

LAKE WELLINGTON PROJECT · MACALISTER IRRIGATION DISTRICT

Nutrient dynamics in the Macalister Irrigation District

Technical summary of key findings for catchment managers and practitioners

Research summary 2020–2025

Gippsland, Victoria



Frost over flood-irrigated pasture bays, July 2023 (winter).

01 Project Overview and Approach

53,000 ha
of flat, intensively irrigated land draining to Lake Wellington

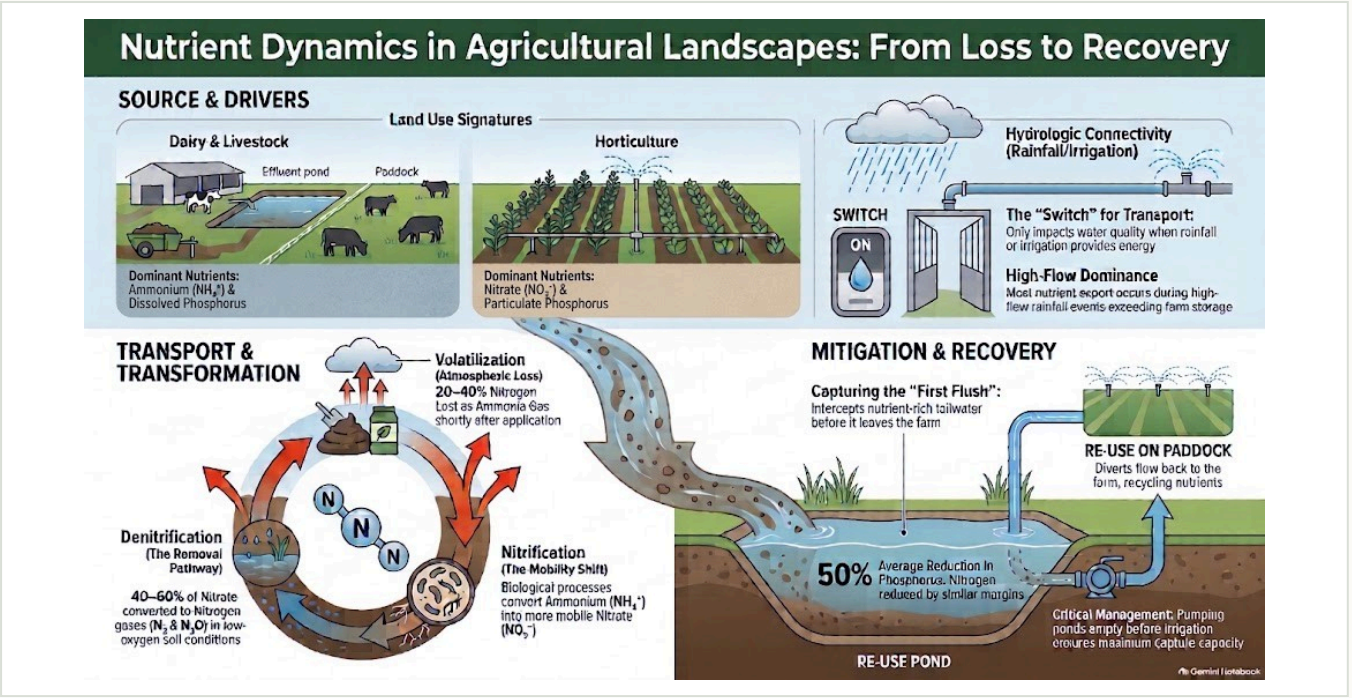
~90%
of the district's area is dairy farming

< 7%
of applied nitrogen is exported in stream flow

This report synthesises findings from a coordinated research program investigating nutrient (nitrogen and phosphorus) and greenhouse gas dynamics in the Macalister Irrigation District (MID), Gippsland, Victoria. The MID is a flat, intensively irrigated agricultural landscape of roughly 53,000 hectares, dominated by dairy farming (around 90% of area) with smaller areas of non-dairy livestock and vegetable horticulture, all of which drain into Lake Wellington and the wider Gippsland Lakes system.

The work combined farm- and catchment-scale nutrient monitoring across contrasting hydrological conditions (baseflow, moderate flow, high flow and a major flood event); tracer-based hydrograph separation to identify water source contributions; isotopic analysis of nitrogen and oxygen in nitrate and ammonium to infer transformation pathways; laboratory tracer incubations to independently verify field-based transformation estimates; deep-learning-based mapping of farm infrastructure and stocking rate; multivariate statistical modelling (partial least squares regression and Bayesian hierarchical modelling) linking catchment and farm characteristics to water quality outcomes; and simulation of irrigation reuse (tailwater capture) systems under varying storage sizes and operating regimes.

A consistent conceptual model emerges from this work: nutrient export is governed by the interaction of three linked components rather than by nutrient inputs in isolation. These are (i) the location and intensity of nutrient sources on farms, (ii) the degree and pathway of hydrological connectivity between those sources and receiving waters, and (iii) the extent to which nitrogen is biogeochemically transformed, and to what form, before it is exported. The sections below present the key findings under each of these themes, along with catchment-scale and management implications.



Nutrient sources, transport and transformation, and where they can be intercepted.

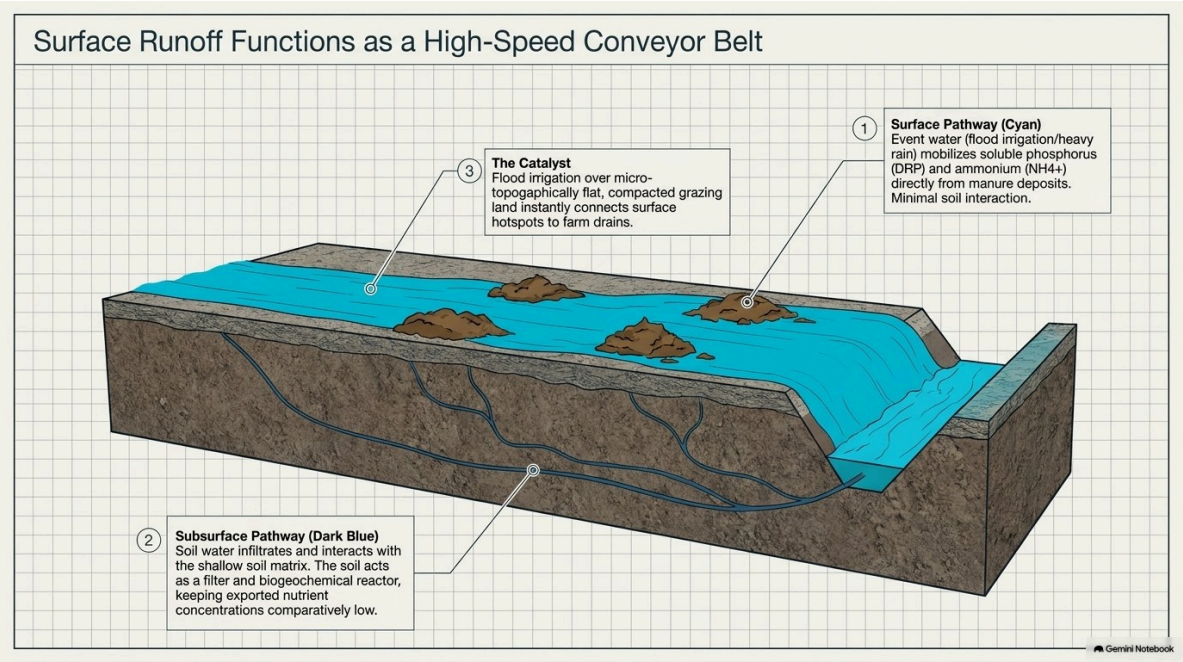
02 Nutrient Sources: Farm Infrastructure and Management Practices

Across multiple independent lines of evidence, farm infrastructure and management intensity, rather than land use category alone, emerged as strong and consistent predictors of stream nutrient concentrations.

- Manure and effluent, rather than fertiliser application or soil leaching, were identified as the principal source of nutrient runoff from dairy paddocks. Concentrations of ammonium and reactive phosphorus were consistently higher in runoff from paddocks receiving effluent than from paddocks that did not.
- Using deep-learning object detection on high-resolution aerial imagery to estimate stocking rate, combined with manually digitised farm infrastructure layers, effluent pond density, effluent pond proximity to streams, dairy shed density and stocking rate were identified as consistently important predictors of ammonium, reactive phosphorus, oxidised nitrogen (NOx) and total nitrogen and phosphorus concentrations in multivariate (partial least squares regression) models.
- Farm dam density (the total surface area of all farm dams, which were defined as any impoundment storing water for an extended period; irrigation reuse dams were not classified separately) and the density of concentrated stock-handling areas showed weak or no relationship with stream nutrient concentrations.

This suggests these features are less influential once effluent infrastructure and stocking intensity are accounted for, although a surface-area metric based on concentrations rather than loads is a coarse test of the detention that dams provide.

- The strength of these relationships was markedly greater during wetter months than during dry conditions, indicating that source presence alone is not sufficient to generate exports; hydrological connectivity is required to mobilise and deliver nutrients to the drainage network.
- At the broader catchment scale, soil nitrogen content, soil clay content and the spatial configuration of agricultural land use (contiguous versus fragmented farm parcels) were also important explanatory variables, particularly during the irrigation season, while land-use composition and hydrological indices were more influential in the forested background catchments used for comparison.
- Farm-level Bayesian hierarchical modelling of nitrogen and phosphorus concentrations and loads found that measured fixed-effect predictors (meteorological, hydrological, physicochemical and farm-management variables) explained a moderate share of variability, while site-level and event-level random effects explained a substantially larger share, indicating that much of the variability in nutrient export is driven by unmeasured, persistent farm characteristics and by event-specific conditions rather than by the measured predictors alone.



Surface runoff carries nutrients from paddock hotspots to farm drains; groundwater contributes little.

03 Hydrological Transport Pathways

End-member mixing analysis (EMMA), using conservative ionic tracers such as chloride, sodium and potassium, was applied to farm drain discharge on flood-irrigated dairy properties to determine the dominant water sources contributing to runoff during rainfall and irrigation events.

- Farm drain discharge was consistently explained as a two-component mixture of event water (rainfall or irrigation water, representing surface runoff) and a shallow soil-water end member, with negligible contribution from shallow (watertable) groundwater during all monitored events. The groundwater end member was sampled from bores with water tables roughly 1 to 5 m below the surface. Minor contributions could not be definitively excluded, and only two farms were monitored.
- Surface runoff was the dominant transport pathway in the large majority of monitored events (approximately 70 to 80%). Nitrate and phosphate concentrations displayed a pronounced first-flush pattern, peaking rapidly at the onset of runoff before declining, consistent with rapid mobilisation of surface-accumulated manure- and fertiliser-derived nutrients.
- The relative dominance of surface runoff versus soil-water contribution varied between farms and was most likely controlled by microtopography, surface roughness and antecedent soil moisture. At the farm where rainfall events were dominated by rainwater, total microtopographic depression storage (derived from a 0.5 m digital elevation model) was lower, at approximately 7.9 mm compared with 12.3 mm at the other farm.

This is consistent with faster generation of overland flow and less opportunity for rainwater to exchange with soil water, although it is a comparison of two farms rather than a controlled test. The wider literature shows that compaction from cattle treading increases soil bulk density and reduces macropores, which lowers infiltration capacity and shortens the time to runoff and may have contributed to observed differences.

However, this mechanism not measured at these farms. Irrigation events largely overrode these differences, because large water inputs filled surface depressions and established rapid surface connectivity, except after a prolonged dry period (approximately 45 days) when soil storage was replenished first. Both monitored farms were flood irrigated, so these results do not show how sprinkler or spray systems would behave.

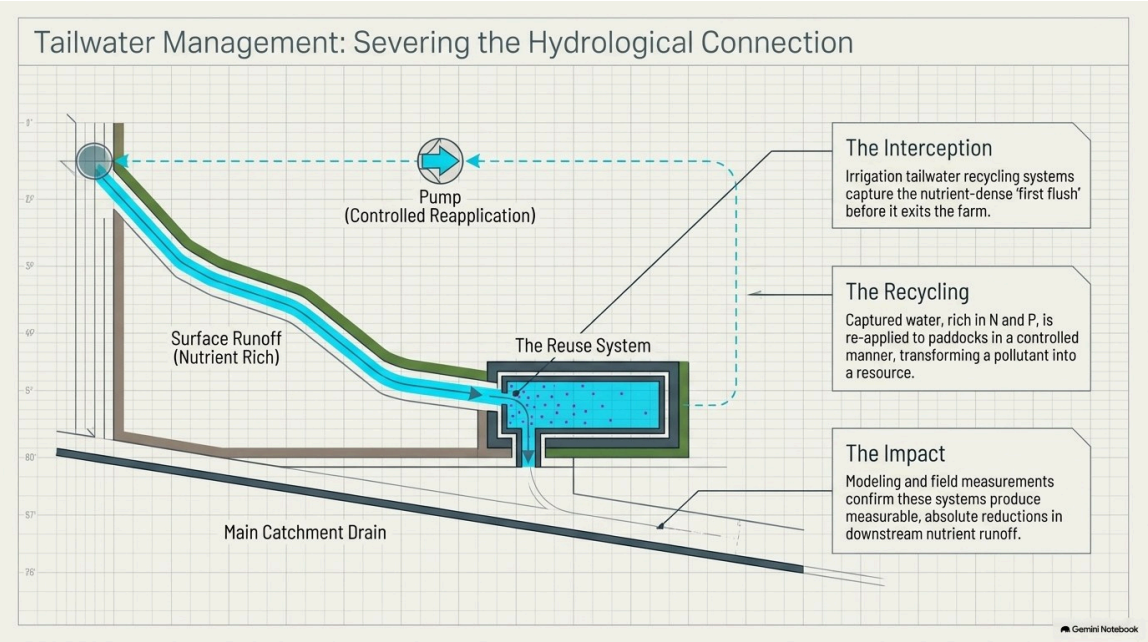


Runoff flowing towards a drain at a monitoring site during the October 2023 storm (spring).

- Flood irrigation generates substantial tailwater by design; under conditions of reduced microtopographic variability and higher grazing intensity, flood irrigation produced markedly higher nutrient loads in runoff than sprinkler or spray irrigation, which produced comparatively little runoff.
- At the paddock scale, both routine irrigation and large rainfall events, generate substantial nutrient loads.

At the whole-farm scale, the periods of highest risk of downstream pollution events occur when no on-farm reuse systems are present, or when on-farm reuse storages were already at capacity and unable to buffer additional inflow.

- At the catchment scale, runoff and its associated nutrient load frequently pass through multiple farms and multiple reuse systems in sequence before reaching a district drain, meaning that catchment-scale outcomes depend on the cumulative performance of reuse infrastructure across many properties rather than any single farm. Large rainfall events can rapidly fill on-farm storage, creating ‘break-through’ nutrient loading events at the catchment scale.



A reuse system intercepts nutrient-rich tailwater before it leaves the farm.

04 Mitigation through Irrigation Reuse (Tailwater Capture) Systems

≈ 50%
average phosphorus load reduction, storage pumped empty before each irrigation

≈ 75%
average retention when also pumped after each irrigation

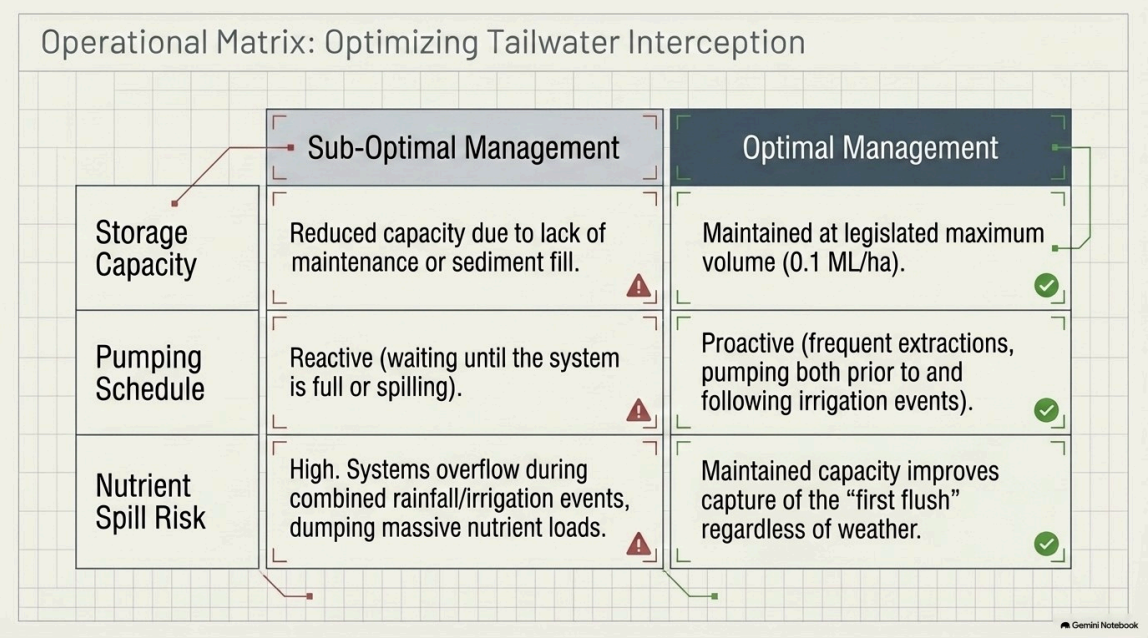
≈ 25%
average reduction when effective storage is halved to 0.05 ML/ha

Simulation of reuse-storage operation, informed by observed paddock-scale runoff on flood-irrigated dairy and beef properties, quantified the effectiveness of tailwater capture as a nutrient mitigation measure.

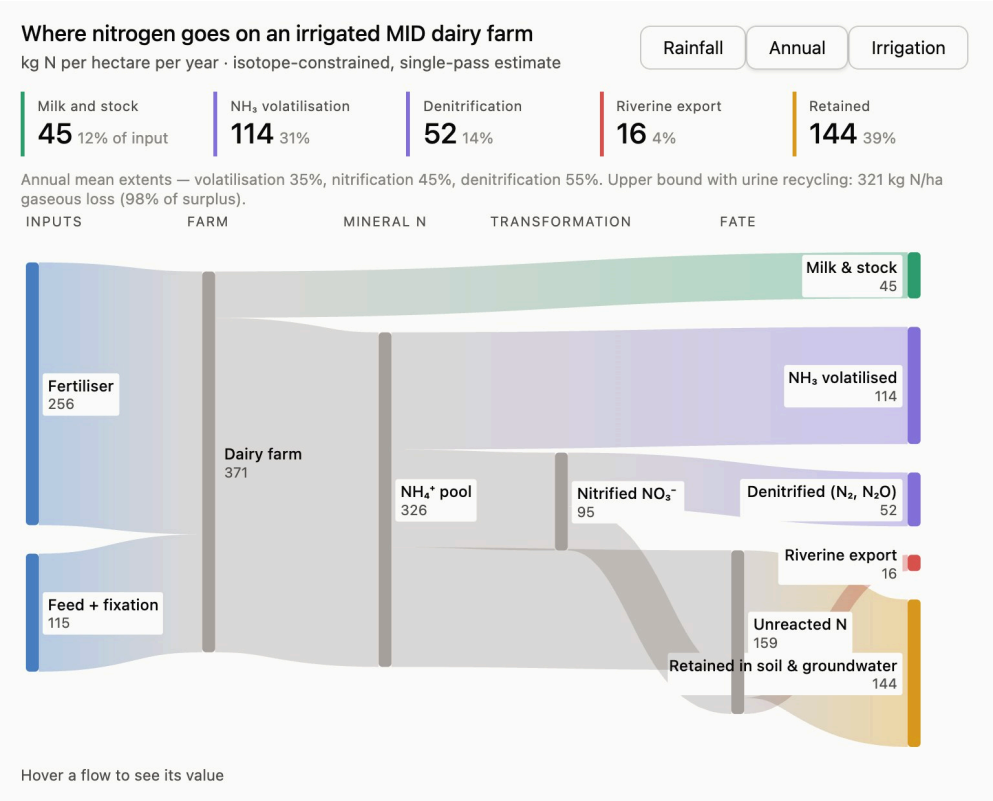
- Under dry conditions, operating reuse storages at the current legislated maximum volume (0.1 ML per irrigated hectare), with the storage pumped empty prior to each irrigation event, produced simulated phosphorus load reductions averaging approximately 50% (range approximately 30 to 72%) and broadly similar proportional reductions in nitrogen.
- Pumping the storage both prior to and following each irrigation event, which frees additional capacity to intercept subsequent rainfall, increased average nutrient retention to approximately 75%, an effect roughly equivalent to increasing storage volume by 50%.
- Reductions in available storage capacity below the legislated maximum, for example due to sedimentation or vegetation encroachment, substantially reduce performance.

For example, halving the effective storage volume to 0.05ML was associated with average nutrient load reductions of approximately 25%, equivalent to a 50% increase in nutrient losses when compared with the 0.1 ML per ha storage

- Reuse systems were considerably more effective at intercepting irrigation-derived runoff (up to approximately 72% of the irrigation-derived nutrient load captured in one case study) than rainfall-derived runoff (as low as approximately 23% captured under the same conditions), because large rainfall events generate runoff volumes that exceed available storage capacity even when reuse systems are well managed.
- Consequently, while reuse systems are highly effective for irrigation tailwater, with well managed reuse systems, large rainfall events are likely to dominate long-term catchment-scale nutrient export, complementary measures (reducing surface-available nutrient stocks ahead of forecast rainfall, active pre-emptying of storages), and ensuring high nutrient areas are unlikely to hydrologically connect to drains, are needed to address this residual risk.
- Expanding the coverage of reuse systems to currently unserved flood-irrigated land, and prioritising properties that apply effluent via irrigation, is expected to deliver the greatest absolute reduction in catchment-scale nutrient export.
- Ensuring that reuse systems are well maintained and managed is also important.



Sub-optimal versus optimal reuse-system management.



Where nitrogen goes on an irrigated MID dairy farm (isotope-constrained estimate).

05 Nitrogen Transformation Processes

A key contribution of this research program was the direct, field-based quantification of nitrogen transformation extents using nitrogen and oxygen isotope ratios in nitrate and ammonium, combined with laboratory tracer incubations and a purpose-built isotope fractionation modelling framework using Monte Carlo simulation to propagate parameter uncertainty. This approach avoids reliance on laboratory-only or purely model-based estimates and instead constrains transformation extents using measurements taken directly from farm drains under operational conditions.

- Volatilisation of ammonium to ammonia was estimated to account for 20 to 70% of nitrogen loss at the paddock scale, with commonly observed extents in the range of 20 to 40%. Volatilisation extents were highest during irrigation events, coinciding with warmer temperatures and more alkaline conditions typical of the irrigation season.
- Denitrification, the microbial conversion of nitrate to gaseous nitrogen forms, was estimated to account for 40 to 60% of nitrogen loss, and was notably more consistent across farms and across rainfall and irrigation events than either volatilisation or nitrification.

This consistency is attributed to the flat topography of the district, which promotes sustained soil saturation and low-oxygen conditions conducive to denitrification under a wide range of hydrological conditions. It should be noted that the denitrification process risks emissions of nitrous oxide, a strong greenhouse gas.

- Nitrification extents were highly variable (5 to 80%), reflecting sensitivity to oxygen availability, soil moisture and temperature, and the fact that nitrification occurs simultaneously with, and is influenced by, both volatilisation and denitrification.
- Isotopic evidence, specifically the co-occurrence of strongly depleted nitrogen isotope ratios in ammonium alongside moderately to highly enriched nitrogen isotope ratios in nitrate, provided field-based evidence for dissimilatory nitrate reduction to ammonium (DNRA), a nitrogen-retention pathway that competes with denitrification. DNRA was most prominent in grass pasture substrates in laboratory incubations, whereas denitrification and volatilisation dominated in aged manure.
- The relative dominance of these pathways was influenced more by hydrological event type and resulting environmental conditions than by irrigation method itself.

Rainfall events were associated with more depleted ammonium isotope signatures, consistent with increased DNRA activity in spatially heterogeneous, locally anoxic microsites; irrigation events, particularly following dry, warm antecedent conditions, were associated with enriched ammonium isotope signatures consistent with volatilisation.

- At the catchment scale, less than 7% of applied nitrogen (from fertiliser, feed and biological fixation) was estimated to be exported in stream flow, a low proportion by international standards. Export in produce was 10-20% of applied nitrogen for livestock landuses. This implies that the majority of applied nitrogen is retained within the farm system, taken up by pasture, or lost via volatilisation and denitrification rather than exported downstream, a favourable outcome for water quality but one that represents an efficiency loss from a farm production and input-cost perspective, and a partial conversion of applied inputs into gaseous emissions when transformation is incomplete.
- In contrast, phosphorus losses as a proportion of farm inputs were comparatively high (of the order of 10%) on dairy land and predominantly in dissolved rather than particulate form, distinguishing this system from many other agricultural landscapes where erosion-driven particulate phosphorus dominates losses.



Fieldwork on a vegetable farm in the district after rain, July 2023 (winter).

06 Differences Across Agricultural Land Uses

Comparative sampling across dairy, livestock and vegetable horticulture farms indicated that land use may impose a distinct chemical and isotopic signature on runoff. However, only one livestock (beef) farm and one horticultural farm were monitored, alongside a small number of dairy farms, so these contrasts are indicative rather than a systematic comparison between land uses, and differences may reflect the particular farms rather than land use.

- Dairy and livestock runoff was dominated by ammonium and dissolved reactive phosphorus, consistent with high organic loading from manure, oxygen-limited soil conditions, and manure-derived nitrification. Isotopic evidence of depleted ammonium alongside enriched nitrate signatures indicated concurrent DNRA activity in these systems.
- On the single horticultural farm monitored, runoff was dominated by nitrate and particulate phosphorus, consistent with direct application of nitrate-based fertilisers, more intensive tillage and reduced ground cover. Isotopic evidence of parallel enrichment in nitrogen and oxygen isotope ratios of nitrate, particularly during irrigation, indicated denitrification of fertiliser-derived nitrate as the dominant transformation pathway on this farm, in contrast to the nitrification-dominated signature observed on the dairy and livestock farms.
- Regional farm nutrient budgets show that vegetable horticulture applies comparatively high phosphorus inputs, elevating soil phosphorus stores. Combined with intensive tillage and reduced cover, this is consistent with the higher particulate phosphorus losses during rainfall-driven erosion seen on the one horticultural farm monitored than on the dairy and livestock farms.

- Only one beef property was monitored, so beef and dairy farms cannot be compared systematically. On that property, nitrogen concentrations were toward the lower end of the range observed on dairy farms and phosphorus concentrations toward the upper end.

Phosphorus in runoff from the livestock site in the land-use comparison was mostly dissolved. With a single farm, these differences may reflect site-specific factors rather than land use, and their cause cannot be determined.



A farm drain running during the October 2023 storm (spring).

07 Catchment-Scale Patterns: Waterway Type, Seasonality and Flood Dynamics

7.1 Irrigated versus forested catchments and seasonal patterns

- Nutrient concentrations and electrical conductivity were an order of magnitude or more higher in irrigated catchments within the MID than in upstream forested background catchments.
- Within irrigated catchments, phosphorus and nitrogen concentrations were significantly higher during the irrigation season, consistent with greater mobilisation of manure and fertiliser by overland flow, whereas electrical conductivity was significantly higher during the non-irrigation season, consistent with reduced dilution by irrigation tailwater and a greater relative influence of saline groundwater and salinity-control pumping.

- Concentration-discharge relationships were more consistent across seasons than concentration levels themselves: phosphorus export was predominantly chemodynamic (increasing disproportionately with flow), while nitrogen (as total Kjeldahl nitrogen) and electrical conductivity were predominantly chemostatic (source-limited, with concentrations relatively insensitive to flow), indicating stable underlying source and transport mechanisms despite large seasonal differences in absolute concentration.
- Landscape configuration, specifically the degree of fragmentation versus contiguity of dairy farm parcels, was a more important explanatory variable for nutrient concentrations than the overall proportional area of agricultural land use, with large contiguous dairy holdings associated with higher nutrient concentrations than catchments with a more fragmented mix of farm types. We interpret this as reflecting source intensity rather than distance to drains. Large contiguous dairy holdings concentrate source hotspots (effluent and manure) and tend to carry higher stocking rates, whereas a fragmented mix of farm types dilutes dairy losses with lower-intensity land uses and may interrupt direct paddock-to-drain flow paths. These are proposed explanations rather than tested mechanisms, and the configuration metrics (largest patch index and diversity indices) describe patch size and mix, not proximity to drains.

7.2 Drains, creeks and rivers as a processing continuum

- Analysis of the relationship between nitrogen and oxygen isotope ratios in nitrate across drains, creeks and rivers identified a clear continuum in nitrogen processing behaviour. Drains exhibited strong, flow-dependent isotopic relationships consistent with nitrate removal, with the strongest relationship observed under baseflow conditions and progressively weaker relationships at higher flow. Creeks exhibited weak isotopic coupling across all flow conditions, consistent with mixing of multiple sources and simultaneous nitrification and denitrification. Rivers exhibited strong and stable isotopic relationships across all flow conditions, consistent with integration of many upstream inputs.
- Apparent nitrate removal, estimated using a Rayleigh fractionation approach constrained by locally derived nitrogen isotope enrichment factors, was greatest in drains (median estimated range 11 to 42%) and creeks (9 to 38%), and substantially lower in rivers (0 to 9%). This identifies agricultural drains and, to a lesser extent, creeks as important but hydrologically sensitive nitrogen-processing locations within the catchment.
- Apparent nitrogen removal was non-monotonic with respect to discharge, peaking at intermediate flow rather than at baseflow or high flow.

This suggests an optimal hydrological window in which nutrient delivery to biologically reactive zones and residence time are both sufficient to support substantial transformation; at high flow, rapid transport and dilution appear to outpace the capacity for biological processing, while at baseflow, delivery of nitrogen to reactive zones is comparatively limited despite longer residence times.

7.3 High-frequency flood event monitoring

- Sampling at approximately six-hourly intervals through a major flood event revealed that agricultural drains responded fastest and with the largest amplitude in nitrate concentration and isotopic composition, creeks showed an intermediate response, and larger rivers were comparatively buffered, consistent with progressively greater integration of catchment inputs with increasing waterway size.
- At the rising limb and peak of the flood, nitrate isotope ratios in both drains and creeks converged toward values closely matching the isotopic signature of farm-exported, manure-derived nitrate, indicating that at peak discharge, when residence times are shortest, the exported signal predominantly reflects direct mobilisation and transport of the source material rather than substantial biological modification.
- As floodwaters receded and residence times lengthened over the following days, nitrate isotope ratios increased again, indicating renewed denitrification activity. This demonstrates a repeatable, within-event switch between a transport-dominated regime at peak flow and a transformation-dominated regime during recession.
- A complementary investigation using organic wastewater tracers (including saccharin and xanthine) alongside environmental tracers (tritium, radon) and boron isotopes found that, under baseflow conditions, groundwater-delivered ammonium of urine origin (subsequently nitrified) was the dominant nitrogen source, whereas during peak surface-runoff flow, nitrate carrying an already-processed, isotopically enriched signature was flushed from the catchment. This points to subsurface or baseflow delivery of urine-derived nitrogen as a significant, previously under-recognised pathway operating alongside surface runoff.

08 Greenhouse Gas Emissions from Farm Drains and Irrigation Reuse Ponds

A dedicated multi-isotope investigation of farm drains and irrigation reuse ponds (also called reuse or tailwater capture dams), engineered features common on dairy properties but typically excluded from greenhouse gas emissions inventories, found that these water bodies are disproportionately important and episodic sources of methane, carbon dioxide and nitrous oxide. The ponds monitored were irrigation reuse ponds that receive runoff from paddocks, drains and surrounding farms; effluent storage ponds were not among them. They are referred to as reuse ponds below.

- Greenhouse gas concentrations and fluxes were consistently and substantially higher in reuse ponds than in drains, particularly during irrigation events, because reuse ponds retain nutrient- and carbon-rich water for extended periods, promoting anaerobic methane production and denitrification, whereas drains have short, flushing residence times that limit these processes.
- Measured methane concentrations exceeded values reported for comparable freshwater systems internationally, while methane fluxes were higher than some published pond studies but lower than others that used floating chambers, which also capture bubble-borne methane that the headspace method used here does not, so methane emissions are probably underestimated.

  Across the six reuse ponds monitored, a single pond accounted for approximately 78% of total estimated annual greenhouse gas emissions (expressed in carbon dioxide equivalents), indicating that a small number of high-emitting reuse ponds are likely to dominate the farm-scale emissions budget.
- Isotopic evidence (nitrogen and oxygen isotope ratios of nitrous oxide, including intramolecular site preference) identified heterotrophic denitrification, rather than nitrification, as the dominant nitrous oxide production pathway, with a secondary but locally important contribution from subsequent reduction of nitrous oxide to dinitrogen gas, particularly in reuse ponds under irrigation-driven, more reducing conditions.
- Methane production pathways shifted between acetate-based and hydrogen-based methanogenesis depending on substrate availability and redox conditions, with isotopic evidence also indicating a role for aerobic methane oxidation partially offsetting methane emissions from drains during rainfall events.
- These findings support the development of reuse pond-specific emission factors for regional and national greenhouse gas inventories, and point to targeted mitigation options such as aeration of reuse ponds, management of carbon and nutrient inputs, and redesign of flow paths to limit prolonged low-oxygen conditions.

We suggest this would work by disrupting stratification (layering that isolates bottom water from oxygen), although stratification was not measured and is inferred from low dissolved oxygen and long residence times.

The data do not show that small ponds emit more per unit area: the highest emission rate and about 78% of estimated emissions came from the largest pond (about 46% of the monitored pond area), which also had the highest ammonium and dissolved reactive phosphorus, so nutrient loading appears a better target than pond size.

09 Management Implications and Conclusions

Collectively, these findings indicate that nutrient and greenhouse gas export from the Macalister Irrigation District is governed by the interaction of nutrient sources, hydrological connectivity and biogeochemical transformation, rather than by nutrient input magnitude alone. This has several practical implications for catchment management and policy.

- Manure and effluent management should be prioritised over further reductions in fertiliser application alone, given the consistent identification of manure and effluent as the dominant source of nutrient runoff. Priority actions include appropriately sized and well-maintained effluent storage, avoiding effluent application ahead of forecast rainfall or heavy irrigation, and rotational grazing or composting to reduce surface accumulation of labile nitrogen and phosphorus.
- Because nutrient export is strongly connectivity-limited, managing the pathways by which water moves across paddocks is as important as managing nutrient sources themselves. This includes maintaining surface roughness and ground cover to slow overland flow, considering lower-runoff irrigation methods such as spray or pivot systems where feasible, and recognising that the first flush of any event carries the highest nutrient concentrations.
- Irrigation reuse systems are a proven, cost-effective mitigation measure, but their performance depends on appropriate sizing and active, ongoing management (pre- and post-event pumping, maintenance of storage capacity). Expanding reuse coverage, particularly on properties applying effluent via irrigation, is likely to yield the greatest catchment-scale benefit, while large rainfall events remain a residual risk that reuse systems alone cannot fully address.
- Farm drains and reuse ponds should be recognised as active biogeochemical reactors rather than passive conduits.

They provide a genuine, low-cost water quality benefit through in-situ nitrogen removal, particularly under low-flow conditions, but this benefit is accompanied by a greenhouse gas cost via nitrous oxide production and elevated methane emissions from reuse ponds, which should be considered jointly when evaluating drain and reuse pond management options such as aeration, vegetated buffers or flow-path redesign.

- Management strategies should be tailored to land use and to position within the drainage network: dairy and livestock systems warrant a focus on manure and effluent management and DNRA-relevant retention processes, while for horticultural systems the single farm monitored points to erosion control, ground cover and fertiliser timing given its nitrate-dominated export profile, a direction that needs confirming on more farms. Agricultural drains and creeks, identified as nitrogen-processing hotspots, warrant different management attention than larger, more hydrologically buffered rivers.
- Monitoring and mitigation planning should explicitly account for hydrological event timing, since the largest nutrient exports and the clearest transitions between transport-dominated and transformation-dominated regimes occur during and immediately after large rainfall events and during flood recession, rather than being adequately captured by routine or seasonal average monitoring alone.
- Further research is recommended to confirm microbial transformation pathways using molecular (metagenomic) methods, to extend monitoring across full annual and multi-year cycles, to test infrastructure-based mitigation measures under operational farm conditions, and to extend the isotope fractionation modelling framework to explicitly incorporate additional processes, such as urea hydrolysis and DNRA, that were identified as influential but not yet fully resolved.

Overall, this body of work provides an evidence-based, process-informed foundation for refining nutrient budgets, catchment models and water quality policy in the Macalister Irrigation District, and offers transferable insights for other flat, intensively irrigated dairy landscapes facing similar water quality challenges.

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