PRIORITISING LOCATIONS, INDUSTRIES AND ABATEMENT ACTIONS FOR ENVIRONMENTAL IMPROVEMENT IN A HETEROGENEOUS CATCHMENT: THE SYDNEY BASIN, AUSTRALIA

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ABSTRACT

Sources of pollution in catchments with heterogeneous land uses are difficult to quantify. This paper describes research over 10 years to quantify nutrient exports from rural industries in the Sydney Basin, which is within the Hawkesbury-Nepean catchment and includes much of the city of Sydney and major rural industries. The aims were to develop sufficient understanding of mobilisation and transport processes to devise farm and catchment scale management plans, and to develop a methodology for prioritising abatement actions.

Monitoring water quality, discharge and land management over 2.5 years in ‘nested’ locations in a subcatchment provided estimates of nutrient export coefficients and data for model calibration. Exports from dairy pasture and vegetable farms were high: about 5 and 15 kg/ha.yr, with soluble phosphorus (P) dominating dairy runoff and particulate P the market gardens. Additional research provided further insight into management and scale effects. Imbalance between inputs and outputs drove high P runoff from farms, hence the need to reduce P loading at source. Mobilisation in runoff will be reduced through better irrigation and effluent management and erosion control. Filter strips and farm dams may manage P in the transport pathway. An export coefficient model in a GIS framework satisfactorily prioritised industries and abatement actions.

Keywords: dairy, export coefficient, GIS, modelling, nutrients, vegetables

INTRODUCTION

Cities often sit within water supply catchments that also support intensive agriculture at the interface between urban and more extensive rural production areas. With a requirement for clean water and a desire to support local rural industry for its economic and social benefit, it is inevitable that conflicts arise over water quality. These are hard to resolve in heterogeneous catchments where it is difficult to quantify the relative importance of different sources of pollution.

The Hawkesbury-Nepean above Warragamba Dam is the water supply catchment for the city of Sydney, which is situated within the Sydney Basin that includes the polluted (Anon 1998) lower reaches of the river system, below Warragamba Dam. The Basin supports an intensive agricultural industry producing A$1 billion annually, national parks, and more than 20 sewage treatment plants, all of which contribute to the total nutrient loading of the river system. The urban fringe also typically hosts large residential allotments or ‘hobby farms’. Whilst the nutrient emissions from point sources such as sewage treatment plants are readily measured and urban runoff was reasonably well documented in the early 1990s, there was no local information on nutrient runoff from rural land (Davis *et al*. 1991).

In the absence of data, the blame for declining water quality and more frequent outbreaks of toxic blue-green algae during the 1980s was readily aimed at intensive agriculture, comprising mainly vegetable production (‘market gardens’) and dairying. With looming changes in environmental legislation and media scrutiny of agriculture, there was a need for research to quantify and address the main sources of diffuse rural pollution (Cornish *et al.* 1992). A program was developed to measure farm-scale nutrient losses from the principal rural land uses and their transport through catchments, on-farm research to identify opportunities to improve environmental performance, and extension to encourage changes in farm practise. Modelling was developed as a tool for applying the understanding gleaned in one area of a catchment to other areas or catchments.

To address public perception that tillage was excessive on vegetable farms, leading to erosion and nutrient loss, participatory on-farm research with farmers over 1993-1996 helped them to develop production methods requiring less tillage (Senn and Cornish 2000). The participatory approach led to rapid change in industry, especially when farmers noted increased profits. However, it appeared that soil erosion rates were still high, later confirmed by Hollinger *et al.* (2001). This research addressed the *perception* that agricultural management could be improved, but did not provide any understanding of the *real* impacts of rural land uses on water quality. Therefore, long-term investigation of a wider range of options for reducing pollution from market gardens was commenced in 1993, in plot-scale experiments that have since demonstrated good potential to reduce soil degradation (Wells *et al*. 2000) and N and P runoff and N leaching at (Wells *et al.,* in preparation). However, plot scale results cannot be directly scaled up to field or catchment scale.

This paper describes those components of the overall program that were designed to quantify the pollution from different rural land uses, encompassing monitoring of runoff in a ‘nested’ set of locations within a representative subcatchment and study of individual farms. The development of a GIS-export coefficient modelling approach to extend results to the wider catchment is outlined, whilst a process model for predicting nutrient exports is described elsewhere (Baginska *et al*. 2003). The prioritisation of industries and geographic locations within the catchment for rectification action is reported, using the GIS-based model.

METHODS

'Nested' sub catchment

Monitoring sites were established in a representative 225 ha area of the Currency Creek sub catchment. It included: a market garden (16 ha), with irrigation and high fertiliser inputs including manure, part of an intensive dairy (44 ha),with fertilised, irrigated pasture (at times with effluent), and carrying 4 cows/ha, importing about one-half of feed requirements, an intensive poultry farm (caged birds, but inactive for much of the study period), and several 'hobby farms' with limited use of fertiliser (112 ha) or native pasture receiving no fertiliser (22 ha), with livestock generally equivalent to < 1 cow/ha (mostly horses, cattle).

An ephemeral stream drained the subcatchment. Two farm dams were located in this stream that discharged to Currency Ck near its confluence with the Hawkesbury River. Farm management was documented during the study period. Adjacent to the site was a hydrologically isolated area of market garden (8.8 ha). Research on farm management and nutrient runoff from this site has been published (Hollinger *et al*. 2001). Results from another, less intensive dairy on which little fertiliser was used have also been published (Cornish *et al*. 2002). A summary of these published results is included for comparative purposes.

Landform of the subcatchment comprises undulating low hills. Elevation is up to 100 m and local relief is 20 - 50 m. Soils in the study area are predominantly deep, imperfectly drained Kurosols and some Sodosols (Yellow Podzolic Soils/Soloths, Dy3.41, Dy2.41, Northcote 1979).

Seven automatic monitoring stations were sited within the study area such that nutrient runoff from individual land uses could be measured, as well as the 'assimilation' of nutrients beyond farms but before discharging to Currency Creek. This approach made field-scale measurements relevant at the sub catchment scale, by providing an estimate of assimilation on the hillslope and its flow lines.

Monitoring stations each comprised a programmable logger to record data, calculate discharge in real time and control operations; a rain gauge; a depth gauge to measure runoff depth in the control structure; and an automatic water sampler that was controlled by the programmable logger. Typical field installations are fully described by Hollinger *et al*. (2001) and Cornish *et al*. (2002). The autosampler took samples using a variable discharge-increment approach, based on changes in the calculated discharge through the control structure. Hydrologic data were recorded at three hourly intervals during dry periods and every 2 minutes during flow.

Monitoring occurred between May 1995 and March 1997. There were 35 rainfall events that generated runoff, although frequently too little to trigger sampling. Water samples were collected from the field within 24 hours. Once in the laboratory, samples were filtered as soon as possible using <0.45 µm Whatman GF/F glass fibre filters. Samples were analysed for a wide range of analytes, but only suspended sediment and species of P are reported here.

Records of discharge and nutrient concentration were obtained for each runoff event and monitoring station, through the event. From these, total export of nutrients passing each monitoring point was calculated for each event using the period-weighted method. Total exports from each landuse over the duration of the sampling period were divided by the area of that land use to provide estimates of total exports per hectare of each land use. These were annualised by dividing the total by the number of months of sampling and multiplying this value by twelve. This is a standard method of calculating nutrient runoff coefficients, but for relatively short monitoring periods it may result in estimates that are biased by hydrological events during the monitoring period. To overcome this problem, modelled runoff and the measured runoff-load relationship were used to calculate the long-term nutrient runoff. The Long-term rainfall records (1881-1993) for nearby Richmond, NSW were then entered into the CATPRO water balance model (Kuczera *et al*. 1993) to estimate runoff.

Additional farm monitoring

Further monitoring was undertaken on 4 market gardens over a 2-year period to obtain information on effects of nutrient and irrigation management, crop type and soil type on nutrient runoff. Multiple crops were monitored on each farm. Aims were to validate findings for nutrient runoff from the 'nested' catchment study and identify opportunities to improve management. Monitoring was at the scale at which farmer's implement management. Soil types were Kurosols and Sodosols and alluvial soils adjacent to the Hawkesbury-Nepean River. Runoff collection procedures were as described earlier, except in some cases tipping bucket samplers were used that provided a record of discharge and a composite water sample for an event. Fertiliser inputs were documented, as well as product removal and total P in product. Nutrient balances were calculated for each crop. Total soil P (persulfate), 'available' P (bicarbonate extract) and P buffer capacity were determined.

Prioritisation of locations, industries and abatement actions

Farmers and regulatory agencies need methods to identify pollution sources and rank potential abatement actions at locations where there has not been research, although research from other areas might be applicable with the use of modelling. The NSW Environment Protection Authority provided impetus for the development of a model to provide a foundation for a pilot nutrient trading offset scheme, to be trialed in nearby South Creek. The issue was to prioritise catchment locations, industries and abatement actions for remedial action. Process models (eg AnnAGNPS, Baginska *et al*. 2003) were rejected for this purpose because they require extensive data inputs and may be of limited value at larger catchment scales. They also suffer from low levels of confidence amongst users and stakeholders because they are 'black box'. A simple export coefficient model was developed for this purpose, based on our experience in Currency Ck, and a participatory process was used to engage stakeholders in evaluating the model and its predictions for South Ck.

The model was first developed and evaluated in Currency Ck, where there was a strong database. Flow weighted estimates of export coefficient, as described previously, were used in a GIS (Idrisi 32) with digital elevation model and land use map that allowed coefficients to be weighted for proximity to drainage lines. Additional published data, mainly for urban runoff, were also used. The method was simple, but addressed concerns of temporal and spatial insensitivity with such models. The model was used to calculate nutrient export for land uses within the catchment and evaluate abatement actions. Both local data and literature were used to estimate likely effectiveness and cost. A workshop was convened with stakeholders to transfer knowledge to the South Creek subcatchment that had similar soils and land uses. The approach met the need for stakeholders to take action in South Creek with sparse data. Scientific 'certainty' was replaced by stakeholder confidence, built through the participation of stakeholders including an 'expert panel' who could see and debate assumptions in the simple, transparent model, and query and adjust the predictions made for South Creek.

RESULTS AND DISCUSSION

Runoff composition

Runoff composition from the different land uses in the nested catchment varied (Table 1). Composition at peak flow also varied between events within land uses, reflecting in particular the effect of peak rainfall intensity on soil erosion (Hollinger *et al*. 2001). Event-mean concentrations (not presented) were less variable between events.

Table 1. *Water quality attributes near peak flow of storm runoff, downstream from different agricultural land uses in the subcatchment of Currency Ck. Ranges in values cover all runoff events.*

Attribute	'Hobby farm'	Dairy	Market garden
Sediment Load (mg/L)	Low (<50)	Moderate (50 to 1,000)	Very high (1,000 to > 100,000)
Phosphorus: - Total P (mg/L)	Low (<0.5)	High (1 to 5)	Very high (2 to 80)
- % Particulate P	Major (~40)	Major (~35)	Dominant (>75)
- % Soluble reactive P	Dominant (>50)	Dominant (>50)	Minor (<10)
- % Dissolved organic P	Minor (<20)	Minor (<20)	Minor (<10)

Market garden runoff was high in sediment, despite the fact that minimum tillage was used on this farm following the work of Senn (2000). Soil erosion from the dairy pasture was evidently much lower than the cultivated market garden. Runoff from the market garden and dairy were both high in total P, but for very different reasons. Particulate P dominated runoff from the market garden, but soluble reactive P dominated in dairy pasture runoff. The high concentration of soluble reactive P from dairy pasture (1-5 mg/L) is of particular interest, as it confirms other Australian data (Nash and Murdoch, 1997; Fleming and Cox, 2001; Cornish *et al*. 2002).

Soluble reactive P also dominated runoff from 'hobby farm' pasture, although generally at much lower concentrations (<0.5 mg/L) than dairy pasture, most likely reflecting the lower use of fertiliser and lower stock densities (<1 *versus* 4 head/ha). Cornish *et al*. (2002) reported total P concentrations in dairy pasture runoff of 1.2-1.6 mg/L in a nearby farm with 2.4 head/ha, thus falling in concentration between the dairy in Currency Ck with higher inputs and stocking rate, and the hobby farms with lower stocking rates.

EXPORT COEFFICIENTS

The annual export coefficients in Table 2 show that intensively used sub catchments such as Currency Ck have much greater exports of P (2.8 kg/ha.yr) than more extensively used (unimproved) sub catchments (0.3 kg/ha.yr, Cullen 1993) within the Sydney Basin. The results of all monitoring showed that nutrient export from market gardens is very high, with the exception of freely draining sandy alluvial soil, from which water runoff was low, but leaching of nutrients was high (unpublished data).

Export coefficients from the dairy pasture were also very high, in particular from the dairy in the nested subcatchment in Currency Ck with the higher stocking rate and therefore higher loading rate of P associated with effluent application, feed imports and defaecation on pasture. The values are higher than in the work of Fleming and Cox (2001) but lower than Nash and Murdoch (1997). Differences between these studies arise from differences in the amount of runoff as well as the concentration of P in the runoff. This leads to the important conclusion that site-specific solutions to pollution reduction from dairy pasture require attention to both loading rates (fertiliser, effluent application and in the future lower-P diets) and runoff reduction (irrigation management, runoff detention measures).

Table 2. Measured (annualised) and modelled estimates of nutrient export coefficient (kg/ha.yr) for rural land uses in the present studies, with other local studies.

	Area (ha)	Export coefficient	
		Annualised	Modelled
Nested monitoring			
- Catchment outlet	225	2.8	3.3
- Market gardens	16	9.6	15.3
- Dairy –stocking rate 4/ha, fertilised	44	6.7	6.4
- Pasture – hobby farm	1.0	0.8	
Other market garden monitoring			
- Alluvial sand – low runoff	1.0	0.6	
- Alluvial silt loam – high runoff	0.5	7.3	
- Duplex soil - very high runoff	0.3	17.6	
Other published local studies			
- Cornish *et al*. (2002)			
Dairy – stocking rate 2/ha, not fertilised	4-140	1.9-2.5	
- Cullen (1993) Unimproved Pasture	4,000	0.3	

Whilst the export coefficient for P was least from pasture on 'hobby ' farms, it was nevertheless much higher than from unimproved pasture (0.3 kg/ha.yr) suggesting that this land use may require some attention, in particular because it comprises the major area of landuse in the Hawkesbury-Nepean, outside urban areas.
The export coefficients for agriculture are amongst the highest found in the literature except in tropical environments. They confirm that the intensive agricultural land uses of dairy and vegetable production have the potential for significant environmental impact, although there are important differences between farms (Table 2) reflecting both management and soil type. High P concentrations in runoff from market gardens reflects both high erosion rates, even with substantially reduced tillage (Hollinger *et al*. 2002), and high soil P (Jinadasa *et al*. 1997) resulting from over use of fertiliser (Hollinger and Cornish, in preparation).

Catchment behaviour

A P budget was constructed for the site of the 'nested' study, showing that >80% of P mobilised came from market gardens and dairy pasture occupying only 26% of the land area. P exports from the study site approximated the sum of the component land uses, suggesting there was no net 'assimilation' in the flow lines, despite the fact that sediment sampling and analysis (not presented) showed substantial deposition of sediment and P in the farm dams. Presumably the flow lines, which included some wetlands, were saturated with P and were behaving as nutrient sources.

Management

Management of soluble P arising from dairy pasture presents a particular challenge because it is highly mobile. The effect of scale appears to be minimal (Cornish *et al*. 2002), unlike sediment (Prairie and Kalff 1986) and the P associated with it. In the Sydney Basin, most dairy pasture is irrigated, and therefore deficit irrigation management can be targeted as one way of reducing runoff volume. There is also potential to concentrate effluent application in higher parts of the landscape to minimise transport to surface water (Cornish *et al*. 2002). Most important, however, is the need to reduce the P loading associated with high stocking rates and the import of P in feed plus fertiliser.

In the nested subcatchment, sediment sampling revealed substantial entrapment in the farm dams, suggesting benefit from greater use of sediment basins and farm dams, as well vegetated filter strips. Gains over time will be made by reducing fertiliser inputs, as farm surveys included in this research program reveal that P inputs always exceed outputs, at times by over an order of magnitude, explaining the very high P concentrations found in soil on most market gardens (Hollinger and Cornish, in preparation). Overuse of P fertiliser is strongly related to the use of poultry manure, that has a high P:N ratio, indicating the need for research on non-polluting fertiliser strategies.

Prioritisation of catchments, industries and abatement actions

GIS-based modelling with export coefficients was used to produce a map of the entire Currency Ck, that was subsequently validated by an 'expert panel' who were asked to critique the model and its underlying assumptions as well as the data for export coefficients used in the model. The grey scale map highlighted those parts of the catchment contributing most to pollution, and thus most requiring action. It highlighted land uses of particular concern. The process of explaining the model and debating assumptions gave participants the conceptual framework to 'make sense' of their own knowledge and experience and apply it to prioritising actions for environmental improvement.

Contributions made by each land use were calculated (Table 3). Market gardens, turf and dairy pasture, which comprised only 2.3, 1.2 and 3.3% of catchment area, respectively, contributed 18.9, 11.4 and 20.4% of total P loading. From the data in Table 3, the cost/effectiveness of a range of abatement measures was estimated using mainly published data. At this stage there was considerable uncertainty in some of the data not generated in the project, so the analysis was used only to rank abatement measures into high, medium and low categories based on their cost effectiveness for reducing nutrient pollution and the expected reduction in pollutant loads in the target catchment. 'High' priority actions for reducing both N and P are listed in Table 4. The full list of actions for all land uses in Currency Creek included urban areas for which published data were used in calculations. Despite imprecision in the values for cost effectiveness, the EPA was given sufficient confidence to proceed with the pilot nutrient offset trading scheme in nearby South Creek, targeting intensive agriculture and the abatement actions identified in this project.

Table 3. Area of the catchment (ha and %) and total nutrient exports attributed to each land use type. (For brevity, some minor land uses are not shown and some are merged.)

Idrisi ID & Land Use Type	Area (ha)	% of catchment	Total P exported per year (kg)	% P exported	Total N exported per year (kg)	% N exported
Roads	66	1.6	32	0.8	333	1.0
Tree / Bush Cover	6	30.2	52	1.1	1622	4.3
Residential	564	13.1	841	18.0	5787	15.2
Market Garden	98	2.3	884	18.9	15773	41.5
Turf Farm	53	1.2	536	11.4	5360	14.1
Poultry Farm	22	0.5	44	0.9	88	0.2
Dairy Farm	141	3.3	955	20.4	955	2.5
Fertilised Grazing	356	8.3	350	7.5	1820	4.8
Unfertilised Grazing	1,358	31.6	583	12.5	4992	13.1
Parks / Active Recreation	9	0.2	15	0.3	110	0.3

Table 4. High priority abatement actions for Currency Ck (and South Ck) based on overall reduction (%) in P and N in the catchment and cost effectiveness ($/unit P reduction/yr).

Abatement action	Cost effectiveness ($/kg/yr)		Potential total load reduction in Currency Creek (%)	
	P	N	P	N
Runoff detention (market gardens)	12	2	4	3
Change fertiliser use (market garden)	10	<1	3	17
Dairy BMP (irrigation, effluent, fertiliser)	17	20	14	2
Grassed drains, diversion banks and filter strips (market gardens)	21	3	21	22

CONCLUSIONS:

Nutrient export rates from agriculture in the Currency Ck subcatchment of the Sydney Basin are high, contributing half of the diffuse pollutant load but occupying just 7% of catchment area. The implications for improvement of water quality in the region are clear. A relatively simple export coefficient model in a GIS with land use and elevation layers successfully quantified the relative contributions to diffuse pollution sources in a catchment with mixed rural land uses. It enabled stakeholders to evaluate and prioritise abatement actions. Success depended upon a good understanding of the processes of nutrient mobilisation and transport, and having a process for working with stakeholders that built their confidence in model predictions despite data uncertainty.

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REFERENCES:

Anon (1998). Independent Enquiry into the Hawkesbury-Nepean River System. Final Report, August 1998. Healthy Rivers Commission of NSW. ISBN 0 7313 1589 8.

Baginska, B, Milne-Home, W and Cornish, P S (2003). Modelling Nutrient Transport in Currency Ck with AnnAGNPS and PEST. *Envir. Model. and Software* (In Press).

Cornish, P.S. (1993). Managing Horticulture in the Sydney Basin to Achieve Better Economic and Environmental Outcomes - A Model for Application of Systems Methodology. Proc. International Systems Society Conf. Richmond, Aust. July 1993. Pp 505-510.

Cornish, P S; Hallissey, R and Hollinger, E (2002). Is a rainfall simulator useful for estimating phosphorus runoff from dairy pasture? A question of scale-dependency. *Aust. J Exp. Agric* **42:** 953-59.

Davis J. R., Coombe, D. C., Marston, F. M., Farley, T. F. and Laut, P. (1991). Final report on applying the Catchment Management Support System to the Hawkesbury-Nepean catchment. CSIRO Division of Water Resources, Consultancy Report 91/19, September.

Hollinger, E, Cornish P S, Baginska, B, Mann, R and Kuczera, G (2001). Farm-scale stormwater losses of sediment and nutrients from a market garden near Sydney, Australia. *Agric. Wat. Managment* **47**: 227-241.

Jinadasa, K.B.P., Milham, P.J., Hawkins, C.A., Cornish, P.S., Williams, P.A., Kaldor, C.J. and Conroy J.P. (1997). Survey of Cadmium Levels in Vegetables and Soils of Greater Sydney, Australia. *J. Env. Qual.* **26**: 924-32.

Kuczera, G., Raper, G. P., Brah. and Jayasuriya, M. D. A. (1993). Modelling yield changes following strip thinning in a mountain ash forest: An exercise in catchment model validation. *J. Hydrol.* **150**, 433-57.

Northcote, K. H. (1979). 'A Factual Key for the Recognition of Australian Soils.' 4th Edn. (Rellim Publications: Glenside, S. Aust.).

Prairie, Y.T., and Kalff, J. (1986). Effect of catchment size on phosphorus export. *Wat. Res. Bull.* **22**, 465-70.

Senn, A.A and Cornish P S (2000). An example of adoption of reduced cultivation by Sydney's vegetable growers. In S*oil 2000: New Horizons for a New Century. Australian and New Zealand Joint Soils Conference.* Vol. 2: Oral papers. (Eds J A Adams and A K Metherell). 3-8 December 2000, Lincoln University. N Z Soc. of Soil Sci. pp 263-264.

Wells, A T, Chan, K Y and Cornish, P S (2000). Comparison of conventional and alternative vegetable farming systems on the properties of a yellow earth in New South Wales. *Agr. Ecos. and Envir.* **80**: 47-60.