tuckean sub-catchment) and Ballina (Emigrant Creek and Maguires Creek sub-catchments) and the flood plain adjacent to the estuary. Although each is hydrologically discrete, they were considered together as a forth “Coastal” sub-catchment. The Bungawalbin sub-catchment is characterised by forest and low intensity beef grazing (Table 1); the Richmond sub-catchment is dominantly beef grazing, forest, and dairying; the Wilsons sub-catchment has the highest population density, and is dominantly beef grazing, dairying, and horticulture (fruit, vegetables and nuts); the Coastal sub-catchment has beef grazing, dairying, horticulture and sugar cane and a high population density. There are approximately 2,000 horses and a small number of sheep, goats and donkeys within the Richmond River catchment. The contribution from these minor rural industries is small and the geographic distribution is unknown, therefore these were not considered.

Data collection, calculation, and estimation of the budget terms

Within the scope of the field data collection, rainfall input and riverine transport were measured. All water samples were analysed using a Lachat Instruments Quikchem Automated Ion Analyser. After persulphate digestion, total nitrogen was determined using cadmium reduction and sulphanilamide and total phosphorus was determined using ascorbic acid and molybdate blue. Associated errors were ±4.4% for TN and ±3.5% for TP. The sample collection procedures and analytical details can be found in McKee et al. (a, b) (in press). Other nutrient input and output terms were obtained from government departments, private companies and literature surveys. Where the magnitude

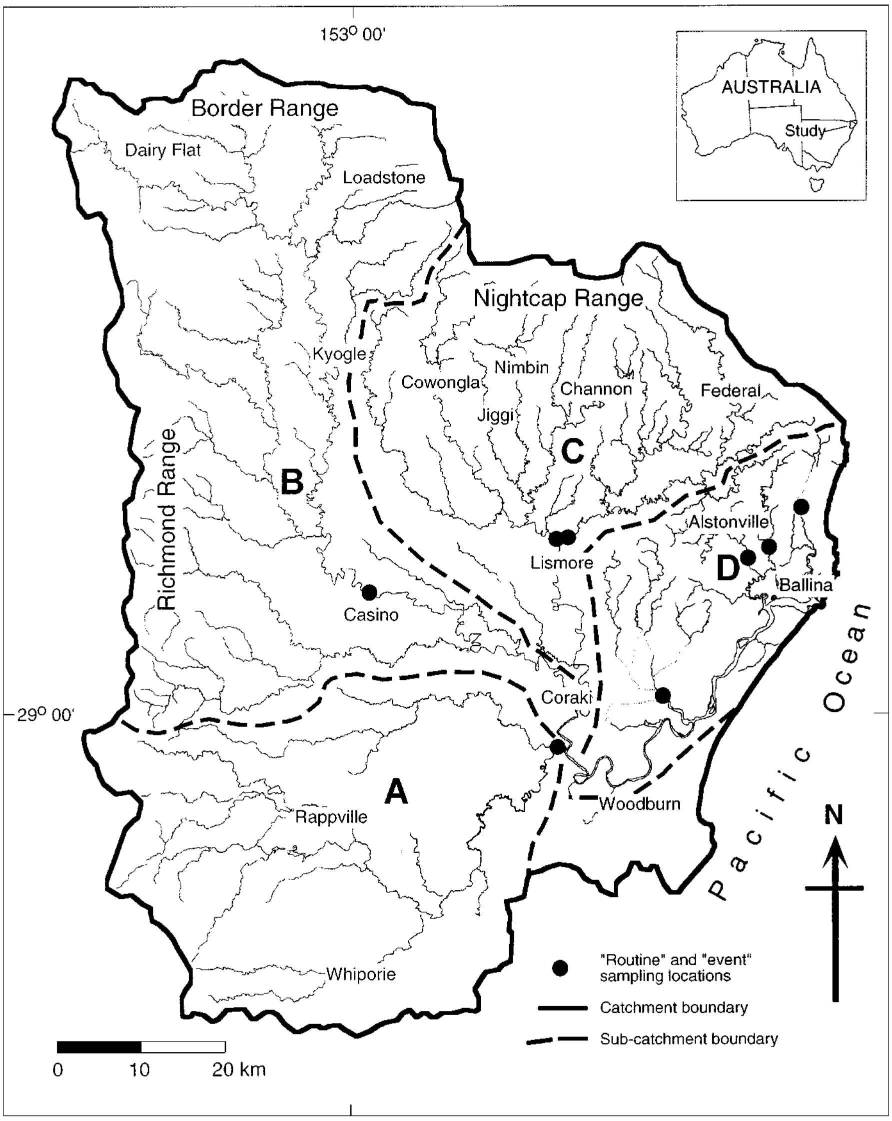


Figure 1. Location of the four sub-catchments used to define the boundaries of the nutrient budget models. A – Bungawalbin; B – Richmond; C – Wilsons; D – Coastal. The sampling locations for rainfall and riverine concentrations, and the measurement of precipitation are also shown (see text for details).

Table 1. Sub-catchment characteristics in the Richmond River catchment.

Attribute	Sub-catchment Bungawalbin	Richmond	Wilsons	Coastal	Total
Area (km^2)	1,686	2,688	1,598	889	6,861
Precipitation (mm)					
Mean	1,200	1,222	1,564	1,448	1,314
1994/95	794	735	1,127	1,492	898
1995/96	1,471	1,363	1,763	1,961	1,531
Runoff (mm)					
Mean	126	380	665	—	385*
1994/95	1	88	294	451	156
1995/96	241	345	754	613	447
Landuse (% area)					
Cropping [1]	0.1	2.1	0.9	19.5	3.6
Horticulture [1]	0.1	0.1	4.3	4.7	1.7
Dairy [2]	0.0	6.3	6.0	3.6	4.3
Beef [3]	31.6	48.8	64.9	49.1	48.3
Forest [1]	68.0	42.0	22.8	20.9	41.2
Urban + roads [1]	0.2	0.6	1.2	2.2	0.9
Total	100.0	100.0	100.0	100.0	100.0
Population					
Urban [4]	109	13,564	28,947	18,101	60,721
Rural [4]	929	6,623	19,954	11,915	39,421
Total	*1,038*	*20,187*	*48,901*	*30,016*	*100,142*
Density (indiv km^{-2})	0.6	7.5	30.6	33.8	14.6
Farm animals					
Dairy [2]	0	19,699	10,476	2,210	32,385
Beef [5]	22,874	67,643	83,005	37,967	211,489
Pigs [5]	1,000?	37,730	18,788?	4,853	62,371

[1]NSW Department of Land and Water Conservation (unpublished data).
[2]NORCO CO-OP Ltd (unpublished data).
[3]Estimated by difference.
[4]Anon (1994a).
[5]Estimated using ABS AG STATS ‘94 (Anon 1994b), area under grazing and the carrying capacity (NSW Agriculture unpublished data).
*Does not include the coastal sub-catchments.
? Uncertain.

of a model attribute was poorly defined by literature surveys, an average value was chosen and a range used to define the error and to ascertain the sensitivity of nutrient budget model to that attribute. The model calculations were constrained by the following equations:

$$(N_{rainfall} + N_{fertiliser} + N_{sewage} + N_{manure} + N_{fixation}) - (N_{runoff} + N_{produce}) = N_{volatilisation} + N_{denitrification} + \Delta N_{storage} \pm \text{error}$$

$$(P_{rainfall} + P_{fertiliser} + P_{sewage} + P_{manure} + P_{weathering}) - (P_{runoff} + P_{produce}) = \Delta P_{storage} \pm \text{error}$$

Precipitation loads

Samples for determination of nutrient concentrations found in rainfall were collected at Coraki, Lismore, Alstonville, Channon, Jiggi, Cowongla, and Casino (Figure 1). Precipitation data were available from the Australian Bureau of Meteorology for Kyogle, Casino, Nimbin, Dairy Flat, Loadstone, Lismore, Federal, Alstonville, Ballina, Rappville, Woodburn, and Whiporie (Figure 1). Nitrogen and phosphorus loads deposited by rainfall were calculated by multiplying monthly averaged rainfall nutrient concentration (C_R) by monthly averaged rainfall (Thesien Polygons, Dingman 1994) for each sub-catchment (R), summing July to June for each year:

$$\text{Load}_{\text{Rainfall}}(\text{kg yr}^{-1}) = \sum_{\text{Jun}}^{\text{Jul}} C_R R.$$

Rainfall concentrations from Alstonville and Coraki were used to calculate areal loadings for the Coastal sub-catchment. Loads for the other three sub-catchments were calculated using average monthly rainfall for each sub-catchment and monthly average nitrogen and phosphorus concentrations calculated using data from the other five rainfall nutrient collection points. Errors in the measurement of rainfall were assumed to be ±10% (Winter 1981).

Fertiliser inputs

To support the diverse farming activities in the region a range of nitrogenous and phosphatic fertilisers are applied annually. Only a small amount of fertiliser is applied in the Bungawalbin sub-catchment, all of which is applied to the crop land on the lower flood plain. In the Richmond sub-catchment above Coraki, 93% of nitrogen and 69% of phosphorus fertilisers are applied for pasture improvement. In the Wilsons River catchment above Coraki, nitrogen fertiliser is applied to pasture (40%) and to horticultural crops (43%) such as fruit, vegetables, and nuts. About 83% of phosphorus is applied to horticultural activities. In the coastal region 95% of nitrogen fertilisers are applied to sugar cane as either urea or urea blends. Phosphorus is applied to sugar cane (73%) and pastures (21%). Averaged for the whole catchment nitrogen is applied as urea (57%), urea blends (22%), and nitrogen-phosphorus-potassium (NPK) mixtures (13%). Phosphorus is applied as concentrated super (32%), NPK (29%), super phosphate (23%), and Di-ammonium-phosphate (DAP) (10%). Fertiliser load information was obtained from the manufacturer (INCITEC fertilizers Ltd). As such, extremely reliable information was available regarding the application of fertilisers to each farming sector. Fertilisation of lawns and vegetable gardens in urban areas were unknown, but believed to be small relative to the rural environment.

Human sewage

Human waste may be considered an input to the catchment budget if the assumption is made that the majority of food consumed by people in the Richmond River catchment is purchased from supermarkets and shops. Some of the produce available from food outlets will have been grown within the catchment and therefore is not a net input. However, all sewage is included as an input because all farm produce is assumed to be exported from the catchment. Total sewage load to each sub-catchment was calculated by multiplying the resident population ($\mathrm{Pop_{Human}}$) in each sub-catchment by typical excretion rates for humans (2.2–6.2 kg N person^{-1} year^{-1} and 0.66–1.8 kg P person^{-1} year^{-1}) (Hoare 1984; Pilleboue & Dorioz 1986; Forsberg 1994; Eyre 1995; Johnes 1996). Calculations for the coastal sub-catchment excluded the population of Ballina (13,160) because the sewage from Ballina is discharged to the estuary (i.e. outside the terrestrial catchment budget area). Rates of 4 kg nitrogen and 1 kg P person^{-1} year^{-1} ($\mathrm{E_{Human}}$) were adopted as the average:

$$\mathrm{Load_{sewage}}(\mathrm{kg\ yr^{-1}}) = \mathrm{Pop_{Human}E_{Human}}.$$

Loads from animal manures

The four main animal industries in the Richmond catchment are beef, dairy, pig, and chickens for eggs and meat. Although some feed supplement may occur during drought, beef and dairy cattle in the region are feed mainly by pastoral grazing and therefore manures from these industries are not included as a budget input. Chicken manures are collected and sold as organic fertilisers and therefore have been counted in the fertiliser inputs. Pigs are fed high protein manufactured foods obtained from outside the catchment budget model and therefore manures from pigs were included as an input to the nutrient budget. Each pig produces 11.0 kg N and 3.8 kg P per year when averaged across a typical Australian grower unit (Kruger et al. 1995). Kruger suggested that loadings may vary by $\pm$40% depending on the type of feed and the age distribution of the pigs in the grower unit.

Phosphorus from bedrock weathering

Much of the bedrock in the Richmond River catchment is volcanic and contains the phosphatic mineral apatite. An estimate of phosphorus loads derived from bedrock weathering ($P_{weathering}$) was made by multiplying riverine total phosphorus concentrations found in upper sub-catchment "pristine" areas by the total yearly catchment flow from each sub-catchment. Loads estimated in this manner correspond to 0.0003 and 0.05 kg ha^{-1} in the Bungawalbin sub-catchment (underlain by sedimentary rocks) and 0.012 and 0.32 kg ha^{-1} in the Wilsons sub-catchment (underlain by basalt) for each study year respectively. The weathering rates in the Wilsons River sub-catchment for the second (slightly above average rainfall) year are much lower than rates found in Victoria, Australia for a small catchment underlain by dacite (Feller 1981).

Nitrogen fixation from the atmosphere

Nitrogen fixation was not measured directly in this study. Symbiotic nitrogen fixation rates for individual crop, forest, grass species, and soils range from $<$1 to $>$500 kg ha^{-1}yr^{-1} and nonsymbiotic nitrogen fixation rates range from $<$1 to 30 kg ha^{-1}yr^{-1} (see reviews: Waring & Schlesinger 1985; Attiwill & Leeper 1987; Boring et al. 1988; Herridge & Bergersen 1988; Gibson et al. 1988; Steele & Villis 1988; Stephensen & Raison 1988). Many of the estimated rates are from controlled plot scale studies and may not be scalable to farm or catchment systems which are subjected to variable economic and climatic factors. On a catchment scale or larger, using individual rates for specific areas (Groth et al. 1978; Anon 1983; de Koning et al. 1997), spatially averaged nitrogen fixation rates ranged between 4 and 40 kg ha^{-1}yr^{-1}. Billen et al. (1985) applied a rate of 10 kg ha^{-1}yr^{-1} across the Scheldt hydrographical basin with no apparent regard for the large variation in rates for different land uses. Other published catchment budgets have only considered nitrogen fixation in legume crops (McMahan & Woodside 1997) or forested areas (Jaworski et al. 1992), without any regard for nitrogen fixation in other parts of the agro-ecosystem. Often, nitrogen fixation makes up a large pro-

Table 2. Nitrogen fixation rates suggest by literature surveys (see text for literature). All rates are in kg $ha^{-1} yr^{-1}$.

Catchment sector	n	Minimum	Maximum	Mean
Crop (legume)	19	7	267	68
Crop (non legume)	8	4	51	17
Horticulture	7	<1	40	10
Pasture (improved)	12	2	45	19
Pasture (unimproved or native)	14	<1	10	5
Forest	34	<1	10	5

portion the total nitrogen inputs into a catchment despite, in many cases, apparent underestimation associated with the estimation methods. There is evidence that symbiotic fixation rates may be higher in tropical forests than in temperate forests (Boring et al. 1988). Forests in the Richmond River catchment incorporate many tree species including three nitrogen fixing species (Castanospermum (Black Bean) in rain forest areas near streams, Casuarina (River Oak) in dry eucalypt forests near streams and Acacia (Wattle) scattered throughout). It is both necessary and difficult to estimate nitrogen fixation on a catchment scale and the budget model is likely to be highly sensitive to the chosen rates. The rates suggested by the literature for producing farm or catchment scale systems are listed in Table 2. It is likely that nitrogen fixation rates may be higher in the sub-tropical Richmond River catchment than in temperate systems (Boring et al. 1988). Therefore, the mean and maximum rates were treated as the lower and upper bounds and the nitrogen fixation loads were estimated by multiplying these rates for each land use by the area of each land use in each sub-catchment.

Riverine loads

Nitrogen and phosphorus concentration data were collected on a flow weighted basis over a two year period from July 1994 to June 1996. Nutrient samples were collected monthly at the outlet of Bungawalbin sub-catchment, at Casino, at Lismore (2 sites), at the outlet of Tuckean, and Emigrant and Maguires Creeks sub-catchments (Figure 1). During periods of high river discharge sampling occurred manually up to six times per day on the rising and falling stages of the flood hydrograph. All samples were taken from mid-depth and at three points across the stream. Details of the collection processes and analytical methods can be found in McKee et al. (b) (in press). At each site, nutrient loads were calculated by multiplying sample concentration with discharge using linear interpolation between samples on an hourly time step. The sample collection points in both the Richmond River sub-catchment and the Wilsons River sub-catchment were upstream of the catchment outlets. There are several methods (ratio, land use, and regression) available for evaluating nutrient loads generated from unmonitored areas (Richards 1989). Richards concluded that although no method offered high precision, the ratio method was less biased than the other methods. Loads calculated for Casino in the Richmond River sub-catchment were adjusted for the area between Coraki and Casino not sampled (33.41%). Loads calculated for each arm of the Wilsons sub-catchment were added and the total adjusted for the area not sampled on the Wilsons River between Lismore and Coraki (11.14%). The loads for Tuckean, Emigrant, and Maguires Creeks, and the coastal plain (cane lands) were added to give a total for the Coastal sub-catchment.

Farm produce

The rural sectors of the Richmond catchment produce a diverse range of fruits, vegetables, grains, and meats. Farm production statistics are collated by the Australian Bureau of Statistics and recorded on the local government area basis (Anon 1994b). Estimates of losses of nitrogen and phosphorus from the sale of farm produce were made for each sub-catchment by combining the mass of each product with its nitrogen and phosphorus content (Anon 1971; Anon 1994b; Kruger et al. 1995). The sale of pork and chickens as budget output terms are not included because the inputs of feeds to these industries are not included as an inputs.

Errors in budget calculations

The calculation of errors associated with sampling frequency and the quantification of nutrient loads in rivers is difficult (Walling & Webb 1985; GESAMP 1987; Cooper & Thomsen 1988; Kronvang & Bruhn 1996). Because, in this study, the “true” mass fluxes are not known it is impossible to make statements about the precision of various mass calculations from the field data collected. The errors associated with riverine nutrient loads were assumed to be the sum of errors associated with laboratory analysis of concentration ($TN_{error} = \pm 4.4\%$; $TP_{error} = \pm 3.5\%$) and measurement of flow using stage-discharge relationships ($Q_{error} = \pm 7.5\%$) (Winter 1981). Errors associated with inputs from rainfall are also difficult to quantify given that regional variability was confined to a broad assessment of “coastal” and “inland” areas. As with riverine loads, the errors associated with the quantification of nutrient loads from rainfall were calculated as the sum of laboratory errors and errors associated with rainfall measurement ($R_{error} = \pm 10\%$) (Winter 1981). The total errors associated with the residual in the nutrient budgets (storage of nitrogen and phosphorus) was calculated using the following formula (Eyre 1995):

$$\text{Error}_{\text{storage}} = ((\text{error}_p)^2 + (\text{error}_s)^2 + (\text{error}_m)^2 + (\text{error}_f)^2 + (\text{error}_r)^2)^{0.5}$$

where inputs to the equation were in kg $ha^{-1}yr^{-1}$ and

error_p = precipitation load calculation errors
error_s = sewage load calculation errors
error_m = manure load calculation errors
error_f = fixation load calculation errors
error_r = riverine load calculation errors

Significant figures

Both nutrient loads and nutrient budgets for nitrogen and phosphorus were constructed using mass in kilograms and all masses greater than or equal to 1 kg were held throughout calculations. This does not reflect the accuracy of the calculations but reduces the accumulative effects of errors associated with rounding.

Results

Nitrogen budget

Rainfall and fertiliser inputs to each sub-catchment changed little between each study year (Table 3). Data used to estimate sewage, manure, and nitrogen fixation were not adequate to distinguish between each year. However, there was a large variation in nutrient loads from each source between sub-catchments. Areal nitrogen loads from the atmosphere varied across the catchment in response to rainfall distributions and concentrations. Greater rainfall occurred near the coast and concentrations increased toward the coast. Fertiliser inputs showed the greatest variation between sub-catchments. Generally, areas with more fertile soils and reliable rainfall (or irrigation) had greater nitrogen fertiliser loadings whereas the Wilsons River sub-catchment had the greatest phosphorus fertiliser loading associated with horticulture. The coastal sub-catchment, with sugar cane a dominant land use, had the greatest fertiliser inputs. Nitrogen fixation did not vary greatly between sub-catchments due to the high percentage of forest cover, dairy grazing and beef

Table 3. A nitrogen budget for the Richmond River catchment. The balance term is the sum of denitrification, volatilisation, soil and vegetation storage, and the errors associated with the other terms. The delivery is the percentage of total inputs that are exported in river flow.

	1994/95					1995/96				
	Bungawalbin	Richmond	Wilsons	Coastal	Total	Bungawalbin	Richmond	Wilsons	Coastal	Total
Inputs										
Rainfall	3.9	3.6	5.3	14.3	5.5	3.7	3.7	4.6	13.6	5.2
Fertiliser	0.1	6.6	7.3	20.5	7.0	0.1	5.4	6.6	19.9	6.2
Sewage	0.0	0.3	1.2	1.0	0.5	0.0	0.3	1.2	1.0	0.5
Manures	0.1	1.5	1.3	0.6	1.0	0.1	1.5	1.3	0.6	1.0
Fixation	7.7	12.4	11.0	20.3	11.9	7.7	12.4	11.0	20.3	11.9
Total	*11.7*	*24.5*	*26.1*	*56.6*	*25.9*	*11.6*	*23.4*	*24.7*	*55.4*	*24.9*
Outputs										
Riverine	0.0	0.7	2.2	3.6	1.2	2.2	3.5	6.0	5.7	4.1
Produce	0.8	4.1	5.3	9.3	4.2	0.8	4.1	5.3	9.3	4.2
Balance	10.9	19.8	18.6	43.7	20.4	8.5	15.8	13.5	40.4	16.6
Delivery (%)	<1	3	9	6	5	19	15	24	10	16

grazing land use in each sub-catchment. However, area normalised loads were greatest in the coastal sub-catchment due to nitrogen fixation associated with large areas of cropping. In the Bungawalbin sub-catchment, which has 68% forest cover and relatively low intensity land use (mainly beef grazing), 99% of the nitrogen inputs are derived from the atmosphere, however, this is not characteristic of the rest of the Richmond River catchment. Inputs averaged across the catchment and for both study years (Figure 2) were 47% nitrogen fixation, 26% fertiliser, 21% rainfall, 3.9% manures, and 2.1% sewage.

Riverine loads varied substantially between sub-catchments and between study years largely as a result of variations in runoff. As such, the delivery of total nutrient input to the catchment rivers varied from $<1\%$ to 9% in the 1994/95 year depending on the sub-catchment and 10% to 24% in wetter 1995/96 year (Table 3). Given limitations in statistical data, estimates of produce exports (kg $ha^{-1}yr^{-1}$) were the same for both years but the coastal sub-catchment produces the greatest volume of produce per hectare. When averaged across the catchment and for both study years (Figure 2), riverine nitrogen exports accounted for 10.5% and produce accounted for 16.3% of the nitrogen inputs. A large proportion (73.2%) of the total inputs are unaccounted for and either lost via gaseous exchange with the atmosphere or stored in soil or vegetation in the catchment.

Phosphorus budget

In the phosphorus budget (Table 4) fertiliser is the main input except in the Bungawalbin sub-catchment where rainfall input dominates. As with nitrogen, there are only small quantities of artificial fertilisers applied in the Bungawalbin sub-catchment due to lower relative farming intensity in response to lower soil nutrition and rainfall. Total loads between sub-catchments vary from 0.25 to 6.62 kg $ha^{-1}yr^{-1}$ with little inter-annual variation between years. On average, 65.5% of the total inputs to the whole catchment occurred as inorganic fertilisers, 13% from rainfall, 12% manures, 5% human sewage, and a further 5% from natural rock weathering (Figure 3). As with nitrogen, riverine outputs from each sub-catchment and between years varied greatly in response to catchment discharge. During the 1994/95 year the delivery of phosphorus to catchment rivers ranged between $<1\%$ and 21% of the total inputs, whereas during the wetter 1995/96 year the delivery increased to 16% to 39%. In general, produce made up a similar or greater proportion of the exports than river loads. On average, produce accounted for 31.5% of the inputs, river loads made up 18.1%, and 50.4% of the total inputs to the catchment were unaccounted for (probably stored in catchment soils or vegetation) (Figure 3).

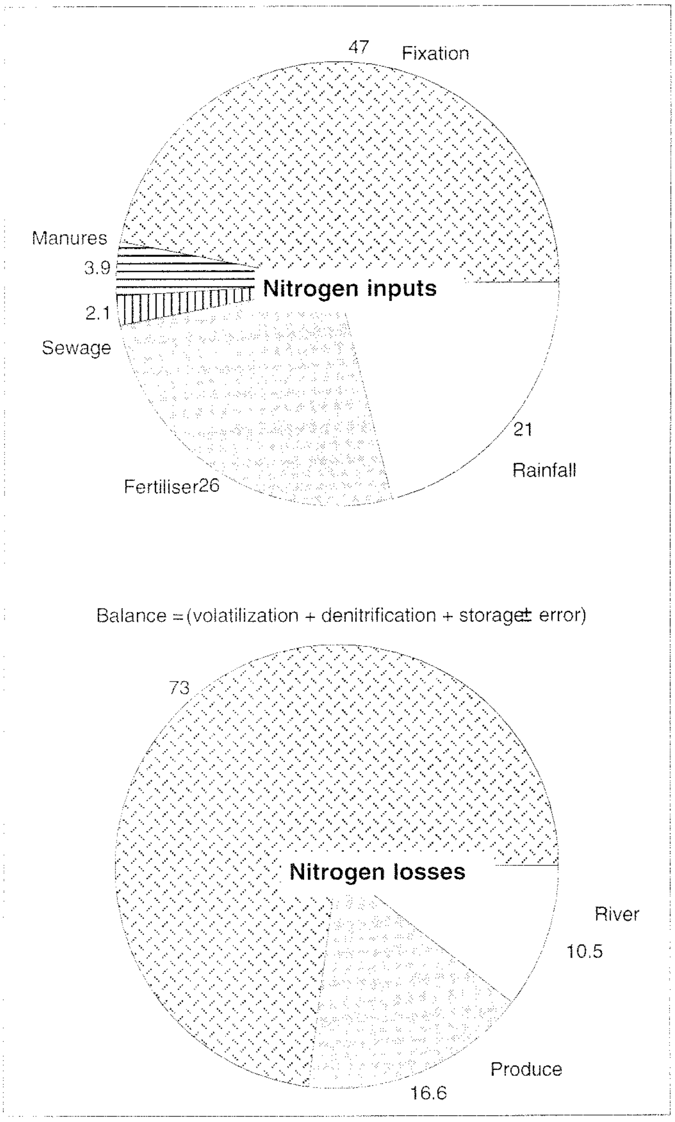


Figure 2. The contribution of each source of nitrogen as a percentage of the total input for the whole Richmond River catchment (top). The fate of nitrogen as a percentage of total inputs (bottom). Losses to the atmosphere were included in the storage term.

Table 4. A phosphorus budget for the Richmond River catchment. The balance term is the sum of soil and vegetation storage, and the errors associated with the other terms. The delivery is the percentage of total inputs that are exported in river flow.

	1994/95					1995/96				
	Bungawalbin	Richmond	Wilsons	Coastal	Total	Bungawalbin	Richmond	Wilsons	Coastal	Total
Inputs										
Rainfall	0.21	0.20	0.29	0.91	0.32	0.32	0.31	0.39	0.87	0.40
Fertiliser	0.01	1.22	4.35	1.67	1.71	0.01	1.45	5.16	1.55	1.97
Sewage	0.01	0.08	0.31	0.25	0.13	0.01	0.08	0.31	0.25	0.13
Manures	0.02	0.53	0.45	0.21	0.35	0.02	0.53	0.45	0.21	0.35
Weathering	0.00	0.05	0.12	0.13	0.07	0.05	0.21	0.32	0.17	0.19
Total	*0.25*	*2.08*	*5.52*	*3.17*	*2.57*	*0.40*	*2.57*	*6.62*	*3.05*	*3.04*
Outputs										
Riverine	0.00	0.22	0.51	0.67	0.29	0.16	0.79	1.08	1.00	0.73
Produce	0.17	0.73	1.09	2.37	0.88	0.17	0.73	1.09	2.37	0.88
Balance	0.08	1.13	3.93	0.13	1.40	0.08	1.05	4.46	–0.32	1.43
Delivery (%)	<1	10	9	21	11	39	31	16	33	24

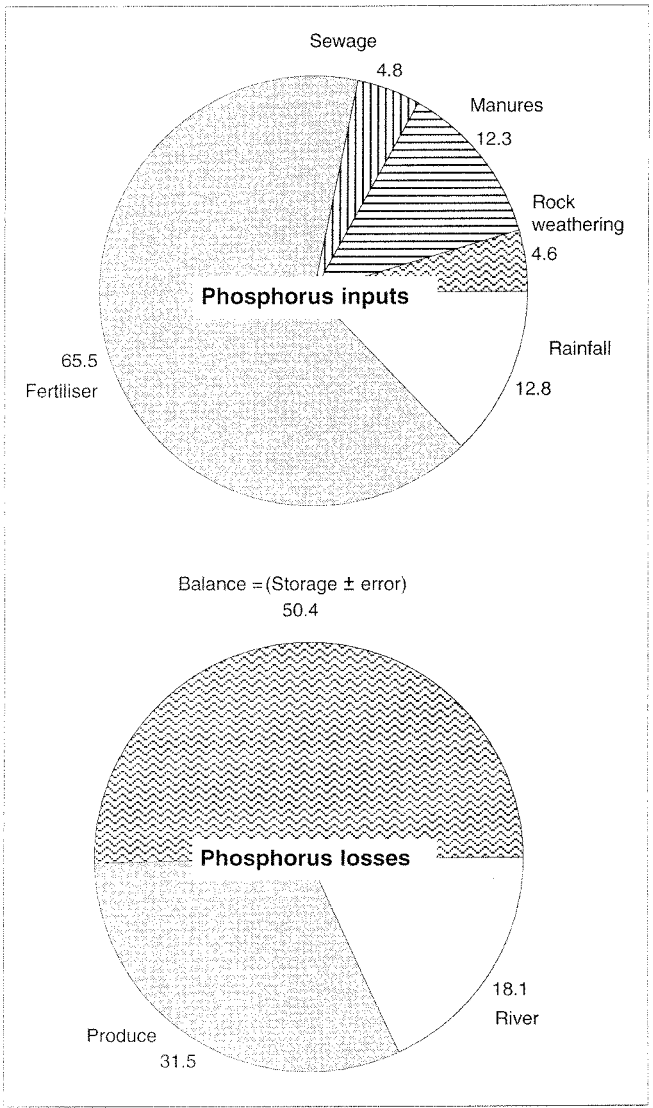


Figure 3. The contribution of each source of phosphorus as a percentage of the total input for the whole Richmond River catchment (top). The fate of phosphorus as a percentage of total inputs (bottom).

Nitrogen: phosphorus ratios

The mass ratios of nitrogen to phosphorus for each input and output term and for each sub-catchment vary from 1.3 to 18.2 (Table 5). Except in the case of the Wilsons sub-catchment, the N:P ratio of the total inputs is greater than the N:P ratio of both riverine exports and produce exports. Fertiliser forms approximately 79% of the annual phosphorus inputs to the Wilsons sub-catchment and the N:P ratios of the produce and riverine exports are typical of the rest of the catchment. The low N:P ratio of the inputs is a direct result of high phosphorus fertiliser loads relative to nitrogen fertiliser loads.

Discussion

Sensitivity analysis

In order to test the reliability of interpretations made from the budget models, a sensitivity analysis was carried out (Table 6). This was achieved by minimising a single parameter (within the bounds of its associated error or likely range) whilst maximising all other parameters in the model and calculating the percent contribution of each parameter. This process was iterated for each parameter thus giving an upper and lower limit to the percent contribution of each parameter. The nitrogen budget model was most sensitive to the magnitude of nitrogen fixation. Nitrogen fixation may contribute between 32 and 58% of the inputs to the Richmond River catchment depending of the chosen rates used to calculate fixation in each land use. Nitrogen fixation also effected the magnitude of the balance term which could range between 62 to 79% depending on the magnitude of the inputs. The phosphorus budget model was much less variable than the nitrogen model due to smaller errors in the individual model parameters. The greatest uncertainty in the model was associated with the contribution of phosphorus fertiliser which could change by up to 12%, and as with nitrogen, the size of the balance was greatly effected depending on the magnitude of the input parameters. When using an average magnitude for each model parameter, the delivery of nitrogen to the river was an average of 10.5% for the two study years. The sensitivity analysis suggests a range from 7 to 16%. The delivery of phosphorus inputs to the river lies between 15 and 22% with an average of 18%.

Comparison to catchment from other parts of the world

The percentage of catchment loadings delivered to waterways in the Richmond River catchment appears typical of other systems (Table 7). For

Table 5. Mass ratios (N:P) of each component of the nutrient budget. The Wilsons sub-catchment appears unique with a similar or smaller N:P ratio in total inputs than in total outputs.

	1994/95					1995/96				
	Bungawalbin	Richmond	Wilsons	Coastal	Total	Bungawalbin	Richmond	Wilsons	Coastal	Total
Inputs										
Rainfall	18.2	18.0	18.0	15.7	17.2	11.8	12.1	11.8	15.6	13.0
Fertiliser	10.9	5.4	1.7	12.3	4.1	10.9	3.7	1.3	12.8	3.2
Sewage	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Manures	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Total inputs[1]	*47.0*	*11.8*	*4.7*	*17.9*	*10.1*	*28.6*	*9.1*	*3.7*	*18.1*	*8.2*
Riverine	11.2	3.0	4.4	5.4	4.3	14.4	4.5	5.6	5.7	5.6
Produce	4.6	5.6	4.9	3.9	4.8	4.6	5.6	4.9	3.9	4.8
Total outputs[2]	*3.8*	*5.0*	*4.7*	*4.2*	*4.7*	*9.3*	*5.0*	*5.2*	*4.4*	*5.1*

[1]Includes nitrogen fixation and rock weathering.
[2]Excludes estimates of volatilisation and denitrification.

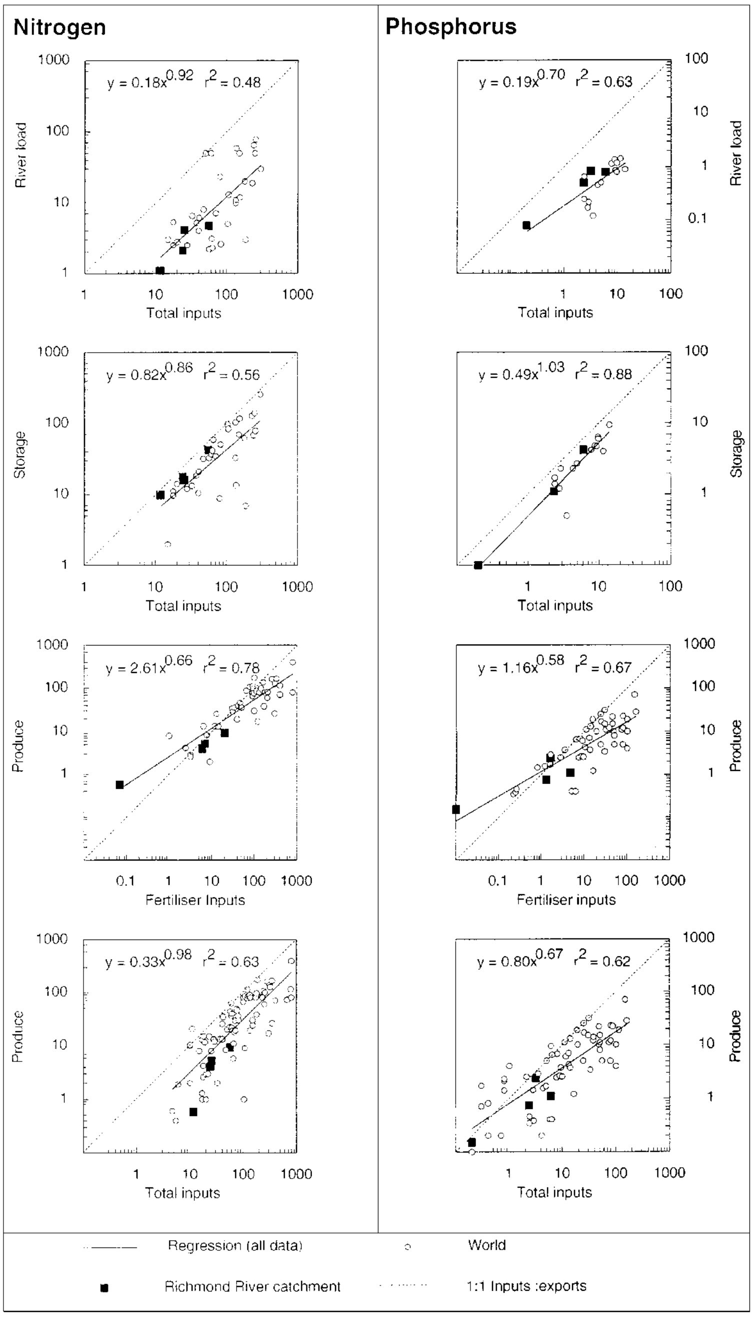


Figure 4. Relationships between total inputs or fertiliser inputs and river load, catchment storage, and consumable produce (all units kg $ha^{-1}yr^{-1}$). After Frissel (1978) with added data from Table 7 and the Richmond catchment (this study).

Table 6. Sensitivity analysis.

	Nitrogen		Phosphorus	
	Average (%)	Range (%)	Average (%)	Range (%)
Inputs				
Rainfall	21.0	15–30	12.8	10–15
Fertiliser	26.0	21–35	65.5	59–71
Sewage	2.1	1–4	4.8	3–9
Manures	3.9	2–7	12.3	7–17
N fixation	47.0	32–58	4.6	4–5
Outputs				
Riverine	10.5	7–16	18.1	15–22
Produce	16.6	13–22	31.5	29–35
Balance	73.0	62–79	50.4	44–57

instance, in a study of eight sub-catchments in Virginia, USA, the delivery of nitrogen to catchment streams ranged from 9 to 30% and riverine phosphorus accounted for 5 to 25% of the total phosphorus inputs (McMahan & Woodside 1997). In the Upper Potomac River Basin, USA, riverine loads accounted for 17% nitrogen and 8% of the phosphorus inputs (Jaworski et al. 1992). The Richmond River catchment, however, has relatively low nitrogen and phosphorus catchment loadings compared to many other catchments (Figure 4). Figure 4 suggests that for both nitrogen and phosphorus, river loads, storage, and farm produce export increase in response to increases in catchment loads. Furthermore, harvest of produce exceeds fertiliser input when application rates are lower that about 5–10 kg $ha^{-1}yr^{-1}$. In a summary of 65 systems from around the world, (Frissel 1978) suggested that the majority of cropping systems had efficiencies of between 50 and 66% of farm nitrogen inputs, livestock systems had efficiencies of $<$10 to 30% and mixed systems showed intermediate results. Higher efficiencies in cropping systems relative to livestock systems were explained by lower losses to the atmosphere. The Richmond River catchment, a livestock dominated mixed agricultural system with 68% of its produce nitrogen export being from meat and milk production, appears to typical of other mixed systems in other parts of the world. The upper Potomac, (Jaworski et al. 1992), also shows a response typical of a mixed system. In contrast, 64% of the nitrogen and 82% of the phosphorus were exported in produce in the Blackwater catchment and

Table 7. Budget studies conducted in catchments in other parts of the world.

			Land use (%)			Mass (kg ha^{-1} yr^{-1})			River
Author / location	Nutrient	Area (km^2)	Forest / wetland	Rural	Other / urban	Input	Output	Storage	(%)
Campbell (1978)									
Merri Ck., Victoria.	P	380	0	79	21	0.101	0.016	0.085	16
Gardiner's Ck., Victoria	P	100	0	0	100	0.092	0.190	–0.098	207
Little Yarra R., Victoria	P	140	65	35	0	0.143	0.083	0.060	58
Cement Ck., Victoria	P	13	100	0	0	0.132	0.024	0.108	18
Feller (1981)									
Myrtle1, Maroondah, Victoria	P	0.3	100	0	0			0.01	
Myrtle2, Maroondah, Victoria	P	0.3	100	0	0			–0.05	
Myrtle1, Maroondah, Victoria	N	0.3	100	0	0			–1.8	
Myrtle2, Maroondah, Victoria	N	0.3	100	0	0			–3.4	
Pilleboue and Dorioz (1986)									
Redon, Lac Leman, France	P	33	25	53	22	11.5	7.5	4.0	12
Hoyas et al. (1997)									
Auli, south eastern Norway	N	366	60	38	2	79.9	71.1	8.8	33
Hoyjord sub-basin	N	0.44	0	100	0	128.0	114.5	13.5	46

Table 7. Continued.

Author / location	Nutrient	Area (km^2)	Land use (%) Forest / wetland	Rural	Other / urban	Mass ($kg\ ha^{-1}\ yr^{-1}$) Input	Output	Storage	River (%)
Freifelder et al. (1998)									
Tomalas bay watershed, USA	N	561	43	57	0	15.0	13.0	2.0	20
Jaworski et al. (1992)									
Upper Potomac, USA	N	29,785	55	40	5	46.9	15.2	31.7	17
	P	29,785	55	40	5	9.7	3.3	6.4	8
Groth et al. (1978)									
Santa Ana, California, USA	N	1,441				169.4	116.5	52.9	
San Joaquin, California, USA	N	17,718				158.2	113.4	44.8	
Peninsular, Florida, USA	N	116,738				32.4	19.0	13.4	20
McMahon and Woodside (1997)									
Blackwater, Virginia, USA	N	1,580	65	30	3	40.1	29.7	10.5	10
	P					3.5	3.0	0.5	5
Nottoway, Virginia, USA	N	3,732	70	28	2	27.9	15.8	12.1	9
	P					2.8	1.6	1.2	7
Meherrin, Virginia, USA	N	1,929	67	30	2	17.7	6.6	11.1	14
	P					2.4	0.7	1.7	9

Table 7. Continued.

Author / location	Nutrient	Area (km^2)	Land use (%)			Mass ($kg\ ha^{-1}\ yr^{-1}$)			River
			Forest / wetland	Rural	Other / urban	Input	Output	Storage	(%)
Roanoke, North Carolina, USA	N	21,947	60	33	5	20.0	5.8	14.2	14
	P					2.9	0.5	2.3	5
Dan, Virginia, USA	N	6,700	66	28	5	17.7	8.0	9.7	30
	P					2.4	0.9	1.4	25
Tar, North Carolina, USA	N	5,755	57	39	4	37.2	18.7	18.5	14
	P					4.3	2.1	2.3	12
Neuse, North Carolina, USA	N	7,024	52	38	9	40.6	19.5	21.1	15
	P					4.9	2.1	2.7	10
Contentnea, North Carolina, USA	N	1,909	45	50	5	70.6	36.1	34.5	10
	P					9.3	4.5	4.7	9
Billen et al. (1985)									
Scheldt, France, Belgium, Netherlands	N	12,600		46		240.4	172.2	68.2	27
Lowrance et al. (1985)									
Watershed N 1979	N	16	30	54	16	86.6	38.1	48.5	3
Georgia, USA	P					13.3	5.7	7.6	8
1980	N					70.9	25.5	45.4	6

Table 7. Continued.

Author / location	Nutrient	Area (km^2)	Land use (%) Forest / wetland	Rural	Other / urban	Mass ($kg\ ha^{-1}\ yr^{-1}$) Input	Output	Storage	River (%)
	P					12.8	3.6	9.2	8
1981	N					90.2	32.8	58.4	<1
	P					15.9	4.6	11.3	4
Watershed O 1979	N	16	32	50	18	69.5	34.8	34.7	5
Georgia, USA	P					9.1	5.4	3.7	19
1980	N					53.2	18.5	34.7	10
	P					8.5	4.0	4.5	27
1981	N					60.6	20.2	40.4	<1
	P					8.8	2.7	6.1	2
Watershed J 1980	N	22	55	40	5	56.7	21.6	35.1	7
Georgia, USA	P					9.8	4.5	5.3	23
1981	N					69.3	21.1	48.2	<1
	P					9.8	3.0	6.8	1
Watershed K 1980	N	17	59	36	5	54.2	20.0	34.2	7
Georgia, USA	P					8.5	4.2	4.3	26
1981	N					58.9	27.9	31.0	<1
	P					7.1	3.0	4.1	1

48% of the nitrogen and 51% of the phosphorus were exported in produce from the Nottoway catchment both of which are used exclusively for cropping (McMahan & Woodside 1997).

Closing the nitrogen budget

The majority of nitrogen budgets include a balance term incorporating volatilisation, denitrification, changes in soil and vegetation storage, and the errors associated with the other terms (e.g. Billen et al. 1985; Lowrance et al. 1985; Jaworski et al. 1992; McMahan & Woodside 1997). The nitrogen budget for the Richmond River catchment was developed using the same methodology so that it could be directly compared to other catchment models. Gaseous exchange with the atmosphere can be estimated using information from other catchments or micro studies within the catchment of interest. However, there are problems associated with measurement techniques (Steele & Villis 1988) and scaling due to the heterogeneity of physical, chemical, and biological catchment attributes (e.g. Freifelder et al. 1998). Ammonia emission can occur from soils, plants, animal excreta, and fertilisers (Steele & Villis 1988) and much of the literature relevant to Australian conditions has been reviewed in Steele and Vallis (1988) and in the work of Denmead (1990).

It is likely that ammonia emission from plant tops amount to only a few kg $ha^{-1}yr^{-1}$ (Steele & Vallis 1988). Denmead (1990), in his ammonia budget for Australia suggested an average soil emission of 3 kg N $ha^{-1}yr^{-1}$ and a net emission from vegetation of 2.4 kg N $ha^{-1}yr^{-1}$. Ammonia volatilised from excreta has been estimated at 26% of the nitrogen deposited in urine and faeces as urea (Denmead 1990) and Steele and Vallis (1988) suggest losses between 20 and 30%. Pig industry estimates suggest about 30% of nitrogen is volatilised during the pond and application process (Kruger et al. 1995). The amounts of nitrogen excreted by farmed animals have been estimated at 33 kg yr^{-1} per head of beef, 84 kg N yr^{-1} per head of dairy, and 11 kg yr^{-1} per pig (averaged across a grower unit) (Kruger et al. 1995). Volatilisation of ammonia also occurs during treatment of human wastes at wastewater treatment plants and from vented septic tank systems in rural areas. Given the dominance of the cattle industry in the Richmond catchment losses from excreta were set at 20%. Losses of around 25% may be experienced following application of urea based fertilisers (Steele & Vallis 1980). Denmead et al. (1990) suggested losses of up to 40% for urea application on sugar cane, however, Denmead (1990) used a loss of 10% in the construction of the Australian ammonia budget perhaps to account for the range of fertiliser chemistries and applications used across the country. In the Richmond catchment 79% of the artificial nitrogenous fertilisers applied are urea, urea blends, or ammonium nitrate and therefore a loss of 25% has been adopted. Estimates of nitrogen losses associated with ammonia volatilisation in each sub-catchment of the Richmond catchment were calculated using the following equations:

$$\text{Volatilization}_{\text{excreta}}\ (\text{kg yr}^{-1}) = 0.20 \times (33\text{B} + 84\text{D} + 11\text{P} + 4\text{H}),$$
$$\text{Volatilisation}_{\text{fertiliser}}\ (\text{kg yr}^{-1}) = 0.25 \times \text{UB (kg)},$$
$$\text{Volatilisation}_{soil+vegitation}(\text{kg yr}^{-1}) = 2\ \text{kg ha}^{-1}\text{yr}^{-1} \times \text{NF},$$

where

B = head of beef,

D = head of dairy,

P = head of pigs,

H = human population,

UB = amount of urea, urea blend, and ammonium nitrate fertiliser applied,

NF = area in each sub-catchment that is not fertilised (i.e. forest + beef grazing).

Estimates for denitrification from catchment surfaces vary by several orders of magnitude and are dependant on pH, soil moisture, organic carbon availability and temperature (Avalakki et al. 1995a–c; Ambus 1998; Flessa et al. 1998). Estimates of denitrification from several nonfertilised grazed pasture areas in New Zealand range from 10 kg N $\text{ha}^{-1}\text{yr}^{-1}$ (771 mm rainfall) to 30 kg N $\text{ha}^{-1}\text{yr}^{-1}$ (1,600 mm rainfall) (Steele & Villis 1988). Another study from grazed pastures in new Zealand found a range of 3–5 kg N $\text{ha}^{-1}\text{yr}^{-1}$ from silt loam soils of 5% carbon content (Carran et al. 1995). Results from field studies near Toowoomba (250 km north of the Richmond River catchment) (Avalakki et al. 1995a–c) suggest denitrification rates are dependant on soil temperature, carbon residues, and soil moisture in soils of low organic carbon (1–2%). They found that emissions from fertilised saturated soils in April ranged from 19 to 29 kg ha^{-1} whereas fertilised unsaturated soil emissions in July ranged from 4 to 6 kg ha^{-1}. This suggests an annual average of about 16.5 kg $\text{ha}^{-1}\text{yr}^{-1}$ or 41% of the applied fertiliser. In a German field study on four sites with high organic carbon (34–43%), losses were 4–20 and 16–55 kg N $\text{ha}^{-1}\text{yr}^{-1}$ for grassland and crop respectively and highest emissions were found on areas of low pH (Flessa et al. 1998). Reviews of nitrogen cycling in forests (Waring & Schlesinger 1985; Attiwill & Leeper 1987) suggest that denitrification is unimportant, however, few detailed studies have been done. Catchment scale estimates

Table 8. Estimation of soil and vegetation storage. Errors are assumed to be a minimum because the individual errors for some terms (fertiliser, produce, volatilisation, and denitrification) were unknown.

	Sub-catchment				
Year / parameter	Bungawalbin	Richmond	Wilsons	Coastal	Total
1994/95					
Total inputs	*11.7*	*24.5*	*26.1*	*56.6*	*25.9*
Riverine	0.0	0.7	2.2	3.6	1.2
Produce	0.8	4.1	5.3	9.3	4.2
Volatilisation	2.9	6.5	7.6	9.4	6.2
Denitrification	1.4	4.2	5.1	10.0	4.5
Soil and vegetation storage	6.6 ± 3.9	9.0 ± 6.3	5.8±5.6	24.3± 10.4	9.8 ± 6.0
1995/96					
Total inputs	*11.6*	*23.4*	*24.7*	*55.4*	*24.9*
Riverine	2.2	3.5	6.0	5.7	4.1
Produce	0.8	4.1	5.3	9.3	4.2
Volatilisation	2.9	6.2	7.5	9.2	6.1
Denitrification	1.4	3.7	4.8	9.8	4.2
Soil and vegetation storage	4.2 ± 3.9	5.8 ± 6.3	1.1 ± 5.7	21.4 ± 10.4	6.4 ± 6.1

were made in the Buttermilk Bay watershed based on rates (kg ha^{-1}yr^{-1}) of 0.65 – forest, 8.8 – nonfertilised agricultural land, and 36.0 – fertilised agricultural land (Valiela & Costa 1988). Organic matter content of soils of the Richmond River catchment are typically about 1.6% ranging from 4.8% in the Wilsons sub-catchment to 0.3% in the Bungawalbin sub-catchment (data from 78 samples (Morand 1994). Given the low organic matter content of Richmond soils, the following denitrification rates were applied to each sub-catchment:

Forest = 0.65 kg ha^{-1}yr^{-1},

Pastures = 3 kg ha^{-1}yr^{-1},

Fertilised land = 41% equivalent of applied nitrogen fertiliser.

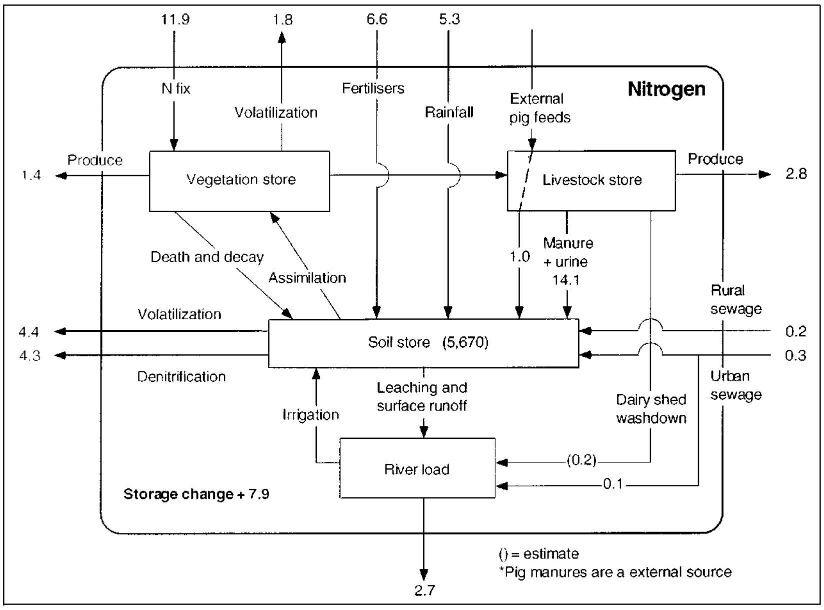
Using the estimates of volatilisation and denitrification, the residual in the nitrogen budget was further distilled (Table 8). It appears that there was a net gain in nitrogen soil and/or vegetation storage in all sub-catchments during both years. Overall, forested area in the Richmond River catchment has increased by 2.2 times since 1977, area of horticulture has increased by

4.2 times since 1977, and crop area has remained relatively constant. For the same period, the number of dairy cattle has decreased by 2.9 times, beef cattle have decreased by 2.0 times, and pig numbers have decreased by 1.2 times. Conceptually it seems likely that over the past 15–20 years biomass nutrient storage should have increased in the Richmond River catchment due to afforestation. An international symposium on agro-ecosystem nutrient cycling summered information from 65 systems including Europe, USA, Argentina, Brazil, Patagonia, Japan, and Australia (Frissel 1978). For livestock systems, Frissel found that between 20 and 66% of nitrogen inputs were lost to the atmosphere and that volatilisation dominated whereas for arable systems, between 3 and 30% of inputs were lost to the atmosphere and denitrification dominated. The Richmond River catchment is a mixed system dominated by meat and milk production. On average, 41% of the inputs to the Richmond River catchment are lost to the atmosphere and 59% of the gaseous losses occur via volatilisation. The coastal sub-catchment has much larger total inputs than the other sub-catchments as a resulting from the cultivation of sugar cane. Approximately 35% of the total inputs to the coastal sub-catchment are lost to the atmosphere and 50% of the losses are due to denitrification. Thus, it appears that the Richmond River catchment is typical of rural catchments in other parts of the world.

Synthesis

Annual averages were calculated for the inputs and outputs for the Richmond River catchment (Figure 5). In general, the Richmond River catchment is a relatively low intensity agricultural system, with low urban and rural human populations. Estimates of effluent entering the river directly from dairy sheds were calculated assuming the cows were in the milking shed for 10% of each day (Anon 1994c) and that 50% of the manure voided at this time finds its way to the river. Urban sewage discharged to the rivers was calculated using data from local authorities. These calculations suggest that 11% of the nitrogen and 8% of the phosphorus in riverine export can be directly attributed to point sources. The remainder of river exports probably undergo complex chemical, physical and biological cycles prior to surface runoff during rain storms or leaching during baseflow.

This idea is borne out when the forms of nutrient inputs are compared to nutrient exports. In the case of nitrogen, 67% of the inputs were in an inorganic form (if urea based fertilisers are discounted) whereas nitrogen exports in the rivers were 49% dissolved organic and 30% particulate organic (McKee et al. (b) in press). The proportion of phosphorus input that was inorganic was 80% whereas 17% of the riverine exports were dissolved organic and an estimated 10% organic particulate. Clearly, a large proportion of nitrogen



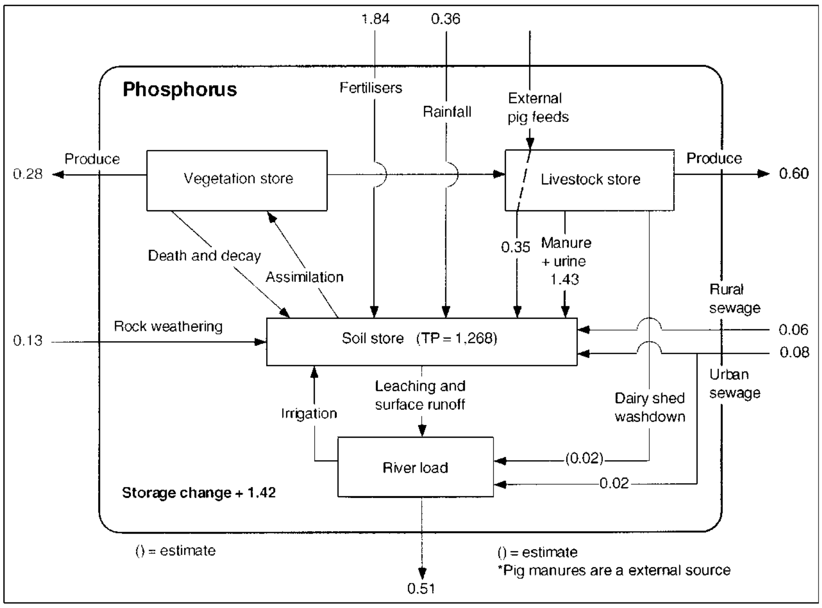


Figure 5. Annual nutrient budgets averaged for the July 1994 to June 1996 period for the whole Richmond River catchment. Nutrient loads are in kg $ha^{-1}yr^{-1}$. The storage in the catchment increased by 7.9 and 1.42 kg $ha^{-1}yr^{-1}$ for nitrogen and phosphorus respectively.

and phosphorus exports were biologically cycled prior to export from the catchment to the estuary.

Estimates of soil nutrient stores in the upper 30 cm of the soil profile were made using average nitrogen and phosphorus soil concentrations in Richmond catchment (McGarity & Munns 1955; Morand 1994) and a bulk density of 1.4 g cm^{-3}. These estimates suggest that soil nitrogen and phosphorus stores are about 200 and 450 times greater than the nitrogen or phosphorus inputs respectively. The magnitude of the soil pool also helps to place the storage changes estimated by the budget models into context. The increase in storage of nitrogen and phosphorus represent approximately 0.14 and 0.11% of the respective soil stores. Other studies have suggested that an increase in nutrient storage associated with anthropogenic activities are likely to increase the likelihood of nutrients being leached to surface waters. It seems likely that "new" nutrients added to catchment may be less strongly bound and more likely to be lost through the hydrological cycle.

There appears to be a relationship between total nutrient loading and nutrient exports in rivers (Figure 4). Even a small increment in catchment nutrient storage may be detrimental to water quality downstream and increase nutrient exports to the Richmond River estuary. A simple comparison between fertiliser inputs and produce exports suggests that about 64% of the nitrogenous fertiliser and about 50% of the phosphatic fertiliser is realised in produce exports. Although some nitrogen is lost to the atmosphere after application of ammonia based fertilisers, these simple comparisons suggest that a large proportion of both nitrogenous and phosphatic fertiliser inputs are not utilised by the crops and animals and may be lost by leaching or runoff to the rivers.

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