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Does complex hydrology require complex water quality policy?*

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Nonpoint-source water pollution is frequently considered intractable because it is hard to regulate large numbers of small sources and because the science associated with assessing the impact of each source is complex. New Zealand has demonstrated that it is possible to implement a simple cap-and-trade system to help reduce nitrogen leaching from many small farms and thereby protect water quality. This paper relates to the second challenge: are complex regulatory systems worthwhile when nitrogen delivery is complex? When nitrogen moves through groundwater to a lake, leaching from different farms reaches the lake at different times and the damage caused is temporally differentiated. Policy that regulates farmers according to the timing of their nitrogen delivery will be more complex than policy that does not. Whether the gain in efficiency justifies this additional complexity can be assessed through modelling. We use an integrated model to estimate the gains from complex nitrogen regulation that incorporates groundwater delivery times relative to simple nitrogen regulation that does not. We find that the gains from more complex regulation are small in the catchment we study and cannot justify the additional complexity required. A sensitivity analysis enables us to identify the types of catchments where complex regulation may be worthwhile.

Key words: groundwater, hydrology, nitrogen trading, nonpoint-source pollution, water quality.

1. Introduction

Nonpoint-source water pollution is a serious problem in many developed countries, including New Zealand, and in an increasing number of developing countries (Sutton *et al*. 2011; Parliamentary Commissioner for the Environment 2006; Millennium Ecosystem Assessment, 2005). It is frequently considered intractable because it is hard to regulate large numbers of small sources and because the science associated with assessing the impact of each source is complex. New Zealand has demonstrated that it is possible to

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implement a simple cap-and-trade system to help reduce nitrogen leaching from many small farms and thereby protect water quality (Young *et al.* 2010; Duhon *et al.* 2013). This paper relates to the second challenge: are complex regulatory systems worthwhile when nitrogen delivery is complex?

The ‘enabling myth’ of the United States Acid Rain program, one of the most recognised tradable permit markets, was that the environmental impact of emissions was not spatially differentiated. The simplicity this allowed may have contributed to the successful legislation and implementation of the program (Stavins 1998) but also led to its ultimate downfall (Schmalensee and Stavins 2012). Muller and Mendelsohn (2009) argue for environmental regulations to match the marginal damages of pollution across space to the marginal costs of abatement. They estimate large gains in the cost-effectiveness of regulation from spatially differentiated air quality policies in the United States. While obviously analytically correct, spatially differentiated policy is significantly more demanding of science and more complex to implement; whether the gain in efficiency justifies this additional complexity is an empirical question.

When nitrogen move through groundwater to a lake, leaching from different parts of the catchment reaches the lake at different times and the damage they cause (eutrophication, toxic algal blooms, declines in water quality) is not spatially differentiated, but is temporally differentiated (even though it comes from spatially heterogeneous sources). So, all damage from nitrogen leaching occurs in the same water body, but these damages differ across time. Just like the spatial case, policy that incorporates the temporal differences between farmers will be more cost-effective but also more complex.

A policy that incorporates the temporal differences between farmers will result in different timings of mitigation actions from a policy that does not. These changes in the timing of mitigation will be such that the environmental impact is unchanged, but the net present value of the cost of mitigation actions will be lower. In this way, more complex water quality policy will be more cost-effective.

Consider two farmers operating in a catchment and suppose we are concerned with nitrogen reaching the lake in 2050. Farmer 1 is a long way from the lake, and nitrogen leached from his farm takes 30 years to reach the lake. Farmer 2 is on the lake edge, and nitrogen leached from his farm reaches the lake immediately. In order to reduce the nitrogen that reaches the lake in 2050, Farmer 1 will have to reduce his leaching (mitigate) in 2020, while Farmer 2 will have to mitigate in 2050. Hence, delaying some mitigation by encouraging Farmer 1 to mitigate less (and to invest those resources efficiently elsewhere), and encouraging Farmer 2 to mitigate more at a later date, will improve the overall cost-effectiveness of regulation (Lock and Kerr 2008).

Let $f_i(x_{it})$ be the farming profit earned by farmer i given leaching x_{it} at time t $(f_i'(x_{it}) > 0, f_i''(x_{it}) < 0)$. If we ignore the temporal nature of damages, then the cost of mitigation is minimised if marginal costs of reducing damages are equal across farmers: $f_1'(x_{1t}) = f_2'(x_{2t})$. If we allow for the temporal nature of damages, then the total cost of mitigation is minimised if the marginal costs of reducing damages at the same time are equal across farmers: $f_1'(x_{1,2020}) = f_2'(x_{2,2050})/(1 + r)^{30}$.

Any catchment with groundwater lags will have a legacy load: nitrogen in the groundwater from historical leaching that is yet to be realised as lake loads. As it is very difficult to prevent nitrogen already in the groundwater from reaching the lake, regulators must account for legacy loads when setting environmental targets for all sources of nitrogen. This is frequently done by a gradual strengthening of the environmental target over time. In this paper, we focus on only those nitrogen loads that arise from ongoing agricultural nitrogen leaching and do not consider the impact of legacy loads. Anastasiadis *et al.* (2011) discuss the design of regulation that allows for legacy loads.

We build an integrated model of one catchment, Lake Rotorua in New Zealand, to estimate the efficiency gain from more complex regulation that incorporates the temporal differentiation caused by groundwater relative to simple regulation that does not. Rotorua is largely an agricultural catchment, with 40 per cent of the land used for dairy or sheep/beef farming, and agricultural emissions accounting for more than 70 per cent of the total nitrogen emissions (Rutherford *et al.* 2011).

Integrated modelling has been used by Bockstael *et al.* (1995) and Ward and Pulido-Velazquez (2008) to consider both water quantity and quality under different regulatory controls. Rosegrant *et al.* (2000) and Berger *et al.* (2007) have also used integrated modelling to assess the design and performance of trading schemes for water usage rights. The contribution of our integrated model is that it links regulation to protect water quality with farm profits, while accounting for the complex delivery of nitrogen to the lake.

The regulations we consider will take the form of nitrogen trading markets. The literature on the design of environmental markets generally is now extensive and sophisticated (Tietenberg 2006 provides an excellent synthesis of the literature); the literature on markets for water quality specifically is mostly more recent. Shortle and Horan (2008) provide a recent survey. Hung and Shaw (2005) consider a trading ratio system, which takes into account spatially differentiated marginal damages. Horan and Shortle (2011) discuss how the reality of water quality markets frequently differs from the theoretical context. In terms of actual experience, Selman *et al.* (2009) identified 57 trading systems focused on water quality worldwide, most of which were inactive. Of these, the majority are concerned with point sources, though some allow point sources to purchase offsets from nonpoint sources (as discussed by Prabodanie *et al.* 2009a).

One of the frequent concerns with markets for environmental rights is the potential for ‘hot spots’ to emerge where environmental impacts are concentrated (Tietenberg 1995). Although hot spots do not appear to have been significant in the Acid Rain program (Swift 2000), Schary and Fisher-Vanden (2004) argue that they are still a potential concern in water-related markets. Ning and Chang (2007) and Prabodanie *et al.* (2009b) discuss approaches to avoiding spatial hot spots, including trading ratios, zonal restrictions and a simulation-based market-clearing mechanism. McDonald and Kerr (2011) consider the trade-offs between environmental certainty and trading efficiency.

Our water body is not vulnerable to spatial hot spots. However, hot spots may also be temporal. To focus on the differences in cost-effectiveness between different designs of regulation, we eliminate the possibility of temporal hot spots, even in our simplest markets, by ensuring that nitrogen loads follow a specified path over time. An investigation of the effectiveness of regulation, including how nitrogen loads may differ with the design of regulation, has been conducted using NTRADER, a companion model (Cox *et al*. 2013).

We find that, for the Lake Rotorua catchment, the efficiency gains from more sophisticated regulation are small and cannot justify the additional complexity required. This result is driven by the proportion of nitrogen that travels via groundwater and how nitrogen leaching is clustered with respect to groundwater transportation times. Our sensitivity analysis suggests more complex regulation, to address temporal differences in nitrogen transport, will be worthwhile only in catchments where nearly all nitrogen travels via groundwater and where nitrogen leaching is dispersed over a wide range of groundwater transport times.

The paper is set out as follows: Section 2 describes our integrated model, NManager, including how complex hydrology is included in the model and two designs of nitrogen regulation. The economic performance of different regulations is evaluated in Section 3 together with the sensitivity of our results. Section 4 concludes the paper.

2. Integrated model: NManager

NManager is a partial equilibrium simulation model that captures the complex biophysical properties of the catchment and the behaviour of farmers under regulation. For a specified regulatory system, NManager determines the pattern of nitrogen leaching that will be chosen by profit maximising landowners. Furthermore, for a specified time path of environmental targets and given design of regulatory scheme, NManager determines the stringency of regulation that will ensure landowners' profit maximising behaviour exactly meets those targets. By requiring different designs of regulation to have identical environmental impact, we can directly compare the cost-effectiveness of different approaches. Full details of the model can be found in Anastasiadis *et al.* (2011). In this section, we detail only those aspects of the model that are critical to this paper.

First, we discuss the transport of nitrogen from the farms where it is leached to the lake. The hydrology of Lake Rotorua has been modelled using the Rotorua and Taupō Nutrient model (ROTAN), a geographical information system-based catchment hydrology and water quality model that has been extensively calibrated to historical data (Rutherford *et al*. 2008, 2009).

We include in NManager a simplified model of nitrogen flows based on results from ROTAN. This model determines nitrogen delivery: what percentage of farms' nitrogen leaching reach the lake each year.

Second, we specify the design of two nitrogen schemes: an export trading scheme (Section 2.2) that ignores the temporal impact of nitrogen leaching; and a two-pulse vintage trading scheme (Section 2.3) that differentiates between farmers according to the groundwater transport time for nitrogen lost from their property (Lock and Kerr 2008). We consider only trading-based regulation as this ensures marginal costs (of leaching or of damages) are equated across farmers, mimics other similarly cost-effective regulations and allows us to focus on the effects of hydrology. We compare the costs of achieving the same path of actual environmental loads under the different regulatory schemes.

Unlike export trading schemes, vintage trading schemes have never been implemented. We do not envisage that a vintage trading scheme would be implemented, but use them to mimic the performance of truly efficient regulation. If there are significant gains from incorporating the temporal impact of nitrogen leaching, then these gains might be captured using a range of approaches rather than vintage trading (such as supplementing an export trading scheme with targeted mitigation in critical zones).

NManager explicitly includes two land uses: dairy and sheep/beef farming. These are modelled using representative farms. The relationship between farm profit and nitrogen leaching is determined according to work by Smeaton *et al.* (2011). Farms of each type are homogeneous and differ only in the speed with which their nitrogen leaching reaches the lake. Mitigation of nitrogen leaching is costly and may take place 'on-farm' or via land-use change.

NManager explicitly includes two agricultural land uses: dairy and sheep/beef farming. Farms of each type are homogeneous and differ only in the speed with which their nitrogen leaching reaches the lake. The template for each of these farm types is drawn from the monitor farm reports (Ministry of Agriculture and Forestry 2010), which draw on unit record farm survey data to describe the performance of representative dairy and sheep/beef farms.

Smeaton *et al.* (2011) use the Farmax (Bryant *et al.* 2010) model to simulate the representative farms under a range of different management practices (including changes in stock numbers, stock type, fertiliser application and land use) and use the Overseer model (AgResearch 2009) to estimate the nitrogen loss under each choice of management practices. Using these two models together gives realistic combinations of profit and nitrogen exports, which we fit with quadratic curves.

2.1. Complex hydrology

It is important to distinguish between nitrogen leaching, the quantity of nitrogen lost from the land (which farmers can control on average), and nitrogen loads, the quantity of nitrogen reaching the lake (which cause damage to the environment). In the context of Lake Rotorua, the translation from leaching to loads is neither complete nor immediate due to attenuation and groundwater lags (Morgenstern *et al.* 2005; Kerr and Rutherford 2008). We only consider groundwater lags in NManager because attenuation has been found to be minimal in most of the Lake Rotorua catchment, with the exception of the Puarenga Stream (Rutherford *et al.* 2009, 2011). For catchments where attenuation is nonzero, it is equivalent to consider leaching net of attenuation.

Nitrogen leaching travels to the lake via two paths: quick-flow (surface water run-off and shallow subsurface flow) and (deep) groundwater. Quick-flow travels to the lake quickly, but groundwater flows are subject to lags that significantly slow the delivery of nitrogen to the lake. The nature of these lags depends on the presence of underground aquifers, the distance of leaching from the lake and the geology of the soil and underlying rock. The total load to the lake at time t can be expressed as the sum of the quick-flow and groundwater loads from all farms.

Nitrogen loads delivered via quick-flow arrive in the lake in the same year they are leached. The load from farm i, delivered via quick-flow at time t, can be expressed as follows:

$$\text{Load}^{i}_{QF}(t) = (1-\rho)x_{it} \tag{1}$$

where ρ is the proportion of nitrogen leaching delivered to the lake via groundwater, and x_{it} is the quantity of nitrogen leached from parcel i at time t. ROTAN suggests that 47 per cent of nitrogen reaches the lake via quick-flow and 53 per cent via groundwater (Rutherford *et al.* 2011). So ρ equals 0.53 for Lake Rotorua, and this value is assumed to be constant across the catchment.

Nitrogen loads delivered via groundwater arrive in the lake over multiple years. The nitrogen load at time t, from farm i, delivered via groundwater can be expressed as follows:

$$\text{Load}^{i}_{GW}(t) = \rho\int_{\tau=0}^{\tau=t} x_{i,t-\tau}h^{i}(\tau) \tag{2}$$

where $h^{i}(\tau)$ is a unit response function (URF). URFs give the nitrogen load from a single unit of nitrogen entering the groundwater as a function of time since it was leached, τ. These are approximated in NManager using the URF for a single, well-mixed aquifer with a 3-year lag:

$$h^{i}(\tau) = \begin{cases} 0 & \text{if}\tau = 0,1,2 \\ 0.58h^{i}(4) & \text{if}\tau = 3 \\ \frac{e^{-(\tau-4)/MRT_i} - e^{-(\tau-3)/MRT_i}}{MRT_i\sum_{\tau=3}^{\infty}h^{i}(\tau)} & \text{if}\tau \geq 4 \end{cases} \tag{3}$$

where MRT_i is the mean residence time for nitrogen from farm i, the mean time that nitrogen spends in the groundwater. *MRT*s for land in the Rotorua catchment have been estimated by Morgenstern *et al.* (2005).

2.2. Export trading

Under an export trading scheme, the regulator provides a supply of annual allowances. Each allowance entitles the owner to leach one unit of nitrogen from their property. Farmers are free to trade allowances during the year. At the end of each year, farmers must surrender allowances to cover the nitrogen leaching from their property for that year. Allowances cannot be banked; any unused allowances are lost. By controlling the supply of allowances, a regulator can manage the amount of nitrogen that reaches the lake. The Lake Taupō scheme has this form (Environment Waikato 2003; Young *et al.* 2010).

Suppose there are M farmers in the catchment ($i = 1, \ldots, M$). Under an export trading scheme, profit for each farmer i at time t depends on their quantity of nitrogen leaching x_{it} and the price of allowances p_t. We assume that farmers are profit maximising and that each farmer uses the optimal inputs for their farm. It follows that farmer i will choose x_{it}*, the quantity of nitrogen leaching that maximises their profit net of the value of allowances surrendered, as follows:

$$x_{it}^* = \mathbf{argmax}[f_i(x_{it}) - x_{it}p_t^*] \tag{4}$$

where p_t^* is the market-clearing price or the minimum value of nitrogen allowances (equal to the shadow value of nitrogen leaching) that ensures as follows:

$$\sum_i x_{it}^* \leq S_t \tag{5}$$

and S_t is the total supply of allowances for year t.

For simplicity, because our focus is on scientific complexity, we assume that economic conditions are certain and stable and that the value of nitrogen leaching in each year is independent of farmers' choices in all other years. We also assume that adjustment for all farmers is instant and costless. These assumptions are extremely strong, but they apply to all our scenarios, and as our focus is on the difference between scenarios, our results are likely to be robust.

2.3. Vintage trading

In a vintage trading scheme, the regulator provides a supply of allowances for each vintage year, where the vintage year corresponds to the year when nitrogen will arrive in the lake. Allowances therefore represent rights to contribute to lake loads in a particular year which equate to conditional rights to leach nitrogen from farms depending on groundwater lag time. Under regulation, farmers must surrender allowances each year to cover the lake loads that will be caused some time in the future by the nitrogen lost from their property that year.

Although groundwater leaching is a continuous process, some approximation is required to implement a vintage trading scheme. Regulation must provide a convention that specifies for farmers the vintage allowances they must surrender in each year. In this paper, we use a convention that simplifies nitrogen delivery into two pulses, following the design of a two-pulse vintage scheme given by Lock and Kerr (2008). We investigated four- and nine-pulse vintage trading schemes, but these did not result in outcomes that were significantly different from the two-pulse scheme. Hence, we are confident that the two-pulse scheme provides a good approximation to the true delivery of nitrogen.

The two-pulse vintage scheme distinguishes between nitrogen that travels via quick-flow and nitrogen that travels via groundwater. Under the two-pulse scheme each farmer is allocated a lag time that approximates the mean travel time of nitrogen from their land through the groundwater to the lake.

Each year, farmers match a fixed percentage of their leaching with allowances from the vintage that corresponds to the current year (to cover nitrogen that travels via quick-flow) and the remainder with allowances from the vintage that corresponds to the current year plus their lag time (to cover nitrogen that travels through the groundwater). For example, suppose a farmer with a lag time of 30 years leaches 100 kg of nitrogen in 2020. In the Rotorua catchment, 47 per cent of nitrogen travels via quick-flow and 53 per cent travels via groundwater. Hence, under the two-pulse trading scheme, he must, in 2020, surrender 47 kg of 2020 vintage allowances and 53 kg of 2050 vintage allowances.

Let v_i be the lag time specified by the vintage scheme for farmer *i*, and p_t the price of allowances of vintage *t* at time *t*. Because allowances are an asset, by the Hotelling rule (Hotelling 1931), their value should be expected to rise at the real market rate of return. Hence, the price of allowances of vintage $t + v$ at time *t* is given by: $p_{t+v}/(1 + r)^v$. Farmers' decisions each year depend on the price of the vintage allowances in that year. In year *t,* farmers must surrender x_{it} allowances of vintages *t* and $t + v_i$. Each profit-seeking farmer *i* will choose x^*_{it}, as follows:

$$x^*_{it} = \mathbf{argmax}\left[f_i(x_{it}) - x_{it}\left((1-\rho)p_t + \rho\frac{p_t + v_i}{(1+r)^{v_i}}\right)\right] \tag{6}$$

where *r* is the discount rate or the real, risk adjusted, market rate of return (these are assumed to be equal for simplicity), and p_t now ensures that:

$$\sum_i (1-\rho)x^*_{i,t} + \rho x^*_{i,t-v_i} \leq S_t \forall t \tag{7}$$

Unlike an export trading scheme, the market-clearing price in each vintage market will depend not only on the supply and demand in that market but also indirectly on the demand and supply in all other vintage markets. We can find a solution to this model if we assume price convergence: for all periods

t beyond some time T, the price of all allowances in their respective vintage years is constant and equal, $p_t = p_T$. In our model with a static world, this assumption is reasonable so long as the number of allowances is constant many periods before time T.

3. The performance of different regulatory schemes

We use NManager to evaluate and compare the economic performance of the export and vintage trading schemes. The gains in cost-effectiveness from the vintage trading scheme over the export trading scheme are initially considered in the context of Lake Rotorua. Following this, we test the sensitivity of our results to different catchment properties. Throughout our analysis, we avoid the possibility of temporal hot spots and ensure comparability of our results by requiring that nitrogen loads follow a specified path over time. We hold all exogenous factors (e.g. weather, climate, commodity prices) constant across years.

3.1. Rotorua specific results

Vintage trading aims to improve the cost-effectiveness of regulation by encouraging mitigation to occur in a more temporally cost-effective manner. Figure 1 gives the long-run effective cost of leaching (the cost to a farmer of acquiring allowances to cover one more kg of nitrogen leaching, accounting for lag times and different vintages under a vintage trading scheme) and the percentage of leaching mitigated, by groundwater lag time, under each regulatory scheme. Under an export trading scheme, mitigation is evenly distributed across the catchment; with any differences driven only by the initial land-use mix. The two-pulse vintage trading scheme increases the effective cost of nitrogen leaching for farmers with short lag times and decreases the effective cost of nitrogen leaching for farmers with longer lag times (this is driven by how the last term in Eqn 6 varies with v_i). This results

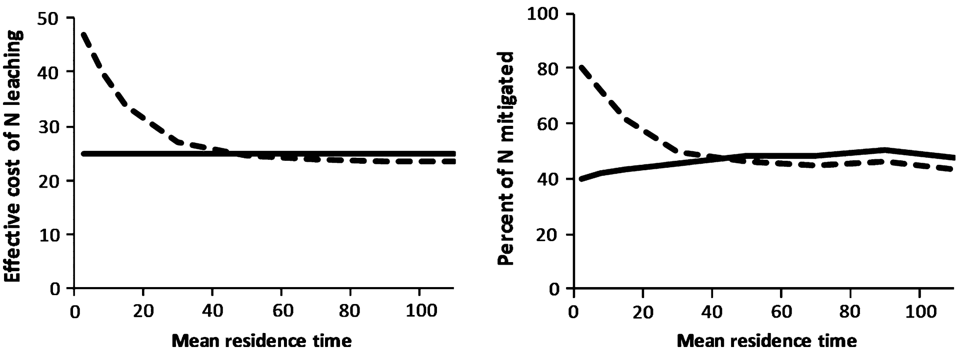

Figure 1 Long run cost and mitigation by lag time.

in an increase in mitigation for those farmers with shorter lag times and a decrease in mitigation for those farmers with longer lag times.

Table 1 gives the net present value of the cost of mitigation with a seven per cent discount rate under each trading scheme for a 50 per cent reduction in loads from ongoing agricultural nitrogen leaching compared to business-as-usual. This cost is the difference between profit under regulation and profit assuming business-as-usual.

The two-pulse vintage scheme is more cost-effective than the export trading scheme, but only by 0.6 per cent. This small gain in cost-effectiveness could be because accounting for the temporal nature of damages has very little effect in the Lake Rotorua catchment or could be because the two-pulse regulation poorly approximates the complex hydrology of the catchment. We investigated vintage schemes with four and nine pulses, as well as different pulse timings for the two-pulse scheme (as a linear function of MRT). This produced little to no improvement (<0.2 per cent) on the results of the two-pulse scheme reported above. Hence, we are confident that the two-pulse scheme provides a very good approximation to the complex hydrology of the catchment and that the small gain in cost-effectiveness is because accounting for the temporal nature of damages has very little effect in the Lake Rotorua catchment.

3.2. Generalised results

The minimal gains in cost-effectiveness between the export trading and the two-pulse vintage trading schemes for Lake Rotorua may be due to the particular nature of the catchment and our modelling assumptions. We now consider how the cost-effectiveness of more complex regulation varies with different factors. The factors we consider are the initial distribution of leaching, the load reduction target, the percentage of nitrogen that flows through the groundwater and the discount rate (different conventions for assigning farmers lag times are considered by Cox *et al.* 2013). This enables us to identify the types of catchments that could benefit from regulation that explicitly incorporates the temporal damages caused by nitrogen leaching.

To account for potential interaction between factors, we varied these factors simultaneously in pairs. However, as we did not observe interactions between any of these factors, we limit our discussion to each factor individually.

The gain from more complex regulation is calculated as the difference between the costs of mitigation from the export and two-pulse vintage trading

Table 1 Costs of different trading schemes, Lake Rotorua catchment

Trading Scheme	Export trading	Two-pulse vintage
NPV ($ millions)	55.2	54.9

schemes. This cost is either expressed in millions of dollars or as a percentage of the cost under the export trading scheme.

The gains in cost-effectiveness from the two-pulse vintage trading scheme arise from delaying mitigation on land with long lag times and offsetting it with more mitigation on land with short lag times. It follows that the small gain in cost-effectiveness estimated for the Lake Rotorua catchment may be due to the small amount of land with short lag times, as this limits the amount of mitigation that can be delayed. We therefore consider three alternative distributions of nitrogen leaching: *Front*, leaching is concentrated close to the lake and has short lag times; *Uniform*, leaching is spread evenly across all lag times; and *Edge*, leaching is concentrated with very short lag times and very long lag times. Figure 2 gives these four distributions. Other than for *Rotorua*, these are constructed as hypothetical catchments where the distribution of land uses results in the required distribution of initial leaching.

From Figures 3 and 5, we observe that the distributions where nitrogen leaching is clustered with similar groundwater transportation times (such as *Rotorua* and *Front*) have smaller gains, while the distributions with less clustering (such as *Uniform* and *Edge*) have larger gains. This suggests that catchments with low clustering of transport times will have greater gains from regulation that accounts for the temporal nature of damages.

We expect the stringency of regulation to affect the gains in cost-effectiveness. Different targets will affect the flexibility with which nitrogen leaching can be rearranged between short and long lag times and hence the cost-effectiveness of more complex regulation. Regulation that requires 0 or 100 per cent of nitrogen to be mitigated offers no flexibility, and in these cases, vintage trading should not increase cost-effectiveness.

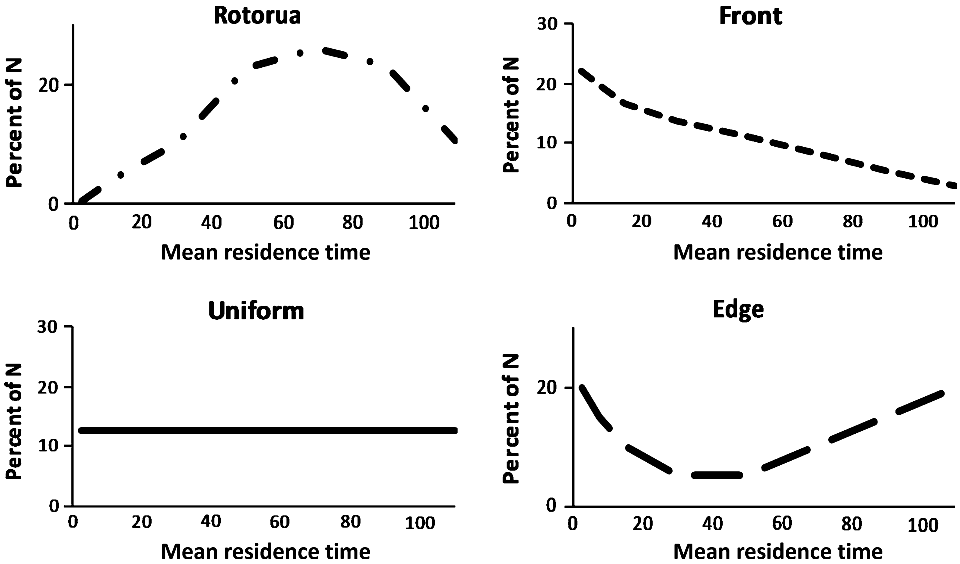

Figure 2 Alternative distributions of initial nitrogen leaching.

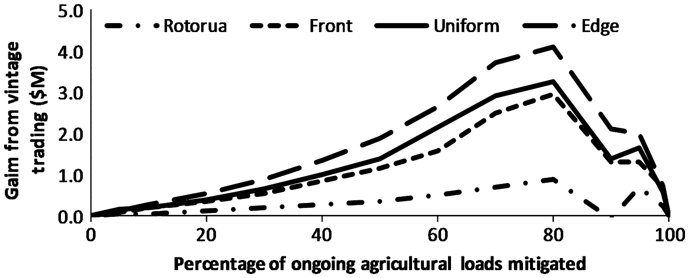

Figure 3 Gain in cost effectiveness from more complex regulation for different mitigation targets.

From Figure 3, we observe that the gain from more complex regulation is initially increasing with the stringency of the environmental target, as a more stringent target provides greater opportunity to delay mitigation on land with long lag times and increase mitigation on land with short lag times. However, once more than 80 per cent of nitrogen is mitigated under the two-pulse scheme, further mitigation on land with the shortest lag times is no longer possible. This prevents the further delay of mitigation and decreases the gains from more complex regulation (the irregularity at 90 per cent in Figure 2 is due to differences in how the land uses – dairy and sheep/beef – in NManager respond to regulation, when the stringency of regulation nears 90 per cent all land that was classified as dairy becomes fully mitigated).

We expect the discount rate to affect the gains in cost-effectiveness. From section 2.3, we can see that the price of nitrogen leaching faced by farmers under a vintage trading scheme depends on the discount rate. A higher discount rate increases the divergence between the prices faced by farmers. We might expect that this would lead to greater gains from more complex regulation.

The gain from more complex regulation is initially increasing with the discount rate, as a higher discount rate provides greater gains from delaying mitigation. However, an increasing discount rate also decreases the cost of future allowance vintages, making mitigation decisions more dependent on the cost of the current vintage used to cover quick-flow (so the vintage trading scheme becomes similar to the export trading scheme). This effect dominates once the discount rate exceeds eight per cent, and hence, the gain from more complex regulation is small for high discount rates. Figure 4 suggests that discount rates around seven per cent produce the greatest gains from more complex regulation.

We expect the percentage of nitrogen travelling via quick-flow to affect the gains in cost-effectiveness. When the majority of nitrogen travels via quick-flow, the export and two-pulse vintage trading schemes will be almost identical and there should be minimal gains from more complex regulation. But, when the majority of nitrogen travels via groundwater, the export and two-pulse vintage trading schemes will be significantly different and there should be larger gains from more complex regulation.

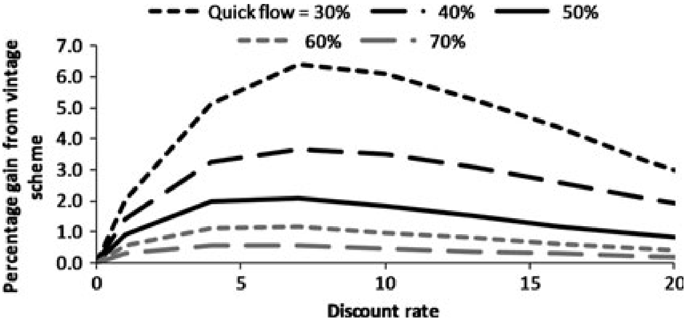

Figure 4 Gain in cost effectiveness from more complex regulation for different discount rates.

Figure 5 gives the percentage gain in cost-effectiveness of the two-pulse vintage scheme over the export trading scheme as the percentage of nitrogen that travels via quick-flow ($1 - \rho$) and the distribution of leaching differs. The discount rate (r) is seven per cent, and loads from ongoing agricultural nitrogen leaching have been mitigated by 50 per cent. We observe greater gains from more complex regulation as the percentage of nitrogen that travels via quick-flow decreases (and the corresponding percentage that travels via ground water, ρ, increases).

Considering all three figures, we observe that the gains from complex regulation are largest where a low percentage of nitrogen travels via quick-flow, where farms are not clustered with respect to lag times and where discount rates are moderate. Our results suggest that catchments that lack even one of these characteristics are likely to have much lower gains from regulation that accounts for the temporal nature of environmental damages.

We have not tested the sensitivity of our results to variations in groundwater lag times (as represented by the *MRT*s) or variations in the relationship between farms' profits and farms' nitrogen leaching. However, with respect to lag times, we anticipate that the *Front* distribution of leaching gives a good approximation to catchments with much shorter lag times, as almost 75 per cent of land under this distribution has *MRT* of at most 30 years.

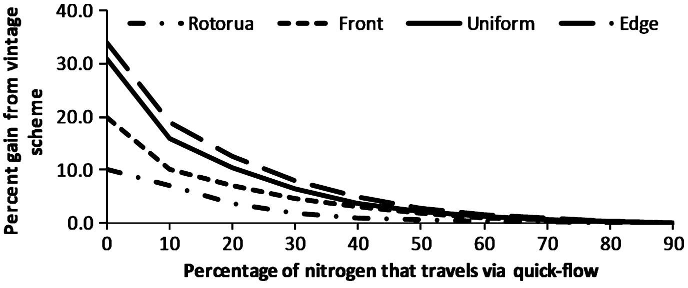

Figure 5 Gain in cost effectiveness from more complex regulation for different percentages of nitrogen travelling via quick-flow.

4. Conclusions

We have assessed the gains in cost-effectiveness from complex regulation that accounts for the temporal nature of environmental damages, due to complex hydrology, in the Lake Rotorua catchment. We find very small gains in cost-effectiveness from regulation that differentiates between farmers according to the timing of their nitrogen delivery. Our results suggest that in the case of Lake Rotorua, the gains from more complex regulation are small and cannot justify the extra complexity required.

We identify more generally the catchment characteristics that make designing regulation to reflect complex hydrology worthwhile. Our sensitivity analysis suggests complex regulation is more cost-effective where the vast majority of the nitrogen travels via slow groundwater and where leaching is not clustered with respect to lag times. Discount rates and the stringency of regulation have more modest effects. The greatest gains in cost-effectiveness are reported for discount rates between five and nine per cent and for regulation that targets 60 to 80 per cent reductions in loads from ongoing agricultural nitrogen leaching, with the magnitude of any gains decreasing towards zero for values outside these ranges.

Our results enable us to quickly identify whether it is important to incorporate the temporal nature of nitrogen leaching into regulatory design in any given catchment. Regulation that accounts for complex hydrology need not take the form of vintage trading regulation. In this paper, we have used vintage trading to mimic the performance of cost-effective regulation. In catchments where there are significant gains from incorporating the temporal nature of damages, regulators might use other forms of intervention, such as targeted land retirement.

Our analysis has assumed that economic conditions are certain and stable. If the costs of reducing nitrogen leaching are decreasing (increasing) over time, then there are greater (smaller) gains from delaying mitigation. As a result, complex regulation that accounts for the temporal nature of damages will be more (less) cost-effective than we have estimated under static conditions.

Throughout this study, we have assumed that mitigation reduces nitrogen leaching before it leaves farms and hence loads from both quick-flow and ground water nitrogen decrease proportionally. If farmers could mitigate in a way that decreased nitrogen loads from quick-flow and groundwater separately (or that had a more than proportional impact on loads from one delivery path), then the gains from complex regulation may differ from those reported here.

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