9 Impacts of Irrigated Dairying on the Environment

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Introduction

Pasture-based dairying is a major land use of the agricultural industry in both Australia and New Zealand. As of 2006, Australia had *c.*2 million cows on 9250 dairy farms producing over 10 billion l of milk with a value of US$2.5 billion at the farm gate (Dairy Australia, 2006). In the same year in New Zealand, *c.*4 million cows in 12,000 herds produced over 1.2 million t milk solids with a value of US$3.8 billion at the farm gate (Australian Bureau of Agricultural and Resource Economics and Ministry of Agriculture and Forestry, 2006; Ministry of Agriculture and Forestry, 2006).

A major impediment to the expansion of the dairy industry in these countries is the lack of water, especially in summer and early autumn. The lack of water, particularly soil moisture, limits pasture productivity and pasture-based grazing, and increases production costs because of the need to source alternative feed supplies (Dillon *et al.*, 2005). Border-check (also called border-dyke or flood) irrigation and spray irrigation can be used to offset water deficiencies and increase production.

While 23% of Australia's dairy farms are classed as 'irrigated' (Dairy Australia, 2006), 52% of dairy farmers supplement natural rainfall with irrigation, either from major irrigation schemes where water is delivered to the farm gate or from other sources including catchments within the farm and groundwater bores (Dairy Australia, 2005). Dairy farms using irrigation water as the basis for fodder production are concentrated in south-eastern Australia including the lower reaches of the Murray River in south-eastern South Australia (Lower Murray), the Murray River plains in northern Victoria and Southern New South Wales and the Macalister Irrigation District in Gippsland, Victoria (Fig. 9.1). In other regions, irrigation is often used to supplement grass production in primarily rain-fed dairy systems. In New Zealand, irrigated pasture production is increasingly prevalent especially around Canterbury and Otago (Parliamentary Commissioner for the Environment, 2002).

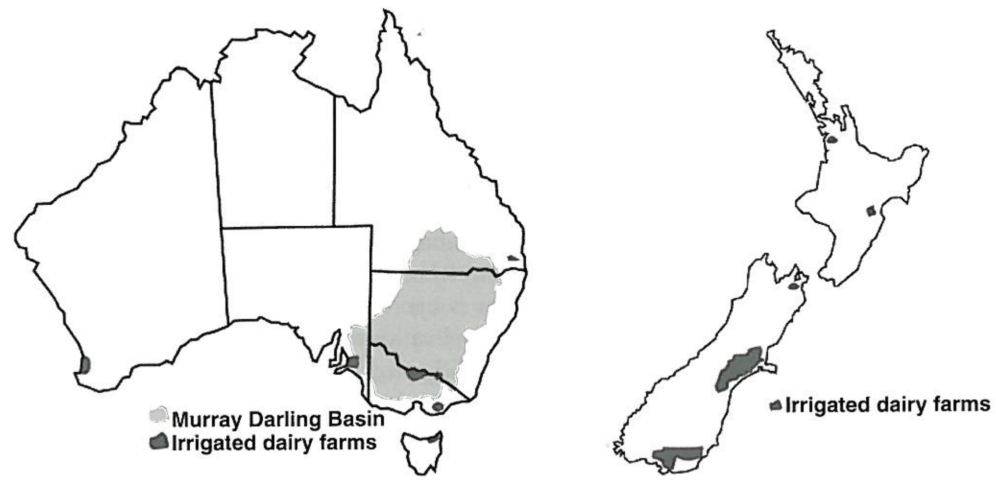

Fig. 9.1. Irrigated dairying areas of Australia and New Zealand. Figures not to scale.

The sustainability of irrigation is threatened by processes that degrade the environment and the economic constraints imposed on any farming system. In this chapter, we examine the properties of border-check and spray irrigation systems, particularly the hydrology of the different systems, the management challenges and the application of alternative irrigation technologies. The chapter then investigates the sustainability of irrigated pastures for dairy production in terms of both environmental constraints (e.g. deep drainage and pollutant export) and productivity constraints, both of which will ultimately affect their economic viability.

Irrigation Systems and Their Hydrology

Irrigation is practised on a range of soils in both Australia and New Zealand. For example, in southern New South Wales and northern Victoria, soils deposited as a result of prior stream activity are irrigated. Coarser soils with higher infiltration rates tend to occur on the levees while finer-textured clay soils, with low permeability, occur on the flood plain (Skene and Poutsma, 1962; Lyle *et al.*, 1986). The properties of these soils, their infiltration rate and hydraulic conductivity, as well as the source of the water (i.e. groundwater or gravity-fed channels) and the existing infrastructure, all affect the methods of irrigation that are used.

Understanding the sustainability (economic and environmental) of the various irrigation systems requires an understanding of the hydrology of the system, the associated risks of adverse impacts on and off the farm and the infrastructure required to support the systems. This section investigates the hydrology of the main irrigation systems used for irrigated pasture production: border-check and spray irrigation. In Australia, border-check is the most common irrigation method used for fodder production (Wood and Finger, 2006), while spray irrigation is the more common irrigation method used on pastures in New Zealand.

Border-check irrigation

The aim of border-check irrigation is to restore the root zone to field capacity (Finger, 2005), with water applied when the soil water deficit, generally measured as evaporation – rainfall (estimated using Class A pan evaporation and normalized for the region), is 40–50 mm. Water is applied to the top of a bay (commonly *c.*350 × 40 m but can be more than 1000 m in length and 30–50 m wide) in excess of the soil infiltration rate and moves down the bay as infiltration excess surface runoff. The water is confined on the bay by check banks (i.e. raised earthen ridges) which run down the sides of the bay. Water is usually applied 10–20 times from late spring to early autumn, with annual applications of between 5 and 10 ML/ha.

Irrigation water moves into the soil through a combination of 'bypass' flow through channels and cracks, and saturated and unsaturated matrix flow. The highest infiltration rates occur at the wetting front where the water initially passes into dry soil, and decline behind the wetting front (Austin, 1998; Fig. 9.2). A major deficiency of border-check irrigation is that water needs to traverse the

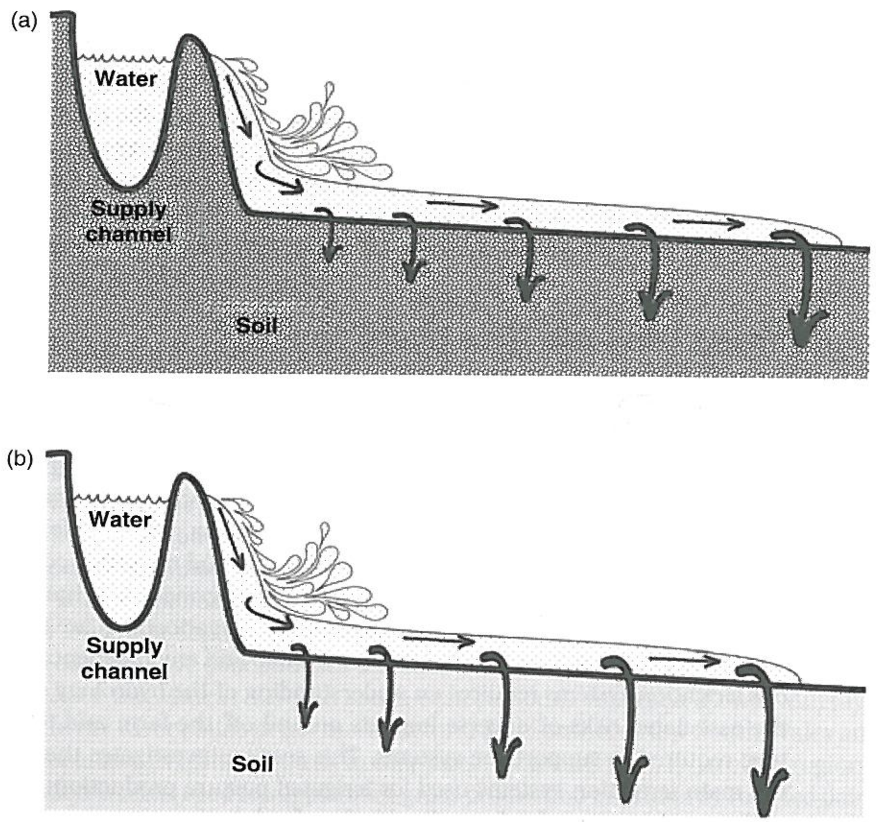

Fig. 9.2. A diagrammatic representation of water movement in border-check irrigation systems on (a) heavy, low-infiltration soils and (b) light, high-infiltration soils.

soil surface for the full length of the bay to ensure that the entire bay is irrigated. This results in *c.*20% more water than required being applied (Nexhip *et al.*, 1997) and passing from the foot of the bay into drainage channels. This surface water is commonly referred to as surface runoff and can include re-emergent interflow (Nash *et al.*, 2002).

In practice, border-check irrigation rarely distributes water as evenly down a bay as might be hoped due to soil variability, particularly infiltration rates, and the variable time that water is ponded on the surface. To assist in the even distribution of water in a bay, most border irrigation systems are graded to a slope of 1:400 to 1:1000, depending on the region and site. While laser grading can manufacture constant slopes on the bays, preferential flow paths and variable infiltration characteristics still occur, affecting the distribution of water and the efficiency of the irrigation system. For example, in some regions, such as the Macalister Irrigation District, bays may traverse two or more soil types with differing infiltration characteristics. Animal traffic also affects drainage via localized soil structural decline, especially when wet, and areas of low infiltration due to animal tracking. This is a particular problem at the foot of bays where surface flow can accumulate and waterlogging can suppress pasture production. Spinner drains (i.e. shallow, <10 cm, scalloped-shaped drains extending longitudinally down bays) are used in some areas to improve surface drainage and fortunately, on many farms, the adverse effects of cattle traffic during the irrigation season are minimized by only grazing when the soil surface is dry.

The water application efficiency of border-check irrigation systems has been enhanced through the use of laser grading to improve water distribution on the paddock, whole-farm planning, the installation of reuse systems that collect outwash (surface runoff) and the availability of higher flow rates that decrease the time available for infiltration (Ewers, 1988; Water Force Victoria, 1990; Malano and Patto, 1992; Douglass and Poulton, 2000). The use of high flow rates during application causing pulses rather than a continual stream has been shown on some soil types to result in more uniform water application and less infiltration below the root zone as water passes over pre-wetted soil (with a lower infiltration rate; Turral, 1993). In addition to soil type, the effectiveness of surge flow irrigation appears to be affected by factors such as water salinity, sodicity and sediment (Heydari *et al.*, 2001; Wang *et al.*, 2005).

The hydrology of border-check irrigation suggests that on many soil types drainage below the root zone and water draining from the foot is to be expected if the whole bay is to be irrigated. It follows that border-check irrigation is most efficient (measured as production per unit water applied) on heavier soils. Where infiltration rates are higher, the probability of water moving below the root zone increases along with the consequences of deep drainage such a rising water tables.

Sprinkler irrigation

Sprinkler systems distribute water much like rainfall. Sprinkler systems and the related infrastructure vary dramatically between regions depending on the size and shape of the area to be irrigated, the topography, physical obstructions such as trees and buildings, the availability of labour, the necessary application rate and the source of the water. The types of spray irrigation used in pastoral industries include fixed, operator shift low-pressure (bike-shift) sprinkler gun, centre-pivot and lateral move sprinkler systems (side-roll; Wood and Martin, 2000).

The basic hydrology of sprinkler irrigation is similar to rainfall. In general, water is added to soil at a rate below the soil infiltration rate and penetrates to a depth determined by the flow characteristics of the soil and the irrigation management. The notable exception is at the circumference of larger centre-pivot irrigators where due to the higher ground speed, greater water application rates are required and some temporary ponding may occur in the immediate vicinity of the sprays. As water moves predominantly in a vertical direction (Fig. 9.3) and there is no requirement for lateral flow, the loss of water and associated pollutants in irrigation surface runoff (re-emergent interflow and overland flow) should be minimal (Ebbert and Kim, 1998).

Theoretically sprinkler irrigation provides more control over water distribution than systems such as border-check due to the ability to match application rates and infiltration characteristics in a sprinkler system (Burt *et al.*, 2000). This maximizes irrigation efficiency and presumably, for example, in the Shepparton Irrigation Region of northern Victoria, centre-pivot irrigators would be expected to operate with 75–90% efficiency while the equivalent border-check irrigation systems are 55–90% efficient (Department of Primary Industries, 2004). While environmental factors including wind affect sprinklers, the efficiency of sprinkler systems largely depends on management particularly in systems that require significant operator intervention, such as low-pressure sprinklers that require the operator to shift them often. Even where sprinkler irrigation is uniform, undulating soil and varying soil infiltration rates can lessen overall irrigation efficiency. This is most noticeable in small depressions where water may temporarily collect. Grazing cattle tend to preferentially compact soil in these areas decreasing the infiltration rate (i.e. poaching) and exacerbating the problem. As a result, a mosaic of small wet areas may develop where the vegetation is different to other sections of the paddock.

An important issue, particularly where centre-pivot and travelling irrigators are used on sloping ground is the lateral flow of subsurface water down slope. Unless irrigation rates are modified in different areas, water moving past the root

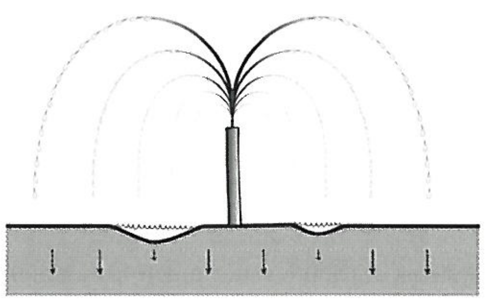

Fig. 9.3. A diagrammatic representation of water movement under spray irrigation.

zone through preferential pathways accumulates down slope (as interflow) leading to either saturated soil (or soaks) and/or subsurface drainage that can export contaminants off site. Unfortunately, in many of these situations there are often few alternatives to this form of irrigation.

Alternative irrigation technologies

With increasing pressure on limited water supplies, there is increasing interest in micro-irrigation technologies such as subsurface drip. Subsurface drip irrigation has been successfully applied across a range of industries, with increased yields and decreases in water use compared to other systems (Ayars *et al.*, 1999; Alam *et al.*, 2002; Lamm and Trooien, 2003). In one trial, subsurface drip irrigation used 200 mm/year less irrigation water than border-check and produced approximately 1.0 t dry matter (DM)/ha/year more pasture (Finger and Wood, 2006). Compared to sprinkler irrigation, subsurface drip can decrease evaporation (Alam *et al.*, 2002), decrease erosion (Bosch *et al.*, 1992) and lessen scalding by entrained salts (Cetin and Bilgel, 2002).

Adverse Impact of Irrigated Dairy Pastures

Rising water tables, salinity and nutrient exports (particularly nitrogen (N) and phosphorus (P)) are major problems that threaten the environmental sustainability of irrigated pasture production. All of these environmental impacts are linked to the hydrology of irrigation systems. Deep drainage contributes to rising water tables and associated soil salinity, and N leaching, while surface runoff can transport N, P and other contaminants into aquatic ecosystems.

An issue of increasing prominence, especially under border-check irrigation where nitrogenous fertilizers are used, is the production of nitrous oxides. Nitrous oxides are powerful greenhouse gases and whether they are produced in significant quantities under irrigation is the subject of continuing research (de Klein *et al.*, 2001; Dalal *et al.*, 2003; Phillips *et al.*, 2007).

This chapter focuses the adverse impacts from deep drainage and surface runoff, while Chapter 1 (this volume) investigates greenhouse gas emissions from pasture systems.

Deep drainage

Deep drainage from irrigation is a major environmental challenge in many parts of Australia and New Zealand. Deep drainage, the movement of water below the root zone of plants and into the vadose zone en route to groundwater, contributes to rising water tables and the associated problem of salinization, as well as the leaching of N and other potential pollutants, including pesticides, to groundwater systems.

Rising water tables and salinity is a significant challenge for irrigated regions in Australia (Lyle *et al.*, 1986). The impacts of deep drainage are well documented in the Murray Darling Basin in Australia, which in the mid-1980s had approximately 96,000 ha of irrigated land showing visible signs of salinization as a result of high water tables. It was anticipated prior to the recent drought that the area affected by high water tables in the Murray Darling Basin would have increased to 869,000 ha of land by 2015 (Blackmore *et al.*, 1999).

The challenge in minimizing the risks associated with deep drainage is that in all irrigation systems some drainage is essential to remove salts from the root zone that have been concentrated via the evapotranspiration of irrigation water (Richards, 1954). For optimum irrigation efficiency, such leaching would result from natural rainfall in the non-irrigation season. However, irrigation management for zero drainage is difficult to achieve, particularly as all but the most unstructured soils have preferential flow paths (macropores) that transmit water below the root zone ensuring some deep drainage occurs (Nash *et al.*, 2002). While small amounts of deep drainage may seem unimportant, it is worth noting that 10 mm of drainage may result in water tables rising 200 mm as the water only occupies pore space in the soil.

The proportion of water draining below the root zone is primarily a function of the soil type, irrigation method and water application rate (i.e. irrigation management) and is generally the result of unsaturated flow processes, which are difficult to measure in the field or to describe quantitatively (Hillel, 2004). Deep drainage is often estimated on the basis of a soil water balance, fluctuations in soil water content, mathematical models of unsaturated flow in soils or through the use of lysimeters (e.g. Bethune and Wang, 2004).

Estimates of deep drainage on heavier soils used for border-check irrigation in the Murray Darling Basin are commonly in the range of 0–100 mm with most around 50 mm. Several studies have estimated that <10 mm of deep drainage occurred annually on the heavier soils in the basin (Holmes and Watson, 1967; Gilfedder *et al.*, 2000; Bethune and Wang, 2004). Shallow water tables may have confounded the results in some of these cases. The estimates for deep drainage on more permeable levee soils using similar irrigation methods range between 100–500 mm. Similar rates of drainage (100–600 mm) have been estimated in trials in New Zealand, where the majority of leaching occurred over winter (Ledgard *et al.*, 1996; Di *et al.*, 1998).

The amount of deep drainage is affected by the irrigation system used, its management as well as soil properties, with a number of studies comparing deep drainage under different irrigation systems. For example, border-check, sprinkler, subsurface drip and surge (i.e. high flow) irrigation have been compared in Northern Victoria on a flood plain soil (Bethune *et al.*, 2003; Wood and Finger, 2006). During the trial, irrigation of the border-check irrigation bays was scheduled when Class A pan evaporation exceeded rainfall by 50 mm, while a 30 mm deficit was used to schedule sprinkler irrigation. The temporal pattern of root zone water depletion for these two systems is shown in Fig. 9.4, with the border-check irrigated bays replenished to field capacity following irrigation, while under sprinklers, soil water depletion was managed within a narrower range and never reached field capacity. Deep drainage was estimated to be 12 and 7 mm for the sprinkler irrigated bays and 248 and 64 mm for the border-check irrigated bays. Other findings from the study were that:

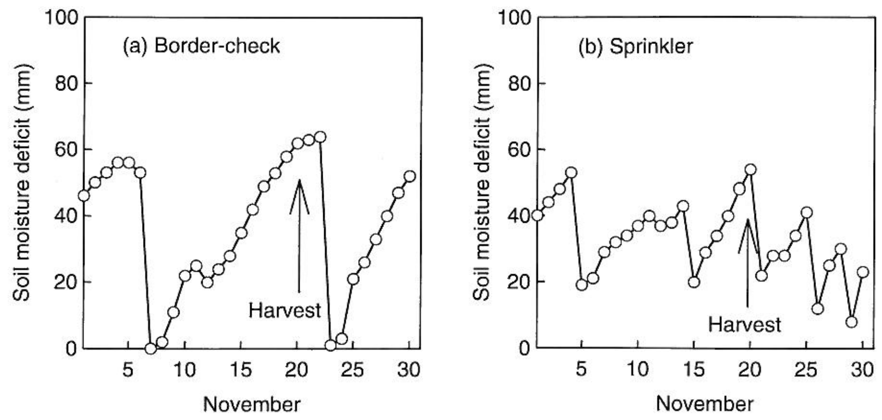

Fig. 9.4. Variation in root zone soil water depletion for (a) border-check-irrigated and (b) sprinkler-irrigated bays. (Adapted from Bethune *et al.*, 2003.)

- Subsurface drip and sprinkler irrigation used on average 20% less irrigation water than border-check irrigation (assuming surface drainage was reused).
- Subsurface drip and sprinkler irrigation had *c.*15% greater water-use efficiency (defined as the quantity of DM produced per megalitre of infiltrated depth plus rainfall) than border-check irrigation.

N leaching associated with deep drainage can affect groundwater quality and can also be discharged into neighbouring water bodies. This problem is particularly acute in parts of New Zealand (Parliamentary Commissioner for the Environment, 2005), where groundwater nitrate concentrations have been found to exceed the World Health Organization drinking water limit of 10 mg N/l in many regions. Intensive agricultural activities, such as dairy farming, are considered to be major non-point sources of nitrate to groundwater systems.

Minimizing deep drainage is important; however, it is possible to recover deep drainage by pumping groundwater. This can lessen the negative effects of irrigation on the environment by lowering water tables and removing salts from the soil. However, the groundwater is often saltier than the original irrigation water as the concentration of salts through evapotranspiration is unavoidable. In some hydrogeologic settings, such as the Murray Darling Basin, salts from other areas may also contribute to salt in groundwater (Greg Hoxley, March 2007, personal communication). The use of saline water for irrigation of pastures either alone or mixed (i.e. shandied) with better quality water (termed conjunctive water use) is one way of lessening the impact of deep drainage from pasture-based grazing systems (Bethune *et al.*, 2004).

Saline drainage can also be used to irrigate field crops (Tanji and Karajeh, 1993). One rather innovative system for managing deep drainage and associated saline irrigation water is Serial Biological Concentration (SBC; Heath and Heuperman, 1996; Heuperman, 1999). These systems concentrate drainage water by reuse on successively more salt tolerant crops and ultimately dispose of the salt in evaporation basins.

Surface runoff

The export of pollutants, especially N, P and microbial pathogens, in surface runoff is a major environmental issue for irrigated dairy systems. There are limited data on the microbial composition of drainage. Loss of the faecal indicator bacteria, *Escherichia coli*, in outwash from border-check irrigated pastures is estimated at about 1.5×10^7 coliform forming units/m^2 per irrigation event (McDowell *et al.*, 2008). However, nutrient exports, both nutrient loads and nutrient concentrations, have been extensively studied (Drewry *et al.*, 2006) and a number of remedial programmes have been implemented (Department of Natural Resources and Environment, 1998). While nutrients loads are the product of the nutrient concentration and flow volume, flow is the major determinant of nutrient loads as it is highly variable (i.e. can vary from almost zero to several orders of magnitude greater than the average), whereas nutrient concentrations are generally within a comparatively narrow range (i.e. vary by an order of magnitude or less; Nexhip *et al.*, 1997; Haygarth *et al.*, 2004). The exception is where a readily available nutrient source such as fertilizer has recently been applied to the pasture (Nash *et al.*, 2005).

At the bay/field scale, there is no question that the nutrient loads exported from most irrigation systems will exceed those from a rain-fed system in the same area (i.e. a non-irrigated farm with the same rainfall). This is especially true for border-check irrigation. Any form of irrigation will increase soil moisture, decrease the soil infiltration rates compared to dry, unirrigated soil and increase surface runoff. Equally important, plants take up nutrients from soil water. To grow higher-yielding plants under irrigation, fertilizers are generally applied to increase nutrient concentrations in soil water. These nutrients are mobilized when runoff occurs. Not surprisingly, at the bay or field scale in the same area, irrigated pastures generally have greater fertility and productivity than rain-fed systems, but also produce a greater volume of surface drainage with a higher nutrient concentration.

Nutrient concentrations in surface runoff are affected by nutrient sources, mobilization processes (including demobilization) and the hydrology of the system. For well-managed irrigated pastures, physical detachment and transport of soil particles (i.e. erosion) and associated nutrients should not be a major contributor to nutrient exports. Consequently, it is the export of dissolved nutrients (<0.45 μm) that is the major concern for well-managed farms.

Nutrient concentrations in surface runoff from irrigation systems depend on the scale at which they are measured. While nutrient loads have often been measured at the bay/field scale and under different management regimes, the associated mobilization and transport processes have received less detailed study. At the bay/field scale, the concentrations of nutrients in irrigation-induced surface runoff increase as water moves down the bay, especially at the wetting front (Fig. 9.5). A simple explanation for the increasing nutrient concentrations in the wetting front would be that labile nutrient stores at the soil surface are being mobilized and that more nutrient is being mobilized than is infiltrated. Consequently, the further the water moves the greater its concentration becomes. This hypothesis is consistent with studies where surface-applied, labile P has been shown to rapidly infiltrate soil (Bush and Austin, 2001). A similar hypothesis would explain why nutrient

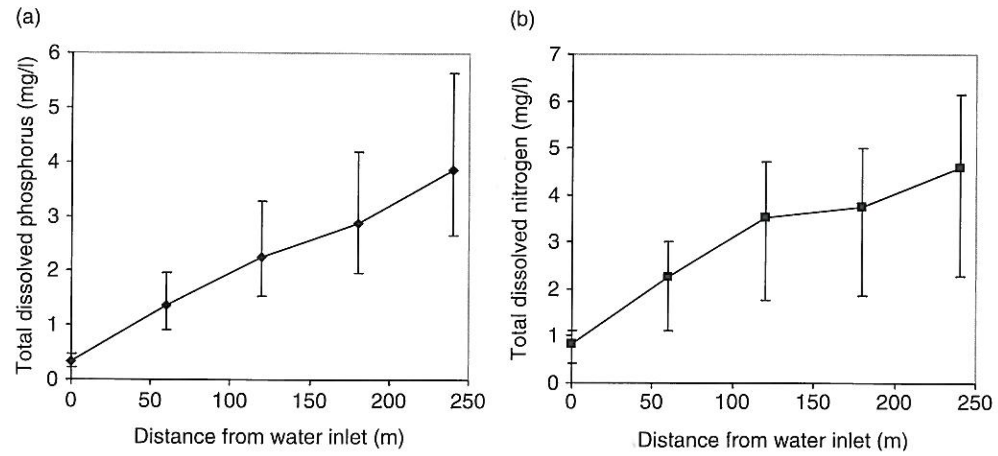

Fig. 9.5. Wetting front (a) total dissolved phosphorus and (b) total dissolved nitrogen concentrations with distance down a border-check irrigation bay from the water inlet.

concentrations also increase behind the wetting front where infiltration rates decline but infiltration does not cease altogether. But is it reasonable that only the nutrients at the surface are being mobilized, especially behind the wetting front?

An alternative explanation for nutrient concentrations increasing with path length is that behind the wetting front the flow of dissolved nutrients into the soil is opposed by intermittent turbulence near the surface (*c.*5 mm) and the quasi-diffusion of nutrients from within topsoil layers into surface runoff (Fig. 9.6). This implies that nutrient concentrations in surface runoff are a function of the soil hydrology, the rate of nutrient release from its primary source, its location relative to the soil surface (i.e. vertical path length and tortuosity), and factors affecting diffusion such as source solubility and demobilization (i.e. fixation) reactions, rather than simply the size of the nutrient source and its solubility. For example, soluble nutrients contained in organic matter may well avoid infiltration at the wetting front. Their subsequent diffusion into surface runoff may result in greater overall nutrient concentrations than would otherwise be the case. Such an explanation may help explain the large between-storm variability often encountered in field studies.

There is circumstantial evidence that processes similar to the one proposed in Fig. 9.6 operate in border-check irrigation systems. In field experiments using within bay sampling to compare two fertilizers with different dissolution rates, single-superphosphate and di-ammonium phosphate were shown to affect dissolved P concentrations at, and possibly behind, the wetting front (Nash *et al.*, 2003b, 2004). In model studies where vertical fluxes had been largely eliminated, dissolved nutrient concentrations in surface flow have been shown to initially increase and then decrease to a concentration well above zero for the remainder of the experiment (Doody *et al.*, 2006). It is difficult to explain such results based on variable solubilities of nutrient sources alone and such studies suggest that the kinetics of nutrient diffusion from the source to flowing water is also having an effect. Similarly, increasing flow path length has been shown to increase

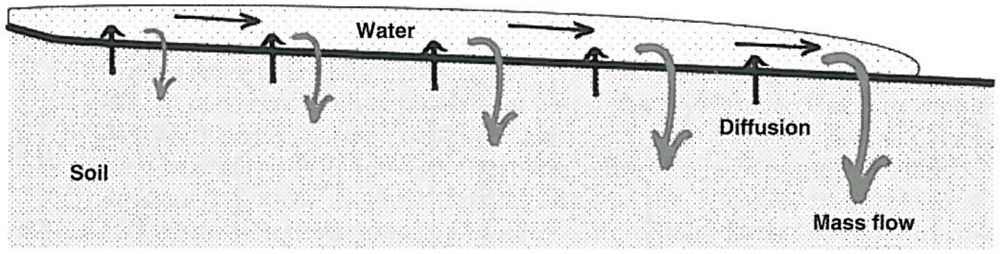

Fig. 9.6. A schematic representation of the roles of mass flow and diffusion in contaminant mobilization in surface runoff.

dissolved nutrient concentrations, while increasing flow rates generally decrease dissolved nutrient concentrations, probably due to dilution. Such a mechanism would also help explain the insensitivity of P concentrations in surface runoff to runoff volume in some field-scale (*c*.2 ha) studies (Nash *et al.*, 2005) and why in some larger-scale and model studies dissolved nutrient concentrations paralleled rain-induced surface runoff rates when, due to dilution, they would be expected to decline (Pote *et al.*, 1999; Heathwaite and Dils, 2000; Lazzarotto *et al.*, 2005). In addition to the physical processes described in Fig. 9.6, increased flow rates are likely to be associated with increasingly larger source areas leading to longer horizontal path lengths, longer residence times, access to additional nutrient sources and therefore, higher concentrations. In some cases re-emergent interflow may also have contributed to nutrient concentrations.

The processes responsible for nutrient mobilization are important because they may provide a guide to opportunities for lessening nutrient exports from irrigated dairying. For example, if the main factor is the rate at which nutrients physically intersect surface runoff, then this will be affected by path length. This implies that location of nutrient sources (i.e. depth) relative to the flow will be as important as the solubility of the chemical species in water in determining nutrient concentrations in surface runoff. Detailed testing of this hypothesis using a conventional rainfall simulator may be difficult as the physical impact of the water droplets would increase surface turbulence and the effective depth of interaction (Ahuja and Lehman, 1983).

Nutrients accumulate at the surface of pasture soils and model studies have suggested that de-stratification (i.e. mixing surface and subsurface soil) can lessen nutrient concentrations in surface runoff (Dougherty *et al.*, 2006; Sharpley, 2003). Recent studies of border-check irrigation in the Macalister Irrigation District of south-eastern Australia have confirmed that hypothesis (Nash *et al.*, 2007). Changes in soil P (0–20 mm), soil water P and N, and P and N concentrations in surface runoff were measured in four recently laser-graded (<1 year) and four established (>10 years) irrigated pastures in south-eastern Australia after 4 years of irrigated dairy production. Laser grading, which involves cultivation and mixing of surface soil, initially lowered soil surface (0–20 mm) total P, Olsen P, Colwell P, water extractable P, calcium chloride extractable P, organic P, P sorption saturation and total C and increased P sorption compared to established pastures but did not affect Olsen P and Colwell P concentrations in the root zone (0–100 mm).

Over the 3 years of the study on the lasered bays, Olsen P, Colwell P and P sorption decreased and water extractable P and P sorption saturation increased while on the untreated bays only Olsen P and Colwell P decreased. These results presumably reflect the inputs and outputs being in approximate balance, incorporation of subsoil into the surface layer and a general decline in P availability.

Three years after laser grading, soil water total dissolved P (TDP) concentrations were greater on the established bays while dissolved reactive P (DRP) concentrations were unaffected. Soil water organic P (estimated as TDP-DRP and also called dissolved unreactive P) comprised 70% and 32% of TDP for the established and lasered bays, respectively. These soil water data were reflected in the surface runoff where after 3 years, compared to established bays, laser grading decreased TDP, total dissolved N, total P and total N exports in wetting front drainage by 40%, 29%, 41% and 36%, respectively. This is an important result for management of dairy systems as it suggests that the regular cultivation used to renovate pasture on more intensive (>2cows/ha) dairy farms probably decreases the short-term exports of P and N compared to an otherwise similar, non-cultivated alternative. But would the results have been the same if this were sprinkler irrigation?

At the farm scale, compared to many rain-fed grazing systems, irrigation farms are often in the unique position of being able to control both irrigation and rain-induced drainage. To prevent waterlogging of the bays, border-check irrigation farms generally have a well-developed drainage network that can be used to collect and recycle surface runoff (also termed outwash). The effectiveness of these systems depends on their management, but in some studies, nutrient exports have been virtually eliminated through drainage reuse (Barlow *et al.*, 2005). It follows that, depending on the farm infrastructure and management, farm-scale nutrient exports from irrigated dairying need not be any worse than from other land uses.

When comparing the overall environmental performance of different irrigation systems, the ability to recycle outwash is a major point of distinction between border-check and other forms of irrigation. At the bay scale, border-check irrigation outwash is almost always greater than from sprinkler irrigation of the same land. However, the volume of rainfall-induced runoff from irrigated areas depends on soil moisture and therefore is a function of both the annual rainfall pattern and, during the irrigation season, irrigation management. In border-check irrigation, soil is intermittently saturated. In spray irrigation, soil is maintained below field capacity, but well above the minimum moisture content used as a trigger before border-check irrigation occurs. It follows that where rain falls immediately after irrigation, runoff will be greater from border-check irrigation bays. However, where rain occurs at the end of an irrigation cycle (i.e. immediately before the next irrigation), runoff will be greater from spray irrigation areas (Nash *et al.*, 2003a).

At the farm scale, the impact of a grazing system on water quality in the surrounding catchment depends primarily on drainage from the farm rather than the bays and there is no reason to believe that any water application system will always generate less farm-scale runoff. It is the irrigation management system, including the reuse system, rather than the water application system that determines the volume of drainage and nutrient loads discharged from irrigated grazing farms. This is increasingly recognized by irrigation agencies who are upgrading infrastructure to support more flexible irrigation management.

Conclusions and the Future of Irrigated Dairying in Australasia

The major impacts of irrigated dairying on the environment are the result of inefficient resource utilization. Water is a limited resource and the more water lost from pasture systems as deep drainage and surface runoff, the less water is available for pasture production. Improved water-use efficiency could therefore yield both environmental and productivity improvements. For the purpose of this discussion, production water-use efficiency (PWUE) will be defined as the amount of milk produced per volume of water (i.e. milk fat + protein per megalitre of rainfall and irrigation). Economic water-use efficiency (EWUE) will be defined as the margin between income generated from pasture and variable costs of producing pasture per megalitre of water. Improving water-use efficiency has been the focus of considerable research (e.g. (Wood and Martin, 2000) with many studies investigating better management of existing infrastructure, often border-check irrigation, or conversion of farms from border-check to spray irrigation.

A survey of water-use efficiency on 170 randomly selected dairy farms in northern Victoria and southern New South Wales (Armstrong *et al.*, 2000) provides some important insights into the improvements possible using existing border-check irrigation infrastructure. High-PWUE farms produced the same amount of milk for approximately two-thirds the water, half the land and grazed a similar number of cows to low-PWUE farms. There was a strong ($r = 0.97$) correlation between PWUE and EWUE: income from pasture of the top 10% of farms had two-and-half times greater EWUE than the bottom 10%. Similar results were obtained in a benchmarking study of the Macalister Irrigation District in south-eastern Victoria (McAinch, 2003). Clearly there are both economic and environmental benefits to improved management (Armstrong *et al.*, 1998). Subsequent analyses of these and other data suggest that decreasing water availability by one-third (i.e. from >150% of the water for which delivery is contracted to 100–120%) had little impact on water-use efficiency (Linehan *et al.*, 2004). In Australia, a water right is defined as a formally established or legal authority to take water from a water body and to retain the benefits of its use. Rights may be attenuated in a number of ways and are referred to in different jurisdictions as licences, concessions, permits, access entitlements or allocations (Productivity Comission, 2003). The impact of the recent drought in these areas on water-use efficiency remains to be seen given the structural changes that may occur in the industry.

Changing infrastructure has been considered an important policy option for enhancing environmental performance in a number of areas and, in Australia in particular, significant resources have been committed to assisting farmers change from border-check to spray irrigation. The potential for sprinkler systems to decrease deep drainage runoff is widely recognized (Cockroft and Mason, 1987; Collis-George, 1991). Improved farm management, productivity, lifestyle and marketability of farms are perceived by farmers as the key benefits of converting border-check irrigation to centre-pivot or sprinkler systems in northern Victoria. Capital cost, operation and maintenance costs, farm layout and unreliability of systems were perceived as the key barriers to adopting sprinkler technology (Maskey *et al.*, 2006). A detailed economic analysis of conversion from border-check to centre-pivot irrigation in the same area suggests that if conversion resulted in 20% less water use and 10% more pasture growth, conversion was profitable. However, returns on investment depended heavily on the land that could be irrigated using centre-pivots, the actual changes in PWUE and EWUE and energy and milk prices (Wood *et al.*, 2007).

It is questionable whether irrigated dairying can survive in some of the areas in which it is currently located. Increasing pressure on the use of water resources and the effects irrigated dairying may be having on them may well result in the fundamental changes over and above those that have been discussed here. Moving from pasture-based grazing to cut-and-carry systems where forage crops are grown to feed animals elsewhere has the potential to increase PWUE (Greenwood *et al.*, 2007). The real question will be how the EWUE of those systems compare to pasture-based grazing and the value of the water used for alternative purposes in the context of other changes that may be occurring in the industry (Garcia and Fulkerson, 2007).

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