BEFORE THE HEARINGS PANEL

IN THE MATTER of hearings on submissions concerning the Proposed One Plan notified by the Manawatu-Wanganui Regional Council

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SECTION 42A REPORT OF DR BRENT EUAN CLOTHIER
ON BEHALF OF HORIZONS REGIONAL COUNCIL

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1. INTRODUCTION

Qualifications and experience

1. My name is Brent Euan Clothier.

2. I hold a B.Sc (Hons, First Class) [1974] from the University of Canterbury, a Ph.D. [1977] from Massey University, and a D.Sc. [2002] from Massey University. I have been elected a Fellow of the Soil Science Society of America [1992], a Fellow of the Royal Society of New Zealand [1994], a Fellow of the American Agronomy Society [1995], a Fellow of the New Zealand Soil Science Society [1995], and a Fellow of the American Geophysical Union [2005]. I received the Don & Betty Kirkham Soil Physics medal of the Soil Science Society of America in 2000. Between 2004 and 2009 I served on the Council of the Academy of Fellows of the Royal Society of New Zealand, and for 2008-09 I was Chair of the Academy. During 2008-09, I was Vice President (Biological & Life Sciences) of the Council of the Royal Society of New Zealand. I am currently President of the New Zealand Soil Science Society.

3. I am Science Leader of the Sustainable Land Use team of the Crown Research Institute (CRI) of Plant & Food Research and I am based in Palmerston North. My responsibilities in that capacity are to provide leadership and science provision within the Sustainable Land Use team and Plant & Food Research in the areas of soil science, nutrient management, irrigation management, natural capital valuation, environmental measurement and modelling.

4. I began work with DSIR in 1976, and transferred to HortResearch upon the formation of CRIs in 1992. HortResearch has just merged with Crop & Food Research to become Plant & Food Research. I have published more than 190 scientific papers on soil science, measurement and modelling of water movement, chemical flows in the rootzone of plants, ground and surface-water protection, and the management of soils, nutrients, pesticides, and irrigation. I am Joint Editor-in-Chief of the international scientific journal of Agricultural Water Management. I have carried out collaborative international research in Australia, New Caledonia, Tonga, La Reunion, Japan, Spain, France, Brazil, USA and Canada. I am Science Leader of New Zealand's multi-CRI research programme of SLURI (Sustainable Land Use Research Initiative).

5. I led the SLURI research team who were contracted to Horizons Regional Council to develop guidelines for best management practices to limit non-point source pollution by nutrients from farms.

Purpose and scope of evidence

6. I will describe research carried out by our team of (the then) HortResearch for Horizons in relation to water allocation for agricultural purposes (Policy 6-12a – Reasonable and justifiable need for water) using our model SPASMO (Soil Plant Atmosphere System Model), which we modified to handle specifically the allocation of water for irrigation. We called this version of the model SPASMO-IR and I will describe how it works and how it has been verified and undergone peer review.

7. I will discuss how we calculated the appropriate daily rate limits for irrigation application and the appropriate annual allocation values, depending on soil and plant specifics (6-12 (a) i). I will discuss how irrigation efficiency can be improved (6-12 (a) ii), and relate that to benefits in minimising water use by referencing soil moisture measurements (6-12 (a) iii) and limiting leaching losses while maintaining production. I will briefly discuss the effects of irrigating with saline water, as might happen in the near-coastal sand country.

8. In relation to Policies 13-2 and 13-3 I will first provide a summary of the fundamentals of the nitrogen cycle in soils under discharges of domestic wastewater (13-3) and productive land uses (13-2), and outline the modelling tools that are available to predict nitrogen dynamics and leaching losses from the soils of the rootzone, and to predict their potential impact on receiving waters.

9. I will describe initial modelling work we carried out for the Palmerston North City Council in relation to the land-based application of municipal wastewater. I will also discuss briefly the modelling results we provided at a hearing in relation to both land and river-based discharge of wastewater from the proposed Masterton wastewater treatment plant. I then go into detail of the results.

10. I will describe the results from the SLURI research project carried out under contract to Horizons, which established the link between land management practices on-farm, and their impact on river water quality in the Upper Manawatu Water Management Zones. I will show how this farm-to-river linkage led into a natural-capital approach based on Land Use Capability (LUC) classes and resulted in Table 13.2.

11. Specifically, in my evidence, I will:
    - i. Provide a summary of my evidence.
    - ii. Describe the development of the mechanistic model SPASMO (Soil Plant Atmosphere System Model) and outline how it has been verified and how it has

undergone peer review and publication in international journals and book chapters (Section 3; Appendix A).

iii. Show how SPASMO is fit-for-the-purpose of determining irrigation allocation policy, and describe how it has been used by other regional and district councils. I will outline how this was used to develop for Horizons irrigation resource consent values that meet a reasonable use test for the reasonable and justifiable taking of water for irrigation (Policy 6-12a) (Section 4). I will also comment on the need to link irrigation practices to information on the prevailing conditions of the soil's moisture content, and I will assess the possible impacts of irrigating with groundwater that is high in either boron or sodium.

iv. In relation to Policy 13-2 (Consent decision making for discharges to land) and Rule 13-2 (Agricultural Activities), I will begin by providing an overview of the nitrogen cycle for both plant-based and grazing-animal systems (13-2) (Section 5). I will describe the deposition of nitrogen onto land from rain and the atmosphere (Section 6) and describe the uptake of nitrogen from soil by plants (Section 7).

v. I will briefly discuss, from international and New Zealand perspectives, the various policy initiatives that have been developed to limit non-point source pollution of water bodies by nutrient loss from farms (Section 8).

vi. I consider OVERSEER® is the most appropriate tool for policy development and implementation for the FARM Strategy (Rule 13-1), and verify its outputs by comparison with the results from the mechanistic SPASMO model (Section 9).

vii. I will outline how nitrogen is attenuated between the losses from farming enterprises and receiving water bodies, establish the link between on-farm practices and water quality in the Upper Manawatu Water Management Zones, and show how this led into Table 13.2 and Rule 13-1 (Section 10). Dr Mackay will in his evidence describe how this then led to the linking of a nitrogen loss right to a Land Use Capability (LUC) class. I endorse his approach.

viii. In relation to Policy 13-3 (Management of discharges of domestic wastewater) I will outline the fate and transport in the soil of nutrient (nitrogen and phosphorus) and contaminants (bacteria) in domestic and municipal wastewaters. I will describe briefly the use of SPASMO for predicting the impacts of domestic wastewater from both Palmerston North's and Masterton's wastewater treatment plants, and I will describe the use of SPASMO to predict the impact of lifestyle block development

ix. on the underlying groundwater (Section 11).

x. I will describe in detail the application of SPASMO for a proposed and intensive lifestyle block development, using septic tanks, behind Levin. I discuss how this can enable Horizons to make decisions on resource consent applications to discharge domestic wastewater, to ensure that the site is suitable and that the discharge does not result in actual or potential contamination of water bodies (Policy 13-3) (Section 12).

xi. I will describe modelling using a meta-version of SPASMO, and its validation, to determine the leaching losses under commercial vegetable production in the Horowhenua, and discuss how the impact of various nutrient management practices can be assessed for minimising the impact on groundwater and water in surface drains (Section 13).

Expert witness code of conduct

12. I have been provided with a copy of the Code of Conduct for Expert Witnesses contained in the Environment Court's Consolidated Practice Note 2006 [2006] NZRMA 357. I have read and agree to comply with that Code. This evidence is within my area of expertise, except where I state that I am relying upon the specified evidence of another person. I have not omitted to consider material facts known to me that might alter or detract from the opinions that I express.

2. SUMMARY OF EVIDENCE

13. SPASMO (Soil Plant Atmosphere System Model) of Plant & Food Research is a mechanistic model that considers the inputs (rainfall and irrigation) and losses (plant uptake, evaporation, run-off and drainage) of water from the soil profile. SPASMO can into account a wide range of farm and orchard practices, because it is a detailed mechanistic model of the soil-plant-atmosphere system, which operates at a daily time-scale using long-term weather records. SPASMO has been validated across a number of regions and for a range of farm types and orchard systems.

14. I describe our application of SPASMO to determine the reasonable and justifiable use of water, by considering the specific factors that determine the need for irrigation, and by taking into account system efficiency and linking application to soil moisture measurements. We recommended that the Horizons adopt a conservative approach to allocation by providing that the irrigation consent meet requirements in all but the one-in-ten driest of years (ie. a probability of exceedance of 10%). This provides farmers with a level of surety for investment in irrigation and that the allocation is justifiable, to account for system inefficiencies. To complement the conservative nature of the probability of exceedance criterion, we suggested to Horizons that an addition 20% be added to the irrigation allocation. So, in summary, we recommended to Horizons that the SPASMO

prediction be used to allocate irrigation for any scenario to meet all but the one-in-ten driest of years, and that 20% be added to that value to account for system inefficiencies.

15. I discuss the nitrogen balance of farms. Nitrogen is an essential plant nutrient and the presence of nitrogen in soil and in water encourages plant growth. The nitrogen cycle in the soil is complex, yet its fundamentals are well understood. In the humid climate of Horizons' region, nitrogen leaches from the rootzone of the soils of farms, and this is dependent on farm management, soil type, rainfall, and fertiliser use.

16. I briefly discuss other regulatory and non-regulatory approaches to reduce non-point source pollution by nutrients from farms. Most approaches have involved capping inputs or charging levies on excess nutrient use. The natural capital approach, based on Land Use Capability classes and as adopted by Horizons, is innovative. The World Resources Institute has called for the use of such an ecosystems services approach to enable "… a way for policymakers to identify how a decision depends on nature's flow and how a decision will in turn affect the flow. It increases our ability to understand and make trade-offs across ecosystem services & so win more and lose less". Horizons' approach through the Proposed One Plan does this; I recommend it.

17. Nitrogen is attenuated between the farmlands and receiving water bodies. A range of empirical evidence suggests that not all of the nitrogen leaching from the soil finds its way into surface water bodies, although this is dependent on conditions in the soil, the configuration of farms plus farming practices, as well as the transit paths and lags in the regional hydrology.

18. Many models are available to predict the functioning of the nitrogen cycle and the amount of nitrogen leaching from the rootzone of farms. Many of these models are detailed mechanistic schemes and therefore not easily parameterised for general use at the farm scale for management purposes, or at the regional scale for policy use. OVERSEER is the most appropriate model for use in the One Plan. Dr Ledgard presents more details on OVERSEER and its use to predict farm-scale losses on nutrients; I agree with his findings.

19. Between the farm and surface water bodies there is attenuation of nitrogen through natural processes. We have found that for the upper Manawatu River upstream of Hopelands, this is 50%. Half of the nitrogen lost from the farm does not end up in the river. This provides a key farm-to-river link in Dr Mackay's natural capital approach to assigning nutrient losses via Land Use Capability (LUC) classes; I recommend Dr Mackay's approach, which is included in FARMS.

20. I discuss discharges of domestic wastewater from septic tanks (Section 11) and outline our application of SPASMO to a proposed lifestyle block development near Levin (Section 12). This enabled an assessment of the minimum size of a lifestyle block to meet a given water quality standard in the overall leachate load from the property. If the criterion for leachate load were a loss value of 22 kg-N/ha/yr then the only scenario to meet this limit would be a two-bedroom dwelling with a modern septic tank on a 5,000 m^2 block.

21. We have developed a meta-model of SPASMO to enable prediction of the impact of nutrient management in commercial vegetable production where there are multiple and different crops and practices within any given year (Section 13). We conclude that the SPASMO meta-model could be used as a tool to work with vegetable growers and croppers, in conjunction with Horizons, to explore options for managing production and to assess the trade-offs between fertiliser practices, irrigation schedules, crop yield and nutrient leaching to shallow groundwaters and surface drains.

3. THE SOIL PLANT ATMOSPHERE SYSTEM MODEL (SPASMO)

22. The research programme by the (now) Sustainable Land Use team of the (now) Plant & Food Research called Water: Requirements and constraints for sustainable systems, began in 1990 and was funded by the Foundation for Research Science and Technology (FRST), albeit with some name changes, through until 2003. In that programme, under my leadership, code was written by Dr Steve Green for the SPASMO computer model which considers water, solute (eg. nitrogen and phosphorus), and microbial (eg. viruses and bacteria) transport through a 1-dimensional soil profile.

23. The soil water balance is calculated in SPASMO by considering the inputs (rainfall and irrigation) and losses (plant uptake, evaporation, run-off and drainage) of water from the soil profile (Figure 3.1). The model includes components to predict the carbon, nitrogen and phosphorus budget of the soil. These components allow for a calculation of plant growth and uptake of both N and P, various exchange and transformation processes that occur in the soil and aerial environment, recycling of nutrients and organic material to the soil biomass, and the addition of surface-applied fertiliser and/or effluent to the land. The filtering capacity of the soil with regard to micro-organisms is modelled using an attachment-detachment model with inactivation (ie. die-off) of microbes.

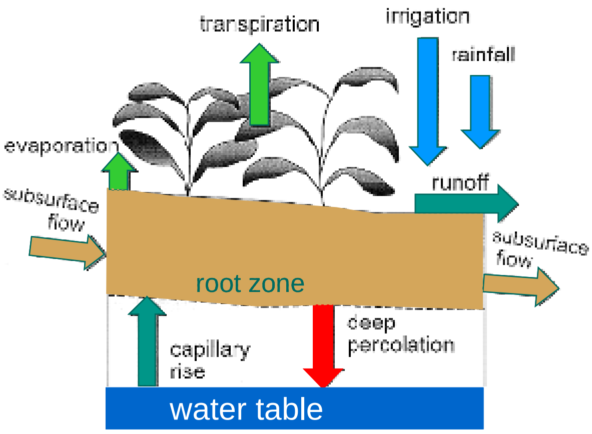


Figure 3.1 The water balance of the system modelled by SPASMO

24. SPASMO uses a daily time-step, and the model is run using long-term weather records of 20-30 years so that natural variability in the weather is accounted for. The soils information can either be measured, or taken from the New Zealand Soils Database. SPASMO can take into account a wide range of farm and orchard practices, because it is a detailed mechanistic model of the soil-plant-atmosphere system which operates at a daily time-scale using long-term weather records.

25. SPASMO has been validated across a number of regions and for a range of farm types and orchard systems. Figure 3.2 shows the predictions of the soil water content in the top 30 cm of soil of a dairy farm near Tikokino, relative to two different systems used to measure the soil's water content – Time Domain Reflectometry (TDR) and the commercial Aquaflex system. This work was carried out over two years under contract to the Hawke's Bay Regional Council (see Green *et al*., 2004b in Appendix B).

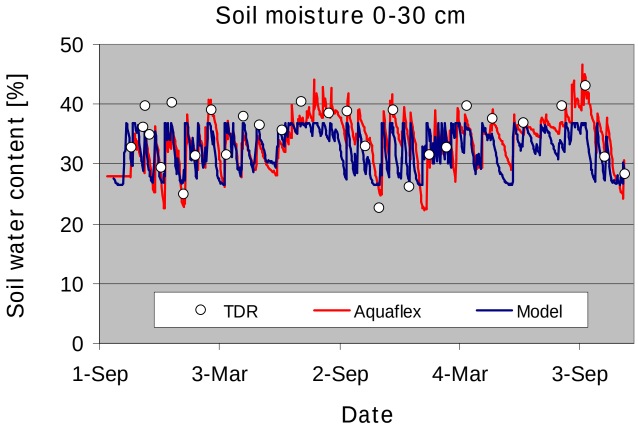


Figure 3.2 A comparison of SPASMO's predictions of the soil water content in the top 30 cm of a dairy farm near Tikokino, with measurements by TDR and Aquaflex

26. An even more critical test of SPASMO is to compare its predictions of the drainage (DR) of water from the base of the rootzone of the pasture with that measured by fluxmeters installed at the dairy farm near Tikokino (Figure 3.3).

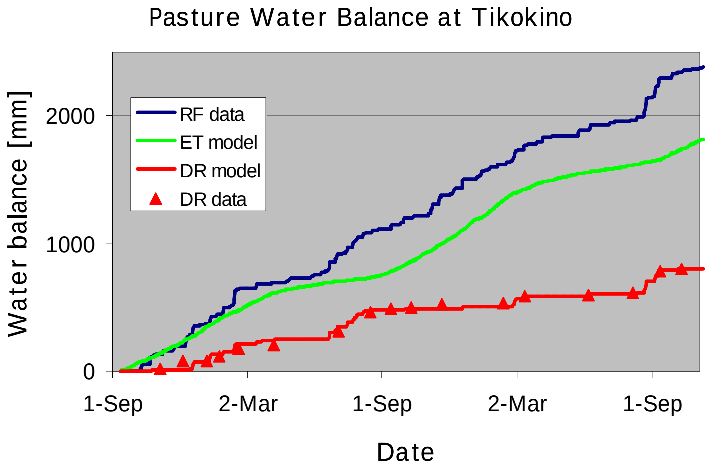


Figure 3.3 Prediction of cumulative drainage (DR) by SPASMO (red line) in comparison with that measured by fluxmeters (red triangles). Also shown is the rainfall data (RF – blue line) and the SPASMO modelled evapotranspiration (ET – green line)

27. Figure 3.3 shows that there is very good agreement in the predicted and measured drainage. Drainage is a sensitive indicator of SPASMO's ability for it relies on successfully predicting pasture cover growth, soil-water dynamics and weather factors. These are all the factors that need to be considered in establishing reasonable and justifiable irrigation consents (Proposed One Plan Policy 6-12 a (i)). In Figure 3.3, it can be seen that drainage occurs only during winter when the soil is close to field capacity. The irrigation on this farm only replaced summer pasture ET, and the farmers there irrigated justifiably because there was no wastage of irrigation water during the summers.

28. The examples above (Sections 3.4 and 3.5) provide two cases where SPASMO has been verified. There are many others and these are contained in other reports. SPASMO has been used under contract to a range of territorial local authorities and regional councils. These include: the Northland Regional Council, Auckland Regional Council, Environment Waikato, Environment Bay of Plenty, Gisborne District Council, Hawke's Bay Regional Council, Horizons Regional Council, Greater Wellington, Masterton District Council, Marlborough District Council and Environment Canterbury.

In Appendix B are listed some of the reports to regional councils that have used SPASMO.

29. As well, many scientific papers have been published in international, peer-reviewed journals in which SPASMO has been used as the basis for the modelling. A list of these is provided in Appendix B. This list of 28 references is not the complete list, but rather it provides a selection has been made to show that SPASMO has been used by a wide range of clients for a number of purposes. As well, there are many papers in top international journals and there have been chapters in books published by prestigious scientific societies.

4. THE USE OF SPASMO TO DETERMINE THE REASONABLE AND JUSTIFIABLE USE OF WATER FOR IRRIGATION

30. In 2001, we were contracted by Horizons to use our SPASMO model to provide recommendations for the reasonable and justifiable use of irrigation, and its hydrological impacts in Horizons' Region (Green & Clothier, 2001, Appendix B). We considered nine different soils and used weather data from only Palmerston North airport. The weather record was 27 years long (1972-1998). One irrigation scenario we considered was 'optimal', in that the model only 'applied' water on any day of the year when it was needed to avoid water stress. That application was then an aliquot of 25 mm. The spread of the results in the justifiable need for irrigation, for two soils, is shown in Figure 4.1.

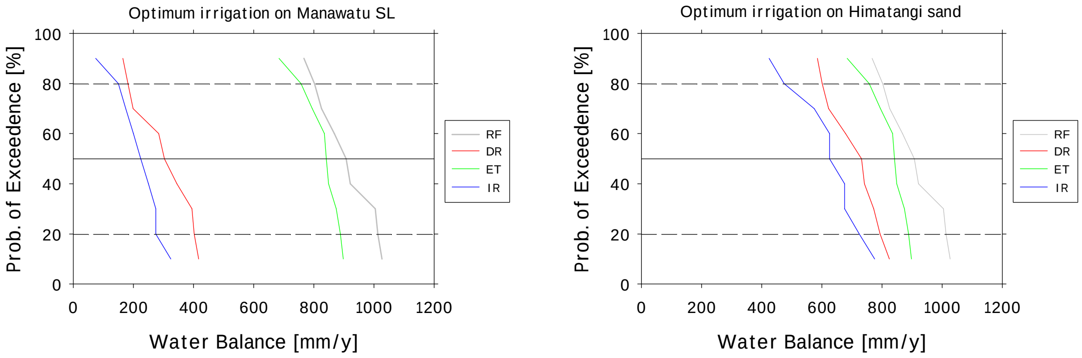


Figure 4.1 The probabilities of exceedance for the major components of the soil water balance under optimal irrigation for the Manawatu fine sandy loam and the Himitangi sand

31. Figure 4.1 shows the water balance components on the horizontal axis in mm/yr, and the vertical axis is the probability of exceedance. The average is a 50% probability of

exceedance (the solid horizontal line). So on average, Palmerston North receives just over 900 mm of rain (RF), and on average well-watered pasture uses 840 mm. However because evapotranspiration (ET) is seasonal, and RF is not uniform throughout the year, there is a justifiable need for irrigation (IR). On the Himitangi sand, the average need for irrigation (that is in 50 % of the years) is some 625 mm of water. That is 625 m^3, namely 625 cubic metres, for every m^2, namely square metre, of pasture. That is a lot of water: 625 cubic metres of water equals 21 rainwater tanks of 30,000 litre capacity, and that is for every square metre of pasture. The Manawatu soil holds more water because it is a finer textured soil, and there the average need for irrigation is just 275 mm.

32. However, it is not reasonable to allocate this justified need for irrigation on the 50:50 balance of probabilities. Greater security is needed by irrigators to justify the investment and running costs of the irrigation infrastructure.

33. Because the mechanistic SPASMO model has produced annual values for the water balance components using daily time steps, it is possible to expand the results beyond the average to look years drier, or wetter, than the average. That is, in essence, what the probability of exceedance does in Figure 4.1.

34. So in the one-in-five wettest of years (ie. an 80% [1-1/5=]4/5 x 100] probability of exceedance), the Himitangi sand and Manawatu fine sandy loam will only need 475 mm and 200 mm of irrigation respectively.

35. However, irrigation is needed most in the driest of years. So in one-in-five driest of years (ie. a probability of exceedance of 20% [1/5 x 100]), irrigationists could reasonably justify the use of 700 mm and 375 mm of irrigation on the Himitangi sand and Manawatu fine sandy loam respectively.

36. Thus, by modelling using SPASMO with long-term weather records and site specific factors, it is possible to determine a range of irrigation applications to meet a reasonable use test.

37. In 2004, Horizons asked us to expand the application of SPASMO to determine reasonable water use for irrigation throughout the Region (Green *et al*., 2004d, Appendix B). Now a range of 20 soils was modelled and this was carried for 50 climates in the Region, such that the SPASMO modelling now covered 1000 (20 x 50) scenarios. As well, we subsequently provided Horizons with a report of climate summaries for the

50 stations, and additional technical information on how the climate data were complied (Green & Laurenson, 2005).

38. In addition, in Green *et al*., (2004d) we carried out, at Horizons' request, a sensitivity analysis of the modelling parameters. These included:

i. The irrigation aliquot was either 10 or <u>25</u> mm;

ii. The refill point that triggers irrigation was either 40%, <u>50%</u> or 60% of the soil's readily available store of water;

iii. The root depth of the pasture was varied between 0.3 m, <u>0.5 m</u> and 0.9 m.

39. The SPASMO default values are underlined. As an example, the results of the sensitivity analysis are shown for the Manawatu fine sandy loam in Figure 4.2. Relative to the differences in relation to the choice of the probability of exceedance (ie. the reasonable-use criterion) there is a reasonably small sensitivity to the change in the key parameters of irrigation amount, trigger value and root depth.

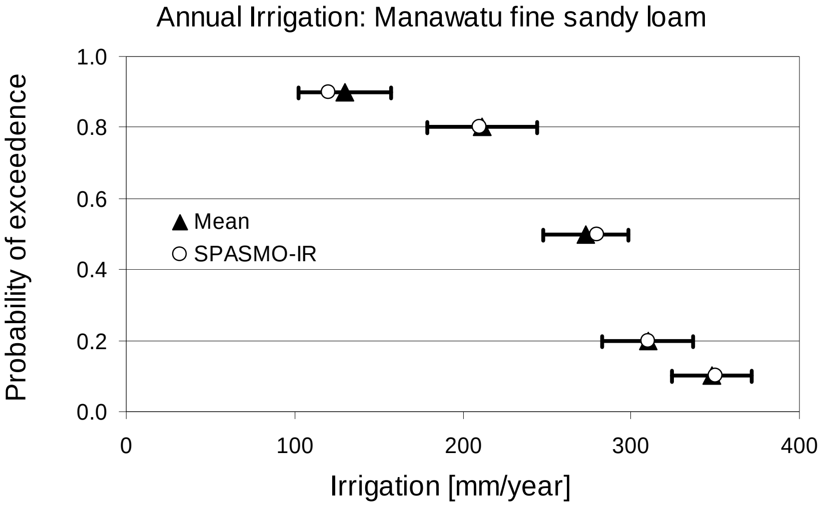


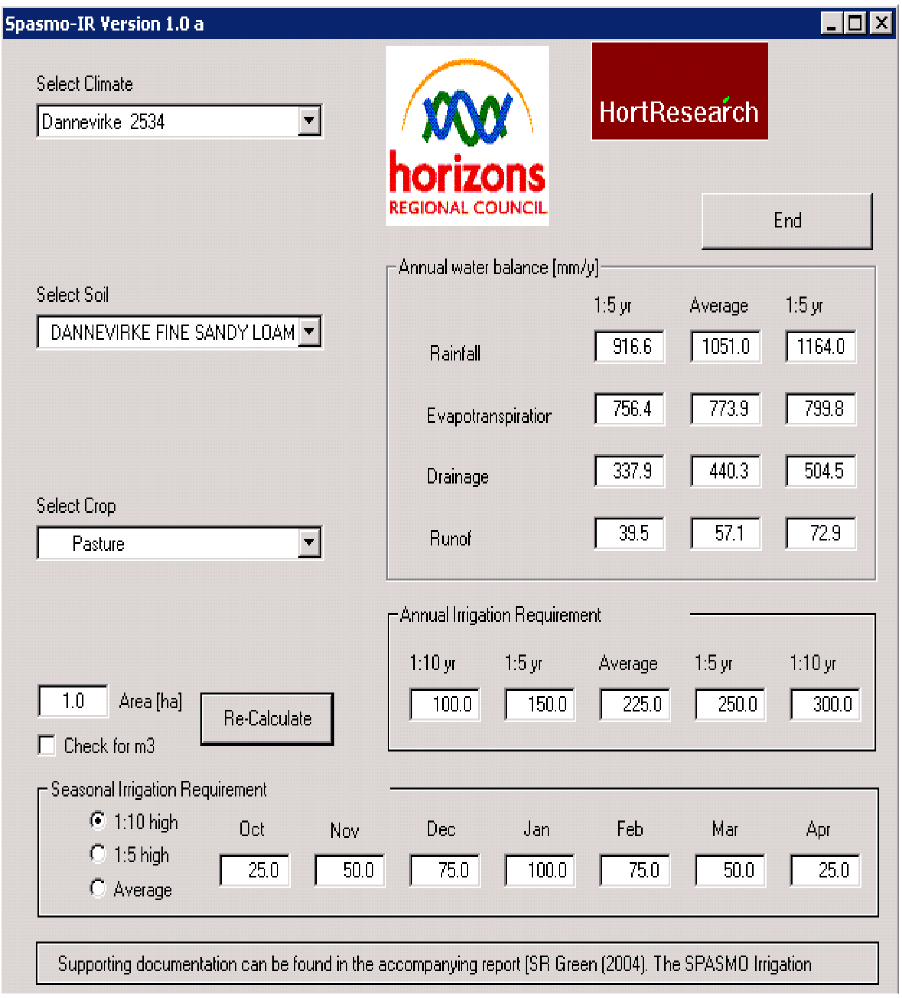
Figure 4.2 A sensitivity analysis of the need for pasture irrigation on the Manawatu fine sandy loam. The open markers are the default SPASMO calculations, and bars and closed triangles are the range and mean of the calculations varying irrigation depth, trigger point and root depth

40. We recommended that Horizons adopt a conservative approach to allocation by providing that the irrigation consent meet requirements in all but the one-in-ten driest of years (ie. a probability of exceedance of 10%). This provides farmers with a level of surety for investment in irrigation and that the allocation is justifiable.

41. SPASMO assumes that 100% of the applied irrigation water enters the soil of the rootzone. Irrigation systems are not 100% efficient and so this cannot be achieved because of design limitations and biophysical processes in the soil. This includes leakages from pipes, evaporative losses, off-target loss through wind, surface run-off, uneven application, and interception losses from the wet canopy of the plants. McIndoe (2002) considered irrigation efficiencies, under the definition that efficiency equals the water stored in the rootzone of the pasture divided by the total amount of water applied. He found that except for low pressure irrigation booms and big-gun irrigators, the efficiency of irrigation ranged from 80-95%.

42. Therefore, to account for system inefficiencies, to complement the conservative nature of the probability of exceedance criterion, we suggested to Horizons that an addition 20% be added to the irrigation allocation. So, in summary, we recommended to Horizons that the SPASMO prediction be used to allocate irrigation for any scenario to meet all but the one-in-ten driest of years, and that 20% be added to that value to account for system inefficiencies.

43. To make easier the allocation procedure, we provided Horizons with a decision support tool (DST) to enable easy calculation of the amount of water that would be reasonable and justified for any scenario. A screen dump of that tool is presented in Figure 4.3. The tool is a meta-model of SPASMO in that all 1,000 scenarios that are possible have been run, and the results stored as a look-up table accessed by the DST. The climate station, soil type and crop type (currently only pasture) are accessed via pull-down menus. Upon hitting the Re-calculate button the various window are populated from the look-up tables. In the box on the upper right is presented, in rows, information on the components of the water balance (rainfall, evapotranspiration, drainage and run-off). There are three columns, being the average values for the components (centre), plus the values of the one-in-five driest of years (left), and the one-in-five wettest years (right). The middle box on the right contains the SPAMSO findings for the reasonable and justifiable use of water at five probabilities: 1:10 wettest of years, 1:5 wettest, average, 1:5 driest and 1:10 driest (our recommended value). The values here are for 100% efficiency, thus another 20% needs still to be added to account for system inefficiencies. In the bottom window are given the monthly needs for irrigation throughout the spring to autumn period. This can be found for any desired probability of exceedance by ticking the right box of the left side for either 1:10, 1:5 driest of years, or the average.



Spasmo-IR Version 1.0 a

Select Climate: Dannevirke 2534

Select Soil: DANNEVIRKE FINE SANDY LOAM

Select Crop: Pasture

1.0 Area [ha]

☐ Check for m3

Annual water balance [mm/y]

	1:5 yr	Average	1:5 yr
Rainfall	916.6	1051.0	1164.0
Evapotranspiration	756.4	773.9	799.8
Drainage	337.9	440.3	504.5
Runof	39.5	57.1	72.9

Annual Irrigation Requirement

1:10 yr	1:5 yr	Average	1:5 yr	1:10 yr
100.0	150.0	225.0	250.0	300.0

Seasonal Irrigation Requirement

● 1:10 high
○ 1:5 high
○ Average

Oct	Nov	Dec	Jan	Feb	Mar	Apr
25.0	50.0	75.0	100.0	75.0	50.0	25.0

Supporting documentation can be found in the accompanying report [SR Green (2004). The SPASMO Irrigation

Figure 4.3 A screen dump of the SPASMO meta-model decision-support tool for irrigation allocation. Each (of up to 1000) scenario can be selected via the pull-down menus on the left, and when the Re-calculate button is pressed the tables on the right are populated. The values in the boxes do not include the 20% add-on we recommend be used to account for system inefficiencies

44. The crop water needs calculated by SPASMO provide Horizons with consent values of irrigation water that meet a reasonable use test (Policy 6-12 (a)). They consider land use, crop water use requirements and on-site physical factors (Policy 6-12 a (i)), and enable assessment on the basis of irrigation efficiency (Policy 6-12 a (ii)). A higher efficiency of irrigation can easily be accounted for by adding on a lower augmentation than 20%.

45. Policy 6-12 a (iii) seeks to link actual irrigation use to soil moisture measurement of the conditions prevailing in the soil at the time of making a decision to irrigate, or not. Here I

provide evidence of the consequences of over-irrigation and indicate how measurement of the soil's water content, in real time, is possible and preferable to ensure justifiable use of water.

46. In our 2001 report to Horizons (Green and Clothier, 2001; Appendix B), not only did we use SPASMO to model optimal irrigation by triggering irrigation when the soil water content dropped to the refill point, we also considered fixed irrigation. In one of the fixed irrigation set-ups we considered applying an irrigation event every week for the 14 weeks of summer, between late November and early March – irrespective of the weather and soil moisture conditions. We considered the following irrigation aliquots: 0, 10, 20, 30, 40 and 50 mm per irrigation. In Figure 5 of that report, presented here as Figure 4-4, we plotted the pasture evapotranspiration (ET) and wasteful drainage (DR) as a function of the applied amount of irrigation for two different soils – the Manawatu fine sandy loam and the Himitangi sand.

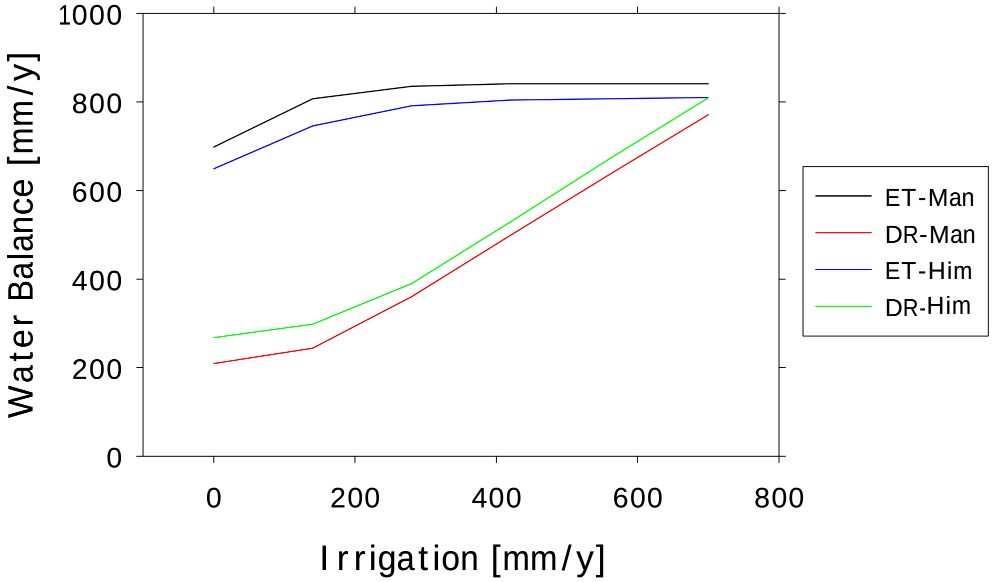


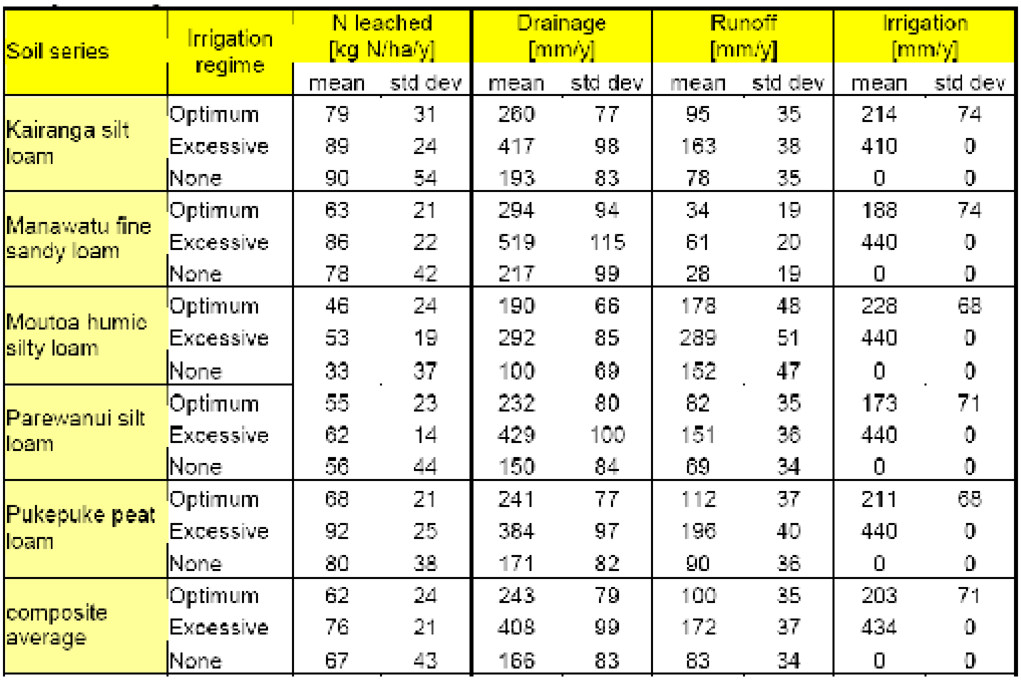
Figure 4-4 The impact of increasing the amount of fixed irrigation (mm/y) on the evapotranspiration (ET, mm/yr) of pasture growing on Manawatu fine sandy loam (black line) and Himitangi sand (blue line), and on the drainage (DR, mm/yr) from the rootzone of the Manawatu fine sandy loam (red line) and Himitangi sand (green line)

47. When there is no irrigation, there is still ET (about 650 mm/y) from both soils as the grass transpires rainwater that is stored in the soil profile. There is also drainage (about 200 mm/y), especially during winter as the low ET and heavy rains mean that the soil's water content exceeds field capacity and drainage occurs.

48. As the amount of irrigation increases from zero, there is a rise in pasture water use as the irrigation enables the pasture increasingly to avoid drought. However, this system of fixed irrigation highlights the folly of irrigating via a fixed schedule, irrespective of rainfall and soil water storage, rather than via an optimal system that applies water only when required. In Figure 4-5, as the amount of the irrigation aliquot in the fixed irrigation increases, there is correspondingly more drainage. This is, in the first instance, wasteful of water, as it is of no value in relieving water-stress for there is none, as evidence by the unchanging ET.

49. To minimise the impact of irrigation takes on the quantity of water resources in surfacewater and groundwater bodies, only the minimum amount of irrigation to alleviate water-stress should be used. The use of SPASMO to predict the water required to meet the 1:10 driest of years, with a 20% add-on to account for inefficiencies in the delivery system, provides a reasonable and justifiable consent allocation.

50. Worse, the drainage water could carry with it contaminants from the soil profile, such as nutrients, endocrine-disrupting chemicals, viruses, bacteria, and pesticide residues. This potential leaching of contaminants can lead to non-point source pollution of both surface water and groundwater bodies. The likelihood and severity of non-point source pollution is greater when there is elevated drainage, as can occur through over-irrigation.



Soil series	Irrigation regime	N leached [kg N/ha/y]		Drainage [mm/y]		Runoff [mm/y]		Irrigation [mm/y]	
		mean	std dev	mean	std dev	mean	std dev	mean	std dev
Kairanga silt loam	Optimum	79	31	260	77	95	35	214	74
	Excessive	89	24	417	98	163	38	410	0
	None	90	54	193	83	78	35	0	0
Manawatu fine sandy loam	Optimum	63	21	294	94	34	19	188	74
	Excessive	86	22	519	115	61	20	440	0
	None	78	42	217	99	28	19	0	0
Moutoa humic silty loam	Optimum	46	24	190	66	178	48	228	68
	Excessive	53	19	292	85	289	51	440	0
	None	33	37	100	69	152	47	0	0
Parewanui silt loam	Optimum	55	23	232	80	82	35	173	71
	Excessive	62	14	429	100	151	36	440	0
	None	56	44	150	84	69	34	0	0
Pukepuke peat loam	Optimum	68	21	241	77	112	37	211	68
	Excessive	92	25	384	97	196	40	440	0
	None	80	38	171	82	90	36	0	0
composite average	Optimum	62	24	243	79	100	35	203	71
	Excessive	76	21	408	99	172	37	434	0
	None	67	43	166	83	83	34	0	0

Figure 4-5. The impact of irrigation on the water balance (mm/yr) and the amount of nitrate-N that leaches (kg N/ha) under a potato field. The composite soil at the bottom of the table is simply the average of all the five other soils

51. Dr Steve Green was contracted by Horizons in 2005 to assess, using SPASMO, the impact of irrigation on water drainage schemes in the Lower Manawatu (Green, 2005b). He considered five soil types and two irrigation regimes. These irrigation practices were those discussed above: optimum irrigation; excessive irrigation of 20 mm at a fixed return seven-day period during the 14 weeks of summer; and none (Figure 4-4). For dairy farms on these five soils, SPASMO predicted that optimum irrigation would result in an increase of soil water drainage of between 60-90 mm/yr, depending on soil type, and this represents a 35-90% rise in the annual rate of drainage. On average, there would be a reduction of nitrate leaching of between 5-15 kg-N/ha/yr, and the mean concentration of nitrate in the leachate was predicted to drop from 27.4 mg/L to 17.5. This reduction is because irrigated pasture grows more and therefore takes up more nitrogen, and irrigated dairy farms bring in less supplemental feed (which contains nitrogen), and simply there is a dilution of the leachate by the addition of irrigation water. Under the excessive fixed-return period irrigation, drainage went up by 192-302 mm/year, or 140-190%, and in this case nitrate leaching went up by 1-12 kg/ha/yr a rise in the loading of between 0-15%. This increased loading occurred even though the concentration of nitrate in the leachate dropped by 50%.

52. For the reasons of water quantity and quality, irrigation should be managed to tailor the application of water so that it is only applied when needed. Maintaining a record of weather conditions, primarily rainfall and ET, is one way to do this. A better way is to measure directly the status of the soil's water content (see Figure 3-2) as this provides a means to determine when the water stored in the soil is dropping to the trigger point that heralds the onset of water-stress, which can be alleviated by irrigation. The sequence of summer irrigations and rainfall events can be seen in Figure 3-2. There are now many hand-held or buried devices on the market that are reasonably priced and which can be used to measure the soil's water content. By plotting records such as in Figure 3-2, it is possible to link the prevailing soil moisture conditions to the need for irrigation such that water is applied when justified. This protects both the quantity and quality of surface water and groundwater.

5. AN OVERVIEW OF THE NITROGEN CYCLE IN PLANT AND GRAZING ANIMAL SYSTEMS

53. While the details of the cycle of nitrogen (N) are complex, the basics are well understood after many years of study by scientists. The N cycle is a dynamic system, and its major components are shown in Figure 5.1. The organic-N pools are on the left, and mineral-N components on the right of Figure 5.1.

54. Nitrogen inputs onto soil can come from fertilisers, rainfall (wet deposition), dry deposition from the atmosphere (mineral N), plus the return of plant material, dung and urine (organic N) from stock. Recycled organic N of dung and plant material first enters a “litter pool” of N, which is part of the more-rapid cycling of N within the soil. There is also a slower cycling “humus pool” of N comprising stable soil organic matter.

55. From these organic pools, nitrogen in mineral form can be produced through ammonification of organic N. These organic pools can also immobilise N by assimilation of mineral N into the biomass of the pools. The strength of these two countervailing processes depends on a range of factors, such as the soil carbon (C) to nitrogen ratio. Higher C/N ratios in the soil favour immobilisation of N, eg. when the ratio of C to N is above 10-15 in the soil. Lower C/N ratios in the soil favour mineralisation of N.

56. The following examples illustrate the different processes occurring in the soil. The land use chosen is primarily dairying, for which exemplary data are available (Ledgard *et al*., 1996).

57. For soils on dairy farms in the Taupo catchment, mineralisation (including that of the dung) is likely to be about 400-500 kg-N/ha/yr, as 2-3% of the soil’s organic N is mineralised annually. For sheep pastures in Canterbury, a net mineralisation (less immobilisation) of 150-180 kg-N/ha/yr is likely. As well, nitrogen can be supplied through fixation by legumes, such as the clover in the pasture, and depending on fertiliser use this can be between 75 kg and 220 kg-N/ha/yr. Gorse, and especially broom, can also supply nitrogen to the soil through fixation. The factors controlling N inputs to soils are well understood.

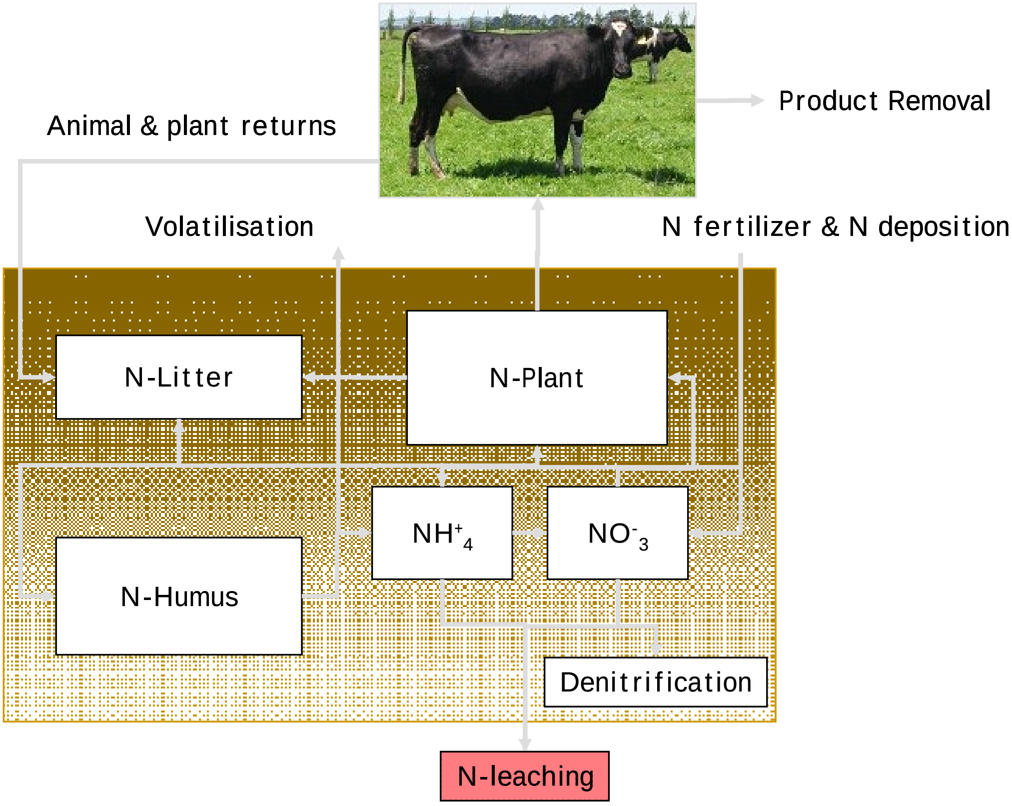


Figure 5.1 A simplified schematic of the flows and fate of nitrogen in the rootzone of a grazed animal system. The organic-N pools are on the left, and the mineral-N components on the right

58. In water that is resident in the soil (the so-called soil solution), nitrogen in mineral (inorganic) form can exist primarily as either ammonium (NH_4^+ - a cation, or positively charged ion), or as nitrate (NO_3^- – a negatively charged anion). The sum of these two ions is termed the soluble inorganic nitrogen content (SIN). Ammonium can be nitrified by bacteria to nitrate, and under certain conditions nitrate can be denitrified to nitrogenous gases. For soils that are generally well drained, denitrification losses tend to be small and are predicted to be around 20-30 kg-N/ha/yr on such a dairy farm. Plants take up both ammonium and nitrate depending on pasture yield, the amount of N taken up by pasture can be between 500-1,000 kg-N/ha/yr.

59. Losses of nitrogen can also occur from soil by volatile gaseous losses. Gaseous losses can be of the order of 20-60 kg-N/ha/yr. Plant material containing nitrogen that has been taken up from the soil can be ingested by animals and then removed from the system in the form of milk or meat. For dairy farms, the amount of N removed in the milk is of the order of 60 kg-N/ha/yr. It has been estimated that the amount of N retained and transferred out by sheep in Canterbury is 50 kg-N/ha/yr. In plant-based systems,

nitrogen can be removed from the system as fruit, roots, leaves, grain, or hay and silage. This varies depending on the harvest fraction, and the nitrogen content of the material removed (Figure 5.2). The non-harvest portion of the plants may be returned to the soil to become eventually incorporated into the litter, and then humus pools (Figure 5.1).

60. The loss of nitrogen by leaching below the rootzone is an environmental concern, for as other expert witnesses will detail, this nitrogen can find its way into the receiving reservoirs of groundwaters, lakes and rivers. As well as the SIN losses due to leaching, nitrogen can also be lost from farms in soluble organic forms (SON) and as particulate organic nitrogen (PON).

61. Scientists have developed a good understanding of the mass-balance components of the N cycle for a range of land uses. In Figure 5.2, I present a table of how land use type and practice can affect the leaching losses of N from farms (see, *inter alia*, Woods *et al*., 2006, The CLUES Report).

	Fertiliser (kg-N/ha/yr)	**Product Removed (kg-N/ha/yr)**	**Nitrogen Leached (kg-N/ha/yr)**
Grapes	15	25	8
Apples	55	75	20
Kiwifruit	95	95	40
Potatoes	268	176	92
Sheep	0	40	16-37
Dairy pasture	225	89	57

Figure 5.2 Examples of typical values of key components of the nitrogen balance of a vineyard, apple and kiwifruit orchards (Woods *et al*., 2006) (rows 1- 3), plus that surveyed under potatoes near Pukekohe (Crush *el al*., 1997) (row 4), and that measured on ryegrass/clover pastures grazed by sheep in the Manawatu (Brock *et al*., 1990) (row 5), in comparison to that measured for a grazed pasture in the Waikato (Ledgard *et al*., 1996) (row 6)

62. The first four rows in Figure 5.2 come from predictions using the detailed SPASMO model (Soil Plant Atmosphere System Model), which is described in more detail in Section 7.

63. The fourth row in Figure 5.2 is that surveyed by Crush *et al*. (1997) under potatoes (*inter alia*) near Pukekohe, and because more nitrogen is removed in the potato crop, generally more nitrogen fertiliser is used. Crush *et al*. (1990) found that the N surplus, and hence propensity to leach N, came in the order: early potatoes > winter cabbage, winter lettuce and squash > dairying, kiwifruit, summer cabbage and summer lettuce > pumpkins, onions and main crop potatoes > dry stock farming. (The symbol > means ‘greater than’.)

64. Brock *et al*. (1990) (fifth row, Figure 5.2) studied the impacts of sheep management on leaching of nitrate from ryegrass/clover pastures in the Manawatu. The stocking rate was 22.5 ewe equivalents per hectare. For set stocking, they found N leaching to be 37 kg-N/ha/yr, for rotational grazing 17 kg-N/ha/yr, and for a combination of both 16 kg-N/ha/yr.

65. The last row in the table of Figure 5.2 is taken from measurements made by Ledgard *et al*. (1996) on a dairy farmlet in the Waikato near Hamilton. Under this grazed system, nitrate leaching was found to average about 60 kg-N/ha/yr.

66. Because nitrate, and generally to a lesser extent ammonium (before it is nitrified to nitrate), is mobile (carried by the flow of water through the soil as a result of rainfall and irrigation), nitrogen is leached from the bottom of the rootzone, and thereafter it may find its way to rivers, groundwater and lakes. The amount of nitrogen that leaches from the soil depends on a range of soil and weather conditions, land use types, and land management practices.

67. Thanks to many decades of scientific studies, we have a good understanding of the mass balance of the nitrogen cycle; more recently we have developed many numerical models to predict the behaviour of the N cycle and to predict the nitrogen flows and fate of nitrogen in many farming systems. In Section 7, I will discuss in more detail the various models that are available.

6. THE DEPOSITION OF NITROGEN ONTO LAND FROM RAIN AND THE ATMOSPHERE

68. It is sometimes thought that rain adds significant amounts of nitrogen to land in New Zealand.

69. In Western Europe, it has been found that on average there is a deposition of 17 kg-N/ha/yr, yet in certain parts of the Netherlands, Czech Republic and Germany this atmospheric receipt can exceed 60 kg-N/ha/yr (McDonald *et al*., 2002).

70. However, this is not the case in New Zealand. From direct measurements around Lake Taupo, Vant and Gibbs (2006) found 3.7-5.1 kg-N/ha/yr from deposition by rainfall, and Parfitt *et al.* (2006) found that even when geothermal emissions were added in, this would only rise to just under 9 kg-N/ha/yr. This is small in relation to other inputs of N onto the soils of farms.

7. THE UPTAKE OF NITROGEN FROM SOIL BY PLANTS

71. Nitrogen is taken up by plant roots as ammonium (a cation NH_4^+) and nitrate (an anion NO_3^-), and different plants have different selection preferences. In most soils, nitrate is the most mobile ion of nitrogen and because soil surfaces have negative charges, anions are not attracted to them. Therefore, ammonium is generally less mobile than nitrate, as opposite charges attract. However, some of our volcanic soils are variably charged, and therefore ammonium can be somewhat more mobile before it is nitrified to nitrate.

72. Nitrogen is an essential plant nutrient that encourages plant growth. The amount of nitrogen taken up by a plant depends on the dry matter yield of the crop (kg DM/ha/yr) times the nitrogen content of the plant components (% N). The pasture grass eaten by cows contains 3-4 kg-N/kg- DM. Here DM is the dry matter of the plant in kg. The nitrogen content of imported feed, such as maize, is 1-2 kg-N/kg-DM.

73. In the case of cut and carry practices (eg. pasture silage/hay and maize), or the harvest of plant parts (eg. in the kiwifruit and potatoes), this plant nitrogen is removed from the site. In grazing systems, plant nitrogen is ingested by the animals and then some part of the N is returned to the soil surface in the form of dung and urine. These deposition points then act as a local source of concentrated N, forming local soil N-pools eventually being available both for plant uptake (the green patches seen in pastoral landscapes), or that destined for leaching. Urine patches are a prime cause of the N 'leakiness' of soil-plant systems that are grazed by animals.

8. POLICY INITIATIVES TO LIMIT NON-POINT SOURCE POLLUTION BY NUTRIENTS FROM FARMING

74. Non-point source pollution of water bodies by nutrients from farms is a worldwide issue, as intensified farming systems are now using more fertilisers and irrigation to ensure economic levels of productivity. Policy initiatives that have been used include: levies on excessive use of nutrients, environmental auctions, and capping of inputs. Horizons has been innovative in the Proposed One Plan and has used an assessment of the landscape's natural capital values, as recorded by the Land Use Capability (LUC) class, to assign a nutrient loss limit to a farm. Dr Mackay discusses this in more detail; I endorse his approach.

75. In 1980, the European Union issued an EU Directive on the Quality of Water Intended for Human Consumption and in 1991 issued the EU Nitrates Directives. Agriculture in the EU is increasingly being affected by environmental policies. The Dutch introduced a nutrient accounting system called MINAS, in an attempt to improve water quality. It provided for levies to be charged if farms exceeded certain nutrient loadings on the environment. However, this had limited success for the levies were not prohibitive, relative to the productive value of fertiliser, and also because the system was complex. The Dutch have now resorted to focusing their controls by limiting applications of nutrients.

76. In New Zealand, both Environment Waikato (Regional Plan Variation 5 for Lake Taupo) and Environment Bay of Plenty (Rule 11 for the Rotorua Lakes) have used nutrient caps based on benchmarking current practices, known as grand-parenting. Trading and demanding changed farm practices is then intended to be used to bring down the loadings on water bodies from farms. This is the so-called 'cap and trade' process. This is a blunt instrument focused on inputs, and there are equity issues involved.

77. Environmental auctions are being used in Australia to procure changes that will improve ecosystem services, and through bundling these, as EcoTender seeks to do, it is hoped to realise water quality improvement, greenhouse gas reduction and habitat provision. I consider that this, because of the small financial incentive in the value of the auction, will not achieve the magnitude of the changes required to address widespread non-point source pollution by nutrients.

78. Horizons has adopted a novel and innovative approach based on the value of the natural capital assets and productive capacity of the landscape. Broadly, this can be called an ecosystems services approach. The World Resources Institute (WRI)

(www.wro.org) in its guide for decision-makers recommended *"… to use ecosystem services – the benefits of nature – to make the link between nature and development. The language of ecosystem services provides a way for policymakers to identify how a decision depends on nature's flow and how a decision will in turn affect the flow. It increases our ability to understand and make trade-offs across ecosystem services & so win more and lose less*".

79. By linking natural capital to a nutrient loss limit, Horizons has answered the WRI's challenge. I recommend this LUC approach to FARMS as outlined by Dr Mackay.

9. AVAILABLE MODELS – WHY OVERSEER® IS THE MOST APPROPRIATE FOR USE IN THE FARMS STRATEGY

80. Land use management and farming practices play a dominant role in the nitrogen cycle. Land management impacts on the nitrogen cycle depend on various complex interactions.

Nitrogen Computer Models

81. Following many decades of scientific study, this complexity is now well understood and over the last 20 years this knowledge has been encapsulated in computer models which can be used to predict the functioning of the N cycle under specified farming scenarios. There are many models available, and therefore potentially useable by Horizons in the One Plan.

82. I consider that OVERSEER is the one model available in New Zealand that is best suited for policy development and implementation, as well as the improvement of farm-scale practices. We have carried out an intercomparison of OVERSEER and SPASMO. Dr Ledgard will discuss OVERSEER in more detail.

Inter-Comparison between OVERSEER and SPASMO

83. In 2004, we reported on a test between our detailed SPASMO modelling of a dairy farm, our measurements of leaching using in situ lysimeters, and the results predicted by OVERSEER. Over the two years 2001-02 and 2002-03 we carried out a measurement and modelling study on an intensive dairy farm near Tikokino in Hawke's Bay, under contract to the Hawke's Bay Regional Council (Green *et al*., 2004). Our measurements showed that over the two years, a total of 112 kg-N/ha/yr was lost as leachate below the rootzone. We used our mechanistic model SPASMO to predict this leaching loss.

SPASMO is a detailed mechanistic model that considers water and solute movement, in daily time-steps, through the soil of the rootzone of crops, using actual weather data. SPASMO successfully predicted a leaching loss of 116 kg-N/ha/yr. The annual, long-term, nutrient budget of OVERSEER successfully predicted a loss 108 kg-N/ha/yr. The agreement between the predictions of OVERSEER in this independent test against our detailed model, and our measurements, is very good.

Stock number (cows/ha)	**Fertiliser (kg-N/ha/yr)**	**SPASMO (kg-N/ha/yr)**	**OVERSEER (kg-N/ha/yr)**	**Ledgard *et al*. (kg-N/ha/yr)**
2.0	0	28	27	
2.4	0	28	32	43
2.7	100	38	38	
3.0	200	54	59	57
3.3	300	78	77	
3.6	400	108	116	110

Figure 9.1 A table of simulations carried out using SPASMO by Green *et al*. (2002) for a typical farm in the Taupo Catchment, showing the rise in nitrogen lost by leaching as stocking rate and fertiliser increases. Also shown are the predictions found using OVERSEER by Ross Gray (accredited OVERSEER user) for the same inputs, soil and weather conditions (Ross Gray, AgResearch, personal communication, 31 October 2007). The final column presents the leaching measurements of Ledgard *et al*. (1996) for farmlets under somewhat comparable fertiliser use conditions in the Waikato region near Hamilton

84. Earlier, in preparation of my evidence for Regional Plan Variation 5 of Environment Waikato, I revisited the SPASMO calculations we had carried out for Environment Waikato in 2002 (Green and Clothier, 2002) for various modelled scenarios on a typical dairy farm in the Taupo Catchment. Parts of the key table from that report are presented here as Figure 9.1, and it can be seen that as the stocking rate rises from 2 cows/ha to 3.6 cows/ha, and the fertiliser rate rises from 0 through 100, 200 and 300, to 400 kg-N/ha/yr, the leaching losses of nitrogen are predicted by SPASMO to rise from 28 to 108 kg-N/ha/yr.

85. On 31 October 2007, I provided Ross Gray, an accredited OVERSEER user of AgResearch, with the input conditions we used for the detailed simulations we carried out using our mechanistic model SPASMO. He then provided me with the OVERSEER

results that are included in the fourth column of Figure 9.1; the agreement between the two models is very good. In the fifth column of Figure 9.1, I have listed the measurements of nitrogen leaching made by Ledgard *et al*. (1996) for the three quite comparable levels of fertiliser they applied to farmlets in their study in the Waikato near Hamilton; the agreement between all three is good. OVERSEER performed very well in these cases.

86. OVERSEER is a long-term average model, and so it is appropriate for long-term planning and policy development. Ledgard *et al*. (1999) extended the measurements of Ledgard *et al*. (1996). They then noted that measurements can vary temporally by carry-over of N from one year to the next, say when rainfall (and so drainage) is low. They noted that in the longer term there will be equilibrium, with inputs equalling outputs. It is this equilibrium that OVERSEER models.

Conclusion

87. In conclusion, I consider OVERSEER is the most appropriate tool that is available in New Zealand for achieving the objectives of the FARM strategy and assessing compliance with Table 13.2 of the Proposed One Plan.

10. NITROGEN ATTENUATION BETWEEN THE FARMING ENTERPRISES AND RECEIVING WATER BODIES

88. At the landscape scale of farming enterprises, there is leaching of N from farms to receiving waters. These receiving waters can be groundwaters and surface water bodies.

89. Not all the nitrogen that leaches below the rootzone makes it to either groundwater or surface water – some goes missing, or in other words there is attenuation between the farm and the local surface water bodies. The reasons for these losses include: gaseous losses (NH_3, N_2O, NO, and N_2 - depending on local conditions in the soil), final residence in groundwaters unconnected to surface bodies, plus uptake by riparian vegetation and riparian ecosystems.

90. Attenuation, or losses farm-to-river (or farm-to-lake) transmission, $\Re$, represents the landscape's capacity to buffer, lag and attenuate nutrients. For example, a transmission $\Re$ of 0.6 means that 60% of the N leached from the base of the rootzone under the farm is transmitted to the river or lake.

91. Attenuation needs to be accounted for in policy instruments such as the FARM strategy, for FARMs relates to practices within the farming enterprise, namely the proposed N loss limits (Policy 13-2 (a)), while the goal of Policy 13-2 (c) is avoiding as far as is practicable any adverse effects on any sensitive receiving environments, in particular (*inter alia*) surface water bodies.

92. Across the five catchments of the Waikato River, Alexander *et al*. (2002) found attenuation ℜs for nitrogen of between 0.25-0.61, with three being in the tight band of 0.55-0.58. The Taupo Catchment was 0.21, which they related to the low level of agricultural intensification, and because 50% of the catchment was either the lake or forestry. Ross Monaghan (*pers. comm.)* of AgResearch has found ℜ to 'range from 0.5 to 0.75'.

93. As part of the background research that led to the FARMS strategy, Horizons contracted the multi-CRI team of SLURI, through AgResearch under my leadership, to establish best management farm strategies for contaminant management that would protect river water quality, starting with case studies in the Upper Manawatu and Mangatainoka Water Management Zones (WMZ) (Clothier *et al*., 2007). The key part of this report, which I will describe in this section, was to link farm practices from dairy and sheep and beef farms to the losses from these enterprises and link them to the loadings they contribute to the river – after attenuation. In Appendix 6 of that report, Mackay *et al*. (2007) then made the link between the enterprise losses of N and that which would be sustainable through consideration of the natural capital value of the soils, as registered by their LUC class. This link back from the river (Policy 13-3 c) to discharges to land on the farm (Policy 13-2) provides a means to balance agricultural production with river protection, and this forms the basis of Table 13-2. Dr Mackay's evidence will cover Appendix 6.

94. Horizons then contracted SLURI to write a second report for refinement of the LUC-based approach to FARMS, and to consider an approach to nutrient management plans for commercial vegetable production, which is more difficult because there are multiple and different crops (up to three) with any given year. Dr Mackay will discuss the refinement of the LUC approach. I was also involved with my colleague Dr Steve Green on the latter part, relating to vegetable production, and I will describe that in Section 13.

95. Here, I describe the findings from Clothier *et al*. (2007) which linked farm practices to river water quality in the Upper Manawatu WMZ (UMWMZ), providing the first step in the FARM strategy. The UMWMZ we consider is the catchment of the Upper Manawatu

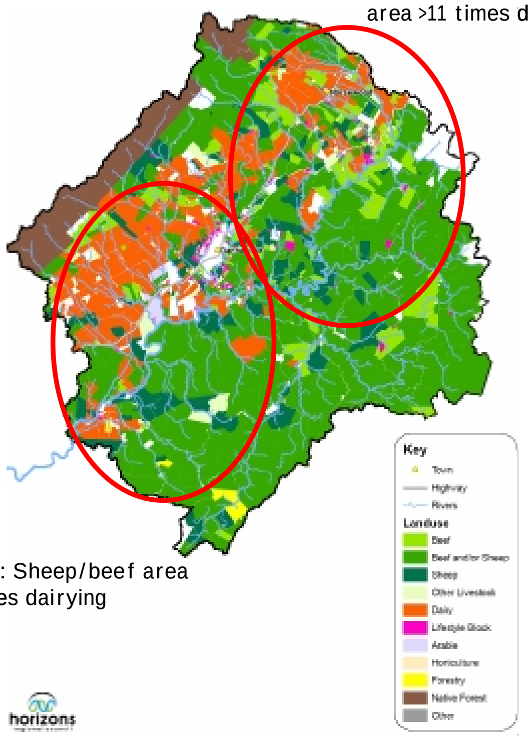
above the Hopelands flow recorder, and this area in total includes five WMZs (from Mana_1 through to Mana_5).

96. We sought to establish what the target best management practices (BMPs) are for sheep/beef and dairy to ensure that water quality in Horizons' Water Management Zones (WMZ) approaches guideline criteria. To establish the BMPs that would meet such guideline water-quality targets, we first need to link what we consider is happening on the farm with what is observed in the river. In so doing, we will address the issue raised by Alexander *et al*. (2002) that "… the description of [nitrogen] sources might be improved by including specific estimates of nutrient inputs from fertiliser and animal wastes".

97. We used OVERSEER calculations to predict the losses from farms. By linking observations of nutrient loadings in the river to OVERSEER calculations of loss at the farm, we would have a tool to link farm practices to water quality, by which we will be able to suggest BMPs that enable water quality targets to be met.

98. We used the contrasting patterns of land use in two monitored subcatchments of the UMWMZ to explore the farm-to-river transmission link for the key land uses of dairying, and sheep/beef. Above the monitoring station at Weber Road, the catchment is dominated by sheep/beef farms. In this Weber catchment the area in sheep/beef farms is more than 11 times greater than that in dairy farms. Whereas in the area upstream of monitoring at Hopelands, and downstream of Weber Road, the ratio is much less, and there is only a two-fold difference in the area of sheep/beef compared to dairying (Figure 10.1).

Weber Road: Sheep/beef area >11 times dairying



Hopelands: Sheep/beef area only 2 times dairying

Figure 10.1 The two subcatchments of Hopelands and Weber Road in the UMWMZ, with their differing patterns of land use: dairying is in red, and sheep/beef in green

99. We defined O^{-1} as the OVERSEER calculation of the N flux q^* from the farm as:

$$q^* = O^{-1}(L_f) \qquad [3]$$

This notation indicates that the flux q^* is estimated from an OVERSEER calculation of loss for a specific farm scenario L_f, which will depend on the specific farm practices that are used, and put into OVERSEER.

However, this predicted loss q^* from a farm will be attenuated in the farm-groundwater-river system, so that from the perspective of the river, a back-calculation based on observations in the river would suggest that actually it only “seems” that farms are losing the flux, q (kg-N /ha$^{/}$yr).

Therefore, we can estimate transmission factors $\Re$ for both dairy (subscript d) and sheep/beef (subscript sb) as:

$$\Re_d = \frac{q_d}{q^*_d} \quad \& \quad \Re_{sb} = \frac{q_{sb}}{q^*_{sb}}.$$

100. There are two river monitoring stations in the UMWMZ: one at Weber Road and the other at Hopelands (Figure 10.1). Because these two catchments, designated W and H, have differing proportions of dairying and sheep/beef farms, we can set up simultaneous equations to find both $\Re_d$ and $\Re_{sb}$, by first calculating the loss values 'seen' by the river: q_d and q_{sb}. The area of each farm-type in each catchment is A (ha), appropriately subscripted (Figure 10.2). As well, we need to consider the contribution from the small areas of forest, both native and exotic, and cropping, designated by subscripts f and c. The point source discharges around Dannevirke, D, (kg-N/yr) also need to be accounted for. This D includes point source discharges at Norsewood, Ormondville and Oringi, plus Dannevirke itself. Horizons has provided us with the annual river loadings of N at Weber Road and Hopelands: *viz* Q_W and Q_H (kg-N/yr) (Figure 10.3).

Land Use Type	**Weber (*W*) - ha**	**Hopelands (*H-W*) - ha**
Dairying (A_d)	5,825	14,709
Sheep/beef (A_{sb})	64,101	33,521
Cropping (A_c)	34	459
Forestry (A_f)	1,987	5,685

Figure 10.2 The differing patterns of land use in the two subcatchments of the UMWMZ

	Weber (*W*)	**Hopelands (*H-W*)**
N loading (kg-N/yr)	343,000	401,000

Figure 10.3 The annual median loadings on N in the two subcatchments

101. Using the values in Figures 10.2 and 10.3 enables us to calculate q_d and q_{sb}. We can then compare these with the OVERSEER calculations of q^*_d and q^*_{sb}, from which we can then estimate the transmissions $\Re_d$ and $\Re_{sb}$ (Figure 10.4). The analysis assumes there is no lag effect, but a direct link between annual N losses at the farm scale with the annual N loadings in the river. In this humid catchment, it would be expected that there is no inter-annual carryover in nitrogen, so our annualised results for OVERSEER can be linked to the annual average nutrient load in the river.

	q (Eq5) kg-N /ha/yr	**q^* (Eq3) kg-N /ha/yr**	Â
Dairying	15.4	31 (25-49)	≈ 0.5
Sheep/beef	3.9	7 (6-9)	≈ 0.5

Figure 10.4 The river-based farm fluxes q, the median (and range) of OVERSEER calculations q^*, and derived attenuations for dairying and sheep/beef

102. Our framework has been able to establish the link between leakage losses to the river from different land use types. In Appendix 2 of Clothier *et al*. (2007) we showed how the amount of nitrogen in the river (Q), after attenuation ($\Re$), could be related through OVERSEER (O), to farm practices on the land (L). The fluxes (q^*) are obtained from OVERSEER calculations (Eq. 3) so that:

$$Q = \Re_d \; O^{-1}\left(L_d\right) A_d + \Re_{sb} \; O^{-1}\left(L_{sb}\right) A_{sb}$$

103. Using this equation we could explore the impact of changing areas of land uses between dairying and sheep/beef (A), as well as the impact of changing on-farm practices (L). In Appendix 2 of Clothier we provided some examples.

104. *Adoption of mitigation practices:* If it were possible through the adoption of mitigation practices to achieve a one-third improvement in dairying practices, then the median loss (q^*), would drop from 31 to just under 21 kg-N/ha/yr, such that, given a transmission coefficient of 0.5 across the 14,709 ha of dairying in the Hopelands subcatchment, there would be a predicted reduction of 73,545 kg-N/yr in the river: a diminution of 18.3% from the 401,000 kg-N/yr currently observed at Hopelands that comes from the Hopelands subcatchment.

105. *Intensive practices:* For an intensive practice scenario, we take the case of the greatest leakage for dairying, namely q^*_{d} being 49 kg-N/ha/yr. This is for farms where OVERSEER simulates leaching when farm practices result in a yield of 1,200 kg MS/ha and in this example no mitigations practices are employed. If these practices were to expand across all dairy farms in the Hopelands sub-catchment, we predict there would be an additional 132,381 kg-N/yr in the river at Hopelands, a 33% increase over the current loading of 401,000 kg-N/yr.

106. *Expansion of dairying.* We considered a scenario of land use change by considering that dairying might expand on all lands up to Class III in the UMWMZ. Landcare Research

(Robert Gibb *pers. comm.*) determined that some 25% of the entire UMWMZ is in Class III lands or better. So from Table 5, this sums to 31,580 ha. Presently, dairying is carried out on only 20,534 ha, so there is potential for dairying to expand over another 11,046 ha. If there were such an expansion, there would be another 132,555 kg-N/yr in the river at Hopelands, a 17.8% increase on the current loading of 744,000 kg-N/yr.

107. In summary, our SLURI report to Horizons provided a framework and produced best management practices for contaminant management on farms in the Region. Primarily, we have considered dissolved nitrogen and phosphorus as the prime contaminants of concern. Dr Parfitt's evidence describes the application of this framework to phosphorus.

108. Further development was carried out by the SLURI team after the submission of our initial report in relation to linking N-loss limits to a measure of the landscape's natural capital, and the results of this research were appended to Clothier *et al*. (2007) as Appendix 6 (Mackay *et al*., 2007). Based on the Land Use Capability (LUC) classes on the Land Resource Inventory, Mackay *et al*. (2007) showed it is possible to assign N loss limits to LUC classes. This can then be linked to the river by summation across the landscape, through the attenuation framework I have described here, to provide the impact on the river system. Such an approach optimises productive and protective uses of a catchment biophysical resources and natural capital. Dr Mackay will discuss this in detail in his evidence. His approach is recommended for the reasons outlined in Section 8. It provides an ecosystem services approach that links natural capital values in the landscape to a nutrient loss limit.

11. THE FATE AND TRANSPORT IN SOIL OF CONTAMINANTS IN DOMESTIC WASTEWATERS

109. The Group of which I am the Science Group Leader has had a long involvement with predicting the fate and transport of wastewaters. Our skills have been used to assess whether sites are suitable for land-based discharges of wastewater, and determining what discharge conditions do not result in actual or potential contamination of groundwaters or surface water bodies, and which do not constitute public health threats.

110. In the mid-1990s, we were contracted by Palmerston North City Corporation to develop guidelines for the ETS (EvapoTranspiration and Seepage) beds that are for domestic wastewater disposal. This followed surface leakages from the ETS beds of several homes on the Tokomaru soils behind Massey University. In 1999, we wrote a report for

(then) Montgomery Watson on the proposed land-based system to dispose of Palmerston North's municipal wastewater (Clothier *et al*., 1999, as listed in Appendix B). Our modelling highlighted some environmental impacts to groundwaters and surface waters that would result from the proposed land-based scheme. Dr Steve Green recently presented his evidence on behalf of Masterton District Council concerning the impacts of the proposed upgrade of the Masterton sewerage scheme, which involves a mix of river discharge and land-based applications. His findings were based on modelling using SPASMO.

111. A typical septic tank system for the proposed lifestyle blocks is shown in Figure 11-1. Household effluent and wastewater goes directly into a septic tank, where it is partially treated to remove solids. The liquid portion of the effluent is then disposed of using buried pipes under a disposal field. Soil is recognised as an excellent medium for treating wastewater, and it is one of the most important parts of the septic system. The role of soil is to remove contaminants by natural physical, chemical and biological processes that are active in healthy soil.

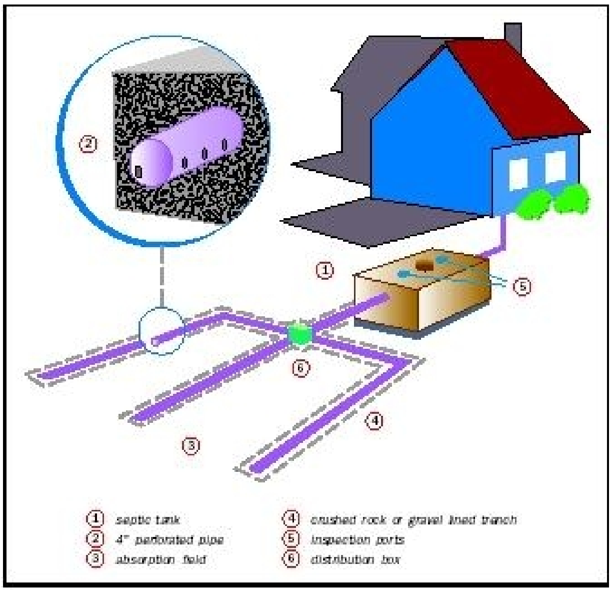


Figure 11.1 Household effluent and wastewater is treated on-site using a septic system. Outflow from the septic tank is disposed to land using a series of buried pipes

112. Barnett and Ormiston (2007) have written a manual for on-site wastewater system design and management.

113. The Proposed One Plan Policy 13-3 seeks to ensure that any selected site is suitable for on-site wasterwater management (Policy 13-3 a), and that the discharge does not result in actual and/or potential contamination of either groundwater or surface water bodies (Policy 13-3 b), and that the discharge does not constitute a public health threat.

12. USING SPASMO TO ESTABLISH CONDITIONS SO THAT DISCHARGES OF DOMESTIC WASTEWATER DO NOT RESULT IN CONTAMINATION OR HEALTH THREATS

114. Dr Steve Green of the Sustainable Land Use team of Plant and Food Research recently provided Horizons with a report that addresses the impacts of on-site domestic wastewater application by houses in two large subdivisions proposed near Levin (Green, 2008. Appendix B). The SPASMO modelling assumed that each septic tank system was operated in accordance with conditions set out by Barnett and Ormiston (2007).

115. For the purpose of modelling a unit lifestyle block the total land area was divided into three parts: 1) a disposal site; 2) an impervious area comprising the dwelling, paths and driveways; and 3) the remaining area that is in grass (Figure 12.1). Each area within the property boundaries was assumed to be on the same soil type. All the grass was mown regularly, and all clippings were returned to the soil surface where they decomposed to release organic matter, in the form of dissolved organic carbon, nitrogen and phosphorus. A tailored version of SPASMO was developed for this project in order to calculate the site's water and nutrient balance, including evaporation, run-off and drainage losses from within the property boundaries of the lifestyle block.

Figure 12.1 A schematic of the typical lifestyle block in the proposed subdivision. The total property area is divided into three parts: 1) a dwelling area; 2) an area of paths and driveways that are impervious to water flow; and 3) a disposal area where all of the household effluent and wastewater is disposed each day. For the purpose of SPASMO modelling, the remainder of the property is assumed to be in grass

116. Two types of septic tank systems were considered: a traditional septic tank, and an improved septic tank with secondary treatment. The purpose of the SPASMO modelling was:

- To calculate the leaching losses of water, nutrients (ie. nitrogen (N) and phosphorus (P)) and contaminants (ie. *Escherichia coli* bacteria) from land in the vicinity of the proposed subdivisions
- To identify the optimum lot size, expressed in dwellings per hectare of rural residential development that will support sustainable wastewater assimilation, SPASMO was used to determine the minimum property size below which the cumulative effects of wastewater are likely to cause the groundwater to become degraded to an unacceptable level.

Therefore, this modelling would ensure that the site was suitable (Policy 13-3a), that the discharges did not result in contamination of either groundwater or surface water bodies (Policy 13-3b), and that there would be no threat to public health (Policy 13-3c).

117. Phosphorus (P) is not a mobile element in the soil environment and the SPASMO modelling predicted that its potential impact on groundwater would be negligible even

after 35 years of operation. The maximum level of P in the soil was predicted to reach about 1,750 mg/kg after 25 years under the traditional septic-tank system and 1,000 mg/kg under the improved system. The phosphorus sorption saturation for this soil was found to be 2,100 mg/kg.

118. The average *E. coli* concentration of the wastewater from the septic tanks was assumed to be 10^5 cfu (colony forming units)/L for the traditional system and about 3 x 10^3 cfu/L for the new and upgraded system. SPASMO modelling predicted that 95-99% of surface-applied *E. coli* are removed during transport through the top 1.5 m of soil. Inactivation accounts for almost all the applied bacteria, while colloidal filtration acts to retard the downward movement by trapping (sticking) *E. coli* to the soil's clay surfaces. None of the simulations predict a build-up of bacteria numbers over time. Leaching to groundwater accounts for the remainder and there were times when the average concentration in the drainage water at a depth of 1.5 m exceeded 15 cfu per 100 ml; this is quite high compared with the current New Zealand Drinking Water Standards, where it is set at 1.0 cfu per 100 mL. However, additional die-off and dilution in the groundwater are expected to reduce these concentrations further. It is concluded that *E. coli* in treated effluent added to land is unlikely to have a detrimental impact on the quality of the groundwater when averaged across the unit lifestyle block.

119. However, nitrate nitrogen (N), is a mobile compound. The effluent from a modern septic tank system contains about 30 mg/L of total N, and the amount of effluent per house can be related to the number of bedrooms (a metric of number of people) in a dwelling. SPASMO modelling was used to relate the block-area averaged annual loss of nitrate-N to the dwelling size, as a function of the block size. The results are given in Figure 12.2 for block sizes of 1,250, 2,500 and 5,000 m^2. We assume that for the lifestyle block the grass will be mowed and the clippings returned to the surface. So even when there is no dwelling on the land, we still consider there to be a mowing regime. Thus, the origin of Figure 12.2 records a nitrogen loss of 18 kg-N/ha/yr even though there is no house. This is simply due to the background N loss due to the natural fertility of the soil, and the process of returning the clippings to the soil.

120. The Proposed One Plan has established N loss values for farms as a function of their Land Use Capability (LUC) class. The soil of the area under consideration in this study is LUC III, so the loss value if the block were a farm would be (in Year 1) 22 kg-N/ha/yr. Thus Figure 11.2 shows that the only lifestyle block scenario to meet this FARMS criterion would be a two-bedroom dwelling with a modern septic tank on a 5,000 m^2 block.

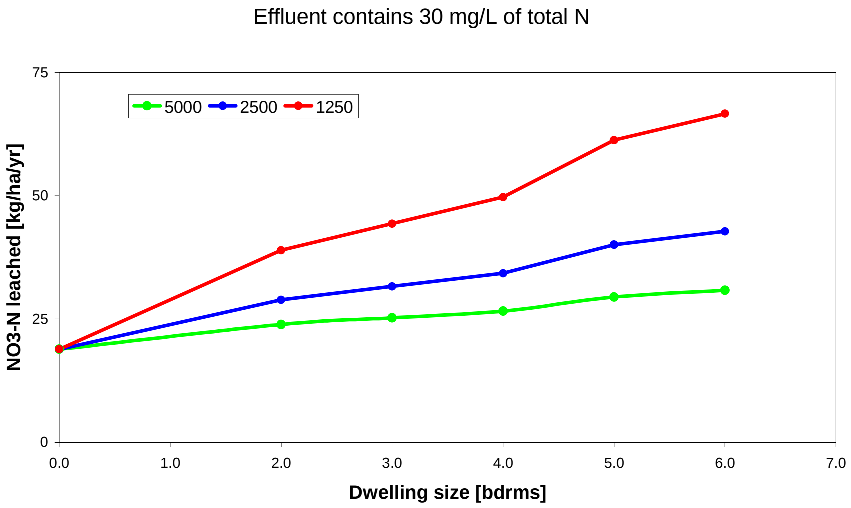


Figure 12.2 The annual leaching of nitrate-N averaged across a lifestyle block on Kawhatau stony silt loam near Levin as a function of dwelling size, measured by number of bedrooms and related to block size. The septic tank is considered here to be a modern system with secondary treatment

121. I have shown here how SPASMO was used by Green (2008) to determine whether a site was suitable for on-site discharge of domestic wastewater (Policy 13-3 a) and to establish the conditions necessary for the discharge not to result in actual or potential contamination of groundwater (Policy 13-3 b) and not to constitute a public health threat (Policy 13-3 c).

13. USING SPASMO TO DETERMINE THE IMPACT OF COMMERCIAL VEGETABLE PRODUCTION ON WATER QUALITY

122. Horizons posed further questions to SLURI in relation to the implementation of FARM strategies, and Question 3 related specifically to commercial vegetable production. My colleague Dr Steve Green developed a meta-model of SPASMO to handle the modelling difficulties associated with commercial vegetable production, wherein there can be a continuous sequence of different crops using different practices, with up to three crops per year.

123. This version of the SPASMO model was set up as a meta-model so it could be run under Microsoft Excel. The meta-model, which can now be run interactively in real-time, enables modelling to be used to explore the impact of different land use practices in commercial vegetable production.

124. We first validated the meta-model using the data results from a Sustainable Farming Fund (SFF) project carried out jointly with (then) Crop & Food Research and supported by Horizons. We collected data on crop performance and nitrate leaching under a sequence of six crops and two cycles of fallow at a large commercial vegetable enterprise near Levin (Snow *et al*., 2004). We use these results here to validate our SPASMO meta-model for predicting the leaching load from multiple sequences of crops in commercial vegetable production. The sequence of cropping and fallow was:

Fallow
Silverbeet
Summer lettuce
Spring onion
Summer lettuce
Spring onion
Winter oats
Fallow

125. The meta-model then predicts plant dry-matter yield based on the pattern of prevailing weather and the water and nutrient status of the soil, taking the fertiliser practices into account.

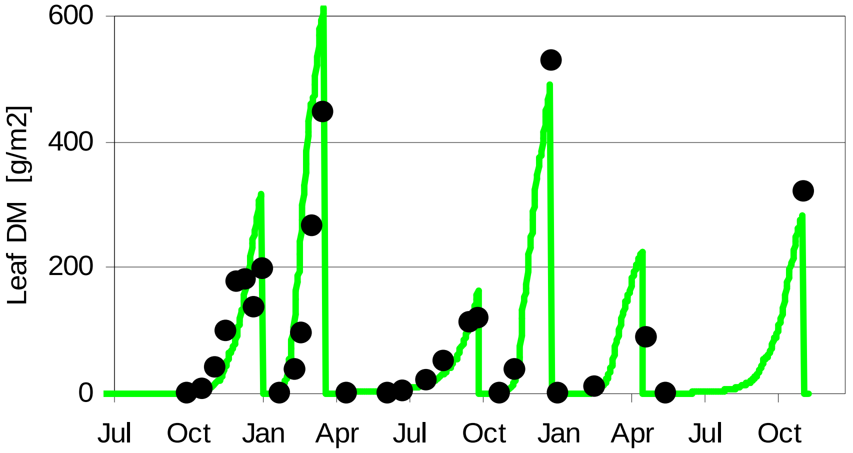


Figure 13.1 Measurements (dot markers) and model output (green line) for the above-ground dry-matter production at the commercial vegetable enterprise near Levin (Snow *et al*., 2004)

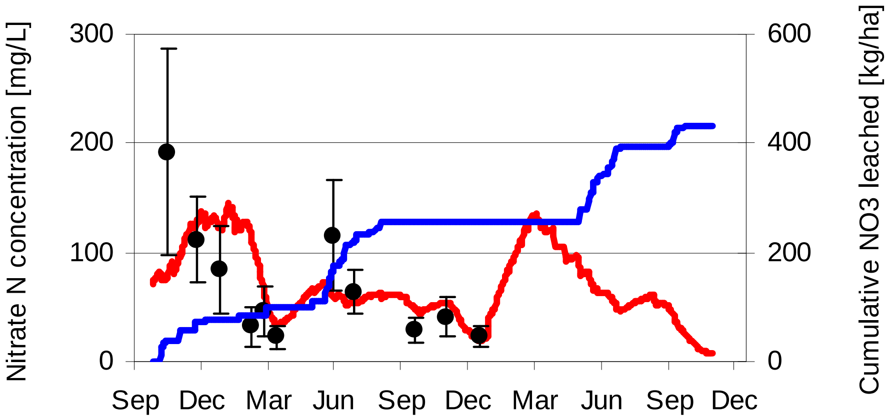


Figure 13.2 Measurements (markers) and SPASMO meta-model output (red line) for the nitrate nitrogen content of drainage water at 60 cm. Open symbols are data from suction cups. The filled symbols are data from soil cores. The blue line represents the model output for the cumulative amount of nitrate-N leached below the rootzone. Our calculations predict that some 431 kg/ha of nitrate-N was leached during the two-year observation period. The average NO3-N concentration was 69 mg/L

126. The comparison of the model predictions with the suction-cup samplings of Snow *et al.* (2004) reveals good correspondence (Figure 13.2). Also shown in Figure 13.2 is the cumulative loss of nitrate over the two-year period.

127. To demonstrate the utility of the meta-model as a tool to explore options to reduce nutrient loadings on groundwater from commercial vegetable production, we presented the predictions from four scenarios. Here, I describe the results from the modelling of the third scenario, when only half the compost was applied at the outset, and none was applied on 11 April at the planting of the first spring onion crop.

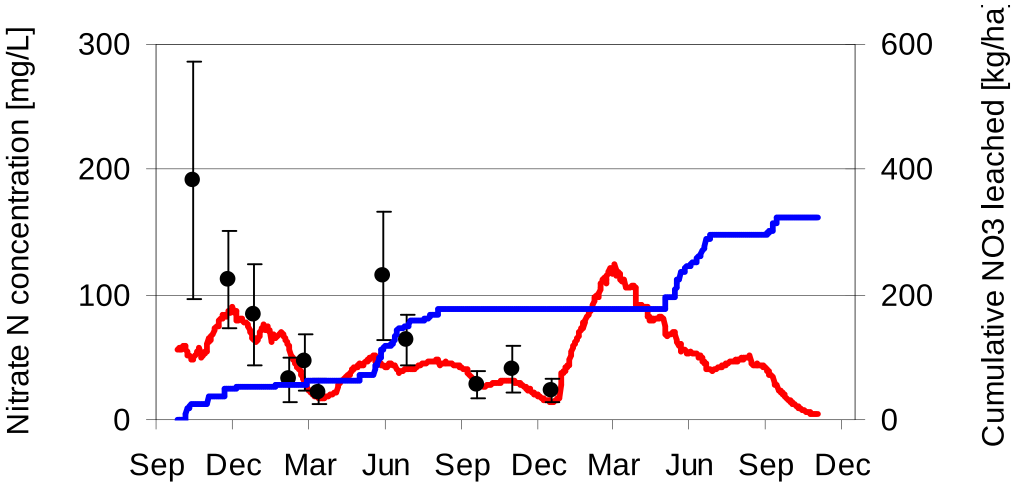


Figure 13.3 As in Figure 13.2 but only applying half the amount of compost at the start and none of the ‘special’ N-fertiliser to the first crop of spring onions. This reduced nitrate leaching by about 100 kg/ha *cf* actual practice, but crop yields were down by ~10%

128. Our SPASMO meta-modelling predicted that if only half the rate of compost were applied at the outset, coupled with no application of the 155 kg-N/ha at the planting of the second spring onion crop, there would only be a 10% loss in crop yield, and a 25% reduction in cumulative N loss (Figure 13.3). The average nitrate concentration would be 50.5 mg NO_3/L, a drop of 27%, resulting from the practices over 2001-2003.

129. The meta-model of SPASMO we developed for this second Horizons project can handle multiple sequences of vegetable crops and runs under Microsoft Excel. We validated the meta-model against our field data from a previous study conducted over years. The meta-model is site specific and uses local weather records.

130. We concluded that the SPASMO meta-model could be used as a tool to work with vegetable growers and croppers, in conjunction with Horizons, to explore options for managing production, and to assess the trade-offs between fertiliser practices, irrigation schedules, crop yield and nutrient leaching to shallow groundwaters and surface drains.

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August 2009

APPENDIX A: SPASMO – GENERAL DESCRIPTION

A.1. A general description of the SPASMO model

The SPASMO computer model considers water, solute (eg. nitrogen and phosphorus), and microbial (eg. viruses and bacteria) transport through a 1-dimensional soil profile. The soil water balance is calculated by considering the inputs (rainfall and irrigation) and losses (plant uptake, evaporation, run-off and drainage) of water from the soil profile. The model includes components to predict the carbon, nitrogen and phosphorus budget of the soil. These components allow for a calculation of plant growth and uptake of both N and P, various exchange and transformation processes that occur in the soil and aerial environment, recycling of nutrients and organic material to the soil biomass, and the addition of surface-applied fertiliser and/or effluent to the land. The filtering capacity of the soil with regard to micro-organisms is modelled using an attachment-detachment model with inactivation (ie. die-off) of microbes.

Model results for the water balance are expressed in terms of mm (= one litre of water per square metre of ground area). The concentration and leaching losses of nutrients are expressed in terms of mg/L and kg/ha, respectively. The microbial concentrations and leaching losses are expressed in terms of colony forming units, cfu/L and cfu/m^2, respectively. All calculations are run on a daily basis and the results are presented at the paddock scale.

A.2. Water and solute flow through the soil

The flow of water through the soil profile is simulated using a capacity model similar to that of Hutson and Wagenet (1993), in which the soil water is divided into mobile and immobile phases. The mobile domain is used to represent the soil’s macropores (eg. old root channels, worm holes and cracks) and the immobile domain represents the soil matrix. The equations describing water and contaminant flow are simple, but lengthy, and so they are not repeated here (see Hutson and Wagenet (1993) for details).

On days when there is rain or irrigation, both applied water and any dissolved solutes are added to the surface layer. The maximum amount of water that can infiltrate the soil is limited by the storage capacity of the profile, and the minimum saturated hydraulic conductivity of the subsoil. The water content of topsoil (0-30 cm) can’t exceed saturation, otherwise some run-off is generated. After rainfall or irrigation, water is allowed to percolate through the soil profile, but only when the soil is above field capacity. The infiltrating water firstly fills up the immobile domain and, once this domain is filled, it then refills the mobile domain as the water travels progressively downward through the soil profile. If the soil is above field capacity, then the infiltrating water and solute resides in the mobile domain where it can percolate rapidly down through the soil profile until it reaches a depth where the water content is no longer above field capacity. This macropore flow is rapid and does not allow enough time for exchange between the mobile and immobile domains. As a consequence, the two flow domains are temporarily at quite different solution concentrations as water percolates through the soil profile.

Subsequently, on days when there is no significant rainfall, there is a slow approach to equilibrium between the mobile and immobile phases, driven by a difference in water content between the two domains. The rules for the subsequent slow approach to equilibrium between the mobile and immobile phases within a depth, or model segment, are described in their original scientific paper (Hutson and Wagenet, 1993).

If a soil layer is below field capacity or if there is no rainfall or irrigation to generate percolation, then each soil segment *i* is brought towards equilibrium with the segment *i*+1 beneath, starting from the top of the profile. This redistribution of water is achieved by (i) calculating the amount of water required to move upwards or downwards so that each soil segment reaches an equilibrium water potential with its neighbour, and (ii) allowing only half this water to move, together with its dissolved solute. After all segments have been adjusted, each solute (ie. ammonium, nitrate, phosphorus and bacteria) is repartitioned between aqueous and solid (sorbed) phases, assuming complete equilibrium between mobile and immobile phases.

The total water content in each soil segment (W_T [mm]), is given by the sum of the water contents in the immobile and mobile soil domains

$$W_T = W_I + W_M \, . \qquad \text{[Eq. A1]}$$

and total amount of solute in each soil segment (M_C [mg/m^2]) is calculated as

$$M_C = C_I W_I + C_M W_M + S\, r\, \Delta z \qquad \text{[Eq. A2]}$$

Here, *C* is the solution concentration [mg/L], *S* represents the amount of sorbed solute [mg/kg], ρ is the bulk density [kg/L], Δz is the segment thickness [mm], and the subscripts *I* and *M* refer to the immobile and mobile domains, respectively. The sorption of ammonium and nitrate is described using a simple linear isotherm of the form

$$S = K_D C \qquad \text{[Eq. A3]}$$

where K_D represents the distribution coefficient [L/kg]. In the case of nitrate, which is considered to be inert, we assume no adsorption and set K_D equal to zero. The equilibrium solution concentration (*C*), in both mobile and immobile phases of nitrate and ammonium, is then calculated as

$$C = M_C / \left(r\ S\, \Delta z + W_T \right). \qquad \text{[Eq. A4]}$$

The sorption of phosphorus is non-linear and is described using a Langmuir isotherm of the form

$$S = \frac{Q\, bC}{1 + bC} \qquad \text{[Eq. A5]}$$

where *Q* is the maximum total mass of phosphorus at saturation per mass unit of dry soil [µg/g], and *b* is an empirical constant, with units of inverse of solution concentration [L /mg]. The *b*-parameter defines the point where the soil is at half-saturation with respect maximum sorption of P.

Bacterial transport is calculated using the same convection-dispersion type equation as for water and solute transport, with additional terms used to represent the kinetic sorption of bacteria to soil's mineral particles as well as the subsequent detachment and transfer of bacteria between the aqueous and solid phases. The attachment-detachment process is described using first-order rate constants that strongly depend on soil water content (Logan *et al.*, 1995). The rate of change in the solid-phase is modelled as

$$r \frac{\partial S}{\partial t} = q\, k_a\, y\ C - k_d\ r\ S \qquad \text{[Eq. A6]}$$

Here k_a is the first-order deposition (attachment) coefficient [d^{-1}], k_d is the first-order entrainment (detachment) coefficient [d^{-1}], and ψ is a dimensionless colloid retention function [-] that describes blocking of the sorption sites. This ψ-factor is calculated from the size of the sand grains and the relative solid-phase concentration (Johnson & Elimelich, 1995). The attachment coefficient is calculated using a quasi-empirical formulation that takes account of the mean grain diameter of the porous media d_c [mm] and the pore-water velocity υ [mm/d], as well as terms to describe the collector efficiency η [-], and the collision (or sticking) efficiency α [-]

$$k_a = \frac{3\left(1-q\right)}{2\,d_c} h\ a\ u \qquad \text{[Eq. A7]}$$

The mathematical formulation of these terms, and suggested parameter values are given in Simunek *et al*. (2005). The collector efficiency accounts for the combined effects of particle size (eg. bacteria or virus), fluid density and viscosity, pore-water velocity, and the water content and temperature of the soil. Because attachment is (approximately) inversely proportional to the grain size of the soil particles, finer grained soils such as silts and clays tend to be more efficient at trapping bacteria that are transported with the drainage waters. Furthermore, the smaller sized microbes (ie. virus cf. bacteria) are less likely to be intercepted by the soil particles (ie. have a smaller collector efficiency), so the relative value of k_a is reduced. For the purpose of modelling, the ratio k_a/k_d has been set to a constant value of 100. Other parameters used in modelling bacterial (ie. *E. coli*) transport through the soil are discussed in Appendix B.

A.3. Calculation of crop water use

A standard crop-factor approach is used to relate crop water use to the prevailing weather and physiological time of development. The procedure is based on guidelines given by the Food and Agriculture Administration (FAO) of the United Nations (Allen *et al*., 1998). Daily values of global radiation, air temperature, relative humidity and wind speed are required for the calculation. These have been downloaded from the NIWA database using historical records. The reference evaporation rate (ET_0 [mm/d]) is calculated as

$$l\,ET_0 = \frac{s\,(R_N - G_H) + r_A c_P (e_s - e_a)/r_A}{s + g\left(1 + r_S / r_A\right)} \qquad \text{[Eq. A8]}$$

where R_N [MJ/m^2/d] is the net radiation, G_H [MJ/m^2/d] is the ground heat flux, T [^{o}C] is the mean air temperature, e_s [kPa] is the saturation vapour pressure at the mean air temperature, e_a [kPa] is the mean actual vapour pressure of the air, s [Pa/^{o}C] is the slope of the saturation vapour-pressure versus temperature curve, γ [66.1 Pa] is the psychometric constant, and λ [2.45 MJ/kg$^-$ is the latent heat of vaporisation for water, and the terms r_S and r_A refer to the (bulk) surface and aerodynamic resistances, respectively. The surface resistance for evaporation from the pasture is set equal to 70 s/m (Allen *et al*., 1998). Similarly, the surface resistance for evaporation from the pond is set equal to zero. The aerodynamic resistance for both the pasture and the pond has been set equal to $208/U_2$, where U_2 is the median wind speed at a height of 2 m.

ET_0 defines the potential rate of evaporation from an extensive surface of green grass cover, of a short, uniform height, that is actively growing, completely shading the ground, and not short of water or nutrients. The potential water use of the crops is then calculated

$$ET_C = K_C ET_0 \qquad \text{[Eq. A9]}$$

using a crop factor K_C derived from the amount of light intercepted by the leaf canopy. Light interception is a function of the Leaf Area Index (LAI) [m^2 of leaf per m^2 of ground area] (Green *et al*., 2003a), and this is re-calculated each day. Coppicing the trees will reduce LAI and this impact on ET_C via a reduction in K_C.

When soil water and nutrients are non-limiting, water is extracted easily by the plant roots, and transpiration proceeds at the potential rate ET_C. However, as the soil dries, water becomes more strongly bound by capillary and absorptive forces to the soil matrix. Plant roots then have to work much harder to extract water from ‘dry’ soil. Plants will tolerate a certain level of water deficit in their rootzone soil, yet they will eventually exhibit symptoms of water stress (ie. reduced transpiration and loss of turgor) if the soil water content drops below a certain threshold value.

An empirical adjustment factor K_R [-] is used to represent the plant’s tolerance to water stress. The Total Available Water (TAW) [mm], as defined by the difference between the water content at field capacity (-10 kPa matric potential) W_{FC} [mm] and wilting point (-1500 kPa matric potential) W_{WP} [mm], is calculated across the depth of the rootzone, z_R [mm]. The Plant Available Water (PAW) [mm] is then defined by a fraction p of TAW that a crop can extract from the rootzone without suffering water stress. Values of p are listed in Table 22 of Allen *et al*. (1998). The pattern of water and nutrient uptake from the rootzone soil is determined from the depth-wise pattern of root development (Green *et al*., 2002).

A.4. Modelling surface run-off

The surface run-off component of SPASMO is based on a daily rainfall total. The calculation uses the Soil Conservation Service (SCS) curve number approach (Williams, 1991). The curve number approach was selected here because: 1) it is based on more 30 years of run-off studies on pasture, arable and forest sites in the USA; 2) it is computationally simple and efficient; 3) the required inputs are available; and 4) the calculation relates run-off to soil type, land use and management practice.

Surface run-off is predicted from daily rainfall plus irrigation, using the SCS curve number equation:

$$\begin{aligned} Q &= \frac{(R-0.2S)^2}{R+0.8S}\,, && R > 0.2S \\ Q &= 0\,, && R \leq 0.2S \end{aligned} \qquad \text{[Eq. A10]}$$

where Q [mm] is the daily run-off, R [mm] is the daily rainfall plus irrigation, and S [mm] is the retention parameter that reflects variations among soils, land use and management. The retention parameter (S) is related to the curve number (CN) using the SCS equation (Soil Conservation Service, 1972)

$$S = 254\left(\frac{100}{CN} - 1\right) \qquad \text{[Eq. A11]}$$

where the constant, 254, gives S in millimetres. Moisture condition 2 (CN_2), or the average curve number, can be obtained easily for any area of land use type from the SCS Hydrology Handbook (Soil Conservation Service, 1972). An example of CN numbers is given below for a range of pasture and drainage conditions.

Table A1 SCS curve number for a grazed pasture (Soil Conservation Service 1972)

SCS CN number		Drainage Condition			
		Excessive	Good	Fair	Poor
Pasture Condition	Good	39	61	74	80
	Average	49	69	79	84
	Poor	68	79	86	89

A pasture in good condition that is growing on a free draining soil will have a low CN value (39), while a pasture in poor condition and on a poorly drained soil will have a high CN value (89). A lower CN value implies a bigger retention parameter (S), so a given soil/pasture combination will yield less run-off for the same daily rainfall total. The SCS run-off calculation also includes an additional adjustment to S, to express the effect of slope and soil water content (Williams, 1991). In the calculations presented here, we have assumed the pasture slope is always less than 5% and have used a reference CN value for a pasture sward in average condition. The only other allowance that we have made, with respect to run-off, is to include any changes in *S* that are due to different soil water contents.

A.5. Nitrogen balance of the soil

The nitrogen component of SPASMO is based on a set of balance equations that account for nitrogen uptake by plants, exchange and transformation processes in the soil, losses of gaseous nitrogen to the atmosphere, additions of nitrogen in the effluent or fertiliser, and the leaching of nitrogen below the rootzone. SPASMO considers both organic nitrogen (ie. in the soil biomass) and the mineral nitrogen (ie. urea, ammonium and nitrate). Dissolved urea and nitrate are considered to be mobile and to percolate freely through the profile, being carried along with the invading water. The movement of dissolved ammonium is retarded as it binds to the mineral clay particles of the soil. The soil can receive inputs of organic carbon and nitrogen from decaying plant residues, which are added to the litter layer of the topsoil, and inputs of ammonium and nitrate in the effluent applied to the soil surface. Details of the nitrogen component of SPASMO are published in Rosen *et al*. (2004).

A.6. Crop growth

The uptake of soil nutrients (ie. nitrogen and phosphorus) by pasture and trees is determined largely by the growth of the above- and below-ground DM, multiplied by their respective nitrogen concentrations. Daily biomass production is modelled using a potential production rate per unit ground area (G (kg/m^2/d)) that is related, via a conversion efficiency (ε (kg/MJ)), to the amount of solar radiant energy (Φ (MJ/m^2/d)), intercepted by the leaves

$$G = e\,\Phi\ f_T\ \ f_N\ \ f_W \qquad \text{[Eq. A12]}$$

Here, f_T, f_N and f_W are response functions that range between zero and unity depending on temperature, plant nitrogen and soil water status respectively (Eckersten and Jansson, 1991). The value of G depends on the daily sunshine and temperature, plus the Leaf-Area Index of the crop, and is moderated by the soil's water and nitrogen status (King, 1993; Thornley *et al*., 1995). Crop growth is maximised only if soil water and soil nutrients are non-limiting.

A simple allometric relationship is used to partition the daily biomass production into the growth of the foliage, stem material and roots. Plant biomass is expressed in terms of the balance between growth and senescence of the plant organs. For each plant organ we write out a simple mass balance equation that considers inputs of DM due to carbon allocation, losses of DM as the plant's senescence, and the removal of DM as the plants are harvested. The total mass of foliage (F [kg/m^2]) is calculated from

$$\frac{dF}{dt} = a_F G - g_F F - H_F \qquad \text{[Eq. A13]}$$

the total mass of stem material (S [kg/m^2]) is calculated from

$$\frac{dS}{dt} = a_S G - g_S F - H_S \qquad \text{[Eq. A14]}$$

and the total mass of roots (R [kg/m^2]) is calculated from

$$\frac{dR}{dt} = a_R G - g_R R \qquad \text{[Eq. A15]}$$

Here α_F is the fraction of biomass partitioned to the foliage, a_S is the biomass partitioned to the stem, and a_R (=1-α_F-α_S) is the fraction of biomass allocated to the roots, and γ is the corresponding senescence rate for these plant components. The variable *H* is used to represent the amount of DM that is removed during harvest. In the case of fruiting crops, additional terms are included in each balance equation to represent an amount of DM transferred to fruit production.

Allocation of DM to the roots depends on the leaf nitrogen content ($[N]_{F)}$, having a minimum value [α_{R0}] at a maximum leaf concentration ($[N]_{Fx)}$, and increasing as N_L decreases (Eckersten and Jansson 1991)

$$a_R = a_{R0} + 1 - \left(1 - \left(\left([N]_{Fx} - [N]_F\right)/[N]_{Fx}\right)^2\right)^{0.5} \qquad \text{[Eq. A16]}$$

This formulation enables SPASMO to accommodate seasonal changes in DM allocation associated with a changing leaf nutrient status. For simplicity, any seasonal changes in senescence rates have been neglected in the model because we are concerned with the long-term consequences of DM allocation.

A.7. Nitrogen and phosphorus uptake

The model assumes plant growth will achieve a maximum potential only if water, nitrogen and phosphorus are non-limiting. The nitrogen demand for crop growth is set by the maximum nitrogen content of the root ($[N]_{Rx}$), leaf ($[N]_{Fx}$) and stem ($[N]_{Sx}$) material. During active growth, the plant tries to supply new DM material with nitrogen corresponding to these maximum concentrations. The potential uptake of nitrogen (U_N [kg/ha/d]) is defined as

$$\begin{aligned} U_N = \; & \left(a_F G[N]_{Fx} - l_F g_F F[N]_F\right) \\ & +\left(a_S G[N]_{Sx} - l_S g_S S[N]_S\right) + \left(a_R G[N]_{Rx} - l_R g_R R[N]_R\right) \end{aligned} \qquad \text{[Eq. A17]}$$

And this represents the new growth at the maximum N content minus an amount of nitrogen translocated from the senescing plant material. The potential (maximum) nitrogen uptake can only be met if sufficient nitrogen exists in the soil. Otherwise all [*N*]s will be reduced in low-nitrogen soils, and crop growth will be curtailed. The potential of phosphorus uptake is modelled in the same way, based on the maximum P content of the respective plant parts.

Daily uptake of nitrogen is assumed to be proportional to the local distribution of the fine roots, and the total amount of nitrate (NO_3^-) and ammonium (NH_4^+) in each soil layer (Johnsson *et al*., 1987). The potential uptake of nitrate is calculated as

$$U_{NO3-} = \min\left(r_R(z)\, \frac{NO_3^{\,-}}{NO_{3-} + NH_4^{\,+}}\, U_N \,,\; f_M NO_3^{\,-} \right) \qquad \text{[Eq. A18]}$$

based on the relative root fraction in the layer ($r_R(z)$), the proportion of total mineral nitrogen as nitrate, and the total growth requirement for nitrogen (U_N). However, the actual uptake of nitrate is limited to a fraction (f_M [-]) of the total nitrate available in each layer. Ammonium uptake is calculated in a similar way, being proportional to the relative amount of ammonium in solution.

Surface roots are the most active (Clothier and Green, 1994) and they preferentially extract soil water and nutrients from the upper soil layers. However, as water and nitrogen stresses develop, the uptake activity typically switches to the deeper roots if more water and nutrients are available there. This feature of root action is modelled in the following way. Whenever the total nitrogen uptake from a given soil layer is less than the potential rate, then the model allows for a compensatory increase in uptake from remaining layers deeper in the rootzone (Johnsson *et al*., 1987). This is achieved by adding a fraction (c_{um} [-]) of the deficit to the potential uptake from the next soil layer, where more mineral nitrogen may be available.

Daily allocation of nitrogen to the new plant material is based on the idea that roots receive nitrogen first, until they reach their maximum concentrations; then nitrogen is allocated to the stem, and finally to the leaves. If soil nitrogen becomes limiting, a reduction factor ($f_{N)}$ is used to reduce the total nitrogen uptake. This reduction function also effectively reduces the leaf nitrogen contents and alters the DM allocation pattern (Eckersten and Jansson, 1991). A similar scheme is adopted for P uptake and allocation across the new plant material.

Pasture growth parameters in this study have been chosen to generate appropriate levels of DM production, ie. the model simulates between 10-15 Mg DM/ha yields from an irrigated pasture, and adds about 1,000 kg DM for every 100 kg N/ha of nitrogen in the effluent.

A.8. Carbon and nitrogen dynamics of the soil organic matter

The decomposition of soil biomass adds an amount of mineral nitrogen, in the form of ammonium, to the soil. This transformation process, known as mineralisation, is modelled by dividing the soil's total organic matter into three pools – a fast cycling litter pool, an almost stable humus pool, and a manure pool (Johnsson *et al*., 1987). The relative amount of organic-N in these three pools changes daily to reflect inputs of fresh biomass, and manure, and the losses of soil biomass and plant residue as it decomposes. The nitrogen demand for this internal cycling of the soil's organic carbon and nitrogen is regulated by the C/N ratio of the soil biomass (r_O), which is one of the model inputs.

Decomposition of soil litter carbon (C_L) is modelled as a first-order process and is specified by a rate constant (K_L) that is influenced by temperature and soil moisture. The products of decomposition are CO_2, stabilised organic material (humus) and, conceptually, microbial biomass and metabolites. The relative amount of these products is determined by a synthesis efficiency constant (f_E) and a humification fraction (f_H). The following mass balance equations, which represent the inputs minus the outputs of soil-C and soil-N, are used to model the turnover of carbon and nitrogen in the litter pool

$$\frac{\partial C_L}{\partial t} = \left[\left(1 - f_H\right) f_E - 1\right] . K_L . C_L + F_{C,L}$$

$$\frac{\partial N_L}{\partial t} = \left[\left(1 - f_H\right) f_E \frac{1}{r_O} - \frac{N_L}{C_L}\right] . K_L . C_L + F_{N,L} \qquad \text{[Eq. A19]}$$

where *F* represents the amount of fresh organic matter that is added to the soil biomass. A similar set of equations describes the turnover of carbon and nitrogen in the manure pool (although this pool is not modelled here).

$$\frac{\partial C_M}{\partial t} = \left[\left(1 - f_H\right) f_E - 1\right] . K_M . C_M + F_{C,M}$$

$$\frac{\partial N_M}{\partial t} = \left[\left(1 - f_H\right) f_E \frac{1}{r_O} - \frac{N_M}{C_M}\right] . K_M . C_M + F_{N,M} \qquad \text{[Eq. A20]}$$

Lastly, the set of mass balance equations describing the turnover of carbon and nitrogen in the humus pool are given by

$$\frac{\partial C_H}{\partial t} = f_E . f_H . K_L . C_L - K_H . C_H + F_{C,H}$$

$$\frac{\partial N_H}{\partial t} = \frac{f_E . f_H}{r_O} K_L . C_L - K_H . N_H + F_{N,H} \qquad \text{[Eq. A21]}$$

Decomposition of soil humus (C_H) follows first-order kinetics with a specific rate constant (K_H) that depends on temperature and soil moisture. The other terms in these mass balance equations have already been described above.

Soil carbon and nitrogen turnover reactions result either in a net production (mineralisation) or a net consumption (immobilisation) of ammonium, depending on the C/N ratio of the soil biomass. From a consideration of mass balances, any increase in NH_4^+-N, due to mineralisation, must equal the decrease in organic-N from the three organic matter pools. Thus, the following mass-balance equation is used to predict nitrogen mineralisation

$$\frac{\partial NH_4^+}{\partial t} = \left[\frac{N_L}{C_L} - \frac{f_E}{r_O}\right] K_L . C_L + \left[\frac{N_M}{C_M} - \frac{f_E}{r_O}\right] K_M . C_M + K_H . N_H \qquad \text{[Eq. A22]}$$

Net mineralisation occurs whenever $\partial NH_4^+/\partial t > 0$, otherwise immobilisation occurs. The calculations recognise that, if no ammonium is available for immobilisation, then nitrate can be used according to the following equation

$$\frac{\partial NO_3^-}{\partial t} = -\frac{f_E}{r_O}\left(K_L.C_L + K_M.C_M\right) \qquad \text{[Eq. A23]}$$

During all simulations reported here, literature values were adopted for most of the parameters: the rate constants were set equal to K_L=0.015/d, K_M = 0.015/d and K_H=0.00005/d; constant values were used for the efficiency of carbon turnover, f_E=0.5, the humification fraction, f_H=0.2, and the C/N ratio of the soil biomass, r_O=10.0, as suggested by Johnsson *et al*. (1987).

For the purpose of modelling, senescing plant material is added to a single pool of organic P in the litter layer. The turnover of this organic phosphorus, to create mineral phosphorus (ie. dissolved reactive phosphorus) is modelled simply by assuming decomposition is a first-order process specified by the rate constant K_L, and moderated by temperature and soil moisture functions.

A.11. Soil transformation processes for nitrogen

All N-transformation processes in the soil are assumed to be first-order with rate constants that are regulated by both temperature and moisture status of the soil. The effect of soil temperature is expressed using a Q_{10} relationship (Bunnell *et al*., 1977)

$$f_T(z) = Q_{10}^{\left[\frac{T(z)-T_B}{10}\right]} \qquad \text{[Eq. A24]}$$

where $T(z)$ is the soil temperature for the layer, T_B is the base temperature at which f_T equals 1, and Q_{10} is the factor change in rate due to a 10-degree change in temperature. The soil moisture factor decreases, on either side of an optimum level, in drier soil or in excessively wet soil (Johnsson *et al*., 1987), ie.

$$\begin{aligned}
f_W(z) &= f_S + (1-f_S)\left[\frac{q_S(z)-q(z)}{q_S(z)-q_H(z)}\right]^M && q_H(z) < q(z) < q_S(z), \\
f_W(z) &= 1 && q_L(z) < q(z) < q_H(z), \\
f_W(z) &= \left[\frac{q\ \ (z)-q_W(z)}{q_L(z)-q_W(z)}\right]^M && q_W(z) < q(z) < q_L(z), \qquad \text{[Eq. A25]}
\end{aligned}$$

where θ_S is the saturated water content, θ_H and θ_L are the high and low water contents, respectively, for which the soil moisture factor is optimal, and θ_W is the minimum water content for process activity. The factor f_S defines the relative effect of moisture when the soil is completely saturated, and M is an empirical constant.

The nitrogen model accounts for the internal cycling and transformation of three forms of mineral nitrogen (ie. urea, ammonium and nitrate). The hydrolysis of urea (U, mg/L) to ammonium (NH_4^+, mg/L) is modelled as

$$\left.\frac{dU}{dt}\right|_{U\rightarrow NH4+} = -k_1\ f_T(z)\ f_M(z)\ NH_4^{\ +} \qquad \text{[Eq. A26]}$$

and this process is defined by a first-order rate constant (k_1). The transfer of ammonium to nitrate (NO_3^-, mg/L) is modelled as

$$\left.\frac{dNH_4^{\ +}}{dt}\right|_{NH4+\rightarrow N03-} = -k_2\ f_T(z)\ f_M(z)\left[NH_4^{\ +} - \frac{NO_3 -}{n_q}\right] \qquad \text{[Eq. A27]}$$

and depends on the potential rate constant (k_2), which is reduced as the nitrate-ammonium ratio (n_q) of the soil is approached. If $NH_4^+ < NO_3^- / n_q$ then no transfer of ammonium to nitrate takes place.

Denitrification is the transfer of nitrate to gaseous nitrogen (N_2 and N_2O) products. This is an anaerobic process and consequently is highly dependent on soil aeration. Soil water content is used as an indirect expression of the oxygen status of the soil. The influence on the denitrification rate is expressed as a power function

$$f_D(z) = \left[\frac{q(z) - q_D(z)}{q_S(z) - q_D(z)}\right]^d \qquad \text{[Eq. A28]}$$

that increases from a threshold point (θ_D), is maximum at saturation (θ_S), and d is an empirical constant. No denitrification occurs below the threshold point. The denitrification rate for each layer is modelled as

$$\left.\frac{dNO_3^{\ -}}{dt}\right|_{NO3-\rightarrow gas} = -k_3(z)\ f_T(z)\ f_D(z)\left[\frac{NO_3^{\ -}}{NO_3^{\ -} + c_S}\right] \qquad \text{[Eq. A29]}$$

and depends on a potential denitrification rate (k_3), the soil aeration status (f_D), and the same temperature factor (f_T) used for the other biologically-controlled processes. The rate constant k_3 is assumed to be a linear function of soil organic-carbon (Smith & Arah, 1990). The factor c_S is the nitrate concentration where the denitrification rate is 50% of the maximum while all other factors are optimum.

The ammonia volatilisation model incorporates the effect of soil and effluent pH, soil and air temperature, wind speed, and soil water content (Smith *et al.*, 1996). The following mechanistic equation of Wu *et al*. (2003) is used to prescribe the soil-surface volatilisation rate (J_V [kg/m^2/s]), as

$$J_V = \left(\frac{q_0}{q_S}\right) h_M \left(\frac{K_A K_H}{10^{-pH}} NH_4{}^+\right)\Bigg|_{z=0} \qquad \text{[Eq. A30]}$$

where h_M is the average mass transfer coefficient, K_A is the equilibrium constant relating the concentrations of ammonium ion and dissolved ammonia in soil solution, and K_H is Henry's constant for the dissolution of gas-phase and liquid-phase ammonia in soil solution. The formulation for these three factors is presented in Wu *et al*. (2003).

A.12. Mass-balance equations for mineral nitrogen and phosphorus and microbes

The nitrogen transport model allows for an input of mineral nitrogen in the form of urea, ammonium or nitrate. The fate of surface-applied urea is determined by two competing processes:

- Losses due to hydrolysis of urea to ammonia
- Losses due to the drainage of urea through the soil profile.

We have assumed that all the urea enters the soil, and that any surface run-off of urea is negligible. The total mass of urea (M_U [mg/m^2]) in each soil slab of thickness (z_R [mm]) is found by solving the following mass balance equation

$$\frac{dM_U}{dt} = z_R \frac{dq\,R_U U}{dt} = X_{U,i} - \left(k_1 z_R q U + J_W U\right) \qquad \text{[Eq. A31]}$$

where U [mg/L] is the concentration of urea in soil solution, θ [m^3 m^{-3}] is the soil's volumetric water content, $X_{U,i}$ [mg/m^2] is the mass of urea added to the i-th segment (=0 if i >1), k_1 [d^{-1}] is the rate-constant describing the hydrolysis of urea to ammonium, $J_W U$ [mm/d] represents the percolation of dissolved urea through the soil. Urea is rapidly hydrolysed to ammonium, in a matter of a few days. The fate of ammonium-nitrogen is determined by six competing processes:

- Inputs from the mineralisation of the soil biomass
- Retardation due to the adsorption of ammonium to the soil particles
- Losses due to the nitrification of ammonium into nitrate
- Losses due to the volatilisation of ammonia gas
- Losses due to the drainage of ammonium through the soil slab
- Losses due to plant uptake.

The total mass of ammonium (M_A [mg/m^2]) in each soil slab is found by solving the following mass balance equation

$$\begin{aligned}\frac{dM_A}{dt} = z_R \frac{dq\,R_A A}{dt} &= \left(X_{A,i} + S_M + k_1 z_R q\ U\right) \\ &\quad - \left(k_2 z_R q\left(A - N/n_q\right) + J_V + P_A + J_W A\right)\end{aligned} \qquad \text{[Eq. A32]}$$

where A [mg/L] is the concentration of ammonium in soil solution, $X_{A,i}$ [mg/m^2] is the total mass of ammonium added to the i-th layer (=0 if i >1), S_M [mg/m^2] is rate of mineralisation, P_A [mg/m^2/d] is the rate of plant uptake, k_2 [d^{-1}] is a rate constant to describe the nitrification of ammonium to nitrate, and $J_W A$ [mg/m^2/d] represents the percolation of dissolved ammonium through the soil slab. Here, J_V represents the volatilisation of ammonia to the atmosphere. For simplicity, we have calculated J_V only for the top 10 cm of soil and set it equal to zero elsewhere. $R_A = (1 + \rho K_D/\theta)$ is the retardation factor for ammonium, ρ [kg/L soil] is the soil's dry bulk density, and K_D [L/kg] is the distribution coefficient that determines how much ammonium gets adsorbed to the cation-exchange sites of the soil.

The fate of any nitrate in the soil water is determined by the following six processes:

- Inputs of nitrate from fertiliser application
- Inputs from the nitrification of ammonium
- Retardation due to the adsorption of nitrate (= 0 in most mineral soils)
- Losses from denitrification
- Losses due to plant uptake
- Losses due to the drainage of nitrogen beyond the rootzone.

The total mass of nitrate-nitrogen (M_N [mg/m^2]) in each soil slab is found by solving the following mass balance equation

$$\frac{dM_N}{dt} = z_R \frac{dq\,R_N\,N}{dt} = \left(X_{N,i} + k_2 z_R q\ A\right) - \left(k_3 z_R q\left[\frac{N}{N+c_S}\right] + P_N + J_W N\right) \qquad \text{[Eq. A33]}$$

where N [mg/L] is the concentration of nitrate in soil solution, $X_{N,i}$ [mg/m^2] is the total mass of nitrate-nitrogen added to the *i*-th layer (=0 if *i* >1), k_3 [d^{-1}] is a rate constant to describe denitrification losses, P_N [mg/m^2/d] is the rate of plant uptake, and $J_W N$ [mg/m^2/d] represents the drainage of nitrate through the soil slab. We consider denitrification to be a microbial process that is rate-limited by the amount of soil organic carbon (the energy source) and mineral nitrogen (the nutrient source).

The total mass of mineral phosphorus (M_P [mg/m^2]) in each soil slab is found by solving the following mass balance equation

$$\frac{dM_P}{dt} = z_R \frac{dq\,R_P\,P}{dt} = \left(X_{P,i} + S_P - P_P + J_W P\right) \qquad \text{[Eq. A34]}$$

where P [mg/L] is the concentration of dissolved reactive phosphorus in soil solution, $X_{P,i}$ [mg/m^2/d] is the total mass of phosphorus added to the *i*-th layer (=0 if *i* >1), S_P [mg/m^2/d] is the rate of mineralisation of organic phosphorus, P_P [mg/m^2/d] is the rate of plant uptake, and $J_W P$ [mg/m^2/d] represents the drainage of dissolved phosphorus through the soil slab. The adsorption of phosphorus is modelled using a Langmuir isotherm (Eq. A5), and so the retardation for phosphorus, R_P, is calculated as

$$R_P = \left[1 + \left(\frac{r}{q}\right)\left(\frac{Qb}{1+bP}\right)\right] \qquad \text{[Eq. A35]}$$

where *Q* is the maximum total mass of phosphorus at saturation per unit mass of dry soil [µg/g], and *b* is an empirical constant, with units of inverse of solution concentration [L/mg].

Bacterial transport is calculated using the same convection-dispersion type equation for water and solute transport, with additional terms used to represent the kinetic sorption of bacteria to the soil's mineral particles, as well as the subsequent detachment and transfer of bacteria between the aqueous and solid phases (Schijven and Hassanizadeh, 2000). The mass balance equation for water-borne bacteria (considering only those bacteria applied in the effluent) is given by the following equation

$$\frac{dq\,B}{dt} = \left(X_{B,i} - k_a q\,y\;B + k_d\;r\,S - m_W\,q\,B - m_S\;r\,S - J_W B\right) \qquad \text{[Eq. A36]}$$

where B represents the bacteria concentration in the liquid phase [cfu/L], S_B represents the bacteria concentration in the solid (sorbed) phase [cfu/g], $X_{B,i}$ is the total mass of bacteria added to the *i*-th layer (=0 if *i* >1) [cfu/m^2/d], the k_a term represents attachment of bacteria to the soil particles, and the k_d term represents detachment of bacteria from the soil particles, and $J_W B$ [mg/m^2/d] represents the drainage of bacteria through the soil slab. The inactivation (die-off) of bacteria is described using a simple first-order decay model, where μ is the mortality rate [d^{-1}] and the subscripts 'w' and 's' refer to the liquid and solid phases, respectively. The overall mortality rate for *E. coli* bacteria in soil has been reported to be between 0.09 and 0.17/d in two contrasting silt loams (Mubiru *et al*., 2000). Sukias and Nguyen (2003) report the rate constant for bacterial die-off in a Te Kowai silt loam, Hamilton, is about 0.056/d. This represents a 'half life' of between about 1.8 and 3.3 days.

Calculation procedure

The model is run using a daily time-step, to track the fate of nutrients and contaminants in effluent-applied land. The model considers the 11 irrigation areas separately, adding different amount of effluent to each site depending on pond disposal requirements and set irrigation rules. The calculations are made in the following sequence:

- Subtract evaporation, transpiration and plant uptake of nutrients from each soil segment
- Add and subtract the nitrogen, phosphorus and bacteria involved in the various transformation processes
- Partition each contaminant between solution and sorbed fractions, assuming complete equilibrium between the mobile and immobile phases
- If there is rain or irrigation, then perform the leaching process
- Redistribute water and contaminants vertically, according to water potential and solution concentration
- Repeat the contaminant partitioning.

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APPENDIX B: SPASMO REFERENCES

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