Strategy for Developing GIS-based Tools for Management of the Effects on Groundwater of Nitrate Leaching from Agricultural Land Use

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EXTENDED ABSTRACT

The end user requirement for this development is to be able to assess the impact of land use changes on groundwater quality, specifically that due to nitrate leaching from agriculture. Implementation will be for alluvial plains at scales up to about 2000 km^2. GIS databases provide information on land use and soils. This information, at individual field and farm scale, enables modelling of nitrate leaching by the companion FarmSim model that is run on a daily time basis in response to climate, soils, crop, and farm management options. The output leaching data are in the form of mean annual drainage and an associated value of average concentration. Upscaling of farm-scale nitrate leaching to the effects on groundwater quality is achieved by use of a steady-state, groundwater flow and contaminant transport models (AquiferSim). A 2-D horizontal groundwater flow model provides a piezometric surface along which land use changes and affected groundwater zones can be related by means of gradient searches that locate principal directions of groundwater flow. Along these principal directions, the horizontal and vertical dispersive transport of nitrate can be assessed within a 2-D vertical, steady-state, groundwater flow model based on stream function analysis. The stream function model allows simulation of steady-state contaminant transport for complex land use patterns and spatially varying aquifer properties, in the form of a mixing-cell model based on the computational grid. The cell size of this model is set to control numerical dispersion, as a surrogate for dispersion in the aquifer, caused by the horizontal and vertical components of the groundwater flux. The resulting distribution of nitrate concentration with depth in the aquifer can thus be determined for any location in relation to the upstream land uses. The transport model also simulates groundwater age, which is treated as a solute undergoing first-order growth. Spatial distribution of groundwater age and steady-state nitrate concentration addresses some of the end user questions that usually require a transient transport model. The groundwater models have been developed as prototypes with Microsoft Excel. These proven computational methods will be incorporated into an application to run on the Microsoft .NET framework. This application is being used as the software architecture that connects GIS databases, nitrogen leaching models, vadose zone and groundwater transport models, to user interfaces and information output displays. The lack of datasets that span the response time of many years between environmental effects and land use changes precludes total model calibration, and an alternative approach is proposed that tracks the predictive effects of contributing uncertainties.

1. INTRODUCTION

Contamination of groundwater by nitrate leached from agricultural land use is a problem in many countries of the world because of the effects on drinking water quality and on the ecology of surface waters. This issue has been formally reported in New Zealand for more than 30 years but has become more important as increasing intensification of agriculture appears to conflict with public expectations for health and environmental quality. In New Zealand, the legal responsibility for environmental management, under the Resource Management Act, is devolved to 12 regional councils. The councils are charged with incorporating environmental standards into their natural resources regional plans. Current standards for nitrate discharge to groundwater from agricultural land use are primarily focussed on the maximum allowable value (MAV) for drinking water (11.3 mg/L nitrate-nitrogen), in terms of effects. The effects on surface water ecology are recognised but are being addressed initially for the most sensitive water bodies.

The research described in the present paper is part of the multi-agency programme, IRAP (Integrated Research for Aquifer Protection), which is directed to management of the impact of land use on groundwater underlying the relatively flat alluvial plains of New Zealand. The primary stakeholders in this issue are the regional councils, responsible to the public for environmental management, and the landowners themselves. Modelling tools provided from the IRAP Programme are intended to be operated, initially, by the regional councils but in a format that is transparent to all parties in the public forum.

2. END USER REQUIREMENTS

The End-user Advisory Group (EAG) comprises representatives of stakeholders who are expected to use or to be affected by use of the modelling tools provided by IRAP. This group provides advice about the requirements of the models. In addition to EAG input, ten senior regional council staff from around the country were convened in a workshop with the objective of further specifying end user requirements. Both groups will continue to have input into model development. The principal requirements of the model have been identified as the ability to answer the questions:

- What are the effects of existing land use?
- What would be the long-term effects, and where, of specific changes in land use?
- What would be the likely response time for attaining the long-term effect?

While the model will be used by technical and policy staff to explore "what if …" scenarios, some of these questions may also need to be addressed as scenario variations during interactive meetings of stakeholders. Therefore it is desirable that a suitable balance be found between model run time and conceptual complexity.

Figure 1. Central Canterbury Plains, New Zealand, showing a typical groundwater flow path provided by the groundwater flow model

The agreed region for pilot study and model development is the 2000 km^2 Central Canterbury Plains, in the South Island of New Zealand (Figure 1). These plains are bounded by the foothills of the Southern Alps, the Pacific Ocean coast, and two large braided rivers that cross the plains from mountains to coast. The underlying aquifers comprise glacial and fluvial outwash material of silts, sands and gravels up to about 500 m thick. Land use is primarily dryland and irrigated agriculture, including sheep, dairy, cropping, forest, and horticulture.

A survey of nitrate concentrations in Canterbury groundwater (Hanson, 2002) showed that about one third of the samples from 2.350 wells exceeded one half MAV. The spring-fed streams around the margins of Lake Ellesmere (Figure 1) typically have nitrate-N concentrations in the range 1-5 mg/L (Environment Canterbury, 2005). Recent development of irrigated dairy farming on former dryland farms in the upper part of the Central Canterbury Plains is expected to increase nitrate discharge to the underlying groundwater. The effects of this development will not be immediate because of transit time time through the vadose zone above the groundwater and the dynamics of the organic nitrogen content of the soils. Therefore, models of farm management and contaminant transport in groundwater are required for supporting decisions about future land use in the region.

3. MODEL ARCHITECTURE

There are four primary components in the current concept of the model:

- A GIS to manage spatial data that is required by the models, including land use, soil, and aquifer characteristics
- An agricultural land use simulation model (FarmSim) that generates soil drainage and associated nitrate concentration at farm scale
- A groundwater model (AquiferSim) that integrates the effects of nitrate-contaminated recharge at farm scale, and provides information about the resulting horizontal and vertical distribution of effects in the aquifer
- An end user interface for the user to define *what-if* catchment-scale scenarios, and to view model outputs.

The common platform for these components will be the Microsoft .NET framework, with appropriate interfaces to GIS for data and information transfer. At the current stage of development (July 2005), end-user workshops are being conducted to ascertain availability of GIS and information transfer requirements, FarmSim is at an advanced stage of construction on .NET, and AquiferSim has been constructed as a prototype within Microsoft Excel.

4. GIS COMPONENT

GIS functionality is needed to manage data layers of land use, soil, and aquifer properties. End users with GIS skills will be expected to manage the data layers required by AquiferSim by using standard GIS tools. Most regional councils in New Zealand use ESRI products.

Good land use, vadose and aquifer information is not generally available in New Zealand. Initially IRAP will have to rely on a combination of AgriBase and the Land Cover Data Base (LCDB) for land use, but it is hoped that remote sensing will be able to improve upon this information, e.g., North et al. (2002). In particular, remote sensing can help with distinguishing sheep from dairy land use, and detecting management practices that increase or decrease the risk of nitrate leaching, e.g., fallow land over the winter. While it is difficult to obtain current land use data, historical land use will be even more of a challenge. Yet, due to a ground water flow time lag of decades, historical data will be essential for predicting current impacts, and for verification of the model.

Part of the IRAP resources will be devoted to characterising vadose zone and aquifer properties as separate process studies. Regional council databases of bore logs can be used to estimate vadose zone depths and provide descriptive information about aquifer stratigraphy

By contrast, soil information in Canterbury is of high quality. A regional digital soil survey has been completed and information on key soil properties is currently being compiled (Lilburne et al., 2004). This soil database will provide the FarmSim component with the necessary soil-related parameters.

5. FARMSIM COMPONENT

FarmSim is described in a companion paper at MODSIM05 (Good and Bright, 2005), and only relevant principles are presented here. This component comprises a set of models that simulate the effect on nitrate leaching of plant growth, animal grazing, irrigation, and farm management decisions. Simulations are conducted at individual paddock (field) scale and aggregated to the whole farm, as outputs of nitrate from one economic enterprise.

The time-varying values of drainage from the root zone of the soil, and the associated nitrate concentration, are then routed through a vadose zone model and into the underlying groundwater. The current version of the vadose zone model simulates advective-dispersive transport but will be modified to include nitrate transformations when adequate knowledge becomes available.

FarmSim is a time-dependent model set, because of the requirements for simulation of agricultural production processes in response to time-varying climatic inputs and daily management decisions. Therefore, this component produces a time-series of drainage fluxes and nitrate concentrations. However, the groundwater transport model (next section) is, initially, a steady-state model that requires only the long term drainage flux and nitrate values. For user-selected scenarios, FarmSim would be run for sufficient length of climatic record to generate the required long term values.

6. AQUIFERSIM COMPONENT

AquiferSim comprises a set of models for integrating all recharge sources for a groundwater body, together with the associated qualities (nitrate), and all discharge sinks so that the long-term three-dimensional distribution of water quality effects can be estimated. The likely computational cost of achieving the necessary spatial detail for regional (~ 1000 km^2) studies led

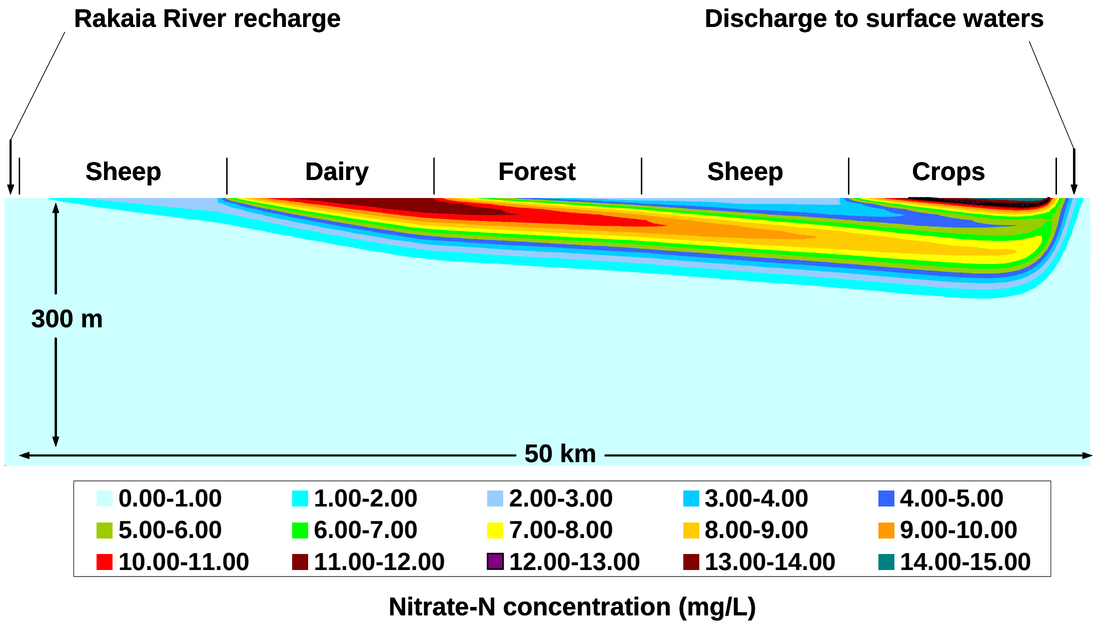

Figure 2. Demonstration example of vertical distribution of nitrate contamination in groundwater, along the flow path in Figure1, for an arbitrary pattern of land use.

to a decision to use steady-state groundwater flow and contaminant transport models. This is because the number of computational cells is governed by the requirements for simulating dispersive contaminant transport, and the likely run time for a transient model would be too long for generation of scenarios for end users. The steady-state models do not preclude addressing questions about the likely time scales of responses to changes in land use, for example. However, validation of present groundwater quality against historical land use will require a model that has transient contaminant transport. The feasibility of this approach at regional scale will be addressed later in the research programme.

6.1. Computational Strategy

The fundamental principles of our present approach are:

1. Select location of proposed land use change
2. Determine the groundwater flowpath through this location from recharge origin to discharge outflow
3. Compute the 2-D vertical distribution of contaminant along the flowpath

This means that the computationally-demanding estimation of contaminant transport can be done for only the locations of interest, or a 3-D picture columnscan be constructed for a larger region by selecting flowpaths at appropriate intervals. The flexibility of these options will enable a range of output information to meet the as yet unconfirmed requirements of end users.

6.2. Groundwater Flowpaths

The regional distribution of steady-state groundwater flow, based on all recharge sources and discharge sinks, is a necessary basis. This is not a trivial exercise for many regions, especially where river recharge is significant. Our experience with the Central Canterbury Plains is that use of a steady-state, finite difference, 2-D horizontal, groundwater model with homogeneous aquifer properties is an appropriate initial approach. Recharge through the land surface is estimated from water balance models or by use of FarmSim. Pumped abstractions are usually estimated, with less precision, from regional council databases. River recharge is very difficult to measure and can be treated as model parameters to be fitted by calibration of the model with piezometric data.

The desired outputs from the groundwater model are the locations and values of all recharges and discharges, and the resulting piezometric surface. The piezometric surface is used for defining groundwater flowpaths through selected locations by means of gradient search methods. Some GIS systems include search and particle-tracking tools for use with a piezometric surface, but it is likely that these functions will be developed within the upscaled aquifer model.

6.3. Nitrate Distribution along a Flowpath

The vertical distribution of nitrate along a selected flowpath is estimated by means of finite-difference stream-function analysis, given the values of recharge or discharge around the boundaries of this vertical section (curved in the horizontal plane). Stream-function analysis can be a more robust technique than piezometric-based methods for modelling contaminant transport (Frind and Matanga, 1985). The limitation on water flux entering or leaving the plane of analysis (by pumped abstraction) is being addressed by inclusion of the "boundary cut" technique.

Longitudinal and vertical dispersion is simulated by a mixing-cell approach. Essentially, the mesh size of the computational grid is adjusted according to relationships with values of horizontal and vertical dispersivities. Then the contaminant mass balance of each cell is iteratively calculated using the horizontal and vertical components of transporting water flux from the stream-function model. This approach contrasts with the analytical methods used by Dillon (1989) for nitrate distribution in the vertical plane of regional models.

The stream-function model can account for spatial variation in horizontal and vertical hydraulic conductivities and porosity. However, this ability exceeds our present knowledge of these properties. In the case of Central Canterbury Plains, the bulk value of porosity is known only within a range of about 0.5 - 2.0 times its estimate. The aquifer thickness varies up to about 500 m, but the information is sparse. At the present state of knowledge the stream-function model provides indicative information about the vertical distribution of nitrate, especially the influence of uncontaminated river recharge, which is new and likely to be important for public debate about the trade-off between economic and environmental values. Figure 2 shows distribution of nitrate, generated by the Excel prototype model, in a vertical cross-section along the example groundwater flowpath in Figure 1.

The dynamics of contaminant response in groundwater to changes in land use can be computed to some extent from the steady-state stream-function model by incorporating a technique from Goode (1996) into the mixing-cell method. This approach calculates the spatial distribution of groundwater age by treating age as a first-order growth process. The resulting association of nitrate concentration at any location with the groundwater age at the same location can address some of the questions that would normally be directed to a transient contaminant transport model.

7. SOFTWARE ARCHITECTURE

The software architecture for AquiferSim has yet to be finally decided however, and an indicative structure is shown in Figure 3. The system centers around the AquiferSim Controller and is based on the Model/View/Controller aggregate pattern (Gamma *et al.* 1994). This component manages the simulation and mediates between the other components. User input is acquired and used to determine the data to be extracted from the GIS and then supplied to the computational engine. The computational engine then constructs the mathematical model of the aquifer and runs the simulation. The results are then returned to the user interface.

The GIS component will be the repository for most of the data required to run the aquifer model. This includes data on land uses, depth to vadose zone and the characteristics of the aquifer. It is also currently proposed that the GIS will hold data generated from FarmSim that reflects the drainage flux and nitrate concentration that result from a range of land uses in differing environmental conditions.

It is intended that the development of AquiferSim will be carried out using the Microsoft .NET framework and Environmental Systems Research Institute (ESRI) GIS components.

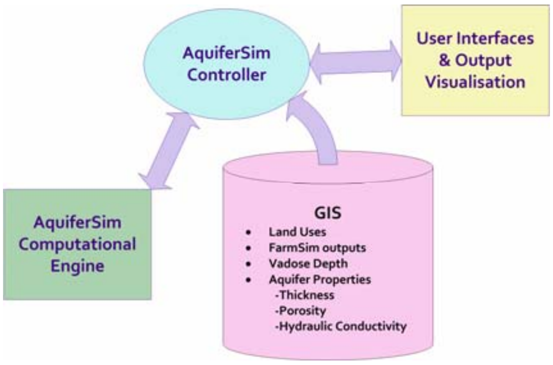

Figure 3. Outline of software structure for the AquiferSim model and associated GIS.

8. USER INTERFACE COMPONENT

The creation of an end user interface that provides a usable and informative experience is a considerable challenge for the AquiferSim project. A GIS-based user interface will be developed for the regional council end user. This interface will allow the user to interactively define a specific *what-if* scenario including:

1. Spatially selecting an area(s) and specifying a new land use or change in management practice.
2. Specifying a level of application of best management practice.
3. Specifying an annual trend of conversion (which is then randomly allocated spatially).

When the scenario has been defined, along with the required outputs of interest, the relevant spatial data will be prepared and passed to the AquiferSim model component. Interpreting the outputs of the simulation is more difficult. The problem of presenting the vast quantity of data generated about aquifer contaminant movement to the user will require careful consideration. After the model has run, output will be displayed either by the model or from within the GIS. Output options will include 1-D and 2-D graphs showing nitrate distribution at a point or on a ground water flow path, either as a predicted concentration or relative to a selected criterion of interest (e.g., the New Zealand Drinking Water Standard). Figure 2 is an example of a two-dimensional visualization of nitrate transport in an aquifer.

Multiple simulation runs of the FarmSim component will be needed to parameterize the land use layer in terms of estimated nitrate flux, i.e., average concentration below the root zone and annual recharge from the land, for each combination of land use (or farm type), climate and soil. This nitrate flux information can be stored in the GIS, prior to running *what-if* analyses.

ESRI's ArcGIS can be customised by adding in objects created in the .NET environment. It is envisaged that the AquiferSim component will be compiled as an ActiveX DLL tool that can be accessed from the GIS user interface.

9. PREDICTIVE UNCERTAINTY

It would be very difficult to "calibrate" the set of models described herein because, apart from the total complexity, there are no easily obtainable datasets that cover the many years between input farm management and output of environment effects. Such a calibration would require use of a transient groundwater contaminant transport model rather than the steady-state model that we have adopted. The alternative approach is to estimate the uncertainties in all contributing databases and model components, and then determine the uncertainty of predictions from the FarmSim/AquiferSim planning tools. We have decided to follow this latter approach by the application of methods similar to the principles described by Moore and Doherty (2005). This is not a trivial exercise and is recognised as being a significant part of our research programme.

10. SUMMARY AND CONCLUSIONS

Prediction of the three-dimensional spatial distribution of groundwater quality at regional scale, in response to changing patterns of land use, provides a challenging set of data handling and modelling requirements. Nitrate discharge from agricultural land use is to be modelled at the scale of individual farm enterprises. Therefore, GIS is the appropriate software for managing the large amounts of data about land use, soils, aquifer properties, and groundwater abstraction. Early involvement of end users in model development is necessary to align available GIS tools and skills with data transfer to and from the model.

Computational mesh spacing is determined by the requirement for simulating dispersive transport of contaminants in groundwater, in the selected approach. Use of a steady-state groundwater flow and contaminant transport model enables reasonable computational run times for user-specified views of nitrate distribution along vertical surfaces that follow groundwater flow paths. Time-based issues related to average contaminant transport times and groundwater age are addressed by the stream function method of modelling groundwater flow, in conjunction with mixing-cell simulation of contaminant dispersion and transformation.

The .NET software environment has been selected for implementation of the existing groundwater model prototype, which is in Microsoft Excel, linking of GIS databases and provision of user interfaces.

The uncertainty of predictions from this set of planning support tools is recognised as a significant part of the research. The selected approach involves systematic quantification and analysis of contributing uncertainties, because of the difficulties of obtaining meaningful model calibrations.

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