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Literature Review - Temporal and spatial variations in nitrogen and Phosphorus fluxes in dairy catchments

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Introduction

Over the last 10 or so years, Dairy Australia (DA), Australian dairy farmers and other stakeholders have invested substantial financial and human resources in the development and implementation of a series of farm-to-catchment research projects based at sites around Australia. These “catchments projects” as they have become known have provided a valuable link between traditional on-farm productivity and sustainability research, and research into the impacts of dairy farm practices on their downstream environments.

Projects were implemented in all States and, through the extensive networks of the catchments projects staff, access was also gained to the work and outcomes of a broad range of dairy-related research activities in addition to those funded directly through the DA catchments portfolio. Project partners included DA regional Development Programs such as Western Dairy and DairyTas, Land and Water Australia and many State Government Agencies as well as universities and Natural Resource Management groups.

A recent review of these projects (Edgar et al. 2006) highlighted their achievements and the benefits which accrued to the Australian dairy industry following their implementation.

Some of the major benefits identified as being attributable to the projects were:

- new knowledge about the way farming practice interacts with catchment processes;
- improved capacity of farmers and the dairy industry to manage change and achieve sustainable farming enterprises;
- the attraction of high quality scientists;
- nuclei for a range of on-farm assistance programs;
- Influencing catchment targets set by regional organisations, and the development of policy and regulatory responses that are appropriate for the dairy industry.

The combined work of the projects was also summarised in a Dairy Australia publication (Dairy Australia, 2006) which outlined the research questions posed and strategies implemented by the projects. One consistent conclusion emerged from these projects:

While we have improved our understanding of how well various farm management practices perform in economic and environmental terms and we now know more about the downstream characteristics of dairy-dominated catchments, the link between farm-scale actions and catchment-scale response is important but still poorly defined.

The link between farm-scale actions and catchment-scale response is complex because of the large spatial and temporal variations in the processes governing the mobilisation of nutrients, their subsequent transport and the characteristics of the downstream environment upon which they may impact.
These issues are presently being examined in research internationally and developing an understanding of them has been described as the “holy-grail of nutrient research” (McDowell and Nash 2007). A number of research centres such as the Western Australian Centre of Excellence for Ecohydrology and the Centre for Ecology and Hydrology in the UK have been specifically established in recognition of the importance of this issue and the scale of research required to provide answers.

This report attempts to summarise and review our understanding of temporal and spatial variations in nutrient fluxes in dairy catchments. The purpose of this review is to contribute to future research and on-farm activities. This task will be completed through an exploration of the issues and mechanisms of nutrient fluxes in both the farm and catchment contexts.

Key References


For reference to the final reports of catchments projects, see: www.dairyingfortomorrow.com
1 Agriculture / catchment conflicts

Nutrient losses from land to air and water (and the subsequent impacts on water supplies, eutrophication of waterways, algal blooms and possible fish kills and contribution to global warming) have been accelerated globally over the last 50 years, including in Australia, due to landscape development for agricultural and urban pursuits. These pursuits bring with them inputs of nutrients (predominantly phosphorus (P) and nitrogen (N)) in forms ranging from commercial inorganic and organic fertilisers to human wastes.

Every farm and every home is in a catchment, and most Australian catchments contain some form of agriculture or grazing activity which has the potential to leak nutrients into the wider environment with adverse effects on natural ecosystems (Crib 2008). Although nutrients are an essential input into farming systems to ensure economic yields of products, their excessive use and subsequent loss to the broader environment, particularly waterways, is known to contribute to degradation of water quality (Hansen et al. 2002). It should be noted, however, that land use in most catchments is diverse and many land uses other than dairying also contribute nutrients to the total catchment load. For example, cropping, urbanisation and sewage treatment plants.

Australia’s coastal rivers, lagoons and inland rivers may all be at risk of contamination with excessive nutrients. Nutrient pollution of these waterways can subsequently result in blooms of nuisance or toxic algae. If the waterbody is mainly fresh water, nuisance algae generally require high P supplies to trigger a bloom. In salt water, N is the limiting nutrient. This means that some waters are more sensitive to the type of nutrient escaping than others, and appropriate measures are needed to manage them.

In estuaries that are well-flushed by river flows, currents and tides, nutrients may have little or no observable impact on marine ecosystems but nutrient losses still need to be addressed in the upper reaches of the catchment to ensure efficient nutrient use and maintenance on water quality in those reaches.

Historically, nutrient inputs into Australian agricultural systems were necessary to overcome deficiencies of elements such as P in naturally infertile soils. However, in many areas, these deficiencies have now been overcome to a large extent and nutrient losses that were once ascribed to current nutrient inputs are transitioning to systematic or background sources due to the accumulation of nutrients in farm systems. Alternately, there are also some soils which are unable to retain nutrients, and fertilisers are still required every year, with the risk that a large portion of these nutrients may be lost from the soil.

1.1 Nutrient use efficiency

Another factor contributing to the accelerated nutrient loss from farmed systems is the shift away from efficient (on the small scale), cyclic, agrarian nutrient management to more linear nutrient utilisation processes common in modern agricultural systems. These two systems are contrasted in Figure 1.

Internationally, nutrient enrichment of waterways (eutrophication) is often the most common form of water quality issue, certainly in the USA (Carpenter et al. 1998) and Australia (Department of Natural Resources and Environment 1996). The problem is, however, exacerbated in Australia by the fact that our waterways are generally
naturally very low in nutrient levels (oligotrophic) meaning that excess nutrient inputs impact on the natural aquatic ecosystems much more easily and with greater consequence than elsewhere.

Prior to the industrial revolution humanity was intimately involved in food production, in fact human wastes were turned into agricultural products. Humans have a small requirement for P and most of ingested P is excreted. Utilising this inefficiency essentially creates a closed P cycle.

Now half of the world's population lives in urban environments, rock phosphate has been discovered and commercial P fertilisers are available. Humanity is now largely disconnected from food production and the system is linear, non-recycling and open ended. This might not be a problem if P rock reserves were infinite, losses to waterways did not cause water quality problems, or if it was economically viable to recover P from deep ocean sediments. Unfortunately none of these are true.

**Figure 1: Nutrient management and recycling in a pre and post-industrialised world** (After Weaver and Neville, 2008)

The use of nutrients in agriculture on a global scale has altered the naturally occurring cycling processes of some elements, particularly of nitrogen, phosphorus and water. Also, because of the generally, inherently low levels of nutrient-use efficiency in agriculture, more nutrients are imported into agricultural catchments than are exported from them in the form of agricultural produce. This results in a net accumulation of nutrients within the farm-catchment system and ultimately in increased rates of nutrient loss from the farm to the broader catchment environment than would naturally be the case.

Nutrient inputs into most agricultural systems often exceed nutrient outputs in products. These excesses are inherent because of the unavoidable inefficiencies in biological and chemical processes. These surplus nutrients may accumulate in the soil, be lost in surface runoff, leached below the root zone or (as in the case of N) be
lost to the atmosphere. Nutrient accumulation in the soil has led to nutrient saturation in some Australian soils and, whilst many other soils no longer require annual nutrient applications, traditional annual applications often still prevail. Increased levels of nutrients in soils can lead to significant losses of nutrients via leaching, sub-surface flow and runoff.

As an example, figure 2 (below) illustrates the inputs and outputs of P through the various components of the Peel-Harvey catchment in Western Australia.

Survey data gathered in 2005 indicated that approximately 2000 tonnes of P was being imported into the catchment annually as fertiliser, with an additional 610 tonnes of non-fertiliser P also being imported (feed, etc). However, only 540 tonnes is exported annually as agricultural produce, leaving a “P surplus” of 2070 tonnes, or 80%, of the applied P every year. Soil P and P retention tests indicate that approximately 1200 tonnes is stored by the catchment soils every year (but this capacity is declining) allowing 870 tonnes a year to be lost to streams and
groundwater. Stream P storage accounts for a large proportion of these losses (again, declining) resulting in a net loss of 140 tonnes of P to the Peel-Harvey catchment annually.

1.2 Nutrient management
Management of nutrients on farm in a systematic and guided manner is important to achieve cost effective, long-term water quality and soil nutrient status improvements. Major responses to date (where they exist) have dealt with the symptomatic treatment of the issue through engineering solutions such as the harvesting of algal biomass, or construction of channels to improve oceanic exchange and flushing of estuarine systems.

Whilst these approaches may deal with the symptoms, ultimately the development, field testing and implementation of Best Management Practices (BMPs) is the best long term solution to potential conflicts between land use and water quality.

Research and development to date indicates that treating the causes of nutrient pollution at their source can concurrently provide water quality improvements and economic benefits. However, there is presently still some uncertainty regarding the effectiveness, economics of, and downstream environmental consequences of the application of the limited number of management practices available to reduce nutrient loss. There is also a general lack of understanding of the extent of landscape remediation required, the scale (temporal and spatial) at which water quality improvements can be seen, and the landuses and landscape characteristics responsible for nutrient enrichment.

In order to better manage nutrients it is important to identify sources of nutrients in the catchment and on the farm. Some catchments, some farms, even some paddocks leak nutrients more readily than others. Within farms or paddocks there may even be small areas, such as urine patches, that are the major source of nutrient loss.

Nutrient loss potential depends on many factors such as: local soil type, landform, water flow and rainfall patterns. Historically there has been a tendency to focus on point sources – such as dairy effluent - when in reality, dairying may contribute only a tenth of the total nutrients entering the catchment, and effluent only a tenth of the nutrients from dairying. This does not suggest that effluent need not be managed, but that the other larger but perhaps less obvious sources of nutrients - on and off-farm – must also be recognised, identified and addresses.

The fact that different nutrients are lost from farms in different ways and in different forms adds to the complexity of the issue. The basic processes involved in nutrient loss are understood but the processes in operation (and their relative importance) at any particular place or time, are less clear without investigation.

<table>
<thead>
<tr>
<th>Key pathways of nutrient loss</th>
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<tr>
<td>• Phosphorus is mainly lost through surface runoff, either bound to soil particles or dissolved in water. However, in some sandy soils it leaches directly into groundwater.</td>
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</table>
Nitrogen is lost as ammonium and nitrate and in organic compounds. The nitrogen in ammonium and in organic compounds is mainly lost in surface runoff while nitrate leaches through the soil profile either into groundwater or back into surface runoff via interflow. When soils are saturated and anaerobic, nitrate is transformed into nitrous oxide and lost to the atmosphere.

1.3 From farm to catchment

Despite years of research both in Australia and overseas, the links between nutrient dynamics on a farm and those lower down the catchment are still far from clear. In some cases an action taken on farm to prevent the escape of nutrients can have an immediate and observable effect. In others it may take years to appear, or may never do so. Differences in farming systems, soil types, land shape, vegetation and rainfall patterns mean that the same action may have contrasting effects in different catchments.

Similarly, within any single catchment, the complexity of the processes influencing nutrient dynamics increases exponentially from the paddock to the catchment scale. At the paddock scale, processes of nutrient cycling and mobilization may be relatively uniform. However, as the size of the area under consideration increases, a greater diversity of processes and systems are present. Whilst every landscape and catchment is different, there are fundamental principles, that if considered allow an understanding of individual catchments to be developed.

Nutrients lost from dairy farms also blend with those lost from other types of agriculture and land use, from industry, infrastructure and urban development. It is often hard to disentangle one source of nutrients from the many others affecting the catchment. This can make the effect of on-farm measures to control nutrients hard to observe in general water quality measurements especially those that are made some distance from the farm gate.

Dairy farm input costs are increasing sharply as climatic variability influences the yield of feed crops and makes access to decreasing water supplies more difficult. Approximately 65% of Australia’s water resources are presently utilised by Australian agricultural industries (ABS, 2006) with 19% of this being used by Australian dairy farmers to produce around 9 billion litres of milk a year (Dairy Australia, 2008). Fertiliser prices also are increasing rapidly due their close association with hydrocarbon prices worldwide.

Dairy farmers who wish to farm profitably and sustainably now seek to make best use of the water, fertiliser and nutrients they apply to pastures and crops, while trying to minimise the scope for nutrients to ‘leak’ off farm into the surrounding catchment and its waters.

As farm productivity improves, so does the demand for nutrients to fuel this production, but not necessarily the efficiency with which those nutrients are utilised. Productivity, in the dairy sense, often goes hand in hand with intensification or at least with pushing the dairy system harder and employing the philosophy of “high inputs for high outputs”. This management philosophy can sometimes mean that dairying can be seen to present more environmental challenges than some other agri-industries.
The major sources of diffuse pollution from agricultural land are excessive fertiliser use and high density livestock operations (Carpenter et al. 1998) although within these systems, there are highly variable rates of nutrient use and loss across the suite of management practices employed at any given time. Catchment nutrient fluxes are determined by a number of essentially simple factors:

- the level of nutrient inputs into the catchment system;
- the efficiency with which those nutrients are utilised within the system and ultimately exported as agricultural products, and;
- the chemical processes and hydrological pathways through which they are stored, transformed and transported whilst they are within the catchment.

Whilst these in-catchment “components” of nutrients are easily defined and in some cases measured, the processes which are internal to each component (such as the processes involved in phosphorus or nitrogen storage and release in soils) are highly complex and variable across landscapes and landuses as well as through time. While this paper considers and describes the principles behind nutrient mobilisation and transport processes in the catchment context, variability in temporal and spatial terms is the major focus of the review.

There is confidence that reductions in nitrogen and phosphorus losses through the implementation of Environmental BMPs can occur (Carpenter et al. 1998, Weaver et al. Brisbane), but the rate of recovery of waterways subject to eutrophication is still highly variable (Carpenter et al. 1998).

**Key Messages**

- Catchments are a mosaic of landuses from urban to rural and everyone in every catchment has a role to play in reducing nutrient losses.

- It is well recognised that the addition of nutrients to agricultural land is often required to maximise productivity, but nutrients must be managed judiciously and their use made more effective.

- While engineering solutions have sometimes been effectively applied to the symptoms of excess nutrient loss, they simply remove some of the more obvious effects and do not address the causes of the problem.

- The links between farm management and catchment response are important, complex, variable and still relatively poorly understood.

- Both point and diffuse sources of nutrients require management. A focus simply on the more apparent sources of nutrients, such as effluent ponds, may miss much more significant, diffuse sources from other parts of the farm.
Key References


2 The pools and fluxes of nutrients – source to catchment

In considering the temporal and spatial variation of nutrient mobilisation and transfer from source to catchment, a useful starting point is a simple conceptual model. The conceptual model can be used to graphically illustrate important pools, processes, fluxes and factors influencing these. Such a model is shown in a schematic format in Figure 3, and represented in a more linear format in Figure 4. This conceptual model has been used as the ‘skeleton’ for the rest of this report. The model considers the key pools, the processes that result in nutrient transfers between these pools, and the factors influencing the pools (their size, form etc.) and factors influencing the transfers between the pools. All these issues are considered in a farm management and catchment characteristics context.

Some key terms defined:

**Nutrient pools** – this refers to places where nutrients are stored or accumulated, either in the short terms or long term, e.g. nutrients stored in the effluent pond are one of many pools of nutrients

**Fluxes** – refers to the movement between one pool and the next, e.g. when effluent from a pond (a nutrient pool) is applied to the soil in a paddock (another nutrient pool) it is referred to as a flux

**Mobilisation** – this typically involves water and refers to the transfer of nutrients from a pool, e.g. the soil to water (such as runoff) which then transports the nutrient to another place in the soil profile, farm or landscape

Nutrient mobilisation and transport processes vary dramatically

There is a great diversity in farming systems, landscape and catchment characteristics which mean that there is an equally diverse set of processes contributing to nutrient transfer. In one situation a particular process or set of processes may drive nutrient losses whereas in another situation these processes may not be important with alternative processes being dominant. This variation can occur at the paddock, catchment, regional and national scales, so it should not be inferred that the processes operating at one site will operate at another without a clear understanding of the process defining circumstances.

There is great diversity in farming systems, landscape and catchment characteristics and climates which means that an equally diverse set of processes occur, such that in one situation a particular process or set of processes may occur whereas in another situation this process may not be important and instead an alternative process is dominant. The following section illustrates the diversity of these and consider why particular processes occur in certain circumstances.
Figure 3 Conceptual model of the pools, process and pathways of nutrient transfer from source to catchment and the factors influencing these.
Figure 4: Conceptual model in a more linear representation.

Conceptual (linear) model

Farm
- Weather factors
- Farm Management
- Import

Catchment
- Profitability
- Climatic factors
- Stream order
- Dams / lakes

Local hydrology
- Transport pathways
- Soil properties
- Landform

Sediment chemistry
- Storage / attenuation / release
- Groundwater flow

Aquatic ecology
- Asset condition

Net export

Management actions
3 Nutrient pools and fluxes on dairy farms

3.1 Nutrient pools on farms

Substantial quantities of nutrients are stored in various pools on dairy farms. These pools tend to be highly variable both within and between farms and are generally thought to be increasing due to the imbalances between nutrients imported and those exported as discussed previously. These pools include the more obvious ones such as fertiliser (applied and stored), soil nutrients, nutrient in feeds, livestock, stored feed and in pasture or forage. Some pools are highly dynamic and turning over constantly, e.g. pasture nutrients, while others are relatively static, e.g. soil nutrients. Inorganic fertiliser nutrients are generally rapidly converted and incorporated into other pools in the system.

A conceptual model of key nutrient pools and fluxes in dairy farming systems is shown in Figure 5. This model illustrates the complexity of fluxes but also the capacity to logically describe these, and hence the capacity to understand and model them. This conceptual model forms the basis for nutrient budgeting proposed for the ‘Accounting for Nutrients on Australian Dairy Farms’ project which will ultimately form the ‘National nutrient accounting standard’ for the Australian dairy industry.

Nitrogen and phosphorus imports to dairy farms are typically greater than the outputs (Gourley et al. 2007). These nutrient surpluses tend to increase as farms intensify and stocking rates increase (Halberg et al. 2005). Gourley et al (2007) reported that P surplus increased by between 8 and 17 kg P/ha/yr as stocking rate increased from
2 to 4 cows/ha, depending on seasonal conditions. In a limited study of seven dairy farms in coastal New South Wales, Lawrie et al. (2004) found that farm gate P surplus ranged from 1 to 127 kg P/ha/yr. In south-west Western Australia (WA), Neville et al. (Neville et al. 2005) determined that the medium annual P surplus from 44 dairy farms across three environmentally sensitive catchments was 17.7 kg P/ha. In Gippsland, Vic., annual N, P and K surplus on a typical dairy farm was estimated at 15 and 19 kg/ha for N and P, respectively (Reuter 2001).

Changes in typical industry management have had major impacts on the size of nutrient pools and cycling. Increased supplementary feeding and increasing forage yields, increased pasture and forage quality due to fertiliser use, particularly N (Eckard et al. 2004a) and subsequent harvesting over the past 25 years has been used to increase per cow productivity (Doyle and Fulkerson 2001; ABARE 2006).

In 1980, most dairy farms were totally reliant on ‘home grown’ pasture and conserved forage. In 2004–05, 91% of all dairy farms used imported concentrates, with the average dairy farm supplementation greater than 1.1 t/cow/year, mostly as cereal grain-based supplements. The other major supplement brought on to dairy farms in Australia is hay, usually fed in equivalent amounts to grain. There is considerable variation in the amount and type of diet supplementation of lactating dairy cows, with grain inputs varying from 0 to 2.5 t dry matter (DM)/cow.year and forage inputs varying from 0 to 1.4 tonne DM/cow.year (ABARE 2006).

Stored feed can include both homegrown and imported feed. A recent survey on Australian Dairy farms reveals that the average dairy farm has about 500 tonnes of stored feeds on farm, representing about 1250 kg P and 12500 kg N (pers. comm. Cameron Gourley, DPI Vic). Whilst these are big stores of nutrients, in their stored state they are unlikely to have a significant environmental impact. However, their flux in the farming system means they may contribute to environmental impact. Large, high intensity dairy farms can be importing multiple truckloads of feed daily, particularly in hot dry periods such as summer when pasture growth can be limited.

Soil is in most cases likely to be the biggest single pool of nutrients on farms. In a typical soil used for grazing or forage production, the total P and N concentrations in soil could be in the order of 0.1 and 0.3% respectively, which equates to ~1000 and 3000 kg of P and N per hectare in the top 10 cm of soil. If a farm has 100 hectares of soil under this landuse, then there may be 100 and 300 t of P and N respectively stored in the soil. Often the concentrations of nutrients may be higher than used in this example. The majority of these nutrients are likely to be native and only a small fraction of them available. For example, typically only 1% of total soil P and N is water soluble or in mobile inorganic forms (Sharpley et al. 1981; Sharpley et al. 1985; Pote et al. 1999). This is illustrated for an example in the figure below.
Manure can be a substantial component of farm nutrients and farm nutrient flows. Cows defecate and urinate about 11 and 12 times respectively (White et al. 2001), each covering about 0.12 and 0.36 m$^2$ respectively a day (White et al. 2001). Dung pats have a life of about 30-40 days only (Aarons et al. 2004a), after which time, their nutrients become part of the soil nutrient pool. As an example of the magnitude of the turnover in manure, cows excrete 477 and 73 N and P respectively per day (Sharon Aarons pers comm., Vic DPI). At a typical industry stocking rate of 1 cow/ha over 80 ha = 2132 kg P (27 kg P/ha/yr) or 300 g N per cow per day = 1kg 3936 kg N (174 N/ha/yr). Many farmers now have higher stocking rates than the 1 cow/ha used in this example and consequently these nutrient deposition rates can be easily twice those indicated above. Urine contains little P but contains N, primarily as urea. The N loading rate under urine patches is in the order of 1000 kg N/ha (Di and Cameron 2007). These faecal pools and their fluxes are of similar order of magnitude or greater than typical fertiliser application rates.

Pasture nutrients can also be a substantial pool and even more substantial flux of nutrients. In a standing pasture biomass of 2 t/ha, there is ~6 kg and 60 kg/ha of P and N respectively. If it is assumed that 10 t/ha is grazed per annum, this is a flux being consumed of 30 and 300 kg/ha P and N respectively. Furthermore, with consumption only representing 50% of net primary productivity, there is 30 and 300 kg/ha P and N respectively being recycled to the soil surface.
The net result of the increased importation, stocking rate and internal turnover of nutrients is a potential increase in the size of the potentially environmentally significant pools (Eckard et al. 2004b; Menneer et al. 2005; Dougherty et al. 2008b).

### 3.2 Spatial variation in nutrient pools and fluxes within farms and between farms

The nature of dairy farming operations has a major influence on nutrient pools and fluxes that makes them unlike any other agricultural enterprises in terms of complexity and magnitude. The shift towards more intensive production via higher proportions of brought on feed and an increase in harvesting and within farm transfers has greatly increased the size of pools and fluxes on farms as described above.

Soil nutrient mapping on dairy farms can be used to show the spatial variations in soil nutrient contents at a point in time. Figure 6 (Gourley et al. 2007) shows the variability within 3 different farms of Olsen P. Farms 1 and 3 tend to have relatively few paddocks with high or very high soil P levels whereas farm 2 has a large number of paddocks with high to very high soil P status. Clearly, there are large differences between the farms as well as within.

On a commercial dairy farm, in Gippsland, Aarons et al. (2004b) found that nutrient levels in 33 distinct areas surrounding the dairy, laneways and stream were also highly variable, with Olsen P levels in loafing areas (0–5-cm soil samples) in excess of 210 mg/kg. Finch (2000) also found similarly wide variations in soil P concentrations. The nature of diversity can be a function of other factors such as manure spreading. For example, Penn et al (2007) observed localised hotspots within grazed paddocks attributed to manure deposition whereas in a paddock to which manure had been applied, there were more widespread hotspots associated with convenience of spreader application. Similar patterns could be expected in paddocks to which effluent is or has been applied.

Soil nutrient concentrations under effluent application can be particularly high (Finch 2000; Cameron and Di 2004; Conteh 2006) as effluent is often applied to the same area repeatedly and the nutrients applied in effluent can be substantial. Jacobs et al. (2008) reported that application of 100 mm of effluent resulted in the application of ~34 and 210 kg of P and N respectively. In an extreme case, Conteh (2006) reported soil Colwell P in a paddock to which effluent had been applied as >1000 mg/kg of Colwell P. Holford et al (1997) reported that the application of effluent reduced the sorption strength of soils, thus increasing the risk of elevated runoff P concentrations. Anecdotal evidence suggests that farmers may apply fertiliser in addition to effluent further increasing nutrient loadings in these areas.
3.3 Temporal variations in nutrient pools and fluxes on farms

Inputs and exports from farms tend to be relatively constant over shorter time frames, e.g. <1 year, except for imports of fertiliser which depending on the nature of the farming system may be highly seasonal, e.g. farmers applying spring or autumn applications of P fertiliser. The fertiliser inputs can represent major pools that can be highly available in the short term and result in large short term exports of nutrients as
will be discussed in later section. However, there is a trend towards farmers applying smaller amounts of fertiliser more frequently that may mitigate against these high concentrations in the case of P particularly. This possibility is currently being investigated by Burkitt and Dougherty. Preliminary investigations suggest that there may be little environmental difference between multiple, small and large single applications of P fertiliser. Seasonal imports of feed can be substantial depending on the district.

Table 1. Potassium and phosphorus inputs in feed, outputs in milk, and difference, for three stocking rates (2, 3 or 4 cows/ha) in a wet (1998–99) and dry (2000–01) season in Victoria, Australia (Gourley et al. 2007)

<table>
<thead>
<tr>
<th></th>
<th>1998–99</th>
<th>2000–01</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 cows/ha</td>
<td>3 cows/ha</td>
</tr>
<tr>
<td><strong>Potassium (kg/ha)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed</td>
<td>28</td>
<td>52</td>
</tr>
<tr>
<td>Milk</td>
<td>19</td>
<td>29</td>
</tr>
<tr>
<td>Difference</td>
<td>+9</td>
<td>+23</td>
</tr>
<tr>
<td><strong>Phosphorus (kg/ha)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Milk</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Difference</td>
<td>–3</td>
<td>0</td>
</tr>
</tbody>
</table>

Once nutrients accumulate in farming systems, and soils in particular, there can be a substantial inertia that prevents rapid decline. There can be a long lag time for nutrient decline, particularly P. Burkitt et al (2002) found the lag time and the rate of decline in soil P highly variable between soils. The decline was more rapid for soils with greater P buffering capacities, but still slow. Dougherty et al (2008) also found that in a grazed pasture system, there was little decline in soil Olsen P in the absence of fertiliser applications because of manure inputs. Consequently, runoff P concentrations didn’t decline. A typical rate of decline in the labile P pool from applied P would be 1 mg/kg/yr. For paddocks with high soil P concentrations as a result of past management, simply halting the application of P fertiliser, may take many years to result in reductions in nutrient exports.

Nitrogen tends to be more short lived in the dairying system and therefore more responsive to management changes. Eckard et al. (2003) showed that nitrate and ammonium in soils can increase upon application of fertiliser N but that the increases in the labile pool tend to be relatively short lived, e.g. 20-30 days. However, soils can accumulate substantial amounts of organic N. Take an example of a soil that starts off with lowish carbon, say 1% and this increases to 5% over time. This represents a 4% (40 000mg/kg) C increase which equates to ~3-4000 mg/kg total N. Eckard et al. (2007) reported substantial surpluses of N in fertiliser dairy pasture systems – that presumably were accumulating as soil organic N.
4 Hydrological mobilisation of nutrients within and transport from dairy farms

Mobilisation of nutrients can be defined as the transfer from a stationary phase—such as soil—into a liquid phase (in this case runoff or leaching water). Mobilisation is just the first in a series of steps that results in the transfer of nutrients from farm to the wider catchment.

4.1 How does the mobilisation of nutrients vary spatially and temporally within farm systems?

Spatially

It is important not to confuse ‘scale’ with ‘spatial variation’, an issue highlighted in a review by Dougherty et al (2004). Spatial variation in nutrient pools (both amount and form) can result in different processes of mobilisation and can result in different concentrations and loads in runoff or leachate being measured. In contrast, changes in scale can mean that fundamental differences in dominant processes change, e.g. rainfall simulation plots will not detect processes associated with hillslope hydrology whereas large scale studies may do so.

The mobilisation of nutrients is a function of the characteristics of the pools of nutrients and the hydrological conditions at the particular site (Dougherty et al. 2004). Typically the pool of nutrients available for mobilisation is only a small proportion of that in the system. For example, typically of the order of 1-5% of total soil P and total soil N are in water soluble or in mobile inorganic forms (Sharpley et al., 1981b; Pote et al., 1999(Sharpley et al. 1985)).

As a general rule, all other things being equal, as the pool of nutrients in soil increases, so does the concentration of nutrients mobilised in leachate or surface runoff (Pote et al. 1996; Ledgard et al. 1998; Pote et al. 1999). With soil fertility varying so markedly within farms (as discussed above), and soil fertility being highly correlated with the potentially mobile pool of soil nutrients, it is not surprising that on this basis there are large variations in the concentrations of nutrients in runoff and leachate. Within a small sub-catchment (~2.5ha), Dougherty (2006) showed that concentrations of P in runoff could range from 0.1 to 4.8 mg/L as a result of variations in soil P concentrations (Figure 7). Davies et al (2005) used this data to illustrate the highly variable zones of likely mobilisation, soil P, runoff P concentrations and nutrient export zones (Figure 9).

There is also large variation in the soil P-runoff P relationships between soils. This was illustrated by Dougherty (Dougherty 2006) in a comparison of Australian runoff data with that published by Vadas et al (Vadas et al. 2005) (Figure 8). This data also suggests that in general, Australian soils may be more susceptible to having higher concentrations of P in runoff than international soils.
Figure 7: The relationship between soil P and runoff total phosphorus (Dougherty 2006)

Figure 8. Relationship between Bray P (0-0.01 m) and runoff DRP for the Flaxley site and several other Australian studies. The shaded area represent the approximate range of values reported by Vadas et al. (2005) from North American runoff studies. ? – Flaxley field simulations; ? Flaxley tray simulations; ? Narellan NSW (Cornish et al. 2002); x - Vertosols - Camden NSW (Dougherty unpublished); ? Chromosols - Camden NSW (Dougherty unpublished); ? Camden rainfall simulations (Chapter 4). The vertical dashed lines indicate the approximate optimal value of Bray P for plant growth. (Dougherty 2006).
Figure 9. Spatial distribution of a) wetness index (dry - low light green, high – dark green, b) soil P, c) predicted runoff TDP (mg/L) and d) resulting phosphorus load generation (Davies et al. 2005).
Whilst there is large variability in nutrient mobilisation within the grazing areas of farms, there are also large variations between grazing and non-grazing areas of farms. Hard surfaces such as laneways and feedpads can generate runoff with high N and P concentrations. For example, Edwards et al (2008) measured concentrations of 100 and 5 mg/L of N and P respectively from areas of farms with substantial manure loadings. Miller et al (2006) found runoff concentrations from manured pens of ~80 and 30 mg/L N and P respectively.

Although these hard surface areas generating high nutrient concentrations represent only a small proportion of dairy farm areas, e.g. 2-5% (pers comm. C. Gourley) they typically would be expected to have runoff coefficients of close to 1, c.f. soil in paddocks which typically have runoff co-efficients of ~0.1. Therefore, laneways and similar hard surfaces may generate 20-50% of farm runoff. This combined with the typically substantial nutrient concentrations of runoff are likely to be major sources of exported nutrient loads and could contribute exports of similar magnitude to those coming from all other areas of farms. Although industry best practice, e.g. Anon (2006) suggests that runoff from these areas should either be captured or diverted to other parts of the farm such as paddocks, it is likely that a large number of farms still generate runoff from these areas that enters streams.

Laneways and other hard areas can be a major source of nutrients

Although representing only small proportions of farms, areas such as laneways may generate relatively large amounts of runoff and this runoff may be very high in nutrient concentrations such that loads from these areas approach those from pasture areas of farms.

Similarly, hydrology can vary markedly within farms based upon soil type, irrigation practice if applicable, and position in landscape. Runoff hydrology can have fundamental differences, e.g. saturation versus infiltration excess or, in the case of soils with high infiltration rates, these can be relatively infrequent occurrences and infiltration and subsequent return to surface can be important as is often reported in WA.

Temporally

The variations in nutrient mobilisation, concentrations, and transport can occur within the space of minutes to years. Typically, it is observed that the smaller the scale of measurement, the greater the potential for variation in relatively short timeframes (Stutter, Langan and Cooper, 2008).

The processes of mobilisation can vary within a storm event, seasonally and between years. Increases in nutrient concentration can occur as runoff rates increase within a runoff event (Haygarth et al. 2004; Holz 2007). However, in contrast, other authors have reported that as flow rate increases, concentrations decrease due to dilution type effects and reductions in residence time (Nash and Murdoch 1997; Dougherty et al. 2008a). There can also be changes within seasons. Fleming (2001) observed that particulate P was the dominant form of P mobilised and transported early in the runoff season but as ground cover improved dissolved P dominated. Longer term trends can be the result of changes in fertility and its influence on groundcover, and a shift from particulate to dissolved P (Dougherty et al. 2006).
Both N and P concentrations in runoff have been shown to vary markedly within and between years even under similar management conditions (Eckard et al. 2004b; Nash et al. 2005; Barlow et al. 2007; Dougherty et al. 2008b). This variation has been attributed to the effects of grazing, changes in fertility and coincidence of fertiliser application and runoff or leaching.

Perhaps the most obvious – although arguably not so important - effect on runoff or leaching concentrations is when runoff or leaching occurs soon after the application of fertiliser – these effects being known generally as ‘incidental’ fertiliser effects. Increases in runoff nutrient concentrations can be in the range of orders of magnitude.

For example, Barlow et al (2007) reported typical N concentrations in runoff of 10 mg/L but these increased to 150 or so if runoff occurred immediately post fertiliser application. Nash et al (2005) reported runoff P increases from 2-5 mg/l up to 80-100 mg/L when runoff occurred immediately following fertiliser application. Dougherty et al (2008b) found much smaller effect than reported by others. These incidental effects may last for between days and weeks, although Hart et al (2004) proposed that the length of this effect was highly variable and often longer than the 3-4 days proposed by Nash et al (2005).

It is also probable that the persistence of these effects in the case of P is a function of P buffering properties. Sandy, low P buffering soils having relatively long persisting fertiliser effects compared to highly buffered soils. This is currently the subject of research by Dougherty and Burkitt.

The elevated concentration of nutrients in runoff occurring immediately after manure deposition associated with grazing also constitute ‘incidental’ nutrient concentrations. These effects are often much smaller than those associated with fertiliser (Nash et al. 2005; Dougherty et al. 2008b).

If manure P loading is distributed over 10 grazings then the loading rate is typically low on a per event basis and may explain the weak effect on runoff seen in some research (Nash et al. 2005; Dougherty et al. 2008b). An exception to this is the findings of Holz (2007) who found that grazing was apparently associated with substantial increases in N and P in runoff. The magnitude of this effect may have been because grazing occurred over several days. Under controlled conditions McDowell et al (2007) showed a more discernible effect of manure on runoff P concentrations.

It is likely that in interpreting such effects, that the number of cows grazed per hectare for each grazing is a key driver, i.e. total cow hours per grazing will influence the P loading in dung and therefore the magnitude of this effect. The degree of saturation of soils may also be an influence, with grazing induced losses higher when soils are saturated and transportation can occur promptly.

Both Dougherty et al (2008b) and Robertson and Nash (2008) proposed that ‘incidental’ effects on runoff nutrient concentrations are not as important as systematic components associated with fertility.
4.2 Hydrological transport of mobilised nutrients within and from farms

In the context of this review, the mobilisation of nutrients occurs by their transfer from the source (discussed above) into water and then transport via several pathways. The two key pathways are infiltration and overland flow. Once the nutrient containing water has commenced moving via these pathways it may then become concentrated in either saturated sub-surface layers or in concentrated flow zones such as drainage lines and ultimately creeks and rivers.

Once nutrients have been mobilised, the completeness and timeliness of transport to receiving waters will depend on a wide range of factors. The connectivity and pathways of nutrients from the farm to the wider environment depend on farm location and proximity to waterways or groundwater. Whilst nutrients may be mobilised in one form they may be transformed into other forms by some of the processes outlined in the Section on transformation.

**Connectivity**

Connectivity between the source of nutrients and receiving waters is a critical factor in the determination of potential environmental impact

Connectivity can be high in the case where the nutrient source is near to a concentrated flow zone, on areas such as laneways or where there is subsurface drainage. Sydney Catchment Authority spatial analysis data (pers comm.) reveals a high proportion (>90%) of that the catchment was within a very short distance of 1st order streams meaning there is very high connectivity between the hillslope and runoff generated from it and waterways. Strategies such as the use of buffer zones are likely to be ineffective in these conditions.

Factors such as farm dams can substantially retard nutrient transport (Cornish 1997). However, the effects of features such as farm drains can be variable. Barlow et al (2005; 2006) reported both decreases and increases in runoff P concentration as it flowed down drainage channels within farms. In the cases where it decreased it was due to bare earth with low P status and in increases was associated with high P earth and decaying vegetation. Substantial decreases in P and N, 76% and 38% respectively, have been observed between paddock scale losses of nutrients and farm scale losses (Rivers 2007). These reductions are being attributed to processes along in-farm drainage systems.

Tile or mole drains may also provide a direct connection between a source of nutrient, predominantly N mobilised by leaching, and the wider farm landscape. These drainage systems tend to occur in SE Australia where wet winters result in periodic waterlogging of soils. Eckard (2004b) inadvertently demonstrated their importance by using them as a tool for collecting nitrate leaching data.

Nutrient exports have been shown to be both similar and dissimilar between paddock and farm scales. Barlow (2005) reported that nutrient exports at the paddock scale were reduced by ~2.3 at the farm scale due to assimilation processes (not dilution). Cornish et al (2002) reported that concentrations at the farm scale were for some events smaller (max ½) and sometimes greater (max 2.5) than those measured at the paddock scale. However, there may have been a range of source and hydrological factors as well as assimilation processes (at the farm scale) that resulted...
in these differences and variations. Similarly, Rivers (2007) observed a complexity of these ‘scaling’ relationships because of differences in source factors within the farm. The variability of nutrient export and transport processes across a landscape result in variable findings when attempts are made to link data between different scales.
The fate of nutrients once off-farm

Nutrients leave the farm systems through five major pathways (Lemunyon and Daniel, 2002):

- Removal as “product” (meat, milk, live animals or crops). This is the desirable form of nutrient removal from the farm system and is the environmentally beneficial form of nutrient “loss” but, even in this case, nutrients are not actually removed in any true sense of the word, but simply transferred across the farm (and sometimes catchment) boundary to form an input into another nutrient cycling system.

- Lost attached to eroded sediment. Often significant in catchments dominated by heavier soils and in intense, highly-erosive rainfall events.

- Lost in the dissolved form in surface water and in the case of P often referred to as filterable, reactive P or Ortho-P. Often significant in sandier catchments and as “base-flow” losses not related to specific, episodic rainfall events.

- Leached vertically down through the soil profile either into local groundwater pools or, more slowly, into regional ground and surface water resources. As per loss in the dissolved form, often significant in sandier catchments and as “base-flow” losses not related to specific, episodic rainfall events.

- When soils are saturated and anaerobic, nitrate is transformed into nitrous oxide and can be lost directly to the atmosphere.

The proportions of nutrients lost via erosion, surface flow and leaching are highly variable across landscapes, soil types, climatic regions and time. This point makes it particularly difficult to develop general rules regarding nutrient loss mechanisms.

The biological response of water bodies downstream of sources of nutrients can also differ widely depending on a wide range of parameters in addition to the actual amount of nutrients incident upon them. Factors such as: location; climate; season; present levels and structure of biological activity; geography; hydrology; shading, and; size and shape of the receiving water body, all have significant roles to play in determining the ultimate effect or otherwise of excess nutrient inputs into the water body.

The physical and chemical processes governing nutrient fluxes in soils, sediment and water have been discussed previously and these processes also apply at the catchment scale.

5.1 Episodic losses of nutrients

The importance of nutrient loss through episodic events mentioned above can be illustrated with numbers of examples:

- Eight storms in three years accounted for 72% of the phosphorus transfer and 56% of the total runoff volume on a dairy farm at Darnum in West Gippsland, (Nash et al. 2000). The turbulence and re-suspension of sediments occurring in streams during these events is the ideal situation for soluble phosphorus to re-attach to sediments and be lost attached to suspended particles in streamflow.
In the dryland, sandy portions of the Peel-Harvey Catchment in Western Australia, up to 90% of phosphorus applied as superphosphate can be leached beyond the root zone of pasture plants directly to groundwater within the first two or three rainfall events of winter.

In the Harvey Irrigation Area in Western Australia, little if any water is lost to the receiving waterbodies downstream of dairies over the summer, irrigation season, but winter rains drive nutrients deposited in the regional drainage network through the landscape to downstream water bodies over the wet winter months.

And on the south coast of Western Australia, a one in 200 year rainfall event recently transported what has been estimated as thousands of tonnes of topsoil and their incumbent nutrient load down through catchments into the Albany harbours, and even between catchments across previously-well defined catchment boundaries.

Most water quality monitoring has historically been based on sampling of streams at regular time intervals rather than continuous monitoring. This means that significant losses of phosphorus during storms may not have been monitored.

5.2 Nutrient movement through the catchment

Nutrients that move beyond the farm boundary may move rapidly down the catchment, or they may be locked up in soils and sediments for years, even decades, until the right conditions occur to release them. This is presently of particular concern as the majority of southern Australia’s catchments (where the majority of the nation’s dairies are located) have experienced lower than average rainfall levels for many years. Nutrients normally stored in soils and sediment may be suddenly released in a one-in-ten year flood or larger event.

Nutrients that leach slowly and constantly in subsoil water can be particularly hard to control, even with the best on-farm and riparian management.

Research has shown that in a typical Australian catchment, seven to ten years of data regarding water flow rates and nutrient loss levels are required to have some confidence that the range of typical conditions that may release nutrients into the system have been observed. Even then, it is proposed that this will then only provide confidence in predicting what one year into the future may look like (Pers. Comm. David Deeley). It may then take a further ten or more years before changes in management on farms at the top of the catchment have an observable effect on the water quality at the bottom of the catchment.

Patience, experimentation, observation and adaptive management are the formula for success.

5.3 Incident-specific vs systematic nutrient loss

Nutrient losses can be regarded as either incidental or systematic losses. Incidental losses are those over which the farmer has some control in the short term and these may account for 20-40% of the annual nutrient loss in many farming areas. An example is the farmer avoiding spreading phosphorous fertiliser 3-4 days before rainfall that results in runoff. Using a 4-day weather forecast can be very effective in reducing direct losses from fertiliser applications, depending on the climatic conditions of the locality.
System losses result from the interaction of the farming system with the soils, landscape and climate. Key components of system losses may be beyond the farmer’s control - for example, the amount of runoff - while others require long term solutions such as maintaining soil nutrient levels at no more than is needed for healthy pasture.

Identifying ways to intervene that deliver the greatest environmental and economic payoff requires an understanding of the relative contributions from each of these processes. Precision farming helps farmers to apply nutrients more strategically, fertilising areas of the farm that need it and reducing inputs where nutrient values are high, or are loss “hot spots”.

Dairy soils are high in the nutrients needed to produce quality milk and farmers like to keep them ‘topped up’, as nutrition is one of the few factors which enable them to control their productivity. The challenge for farmers is to reduce the proportion of the nutrients they need to grow grass that is lost in runoff and to groundwater.

In the Peel-Harvey area, nutrient levels in the water running through paddock drains is often observed to be very high, but these levels can drop sharply until they are barely detectable in water leaving the farm. The mechanisms behind this are still unclear, but dilution, in-drain nutrient assimilation by sediment and in-drain algal growth are all proposed as explanations. This has led a number of WA dairy farmers to experiment with techniques for capturing the nutrient-rich water while it is still in the drain, and then recycling it back onto the pastures (water re-use, even irrigation runoff, is not a common practice in WA). It is now widely accepted that water is a resource that has to be re-used, so it makes sense to re-use the nutrients too.

Farmers, like everyone else in a catchment, should be doing what’s practical to minimise nutrient losses to waterways, but we need to understand what outcomes are achievable and what management practices will work best in different environments.

A major issue is the question of where the nutrients finally end up and what impact they have on the receiving environment. If a waterway runs straight to the sea and the nutrients are diluted and lost in a high energy ocean, apart from the economic cost to the farmer of losing valuable nutrients is there really an environmental problem? On the other hand if there is a sensitive receiving waterbody like the Peel-Harvey Inlet or the Gippsland Lakes, where algal blooms are a real risk, it may require significant effort upstream to reduce nutrient inflows.

However, measurements at the bottom of the catchment reflect many actions taken higher up, with built-in time lags – certainly not just what happens on individual farms.

Sediments can store phosphorus for years and release it suddenly in one major flood event. This means that systems may need to be monitored for several years in order to understand the dynamics of nutrient losses specific to that catchment.

### 5.4 Spatial dynamics of water quality measurements

The issue of the confounding relationship between observed water quality and the scale of measurement has been alluded to a number of times but now warrants more serious consideration.

Issues regarding the relationship between field and catchment-scale observations of nutrient fluxes, and the need to develop an improved understanding of nutrient and
hydrologic properties at this range of scales are already recognised (Gburek et al. 2002).

The specific relationship between scale of observation and observed nutrient transfer has been reviewed previously in Australia (Dougherty et al. 2004). They provided a comprehensive overview of the body of work completed to that point examining phosphorus transport from grazing properties to waterbodies with a focus on surface runoff in the Australian context. They categorised the major scales of research as laboratory, profile, plot, field and watershed and summarised that phosphorus is predominantly lost as the dissolved and colloidal forms in surface runoff but that research into organic phosphorus sources is presently limited.

However, the relative contributions of inorganic and organic phosphorus also varies. Stutter, Langan and Cooper (2008) showed that organic phosphorus, from field trials at a variety of scales in the UK, was the dominant form of P lost in surface waters.

Phosphorus levels in runoff water are primarily related to increasing soil phosphorus test levels and the proximity of fertilising events to subsequent rainfall or irrigation. In attempting to provide a consistent, concise approach to the question of scale effects on phosphorus transfer they show that it is necessary to consider issues such as source, mobilisation and transfer processes - which vary with scale just as much as the simple spatial variation itself.

Temporal variations are most marked and easily observable at the small scale where soil nutrient losses are more significantly influenced by storm-flow events (Stutter, Langan and Cooper, 2008).

A study by Bohl et al (2007) indicates that measurement of water quality parameters at the plot (1m$^2$) scale and the subwatershed (c 10ha scale) were reasonably well correlated in a cropping situation. This gives confidence that small plot measurements of soil and water quality relate reasonably well to at least the scale of 10 ha or so but no clear scaling effects were found.

Barlow, Nash and Grayson (2007) measured water and phosphorus loss at paddock, farm-section and whole-farm scales on a research farm in south-eastern Australia and found that the relationship between phosphorus export at these scales and for an irrigated dairy farm was poor.

A comparison of water quality with stream order for the Oyster Harbour catchment in WA by Weaver, Reed and Grant (2001) did, however, find a significant relationship between these two parameters. That is, phosphorus concentrations decreased with increasing stream order (catchment size). This is illustrated in Figure 10.

An earlier paper by Prairie and Kalff (1986) specifically examined the relationship between catchment size and phosphorus export. While they found that the assumption that there was a linear relationship between phosphorus export and catchment area was invalid for some cases, there were linear relationships in some instances, and others were related, but via a more complicated relationship. In general, they found that in agriculturally-dominated catchments, TP export varies as the 0.77 power of basin area. P delivery per unit area decreases with catchment size. Load vs catchment size was a linear relationship for non-row cropping, mixed agriculture and forested catchments.
Deasy et al. (2007) investigated P transfer between points within a small agricultural catchment over a series of rainfall events. They found that, while, scale-relationships were not distinct between closely-related scales (for example, down a hillslope) scale-relationship did exist across more disparate scales – hillslope surface runoff, hillslope drainflow – drainflow – catchment outlet streamflow.

Cornish, Hallissey and Hollinger (2002) studied runoff water from a dairy in NSW and found no significant difference between water quality measured at the whole farm (120ha) scale and that measured at the 4ha scale. Smaller scale measurements using a hand-held rainfall simulator also gave a similar result.

**Key Messages**

**Losses of nutrients can be highly episodic**

90% or more of losses occur in a few events. However, this is highly dependent on climate and episodic losses are less likely in winter dominant climates.

**Water quality improvements may take a long time**

Expecting to always see quick improvements in water quality from farm management changes is liable to lead to disappointment and discontinuation in the necessary effort and expense. In some cases, “improved management” may actually reduce water quality until a new equilibrium is reached and water quality improves.

**Effect of scale on nutrient concentrations**

There is no consistent relationship between size of runoff generating area and nutrient concentrations.
Key References


6 Models of nutrient fluxes in catchments

Developing a realistic understanding of something as complex as water or nutrient transport processes through farms and catchments can be a very difficult and resource-intensive task. To develop a good understanding of nutrient transport on only one dairy farm may involve the establishment of a series of soil and water sampling points and their management over a number of years. The fact that every farm and catchment is unique then makes it difficult to transfer results from one monitored location to other locations – even nearby.

This makes the development of more generic principles which can cross between locations, scales and time even more difficult. Even so, important decisions at farm and catchment scales need to be made and they must frequently be based on limited amounts of information.

One way of attempting to relate measured data from one point to others, or of applying well understood, if not well measured, principles to a range of locations is to use models. Pike 2003 states that “Models are simplifications of reality that reflect our understanding of the processes they represent. Hydrologic models simulate the movement and storage of water [and sometimes water-driven contaminants] within a catchment.” Modeling allows us to apply measured relationships or systematic understanding developed in one location or time-frame to others.

It is imperative to note, however, that “as with any tool, the answers they give are dependent on how we apply them, and the quality of these answers is no better than the quality of our understanding of the system” (Butcher et al. 1998). When used for particular purposes, some models are referred to as Decision Support Tools. It is very important to understand that they “support” the decision making process and their outputs should always be viewed critically in the light of measured data or locational and system-specific knowledge.

In modelling terms there are generally two types of models used for natural systems – conceptual models which seek to simply illustrate the relationships between various system components, and numerical models which seek to build on conceptual models and develop mathematical relationships between the system components.

A summary of the various types of models is shown in Table 2.

Radcliffe and Cabrera (2007) concentrate on numerical or mathematical models and define three distinct types of models used to model the flow of nutrients (particularly P) through the environment:

- Process-based models which model the actual processes involved in governing nutrient storage, transport and loss mechanisms in a catchment by the use of algorithms or mathematical equations – often derived from measured data. (For example, the WEND models (Cassell et al. 1987)).

- Empirical models which derive the algorithms controlling nutrient transport from simpler observed relationships between catchment characteristics and subsequent water quality levels.
Export coefficient models which are based more on simple categorisation of the efficiencies of various land uses in the catchment context and, within a land use, the efficiencies of the various nutrient storage, utilisation, transport and release sectors. (For example Weaver et al. (2004)).

Table 2: Definitions of the various models commonly used to describe natural systems

<table>
<thead>
<tr>
<th>Models used to represent natural systems</th>
<th>Conceptual models</th>
<th>Numerical or mathematical models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptual models</td>
<td>Used primarily for illustrative and educational purposes or for systems analysis. Describe the components and relationships of a system.</td>
<td>Used to predict future system characteristics based on various computational strategies</td>
</tr>
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<table>
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<tr>
<th>Process-based models</th>
<th>Empirical models</th>
<th>Export coefficient models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on mathematical relationships developed for specific system components derived from actual measurements, and then the relationships between the various components.</td>
<td>Based on simpler mathematical relationships between the various system components.</td>
<td>Based on measured or derived system efficiencies or inefficiencies at critical control points within the system.</td>
</tr>
</tbody>
</table>

All of these model types can be used to produce absolute numerical results or results expressed as probabilities of various outcomes. Probability-based models are often referred to as “stochastic” and are referred to as “deterministic” when they are based on “best guess” estimates of model parameters rather than unaltered probabilities.
Conceptual models can also be used at the broader scale to schematically or diagrammatically represent processes within and beyond the farm scale in a less empirical manner. This can be useful to illustrate those processes with the farm-catchment system which are well understood and which can be specifically expressed with a degree of confidence, as well as those process which are less well understood and which can only be inferred. This may be a valuable tool to assist with gap analyses and future research needs planning.

These types of conceptual models are often expressed diagrammatically and are useful as educational and influencing tools – especially for non-scientific audiences. The more complex, mathematically-based models are generally used by research scientists to provide tests of various farm and catchment scenarios.

A very simple conceptual model for P transfer is shown below in figure 1 and adapted from Haygarth and Jarvis, 1999.

![Conceptual model of P transfer](image-url)

**Figure 11: Conceptual model of P transfer. The text in bold denotes the critical transport and source factors without which P transfer will not occur.**

The conceptual model proposed in this paper (shown in Figures 1 and 2) attempts to outline in a relatively simple format, a schematic representation of farm to catchment nutrient impacts, but also to illustrate those areas of the simple model for which we have a more in-depth understanding of the driving processes.

Stochastic (or probabilistic) models, are based more on the underlying processes controlling, in this case, nutrient transport. Rather than being based on discrete datasets composed of realistic data, they rely on an understanding of the inherent processes governing variations in observed data.

A complex example of a probabilistic model is that of Bayesian inference or Bayesian belief networks. Bayesian inference is based on the assumption that as the amount of evidence gathered to prove or disprove an hypothesis increases (through
observation and measurement) then the “belief” in the hypothesis also varies. This method is increasingly being used to develop models of complex, natural systems where empirical evidence can often be incomplete or misleading due to inherent complexities of the systems being modelled. Outputs of Bayesian-based models are often represented as static, increasing or decreasing likelihoods of an event occurring, rather than absolute, numerical outputs as in the case of conceptual and some other deterministic models.

There are many well-known examples of the use of models of water and nutrient movement through catchments:

- Brossier et al. (1992) used a linear programming model to analyse the technical and economic parameters of farming that could be compatible with the demands of a mineral water company for a limit of 10 mg N/L in underground water.
- Reck et al. (1994) used modelling of BMPs (GLEAMS) to estimate the effect of conservation practices in reducing nitrate leaching in Middle Suwannee River area, USA.
- Ejaz & Peralta (1995) used a simulation/optimisation model as an aid to managing multi-objective waste water loading to streams while maintaining adequate downstream water quality. The conflicting objectives were to maximise the human and dairy cattle populations while maintaining acceptable levels of nutrients in the treated wastewater discharged to the river system.
- The neural network approach was used by Lek et al. (1996) for a large number (927 in total) of tributary sites throughout the USA. They used a large “training” set of tributary monitoring data to develop the model and then applied the model to the rest of the “testing” set of the data. Although correlations between modelled and measured data were high, the model was implemented at a gross scale and modelled water quality as a function of overall land use only.
- Johnes (1996) undertook an export coefficient modelling approach to examine the transport of both N and P to waterways in the UK and developed very strong relationships between predicted and actual nutrient losses (within 2% and 0.5% for N and P respectively). This approach is similar to that undertaken by Weaver et al. (2005) in WA where nutrient input/output data was captured from a large number of agricultural properties by undertaking one-on-one farmer surveys to develop individual nutrient budgets which were then amalgamated to develop budgets for each catchment land use category. The benefit of this export coefficient approach over more process-based models is that, although some simple processes are included as algorithms in the model, they are developed from measurable data at the farm scale rather than at the scale of environmental samples (water, soil and sediment) which then need to be somehow related to farm-scale observations.
- Tufford et al. (1998) developed a multiple regression, process-based model (again, in the USA) to better determine relationships between land use and water quality, but this model also allowed a focus on only non-point source pollution as well as the implementation of a variety of alternative management practices.
• Rodda et al. (1999) looked at the effects of intensive dairy farming on stream water quality of the Toenepi basin, near Hamilton in New Zealand’s North Island.

• Cassells & Meister (2001) use mass balance equations to model the probable impact of cost and trade impacts of environmental regulations New Zealand has set for water quality.

• Stout et al. (2001) evaluated nitrogen management options for reducing nitrate leaching from Northeast U.S. pastures, using the Cornell Net Carbohydrate and Protein System Model.

• Sharpley et al., (2002) undertook a comprehensive review of the “salient issues facing scientists that model P transport”. They developed a variety of useful relationships between model parameters such as the rates at which P is both stored and released from both soil and water and those relating principally to land cover and erosion. They also stated that measured BMP information (such as that developed through DA’s previous catchment work) should be used in model development and use, and that it is essential to select models appropriate to both the purpose and scale of the questions at hand.

• Lee et al. (2003) developed an artificial neural network model to examine the incidence and severity of algal blooms in Hong Kong. This complex modelling approach uses a set of computer algorithms which allow the model to be “trained” or to learn from each iteration of the model that is run. They proposed (expectedly) that the accuracy of model predictions is linked to input data of an appropriate frequency which can reflect system algal responses to varying water quality.

• Radcliffe and Cabrera (2007) reviewed a number of environmental phosphorus models including: the Soil and Water Assessment Tool (SWAT) and the Watershed Ecosystem Nutrient Dynamics – Phosphorus (WEND-P) Model developed by the US Department of Agriculture. Both used extensively to model catchment nutrient movement and to predict the effectiveness of a range of environmental Best Management Practices.

• Recently Davison et al. (2008) developed PSYCHIC, a process-based model for phosphorus and sediment mobilisation in the UK which can be used to model phosphorus and sediment transport at field and catchment scales.

Through a review of the various modelling approaches already undertaken and discussed in some detail above, it is apparent that a combination of process-based modelling coupled with export coefficient modelling may be the ideal approach.

Process-based modelling allows for the use of long-term, robust water quality datasets and well-defined nutrient use, accumulation, storage, transformation, transport and release mechanisms to be used as algorithms determining nutrient flow through the model. The use of an export-coefficient component in the model allows for a more farm and catchment-scale understanding of the gross levels of nutrient movement. This may be described as ground-truthing of the process-based, often interview-based data.

To build on previous work in this field then it will be most beneficial to build a conceptual model of nutrient transfer in dairy-dominated catchments which builds on existing models, but also captures those areas which have been indicated as
requiring more thorough representation of the farm – catchment system. Dougherty et al. (2004) indicate that the additional issues requiring consideration include: runoff rates (as related to infiltration and runoff excess); nutrient source (inorganic and organic); nutrient mobilisation processes; transport pathways and processes including hillslope hydrology, and; the full range of “scale” issues including scale-dependent concepts such as preferential drainage pathways, varying mobilisation processes and actual measurement methodology.

**Key Messages**

Natural systems (such as nutrient fluxes within a farm or catchment) are extremely complex and variable. To better understand them in general terms we need to develop models that illustrate our understanding of these systems and allow us to predict scenarios for which we do not have appropriate measured data.

Models are simplifications of reality that reflect our understanding of the processes they represent.

The answers models give are dependent on the data assumptions we use to build them and on how we apply them. The quality of these answers is no better than the quality of our understanding of the system.

**Key References**


7 Conclusions

There is great diversity in farming systems and operations and similarly great diversity in landscape characteristics in which farms operate. Hence, the diversity of processes that result in the mobilisation and export of nutrients from farming systems is great. Acknowledging and understanding this diversity is critical to developing effective programs and plans for reducing nutrient transfers from farm to catchment.

Symptomatic treatment of eutrophication may be necessary in the short term to address water quality problems. However, these short term responses do not reduce nutrient loss from the landscape. The development and implementation of management practices that treat the causes of nutrient loss are required.

No one management practice is likely to reduce nutrient loss to levels that are acceptable for receiving waters. Some practices such as soil amendment can reduce P loss significantly, however, these practices need to be supplemented with other practices in order to achieve water quality targets.

Because of the large number of properties in catchments, the implementation of management practices on one farm only is unlikely to result in any change in catchment water quality. Changes need to be made by a large number of land managers to result in improvements in water quality. The best way to assess if a farm is doing the right thing is to compare its nutrient management with industry best practice.

Water quality responses to the implementation of management practices at the catchment scale (10’s to 100’s of thousands of hectares) may take many decades. Experimental scale research and monitoring may reveal water quality improvements in the shorter term if undertaken at a small scale (<200 ha) with high levels of management implementation.

Because of the dilution and buffering in streams, from a planning perspective, consideration should be given to locating high nutrient emitting activities at the most practical distant parts of catchments.

There is presently enormous interest worldwide in establishing the links between management on farm and what occurs further down the catchment, but currently nobody has the complete answer.

A key issue is whether progress is measured by what is observed in a river system today – natural resource targets – or by the rate at which landholders are adopting environmental best practice for sustainable farming. Adopting good management practices shows that the industry is serious about addressing the issue. They can be measured ‘immediately’ a change occurs, whereas changes in natural resource condition may lag years behind management and are affected by multiple land uses. For confidence that changed management is effective it is also necessary to continue monitoring the environment to detect predicted improvements.

We must continue to study the local interactions between different management practices and the environment, help farmers to subsequently identify and adopt what look to be best local management practices then monitor the extent of change in both management and the environment.

In this way we will continue to learn how to best manage our unique Australian environments and to achieve realistic goals for production and the environment.
**Key Messages**

| It is difficult to manage catchments, but you can start with a farm, |
| Farmers and catchment managers should invest their time and money strategically in measures that can be shown to sustainably cut nutrient loss and environmental impact, |
| Evaluating land management solely by its short-term environmental outcomes may be counter-productive, and |
| Research, such as that sponsored by Dairy Australia, helps farmers and catchment managers to have a shared understanding of farms and catchments and to produce better tools for their management. |
8 References


Department of Natural Resources and Environment. (1996) Blue green algae and nutrients in Victoria: A resource handbook. Department of Natural Resources and Environment, Melbourne, Australia.


N and P fluxes in dairy catchments


