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Linkages between land management activities and stream water quality in a border dyke-irrigated pastoral catchment

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ABSTRACT

This paper describes key linkages between land management activities and stream water quality for a 5230 ha catchment used for intensive pastoral agriculture in southern New Zealand. Due to low annual rainfall and the wide coverage of soils with low available water-holding capacities, flood irrigation of the 2400 ha of flat land within the catchment is an important feature impacting on farm business profitability and stream health. Water quality variables and nutrient and sediment yield estimates are reported for a four-year period. This monitoring shows that some improvement in farm environmental performances would generally be desirable, with stream concentrations of nutrients (N and P), sediment and faecal bacteria regularly exceeding guidelines recommended for surface waters. Field measurements, farm management surveys and farm systems modelling have identified some land management practices that appear to be key sources of many of these pollutants. Border dyke irrigation runoff has a potentially large effect on a range of water quality parameters, due to both the excessive stream flows generated by over-watering and the entrainment of P, N and faecal bacteria in this flow as it passes from land to stream. Stock access to some of the remaining un-fenced lengths of the stream was also recognised as an important land management practice that needed to be addressed if some of the key catchment values identified by stakeholders, such as maintaining a healthy trout fishery and a stream suitable for recreational use, were to be protected. Assessments of the effectiveness and cost-effectiveness of a number of potential mitigation practices identified that managements which targeted reducing irrigation runoff (e.g. by installing bunds or using appropriate watering times) and fencing and planting riparian margins showed the greatest potential to meet these key values with least cost to farm businesses. Other farm practices were also identified that incurred nil or minimal cost while also delivering small or moderate benefits to stream water quality.

1. Introduction

Runoff from pastoral land is known to be a significant contributor to declining water quality in many regions throughout the world, particularly those managed under intensive farming practices where inputs, nutrient recycling rates and stocking densities are high. The transfer of nutrients, sediment and faecal bacteria from soil to water has been documented for a range of pastoral farming systems and intensities (e.g. see reviews by Haygarth and Jarvis, 1999; Gillingham and Thorrold, 2000; Monaghan et al., 2007a; Oliver et al., 2005; Watson and Foy, 2001). These studies show that soil type, drainage pathways, topography, climate, stock type, stocking rate and grazing management practices are some of the key factors that determine the size of nutrient and faecal bacteria transfers from land to water. Studies in Australia have also shown that flood-irrigated systems have the potential to significantly impair stream and river water quality, due to the pollutants within runoff exiting the end of irrigation bays (Austin et al., 1996; Bush and Austin, 2001; Mundy et al., 2003; Nash et al., 2004, 2007). In border dyke irrigation (also called border or border check irrigation), water is applied to the top of an irrigation bay at flow rates that exceed soil infiltration rates.

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Excess flow moves down the bay confined by check banks (i.e. raised earthen ridges approximately 250 mm high) typically spaced between 20 and 40 m apart. Excess water then drains from the lower end of the bay into drainage channels where captured water may be re-directed for irrigating another part of the farm or discharged to a stream (Nash et al., 2007). Once installed, border dyke irrigation is a relatively low cost system to operate. In Canterbury, New Zealand, large areas (>60,000 ha) of intensively farmed grassland are flood-irrigated using border dyke systems. The impacts of this land management practice on stream water quality have recently come under closer scrutiny as the community raises concerns about the health of streams and rivers in catchments used for intensive, irrigated dairy farming. Direct linkages between land management activities and stream water quality are seldom obvious, although observed effects on stream health usually arise from the cumulative impacts of several farm management activities like stock grazing practices (particularly around riparian zones), effluent, fertiliser and irrigation management, and runoff from farm tracks and lanes. Consequently, the cost-effectiveness of remedial measures targeted to improve stream water quality is often difficult to define, making the task of prioritising on-farm actions, to ensure farmers get the best return on investment, challenging.

The Waikakahi catchment, situated in South Canterbury, New Zealand (Fig. 1), is a catchment that has attracted local and national attention for the impacts of intensive irrigated dairy farming on stream water quality. It is also one of five study catchments involved in research initiatives to identify and evaluate dairy farm management systems that address both farm productivity and catchment-specific environmental issues (Wilcock et al., 2007). Research has focused on land management activities that contribute to pollutant losses to surface and ground water, and on the development of farm management practices that mitigate these water and pollutant transfers. Each catchment has distinctive features, but the Waikakahi catchment differs principally from the others by having a relatively dry climate (<600 mm annual rainfall) and requiring irrigation to maintain farm production. In 1999 the catchment attracted some negative media coverage for poor riparian management and its impact on habitat for trout. This attention spurred community debate between stakeholders about the values that need protecting within the catchment, expectations of farming practices that aim to preserve these values, and the balance between maintaining profitable farming systems and meeting some of these expectations and catchment values. These discussions inevitably raised questions about the role of border dyke irrigation in the deterioration of stream health in the catchment.

The scientific tools and analyses used to inform the above debate and guide farm planning initiatives within the Waikakahi catchment are reported on. We monitored a planning process involving a diverse group of farmers, researchers, extension agents, regulatory authorities and resource care agencies, which

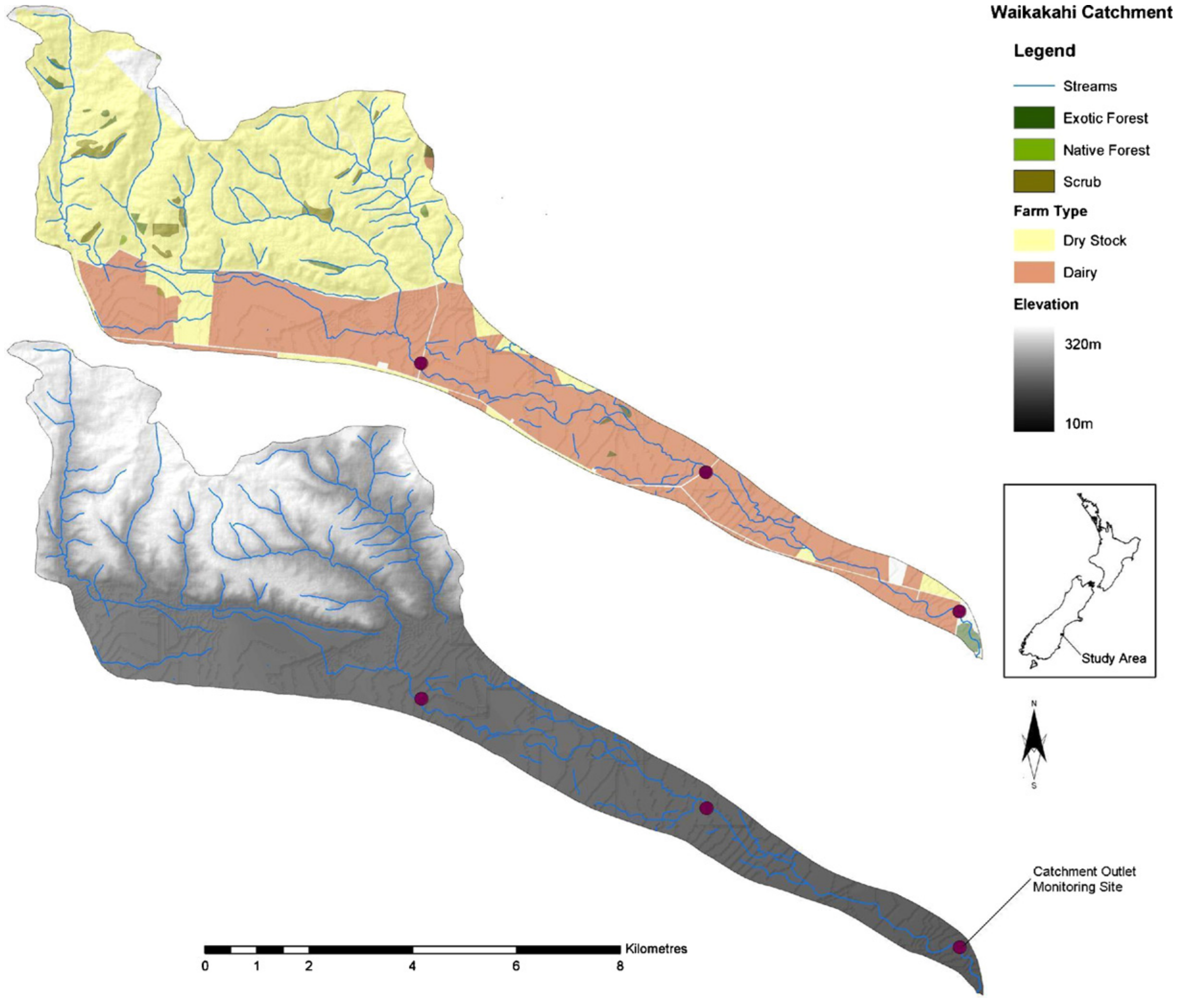

Fig. 1. Location and topographic map of the Waikakahi catchment showing streams and outline.

strategically directed science activities and extension efforts that targeted farmer adoption of key land management practices. The process also involved applying a spatially explicit modelling framework to quantitatively link land management activities to stream water quality and farm economic indicators. The planning process has, in order:

(i) assessed stream water quality status,
(ii) identified the key linkages between land management activities and water quality, with a particular focus on the role of border dyke irrigation,
(iii) defined the key values associated with the catchment, which in turn defined a set of catchment-specific water quality targets,
(iv) determined the most appropriate land management guidelines required to deliver to these targets, and
(v) developed and implemented farm plans of varying complexity that address the key environmental performance indicators identified.

The specific questions answered were:

- What is the baseline water quality in the catchment under present farming methods?
- What are the key sources of water pollutants, with particular focus on the role of border dyke irrigation runoff as a source of stream contamination?
- Where required, what is the most cost-effective strategy for limiting the transfers of these pollutants from land to water?

2. Materials and methods

2.1. Catchment formation and characteristics

The Waikakahi catchment forms part of the lower Waitaki region, an area of approximately 80,000 ha consisting of the fans, terraces and floodplains of the Waitaki River, laid down at the end of the Otiran Glaciation, probably about 20,000 years ago (Molloy, 1988). Bounded to the south by the Waitaki River catchment, and to the north by the surrounding Morven Hills, the Waikakahi catchment is part of the Morven fan formation, a set of intermediate and lower gravel terraces. These consist predominantly of greywacke gravels, but admixed with minor amounts of locally derived material, mainly older greywacke, schist and other metamorphic rocks (Suggate, 1978). The catchment is situated north of the Waitaki River and is about 5 km at its widest point, descending 100 m along its approximate 17 km length to almost sea level near the Waitaki River's exit point at Glenavy (Fig. 1). The farmed catchment itself occupies an effective area of some 5230 ha. The Waikakahi Stream is fed predominantly by spring water from the Morven Hills to the north of the alluvial terrace that makes up the flat part of the catchment. Prior to European settlement, the Waikakahi Stream, and the land surrounding it, was a periodically active flood channel for the adjacent Waitaki River. Being spring-fed, the water would have consequently been clear, clean and of a constant temperature, and abounding in freshwater mussels ("kaakahi", hence the stream's name), freshwater crayfish (koura) and eels (MfE, 2001). The once numerous wetlands have been drained, with much of the Waikakahi flats given over to dairy farming in the last 15 years.

Soils within the catchment are essentially similar to those of the Canterbury Plains, being mainly stony soils derived from the terrace gravels, with some loess accumulation on the higher terraces. Eyre and Paparua stony sand and silt loam soils cover approximately 2980 ha of the intermediate terraces. Finer textured and less stony Temuka, Wakanui and Templeton silt loam soils are also present, particularly in the upper catchment, and cover approximately 1210 ha in total. Loessial Taiko, Timaru and Waikakahi silt loam soils occupy 2700 ha of hill country at the northern end of the catchment. The consequence of this soil pattern is major areas with limited soil water-holding capacity, and therefore a need for continual water to maintain agricultural production, especially over summer. Approximately 95% of the flat farmland contained within the catchment is irrigated via the Morven-Glenavy-Ikawai scheme, sourced from the Waitaki River. About 80% of this area is flood-irrigated using border dyke systems. Irrigation water taken from the Waitaki River is low in nutrients, abundant and cheap (base charge of NZ$25 ha^{-1} $year^{-1}$ for up to 810 mm of delivered water).

2.2. Monitoring of stream water quality

Water quality monitoring of the Waikakahi Stream was conducted at frequencies of 1–3 months during 1995–1998 (Meredith et al., 2003). Monitoring was resumed at monthly intervals (augmented by additional ad hoc sampling) at the catchment outlet in April 2001. In addition, a permanent flow recorder and turbidity sensor were installed in May 2001, giving continuous records of both variables. Turbidity data were collected because of past instances where large masses of sediment entered the stream, causing increases in suspended solids (SS) concentration and turbidity. Stream water is presently analysed for pH, conductivity ($\mu S\ cm^{-1}$), *in situ* temperature (°C), turbidity (NTU), dissolved oxygen ($g\ m^{-3}$ and % saturation), SS and volatile SS (the organic component of total SS, $g\ m^{-3}$), faecal coliform (MPN 100 mL^{-1}, during 1995–1998), *Escherichia coli* (*E. coli*, MPN 100 mL^{-1}, from 2001), nitrate plus nitrite N (NO_X-N), ammonia N (NH_4-N), total-N (TN), filterable reactive P (FRP), total-P (TP), dissolved organic C (DOC) and total organic C (TOC). Results are expressed as $g\ m^{-3}$ except where shown otherwise. Standard protocols for sampling, sample stabilisation and analysis were adopted for all water quality variables (Wilcock et al., 2006; Meredith et al., 2003; APHA, 1998). *E. coli* were determined by the Colilert most probable number (MPN) method (IDEXX Laboratories, USA).

Summary statistics for the period September 1995 to May 2005 are presented for selected water quality variables. Non-parametric statistics are used to show central tendency (median) and dispersion (interquartile range, IQR) because datasets are frequently non-normally distributed. Annual loads leaving the catchment in stream water were calculated using the product of discharge-weighted mean concentration for June 2001–May 2005, and the true mean flow, for SS, NO_X-N, TN, FRP, TP, DOC and faecal bacteria (Fergusson, 1987). Because *E. coli* comprise 80–90% of faecal coliform in natural waters (Rasmussen and Ziegler, 2003) we have pooled the two data sets to get a combined faecal bacteria yield.

2.3. Linkages between land management activities and water quality

2.3.1. Surface runoff from border dyke-irrigated land

Preliminary observations and discussions with stakeholders within the catchment indicated that surface runoff from border dyke-irrigated land was likely to be a significant source of water and pollutants within Waikakahi Stream. An experimental program was therefore initiated to quantify these transfers and refine our modelling analysis. In year 1 of the study (2002–2003), a set of borders situated on a dairy farm in the upper half of the catchment was chosen to quantify water, nutrient and bacteria transfers in border dyke irrigation runoff from the poorly drained Temuka silt loam (Typic Orthic Gley soil). Measurement points were established on the lower reaches of three adjacent borders, 20 m wide, to restrict flow across a 0.5 m wide weir in each border (Fig. 2). All three borders were approximately 130 m long and were irrigated simultaneously from a 2 m wide weir at the headrace of each border. The paddock was fertilised twice, in September 2002 with 30, 20, 20 and 15 kg ha^{-1} of N, P, K and S, respectively, and in April 2003 after the main irrigation season with 80, 22, 60 and 58 kg ha^{-1} of N, P, K and S, respectively. Of the seven irrigation events monitored in year 1, most were nominally 90 min duration, with on average 250 m^3 of water entering each border to provide a potential infiltration depth of 90–100 mm. In-flow volumes were calculated from recording in-flow heights above each weir for each event. A hydrograph for each border was constructed by measuring outlet weir flow height concurrently with the collection of 12–15 water samples over the outlet height range. An in-flow water sample was also collected for later analysis of nutrient, sediment and *E. coli* concentrations. Numbers of cowpats, residual pasture dry matter levels and soil moisture contents were recorded prior to irrigation within each border. At the completion of the normal irrigation schedule, an additional irrigation event was staged to observe the effects of reducing irrigation time from 90 to 45 min, and to examine the effect of irrigation on the runoff of P (superphosphate) and N (urea) fertiliser that had been applied to the site 10 days previously as per normal farm practice. No attempt was made to modify farmer irrigation practice until this last event. Analytical tests for FRP, TP, total dissolved phosphorus (TDP), inorganic-N (ammonium and nitrate), SS, *E. coli* and basic cations (determined using ion exchange chromatography) were conducted on six selected samples from each border plus an in-flow sample which covered the range over each hydrograph. Total runoff volume and nutrient mass transfers were calculated using flow-weighted arithmetic means; geometric means were used for calculating *E. coli* transfers.

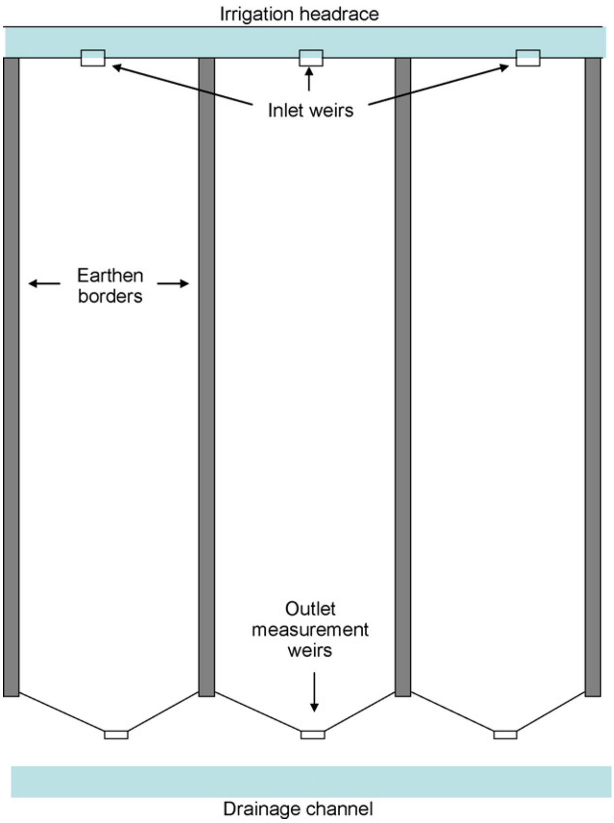

Fig. 2. Diagram of the measurement system used to monitor surface runoff from border dyke irrigation bays.

In year 2 of the study (2003–2004), measurements focused on quantifying the volumes of border dyke irrigation runoff yielded from the free-draining Eyre and Paparua soils in the lower half of the catchment. Six U-shaped weirs similar to those used in year 1 were established on sites across several farms and farm blocks, using border dyke areas ranging from 0.25 ha (single border) to 4.5 ha (paddock size). Each border or sets of borders were typically 180–240 m long, although there were some geometrical differences between borders within paddocks, and a significant number of shorter borders contributing to runoff flow. As many irrigation events as possible were attended based on normal irrigation scheduling, with most weirs having two events recorded. The duration of irrigation events varied, but typically ranged from 60 to 120 min. In-flow volumes for each event were calculated, as in year 1, from in-flow heights for each contributing weir. A hydrograph for each border was recorded by measuring outlet weir height and calculating the volume lost. Fields were fertilised as part of normal farm practice, which typically involved the annual application of between 40 and 50 kg P ha^{-1} as superphosphate and 150 and 200 kg N ha^{-1} as urea. While monitoring in year 2 focused mainly on recording runoff volumes, analytical tests were also conducted for FRP, total-P, inorganic-N and total-N. Faecal coliforms were measured for only four of the events. Measurements for P and N were averaged to indicate overall variation between sites. Statistical analysis was conducted by calculating means and standard errors for variation between borders (or standard deviations for geometric means).

2.3.2. Farm and catchment modelling approach

Due to the complexity of the farming systems within the catchment, a modelling approach was relied upon to identify some of the key linkages between catchment water quality and land management practices. A schematic diagram of the components and systems approach considered in our analyses is shown in Fig. 3. Export co-efficients for N and P emissions from livestock farms were derived from nutrient budgets calculated for model farms within the catchment using the OVERSEER® Nutrient Budgets program (hereafter referred to as OVERSEER®; Wheeler et al., 2003). Model farms were defined based on detailed surveys of each farm within the study catchment area, and a detailed biennial survey of soil chemical, biological and physical properties on dairy farms. These surveys gathered data on farm productivity levels, feed purchased and sold, stock and effluent management systems, soil management and fertiliser use. A model farm was also defined for dry stock farming systems within the catchment, based on interviews with nine sheep–beef farmers and cattle graziers. Farm survey data were aggregated to define each model farm system, which included both on-farm (milking platforms) and off-farm (supplement and wintering blocks) areas. For some land uses where little information was available, e.g. dairy cow wintering, N and P export co-efficient estimates were derived from on-going field trials and values reported in the literature (McDowell et al., 2005). Due to the presence of two soil groups of contrasting drainage status within the flat part of the catchment, OVERSEER® model farms for each farm type were further divided into poorly drained (Wakanui and Temuka soils) and well-drained (Eyre, Paparua, Ngapara, Waimakariri and shallow Templeton soils) categories.

The contribution of each farming and management system to catchment loads of N and P was then determined by incorporating the export co-efficients into a GIS environment. Although the OVERSEER® modelling tool used to derive estimates of farm P loss is constructed as a farm scale risk-based model, reasonable

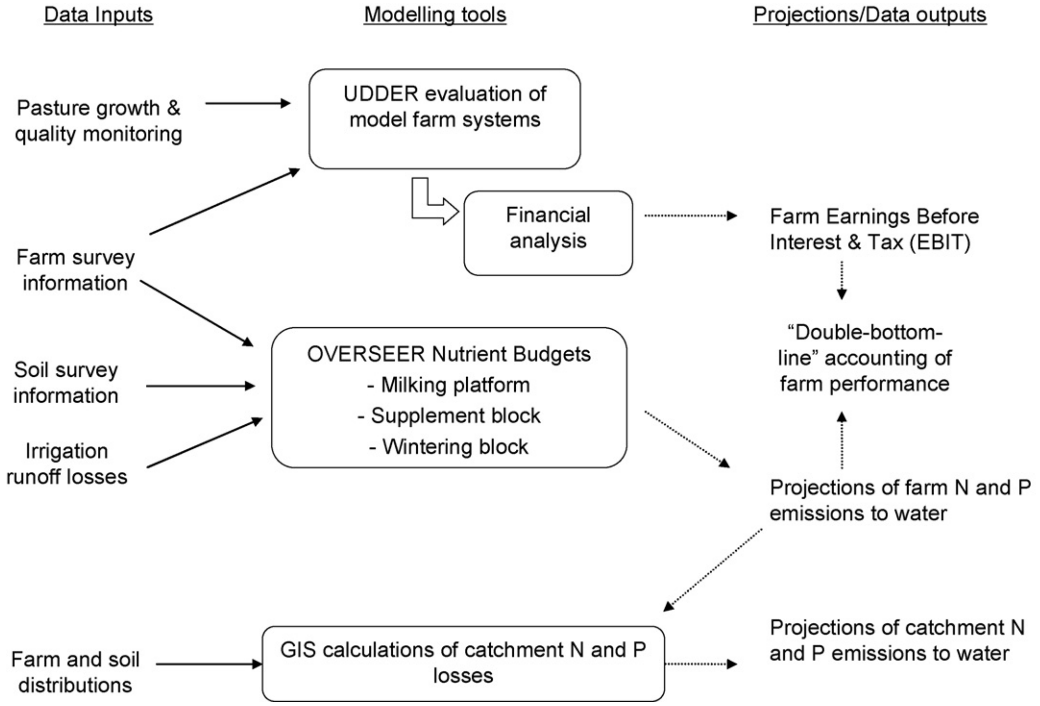

Fig. 3. Schematic representation of farm and catchment modelling framework, including economic and environmental evaluations of model farm systems.

agreement has been observed between measured and estimated loss/risk (McDowell et al., 2005); because the model is focused at a farm management level, linkages between farm management systems, soil drainage, farm nutrient emissions and catchment nutrient loads could be made and the cost-effectiveness or "double-bottom-line" accounting of farm mitigation strategies that could potentially reduce N and P emissions to water evaluated. Due to their relatively high contribution to catchment loads, dairy farms were identified as the initial target for many of these mitigations. The financial implications of introducing each potential mitigation strategy into the dairy system were determined using a spreadsheet-based full farm budget that accounted for all recognised costs of inputs and expenses based upon locally available data. To allow comparison between mitigation options, depreciation, maintenance and capital costs (8%) were annualised for mitigations that required additional farm infrastructure or capital works such as re-levelling old irrigation bays, riparian works, wintering pads and improved effluent management. Where the adoption of a mitigation resulted in changes to farm feed supply and/or stock numbers, the UDDER farm systems modelling tool was run to determine the practical and wider financial implications of such a management change. The cost-effectiveness of each mitigation strategy was then calculated by dividing the net annualised per hectare cost by the estimated per hectare reduction in nutrient loss if the mitigation was implemented on the model farm described above. Further details of how these practical and financial implications were considered can be found in Monaghan et al. (2008).

3. Results

3.1. Stream flow and water quality

Flood peaks in the Waikakahi Stream are small because of the free-draining soils and the low rainfall in the catchment (Duncan, 2000). Irrigation runoff results in an "inverted" hydrograph, where summer flows are 4–9 times those in winter. The flow range during May 2001–2005 was 33–3177 L s^{-1}, with mean and median flows being 581 and 538 L s^{-1}, respectively (Table 1). The long period of border dyke irrigation and resulting runoff (September–May) produced a higher than expected water yield (9 L km^{-2} s^{-1}) for a spring-fed stream in the Waitaki Valley (WCCRWB, 1982). The median turbidity of water sampled since 1995 is higher for the Waikakahi Stream than that for most lowland streams in Canterbury (Meredith et al., 2003). Continuous measurement at the catchment outlet indicates that, although occasional spikes of very high turbidity (>90 NTU) still occur, water clarity has improved at

Table 1
Water quality summary statistics and average annual specific yields derived from fixed interval monitoring (1–3 monthly) of the Waikakahi Stream at the catchment outlet during 1995–2005. Flow statistics are from the continuous flow recorder for May 2001 to May 2005. Concentrations are g m^{-3} except where noted. Average annual yields are for June 2001–May 2005 (L km^{-2} s^{-1} for water, kg ha^{-1} year^{-1} for solutes and MPN ha^{-1} year^{-1} for *E. coli*)

Variable	Flow (L s^{-1})	Turbidity (NTU)	SS	DO (% saturation)	[a]Faecal bacteria (MPN 100 mL^{-1})	NO$_X$-N	TN	FRP	TP	DOC
Maximum	3177	95	365	128	21800	3.50	5.40	0.81	0.77	14.5
Minimum	33	1.4	1.4	13	2	0.74	1.16	0.00	0.03	1.9
Mean	581	10	22	93	1224	1.70	2.30	0.12	0.18	3.7
Median	538	5.9	10	99	320	1.60	2.10	0.07	0.12	2.7
Interquartile range	605	5.4	20	20	710	0.75	0.90	0.14	0.13	1.4
Average annual yield	11	–	46	–	7.7×10^{10}	5.5	7.6	0.56	0.83	14.7

[a] Faecal coliform from 1996 to 2000 and *E. coli* from 2001 to 2005.

this site since about 2001. Comparison between 1995–1999 and 2003–2005 data showed a marked reduction in turbidity at an additional monitored site in the upper part of the catchment, with medians for the two periods being 9.6 and 3.4 NTU, respectively ($P < 0.05$). Turbidities at the catchment outlet during summer–autumn of 2005 averaged 2 NTU, and are comparable with a similar low-turbidity period in 2002.

Median values of water quality variables for 1995–2005 (Table 1) indicate that the stream is moderately turbid, is generally well-oxygenated, and has relatively high concentrations of nutrients, similar to other streams in intensively farmed catchments in New Zealand (Davies-Colley and Nagels, 2002; Larned et al., 2004; Wilcock et al., 1999, 2007). Temperature, DO, pH and conductivity were typical of many New Zealand streams, and within guideline values for the protection of slightly disturbed lowland river ecosystems (NZ Ministry for the Environment, 2000; Smith and Maasdam, 1994). In common with findings from other dairy studies, TN was predominantly NO_3-N (77% of median value) and FRP was a major fraction (64%) of TP (Monaghan et al., 2005; Wilcock et al., 2007). Concentrations of nutrients, faecal indicators and turbidity were compared for two periods, September 1995–April 2000 and April 2001–May 2005 (Fig. 4). Medians are very similar for the two periods, with both NH_4-N medians well below (3–4%) the trigger value. Medians were expressed as a proportion of ANZECC guideline values: default trigger values for turbidity, TN, NO_X-N, TP and FRP; contact recreation guidelines for faecal coliform and *E. coli*; and the toxicant trigger values for NH_4-N. Differences between the medians were all well within the IQR values.

The specific annual yield of SS was low (<50 kg ha^{-1} year^{-1}; Table 1), despite a median SS concentration of 10 g m^{-3}, and reflects the low frequency of natural flood flows and associated sediment transport in Waikakahi Stream (Duncan and Woods, 2004). Other yields are typical for New Zealand dairy catchments, but are lower than average for NO_X-N and TN (Wilcock et al., 2006, 2007). The DOC yield was less than half those reported for New Zealand hill-land catchments (Quinn and Stroud, 2002).

3.2. *Losses of water, nutrients and faecal bacteria in irrigation runoff*

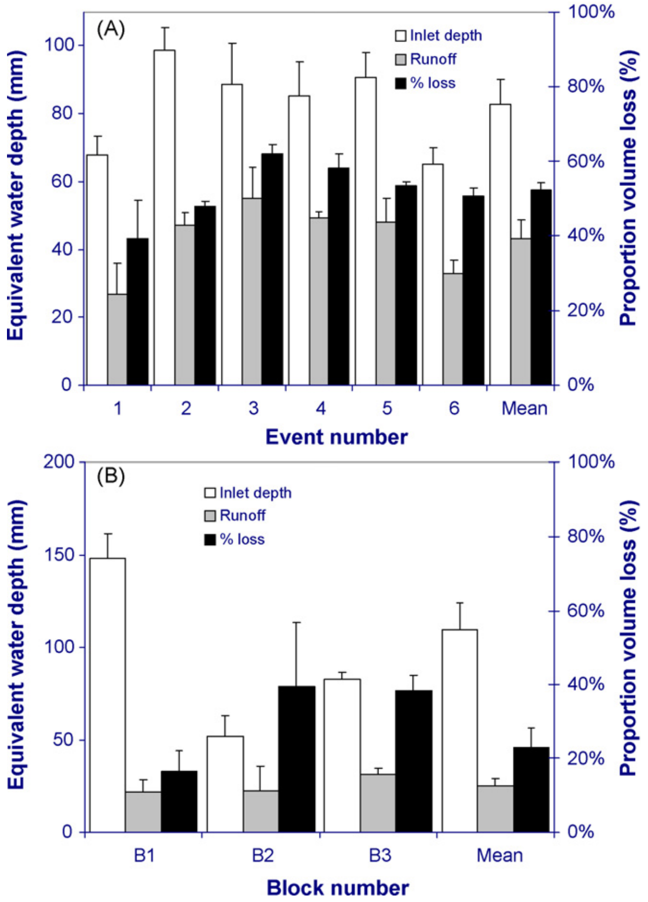

Fig. 5. Irrigation water inputs and surface runoff losses from (A) the Temuka and (B) Eyre/Paparua soils within the catchment. Standard error bars shown.

Runoff volumes from the seven irrigation events attended in year 1 were considerable, and exited the paddock through open drains and culverts, with water losses for individual borders ranging from 120 to 600 m^3 ha^{-1}. The average proportion of inflow volume lost as runoff was approximately 52% (range 40–60%), and totalled 2600 m^3 ha^{-1}, an effective water depth loss for the first six events of 260 mm (Fig. 5). Extrapolating on this basis, the

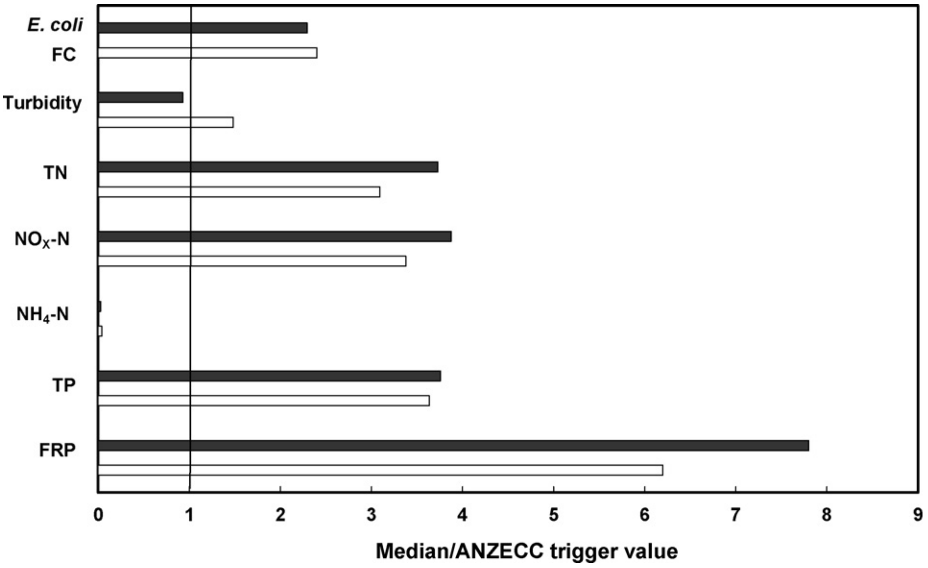

Fig. 4. Comparison of median values of water quality for September 1995–April 2000 (white bars) and April 2001–May 2005 (black bars). Each median value is divided by the relevant guideline value for slightly disturbed lowland river ecosystems (ANZECC, 2000). The solid vertical line indicates where medians are equal to default trigger values (turbidity, TN, NO_X-N, TP and FRP), the toxicant trigger value for NH_4-N (ANZECC, 2000) or contact recreation guidelines for faecal coliforms (FC) and *E. coli*.

total loss over the irrigation season would be at least 50% as much again, after adding in runoff losses from the five irrigation events not attended. Event 7 (45 min duration), which was additional to the normal irrigation scheduling, had the lowest overflow volume of all the events. However, this still led to a flow loss of 40% of applied water, which could be expected given that the volumetric soil moisture content was relatively high beforehand, at 34%.

In year 2, a total of eleven events (at six weirs) were attended over the irrigation season, of which ten produced sufficient runoff to record. This was less than anticipated, but there was less irrigation due to an unusually wetter and cooler summer. Overall, runoff volumes were large, with a mean loss of 25% of inlet volume. Losses of less than 20% of water inputs were recorded for only four of the eleven events monitored. The volume of water delivered per unit area (mm depth) to each border or set of borders differed three-fold.

Bacterial contamination of all sampled irrigation runoff waters was high, especially during summer (Table 2) when measured *E. coli* concentrations were up to 3 orders of magnitude higher than current guidelines that are recommended if water is used for recreational purposes (NZ Ministry for the Environment, 2003). Total-P concentrations in irrigation runoff were also high for both years. The exceptional circumstance to the irrigation events attended in year 1 was the staged event 7, where FRP concentrations were extremely high (~5 g P m^{-3}) due to the presence of recently applied soluble P fertiliser in the paddock. About 80% of the P present in events 1–6 was as FRP, with mean concentrations around 0.6 g P m^{-3}. However, where irrigation occurred within 1 day of grazing (event 3), filterable un-reactive P (Total dissolved P − FRP) comprised a greater percentage of the P lost. Total-P exported in irrigation runoff in year 1 ranged between 0.2 and 0.4 kg P ha^{-1} for each event where irrigation occurred between 4 and 28 days after grazing. However, for events 3 and 7 (both had a 1 day lag period between grazing and irrigating), P losses were considerably higher at 0.7 and 0.8 kg ha^{-1}, respectively. Year 2 exports of FRP and TP were lower than year 1 at about 0.2 kg P ha^{-1} per event (87% present as FRP), but this was due to the lower proportion of inlet flow (25% vs. 52%) lost as runoff, rather than lower P concentrations.

Concentrations of inorganic-N (ammonium + nitrate) in irrigation runoff water were approximately 0.4 g m^{-3}, with runoff losses of around 0.2 and 0.1 kg N ha^{-1} per event, estimated for years 1 and 2, respectively. Estimated TN losses via runoff at 2 kg N ha^{-1} year^{-1} were lower than P losses at 3.4 kg P ha^{-1} (Table 3). The staged event 7 in year 1 showed that N runoff losses could be exacerbated where N fertiliser had been recently applied (40 kg urea-N ha^{-1} had been applied 10 days previously).

Table 3
Net export (kg ha^{-1}) of TP, inorganic-N (IN), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na) and suspended solids (SS) in irrigation runoff from the Temuka soil field sites monitored in year 1

	Water depth (mm/ha)	Annual nutrient transfer (kg ha^{-1})						
		TP	IN	Ca	Mg	K	Na	SS
Irrigation input	520	0.4	1.3	48.6	4.3	5.5	12.1	151
Irrigation runoff	260	3.4	2.0	28.0	5.8	18.8	11.0	83
Net export	260	3.1	0.7	−20.7	1.4	13.3	−1.1	−68

Negative values denote a net gain.

Other significant nutrient losses recorded in irrigation runoff in year 1 were potassium (K) and magnesium (Mg) transfers of 13 and 1 kg ha^{-1} per annum, respectively (Table 3). The main net import of nutrients in the irrigation water was calcium (~20 kg Ca ha^{-1}).

3.3. Farm characteristics and nutrient emissions

Dairy farms occupy 40% of the total catchment area and 90% of the flats. Dry stock farming (sheep and sheep–beef) accounts for virtually all of the remaining land area. The average dairy farm occupies 213 ha (effective) and comprises approximately 600 cows. Dairy farm production levels are relatively high, at an average of 982 kg milksolids ha^{-1} year^{-1}, supported by considerable inputs of purchased feed, fertiliser and irrigation water (Table 4). Of the 2300 ha of flat irrigable land within the catchment, approximately 84% of this is watered via border dyke irrigation, with spray irrigation accounting for the remainder. Most of the dairy farms within the catchment are relatively recent conversions from dry stock farms, with the time in dairying averaging only 13 years. All dairy farms in the catchment irrigated dairy shed effluent to land, with some pumping effluent into the irrigation water for disposal as part of their normal irrigation system. Virtually all dairy farms wintered their cows off-farm, typically on a brassica forage crop.

OVERSEER® model predictions of nutrient emissions to water from farms within the catchment varied widely according to land use and soil type (Table 4). Nitrogen losses from the free-draining Eyre and Paparua soils under dairy land use were estimated to be relatively high, at 52 kg N ha^{-1} year^{-1}. Such large losses can be attributed to the high N inputs to these pastures, via clover fixation, N fertiliser and imported feed, and the large amount of drainage yielded from these shallow soils as a result of border dyke irrigation. Estimated nitrogen losses from the poorly drained Wakanui and Temuka soils under dairy land use were 27 kg N ha^{-1} year^{-1}. This figure is similar to losses measured from other New Zealand dairy pastures (Monaghan et al., 2007a).

Table 2
Nutrient and bacterial contamination of sampled irrigation runoff waters

Event	FRP		TDP		TP		*E. coli*	Inorg-N		TN	
Year 1											
1	0.7	*0.24*	0.8	*0.26*	0.9	*0.30*	6.3.E+03	0.2	*0.01*		
2	0.5	*0.10*	0.7	*0.14*	0.8	*0.16*	5.7.E+04	0.1	*0.01*		
3	0.7	*0.13*	0.8	*0.23*	0.9	*0.31*	2.8.E+05	0.7	*0.10*		
4	0.6	*0.12*	0.7	*0.14*	0.8	*0.14*	9.0.E+04	0.4	*0.08*		
5	0.8	*0.20*	0.8	*0.21*	0.8	*0.23*	6.8.E+04	0.4	*0.08*		
6	0.9	*0.27*	0.9	*0.29*	1.0	*0.29*	7.8.E+03	0.3	*0.08*		
7	4.6	*0.75*	4.9	*0.72*	4.9	*0.79*	3.0.E+04	3.4	*0.48*		
Year 2											
Block 1	0.44	*0.07*			0.53	*0.12*	3.7E+05	0.15	*0.12*	1.40	*0.37*
Block 2	1.00	*0.58*			1.19	*0.74*	1.1E+04	0.74	*0.74*	1.52	*1.25*
Block 3	0.72	*0.19*			0.78	*0.21*	9.6E+03	0.40	*0.21*	0.84	*0.34*

Mean concentrations are expressed in g m^{-3} (nutrients) or MPN 100 mL^{-1} (*E. coli*); standard error values shown in italics.

Table 4
Nutrient and water inputs to, and predicted N and P emissions from, model farm systems within the Waikakahi catchment

	Dairy		Sheep/beef (flats)		Sheep/beef (hill)
Soil drainage status	Free-draining soils	Poorly drained soils	Free-draining soils	Poorly drained soils	Well or adequately drained soils
Representative soils	Eyre, Paparua stony sand and silt loams	Temuka, Wakanui silt loams	Eyre, Paparua stony sand and silt loams	Temuka, Wakanui silt loams	Ngapara, Timaru and Taiko fine sandy and silt loams
Area within catchment (ha)	1176	886	83	148	2938
Average farm size (ha)	213		188		354
Animal stocking rate (SU ha^{-1})	24 (2.8 cows ha^{-1})		14		8
Irrigation inputs (mm $year^{-1}$)	700		600		0
Fertiliser inputs (kg ha^{-1} $year^{-1}$)					
N	172		95		33
P	60		33		46
K	59		29		0
Imported feed (T DM ha^{-1} $year^{-1}$)	2.4		0.3		0
Milksolids (kg ha^{-1})	982 (range: 695–1177)				
Milksolids (kg cow^{-1})	356 (range: 334–380)				
Nutrient emissions to water (kg ha^{-1} $year^{-1}$)					
N	52	27	21	8	9
P	0.6	1.0	0.5	0.9	0.2

Nitrogen leaching losses from dry stock farming systems were estimated to be considerably lower than those from dairy farms on similar soil types, and ranged from 8 kg N ha^{-1} $year^{-1}$ on the poorly drained Temuka/Wakanui soils, to 21 kg N ha^{-1} $year^{-1}$ on the irrigated and free-draining Eyre and Paparua soils. Estimates of P loss risk from farms within the catchment ranged between 0.2 and 1 kg P ha^{-1} $year^{-1}$ and, in contrast to N, were greater from poorly drained soils compared to well-drained soils. The P loss risks estimated for land on the irrigated flats are considerable, reflecting the large contribution from border dyke irrigation runoff directly entering the stream.

4. Discussion

4.1. Water quality and key sources of pollutants

Water quality of the Waikakahi Stream is typical of other dairy catchment streams in New Zealand, and can be characterised as having higher concentrations of *E. coli*, SS and nutrients compared to other low-elevation streams in New Zealand (Larned et al., 2004; Wilcock et al., 2007). Waikakahi Stream exceeded New Zealand water quality guidelines for lowland streams (ANZECC, 2000) 4-fold for *E. coli*, 2-fold for turbidity, 3-fold for FRP and 6-fold for NO_X-N (or by 2–6 times for those variables). Sediment values were less than those observed in soft-bottom streams with high macrophyte biomass, but were at the high end of ranges measured in 17 lowland English rivers of moderate-high trophic status (Clarke et al., 2001; Sand-Jensen, 1998; Wilcock and Croker, 2004). Yields are, apart from NO_X-N and TN, similar to what is reported for other dairy catchment streams in low-gently sloping terrain. Past episodes of very high SS loads associated with cattle grazing near the stream bank are much less frequent, presumably because of improved protection of riparian areas. Field measurements of nutrient fluxes in irrigation wash water (Tables 2 and 3) and catchment inventory assessments of nutrient yields (described below) indicate that irrigation runoff is the major cause of most of the elevated contaminant concentrations and loads in the Waikakahi Stream. High loadings of N, P and faecal matter are a direct result of dairying, a land use only possible because of irrigation. Less intensive (and non-irrigated) land uses generate much lower specific yields and stream water concentrations (Wilcock, 1986). Most dairy farms in the catchment dispose of dairy shed wastewater by irrigation to pasture, so point sources have less impact on the stream than diffuse runoff. This contrasts with identified discharges from oxidation-ponds and mole-tile drains that have a marked impact on stream quality in other intensively farmed New Zealand catchments (Monaghan et al., 2007b; Wilcock et al., 1999, 2006).

The most significant feature of the monitoring and field studies undertaken throughout the course of the study was the large volume of irrigation water lost in the catchment as runoff. Mean stream flows in summer (December–February) are typically three to four times greater than in winter (June–August) (865 L s^{-1} vs. 207 L s^{-1}, respectively). Field studies confirmed the large potential for water loss via irrigation runoff. While the 50% loss measured from the end of border dyke bays in year 1 was not expected to be typical for the catchment as a whole, the 25% loss recorded from free-draining soils during year 2 would appear to indicate that runoff losses of this scale are not unusual. Australian flood-irrigation studies have recorded runoff events as high as 32% of in-flow water (Austin et al., 1996; Bush and Austin, 2001), a value which lies mid-range in the losses reported here. A number of factors were observed that probably contributed to the variability observed in flow losses in the present study. Headrace condition was an important feature, with flow heights over the weirs considerably greater for the border nearest the inlet gate of the headrace, compared with borders further away. Obstacles (e.g. weeds, eroded banks, etc.) within the headrace channel obstructing flow created mean inlet depths that varied by up to 36%. Incorrect timing of watering also likely contributed to the large flow losses observed, particularly for short borders or sets of different length borders. Antecedent soil moisture content, pasture mass, equipment malfunction, and lack of border maintenance were other factors identified that probably also contributed to the variability in recorded flow losses.

Inventory assessments of the key sources of N and P within the catchment indicate that dairy farms contribute a disproportionately large percentage of both nutrients to stream losses (Fig. 6), accounting for more than 70% of loads despite occupying only 40% of the total catchment area. As already discussed, much of this can be attributed to the intensive use of the irrigated soils within the catchment. Because of the less intensive nature of farming on the hill soils at the northern end of the catchment, these farms are estimated to contribute only approximately 20% of the N and P loads in the Waikakahi Stream, despite covering 54% of the catchment area. Measured loads of N and P exported from the catchment amounted to 6.3 and 0.69 kg ha^{-1} $year^{-1}$, respectively. These figures contrast with area-averaged modelled farm losses of

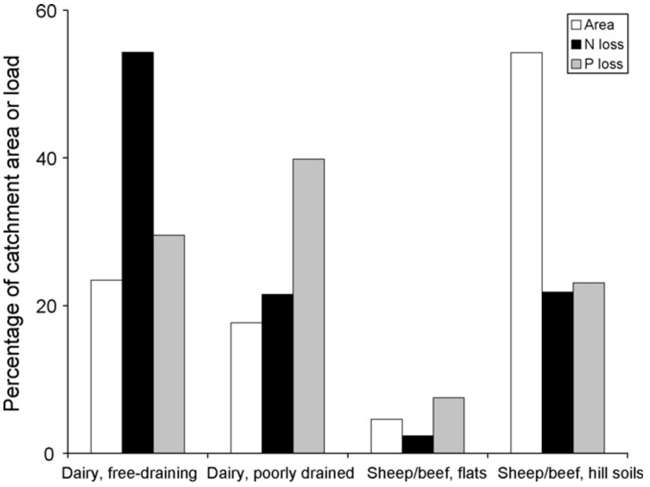

Fig. 6. Relative area occupied and predicted contributions to stream N and P loads of the different modelled farm-soil type combinations within the Waikakahi catchment.

20 and 0.4 kg ha^{-1} year^{-1}, respectively. The disparity between measured and modelled losses of N is considerable and may be attributable to a number of factors. In-stream attenuation, which was not considered in the aggregated farm scale modelling approach used here, is likely to account for some of the difference between measured and modelled losses. Additionally, it is probable that N leaching losses are overestimated for many of the farms on the flats that have been recently converted to intensive dairy farming. Relatively high rates of N immobilisation in these soils are expected (Monaghan et al., 2005) and would likely contribute to lower levels of soil mineral N and thus lower rates of N leaching than we have predicted using the OVERSEER® model. It should be noted, however, that this is expected to be a short-term (<20 years) effect and leaching losses are, accordingly, likely to gradually increase over time. Underestimation of denitrification rates for the frequently irrigated soils on the flats may also have led to over-predictions of N leaching losses, although given the very free-draining nature of the major soils present in the catchment, this would seem unlikely.

For P, aggregated modelled farm losses account for only approximately 60% of catchment discharge, indicating that other sources such as direct excretal nutrient deposition to riparian areas or stream bank erosion may be important contributors to P loss. Field surveying during 2002 indicated that more than 85% of the stream length was fenced to exclude stock from grazing in or near the stream, with good progress being made towards establishing full exclusion and thus eliminating one of the above potential P sources. Under-estimation of P losses via surface runoff from border irrigation may also account for the large discrepancy between aggregated modelled and measured catchment losses. Based on field assessments, it was assumed that only 20% of the border dyke-irrigated land area was directly “connected” to drains or stream channels, and that one third of the irrigation water applied to these areas was lost directly as runoff; both of these assumptions may be conservatively low. However, using these values indicates that border dyke irrigation of dairy farms within the catchment accounts for approximately 57% of P losses from farms, and is therefore a key land–water linkage.

Compared to current microbiological guidelines for freshwaters (NZ Ministry for the Environment, 2003), *E. coli* levels in irrigation runoff were generally very high in both years, and similar to concentrations measured from rainfall-induced runoff experiments (Collins et al., 2005; Crane et al., 1983; Edwards et al., 1997; McDowell et al., 2008). Multiple regression analysis showed that maximum daily temperature and time between irrigation and grazing were two factors accounting for much of the observed variability in *E. coli* concentrations in irrigation runoff, as described by the following equation:

$$\log_{10}(\mathrm{MPN}) = 3.15 - 0.03 \times \mathrm{Days}^{*} + 0.09 \times \mathrm{MaxTemp}^{**}$$
$$R^2 = 0.84$$

where Days is the interval between grazing and irrigation, MaxTemp is the average daily maximum temperature between grazing and irrigation, and */** denotes the probability significance of each variable at $P < 0.05$ and $P < 0.01$ levels, respectively. With peak pasture and dairy production occurring in late spring, resulting in greater dung deposition, bacterial numbers can reach very high levels under the warmer temperatures. Faecal bacteria loadings discharged from the catchment will generally be less than the total inputs to the stream, due to retention within drainage channels and in-stream processes (sedimentation and die-off) that reduce bacterial numbers. However, even allowing for the crudeness of our estimations and without any other obvious point sources of faecal indicator bacteria of this magnitude, irrigation runoff remains the most probable source of stream faecal contamination.

4.2. Catchment values and farm practices

As part of the catchment study process, workshops were held with stakeholders to define the key values of the catchment, which in turn helped to define a set of catchment-specific water quality targets. Land management guidelines and farm plans were then tailored to help achieve these key values, and included an evaluation of the cost-effectiveness of some mitigation strategies. This process determined that the trout fishery (particularly spawning and rearing) and drainage for the land (given the localised surface flooding occasionally observed) were the key values associated with the Waikakahi Stream. Although faecal pollution of groundwater bores used for domestic water supplies was identified as an issue, nutrient contamination of this groundwater was not. Consequently, low turbidity, sediment loadings and water temperature, and maintaining stable stream flows, were identified as some specific water quality targets for the stream. Some of the key land management practices influencing these variables therefore included: stock exclusion from stream margins (to protect stream banks and beds), provision of riparian shading, and minimising excessive losses of irrigation water and nutrients (which promote nuisance weed and algal growth within the stream, also impeding flow and reducing habitat value).

Given the large volumes of water lost in irrigation runoff, strategies for reducing land–water transfers of stream pollutants within this particular catchment should focus on water management to reduce runoff losses. Bunding of border ends or capture and re-use of irrigation runoff would eliminate these transfers altogether. Border renewal and laser-levelling of old borders would also help to minimise water losses in runoff. Technological and management solutions to the problems of over-watering need to be targeted firstly at the “leakiest” borders, i.e. those borders nearest stream areas, and the most difficult borders to manage because of their geometry or topography. Field observations also indicated that some key land management practices may help to minimise pollutant losses in irrigation runoff. The large increases observed in nutrient and faecal concentrations in irrigation runoff events that shortly followed fertilisation (and grazing) suggests that the timings of fertilisation and irrigation are important factors influencing losses of these pollutants. Maximising the interval

Table 5
Some key management practices relevant to the farm plans prepared for dairy farms within Waikakahi catchment

Management practice	Issue	Net annualised cost ($\$\ \text{ha}^{-1}\ \text{year}^{-1}$)	Cost-effectiveness[a]	Environmental impact
Irrigation management				
Adjust clock timings to reduce wash volumes to <10% of applied	All[b]	Nil	1	High
Bunding[c]	All	5–10	2	High
Re-levelling old borders[c]	All	110–315	3	High
Converting to spray irrigation[d]	All	370–440	3	High
Delayed fertiliser application	Nutrients	Nil	1	Moderate
Soil and effluent management				
Optimum soil Olsen P	Nutrients	Nil	1	Moderate
Low solubility P fertiliser	Nutrients	Nil	1	Moderate
Nitrification inhibitors[e]	Nutrients	36––95	1–2	Small
Increased effluent area	Nutrients	<5	2	Small
Improved effluent application methods	Nutrients	17–38	2	Small
Wintering pads	Nutrients	100–200	3	Small
Stream/riparian management[f]				
Fence off waterways	All	1.30–10	2	Very high
Fence off and plant waterways	All	10–14	2	Very high

[a] 1 = nil cost or net gain for farmer assumed; 2 = slight net cost of between 0 and $\$10$/kg nutrient conserved; 3 = significant net cost of >NZ$\$10$/kg nutrient conserved.

[b] All = Nutrients, flow, sediment, faecal pollution.

[c] Bunding and border re-levelling options assumed to incur capital costs of $\$50$–100 and $\$1250$–3500 ha^{-1} and are depreciated over 50- and 100-year periods, respectively.

[d] Assumed to only be required for the 20% of irrigated farm area that drains directly to the stream.

[e] Assuming a 2–5% pasture yield response, a 15–25% reduction in N leaching losses from milking platforms and a payout of NZ$\$6$/kg milksolids.

[f] Assuming (i) a stream channel density of 30 m/ha, 15% of which remains un-fenced and un-planted, and (ii) an opportunity cost of capital of 8% per annum.

between these two managements would be a low cost mitigation strategy for reducing the potential for N and P losses. Research conducted in Australia has also shown the increased risk of P loss from irrigation runoff after recent fertiliser addition (Austin et al., 1996; Bush and Austin, 2001; Nash et al., 2004). Although not specifically addressed in this study, the form of P fertilisation would be another important consideration, with lower losses of P observed in overland flow from soils recently fertilised with low P solubility products, such as reactive phosphate rock, compared to more soluble forms of P, such as superphosphate (McDowell et al., 2003). Of the stream habitat managements identified, riparian fencing and planting are two important mitigation options for protecting the stream. Field surveys in 2002 (data not shown) indicated substantial progress with stream fencing and planting in the preceding decade, with more than 85% of stream reaches now fenced to exclude stock. Much of the length of the stream has also been planted to improve riparian habitat and shading.

Many of the above management practices were considered as part of farm planning initiatives prepared for dairy farms in the catchment, starting in 2005. This exercise represented the end of phase I of the catchment study process, with plans put in place to address the water quality issues identified above. Two components of this planning approach that were critical to its success were:

- Most farmers desired flexibility in their management approach to solving water quality issues. This in turn required scientists and agency staff to provide a range of options (or a mitigation “toolbox”) for consideration, rather than a narrow set of prescriptive practices (Table 5).
- In addition to the “environmental” information provided, financial costing was an important set of information needed in the planning process. Assessments of the cost-effectiveness of each mitigation option were particularly helpful when it came to prioritising actions/expenditure.

Preliminary indications show reasonable rates of progress in farmers adopting some of the critical management practices identified in Table 5. For example, mean annual rates of fertiliser P inputs to dairy farms in the catchment have decreased from 62 kg P ha^{-1} in 2001, to a maintenance input of 42 kg P ha^{-1} in 2006. Additionally, 4 of the 11 dairy farms have recently undertaken extensive re-bordering and re-levelling works to improve irrigation performance.

5. Conclusions

On-going monitoring of the Waikakahi Stream shows it is moderately turbid, and contains relatively high concentrations of nutrients, notably P and N, and faecal bacteria. Values often exceed guideline standards, with a high proportion of the P and N present in readily available FRP (64%) and nitrate (77%) forms, respectively. Field measurements and model evaluations indicate that border dyke irrigation runoff has a potentially large effect on a range of water quality parameters, due to both the excessive stream flows generated by so much over-watering, and the entrainment of P, N, and faecal bacteria in this flow as it passes from land to stream. Stock access to some of the remaining un-fenced lengths of the stream was also recognised as an important land management practice to be addressed, to protect key catchment values identified by stakeholders such as maintaining a healthy trout fishery and a stream suitable for recreational use. Specific water quality targets developed to achieve these key values focused on maintaining acceptable levels for water turbidity, flow rates, temperature and sediment and nutrient loadings. Assessments of the effectiveness and cost-effectiveness of a number of potential mitigation practices identified that managements which targeted reducing irrigation runoff and fencing and planting riparian margins, showed the greatest potential to meet these key values with least cost to farm businesses. Other farm practices were also identified that incurred nil or minimal cost while also delivering small or moderate benefits to stream water quality. These practices have accordingly been used to help develop farm plans for individual properties within the catchment.

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