# The application of geographical information systems to water quality modelling in New Zealand

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**Abstract** This paper describes the development of a decision support system as a result of the application of a basin scale distributed water quality model to a small agricultural basin in New Zealand. The model, known as Basin New Zealand (BNZ), was applied to the 15 km$^2$ Toenepi basin in the central North Island of New Zealand as part of a study to investigate the effects of intensive dairy farming on stream water quality. Model predictions of average annual sediment and nutrient loadings were made using climate data for the period 1980–1987. The model simulation required the input of climate information over the whole basin, and soil, land use and topographic data on a grid cell basis. A decision support system, known as the Catchment Decision Support System (CDSS) was developed which linked the BNZ model to national databases of climate, hydrological and land use information, within an ARC/INFO GIS interface.

## INTRODUCTION

There has been increasing concern in New Zealand over the quality of surface and groundwater in recent years, relating in particular to degradation resulting from the effects of intensive agriculture (Smith *et al.*, 1993). Government policy recognizes the risks to the sustainable management of the quality and quantity of New Zealand's waters and the need for promoting integrated water and land management, as indicated in the Environment 2010 Strategy. The Strategy report states that unsustainable land use practices and agricultural effluents such as sediment and nutrients, from both point and non-point sources, are some of the main reasons for deteriorating water quality in New Zealand. Sound and detailed models are required to predict water quality resulting from changes in land use at the basin scale, so as to advise policy makers how agricultural production can be maintained while at the same time minimizing the amount of non-point source pollution.

In 1994, the New Zealand Dairy Board, through the Dairy Research Institute contracted NIWA to undertake a study with AgResearch (the New Zealand Pastoral Agriculture Research Institute) to investigate the effect of intensive dairy farming on

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stream water quality. The main objectives of this study were to monitor stream water quality and ecology for a typical intensively farmed dairy basin and to use a model to predict the effects of land use change on the stream water quality.

## Study area

The study focuses on the 15 km$^2$ Toenepi basin (Fig. 1), situated 30 km east of Hamilton in an intensive dairying area (175°38'E, 37°45'S). The basin topography is characterized by rolling hill country ranging from 40–130 m above sea level. The underlying geology is mainly Tertiary ignimbrites of the Pakaumanu group, with some areas of Wairoa siltstones interbedded with pumice and ash, on a basement of Jurassic sandstones and conglomerates. The soils of the area are divided into the poorly drained Topehaehae clays found along the flood plain, the well drained Kiwitahi and Kereone yellow brown loams on the lower slopes, and the well drained Morrinsville clay loams on the upper slopes. Original and revised distributions of soils are illustrated in Fig. 2. Average annual rainfall for the basin is approximately 1200 mm. These conditions are ideal for intensive dairy farming, and a total of 22 dairy farms are partly or wholly located

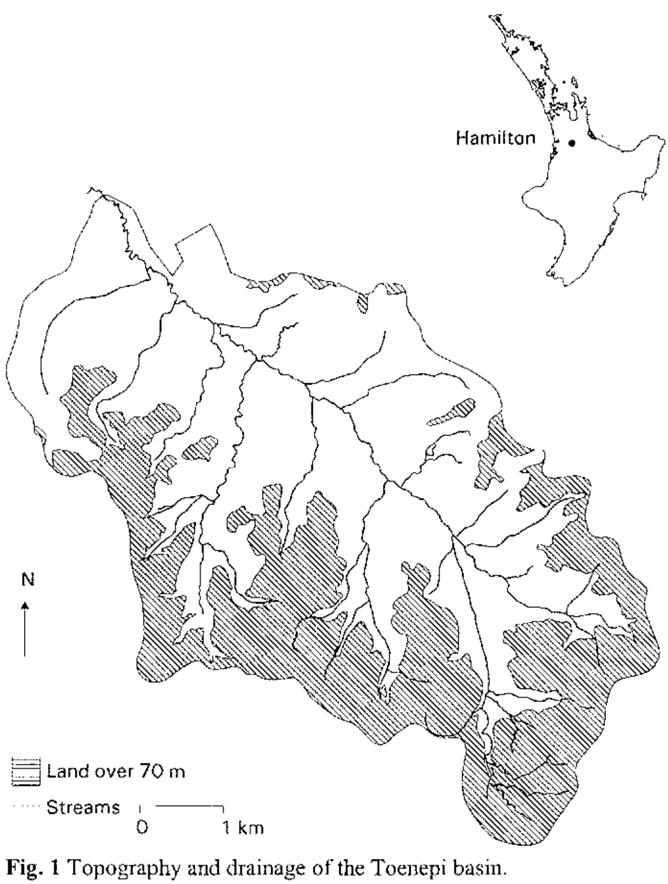


**Fig. 1** Topography and drainage of the Toenepi basin.

within the basin. The basin average stocking density is 2.9 cows $ha^{-1}$ and fertilizer applications are as high as 200 kg P and 177 kg N per year.

## BNZ model details

The Basin New Zealand (BNZ) model was developed by Cooper *et al.* (1992) from the US Department of Agriculture CREAMS model (Knisel, 1980). The CREAMS model was designed to predict runoff, soil erosion, and the transport of nutrients and pesticides from agricultural land in the USA. The development of CREAMS into BNZ required changing the model parameters so that it could be used under New Zealand agricultural conditions, and increasing the scale at which the model was employed. CREAMS only works on a field scale, but BNZ can be applied over the whole drainage basin, by dividing the area into equal size grid cells and applying the modified CREAMS routines to each of these. The outputs from each cell are first routed, using a

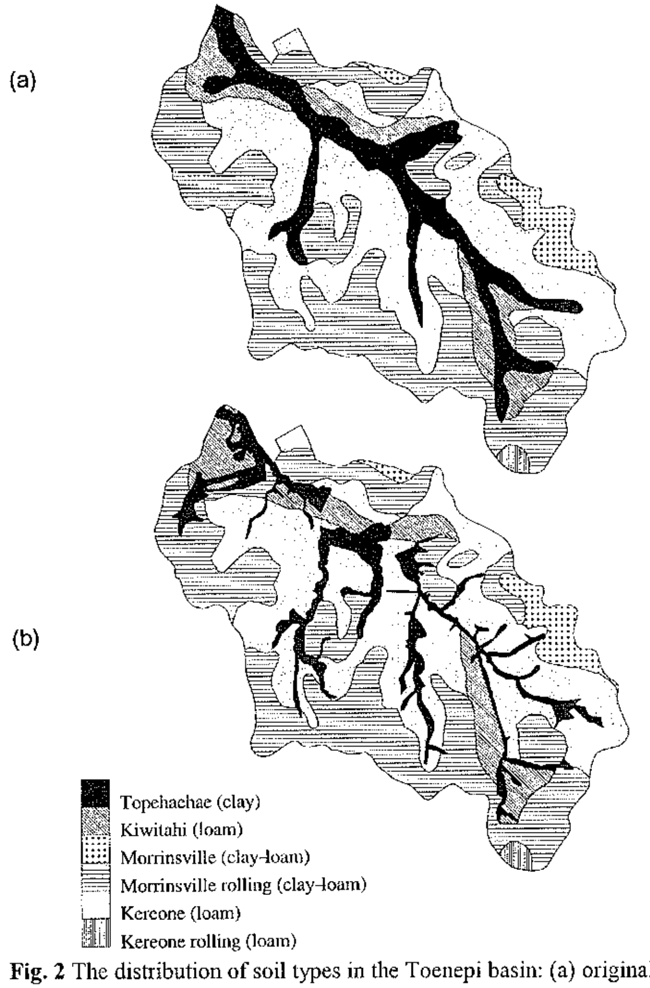


**Fig. 2** The distribution of soil types in the Toenepi basin: (a) original map, (b) updated survey.

two-dimensional routine, to the stream channel, and sediment and nutrient concentrations are attenuated depending on the nature of the riparian zone (Bottcher & Cooper, 1994). These outputs are summed to give the amount at each of the sub-basin outlets, and these sub-basin outputs are then combined, and further modified from in-stream attenuation, before reaching the basin outlet. The structure of BNZ is illustrated in Fig. 3.

The BNZ simulations are performed on a daily basis and model outputs can be generated for daily, monthly, and annual time spans. Output can also be averaged to give generalized results from runs spanning a number of years, and it is in this mode that BNZ is most applicable (i.e. predicting long term consequences of land use practice). The main results given in the output are the runoff (divided into stormflow and baseflow components), and the sediment, nitrogen, and phosphorus loads and concentrations.

In its original form, BNZ is a free standing DOS based model. In order to undertake a simulation, data for each grid cell had to be entered manually for overlays of soil type, land use and topography. Climate data in terms of daily rainfall and mean monthly temperature and radiation had to be entered into input files using a fixed format. Initial BNZ simulations were undertaken for the Toenepi basin in order to assess the applicability of the model, with the aim that further modifications would be made. For these simulations, information on soil type was available from published

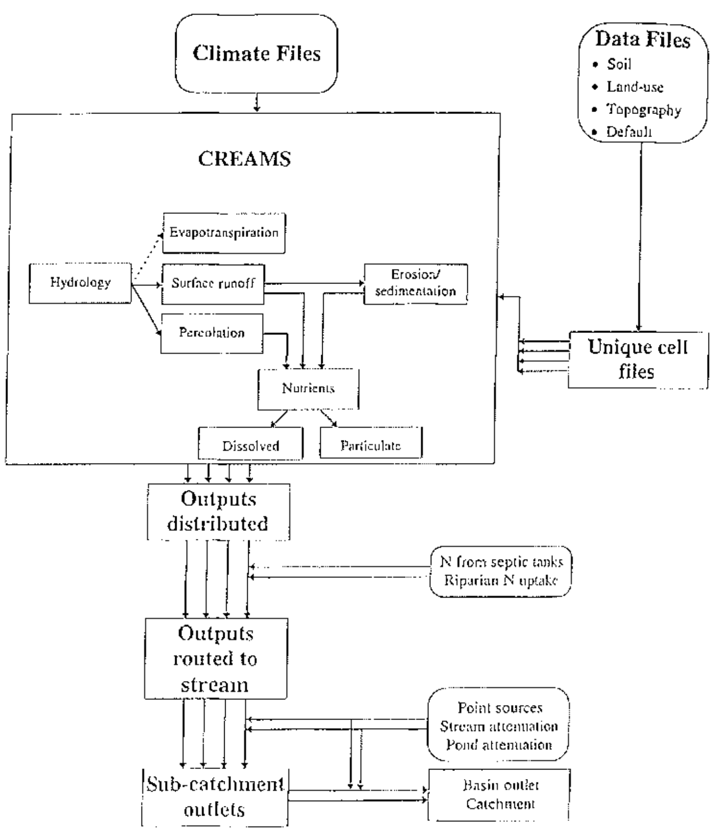


**Fig. 3** Structure of the BNZ model (after Stroud & Cooper, 1997).

maps (Fig. 2(a)) and surveys (Wilson, 1980), and land use information was obtained from a farmers questionnaire survey. Information concerning the drainage network, slope, and elevation was obtained from 1:50 000 topographical maps. Climate data was taken from the Ruakura meteorological station in Hamilton. The Toenepi basin was divided into 84 square cells of 18.9 ha. This size was chosen to represent a farm scale and to ensure a reasonable resolution for the area in terms of soil and topography, while maintaining a manageable number of cells. As this was an initial simulation, no prior information on catchment hydrology and nutrient characteristics was available to assist in defining the grid cell size. Land use was lumped into six classes to reduce the amount of work required for formatting all the data. These were: dairy high, dairy medium, dairy low, mixed high, mixed low and drystock (Fig. 4). Each class was attributed average values for stocking rate and fertilizer application (Table 1). The model was run on a daily time-step, using climate data from 1980–1987. Model outputs are calculated as annual average values over this period.

## INITIAL MODEL RESULTS

The results of the initial BNZ simulations for the Toenepi are presented in Table 2. At the time of writing, the results from the field monitoring programme were not yet available to validate the model. This is because the monitoring programme commenced at the same time as the modelling, and the complete set of measured water quality data was not to be available until 1998. It was evident however from these initial

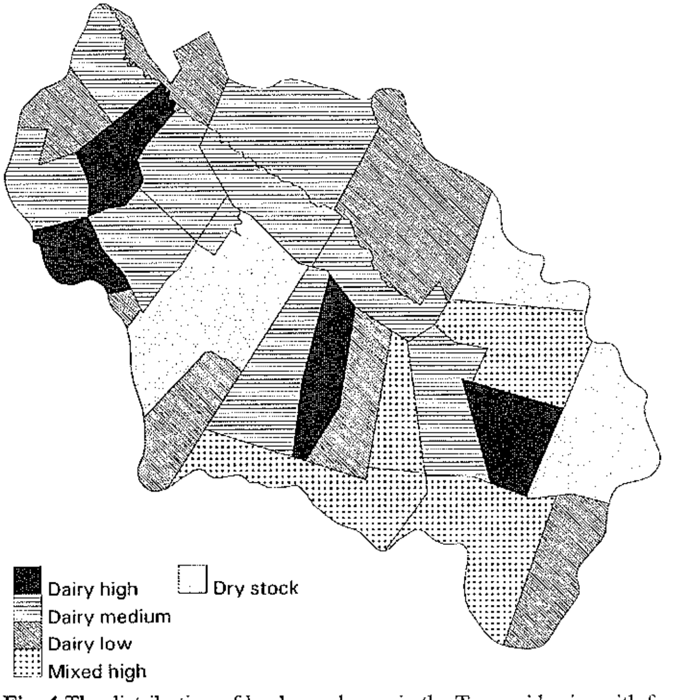


**Fig. 4** The distribution of land use classes in the Toenepi basin, with farm boundaries.

**Table 1** Stock density and fertilizer rates for land use classes used in the BNZ simulations of the Toenepi basin.

| Land use class | Cows/ha | Cattle/ha | Sheep/ha | N Fertilizer (kg N ha$^{-1}$ year$^{-1}$) | P Fertilizer (kg N ha$^{-1}$ year$^{-1}$) |
|---|---|---|---|---|---|
| Dairy high | 3.6 | 0.5 | 0 | 106 | 69 |
| Dairy medium | 3.2 | 0.5 | 0 | 67 | 81 |
| Dairy low | 2.8 | 0.5 | 0 | 59 | 78 |
| Mixed high | 2.2 | 0.9 | 0.1 | 67 | 97 |
| Mixed low | 1.4 | 1.9 | 0.7 | 64 | 64 |
| Dry stock | 0 | 3.1 | 3.3 | 40 | 40 |

**Table 2** Initial BNZ predictions for the Toenepi basin, showing the average annual outputs for the period 1980–1987.

| Output | Whole basin | Topohaehae soils | Other soils |
|---|---|---|---|
| Hydrology (mm): | | | |
| Rainfall | 1192 | 1192 | 1192 |
| Total runoff | 364 | 364 | 364 |
| Stormflow | 85 | 364 | 0 |
| Baseflow | 279 | 0 | 364 |
| Water quality (kg ha$^{-1}$ year$^{-1}$): | | | |
| P load | 7.2 | 82.0 | 0.4 |
| N load | 40.0 | 417.0 | 69.0 |
| Sediment load | 2120.0 | 26790.0 | 0.0 |

simulations that both the hydrology and water quality of the basin were controlled by the spatial extent of the poorly drained Topehaehae soils.

A more detailed soil survey of the area was undertaken to map the extent of the Topehaehae soils (Singleton & Addison, 1996). It was found that the extent was much less than indicated in the original soil map (Fig. 2(b)), and that a much finer resolution grid cell size (e.g. 1 ha) was required for accurate modelling of the basin. The reformatting of the model input data using the smaller cell size was too time consuming and detailed a task to be undertaken by hand, so it was against this background that it was decided to use a GIS to automate this procedure.

## DEVELOPMENT AND APPLICATION OF THE CDSS

A system had already been developed at NIWA, which links data held in national databases with a user interface for the rapid locating, down-loading, and formatting of data (Shankar, 1995). This system, known as the Integrated Climate Information System (ICIS), uses the ARC/INFO GIS as a platform to integrate temporal and disparate spatial data sources. The ICIS has been set-up to access climate-related data remotely from the National Climate Database in Wellington, river flow records from the Water Resources Archive, and land classification information from the Land Resources Inventory supplied by Landcare Research New Zealand Ltd.

The ICIS was used as the basis for developing a Catchment Decision Support System (CDSS) linking the BNZ model within an ARC/INFO interface. Although BNZ itself can be used for management and decision support purposes (e.g. Thorrold *et al.*, 1996), the results need to be interpreted by an expert before they can be used by policy makers and managers. The CDSS however has the ability to present results which can be used immediately by these parties, hence it is described as a decision support system. In addition, the CDSS has been designed to incorporate additional models when they become available (as discussed later in this paper), making it a highly adaptable tool for assisting decision makers.

The development of the CDSS involved writing a number of ARC/INFO and pre- and post-processor routines. The development of the CDSS and these specific routines are described in more detail in Rodda *et al.* (1996, 1997). Pre-processor programmes were written to enable any climate data downloaded from the database to be converted into the format as required by BNZ. Using the CDSS, the climate database could be interrogated for available data from stations within or near the selected basin. Routines using the ARC/INFO GRID option were created to automate the overlaying and gridding of the BNZ spatial parameters (soil, land use, drainage and topography maps). This does require the maps to be digitized and converted to ARC/INFO format, but in many cases existing soil, land use and topographical maps can be obtained in digital form from regional councils. Further pre-processor programmes were written to download the gridded data into the correct BNZ input file format. Through the ARC/INFO interface options were also available to display and query any of the mapped input data, and also to display the model output data as a series of colour coded grid maps. The user interface of the CDSS, based on a series of pull-down menus, enabled all of the tasks from inputting and formatting data, running the model, and displaying the results in the one environment (Fig. 5). The CDSS not only rapidly reduces the time required for formatting the BNZ data, but it also vastly improves the degree of accuracy associated with that data.

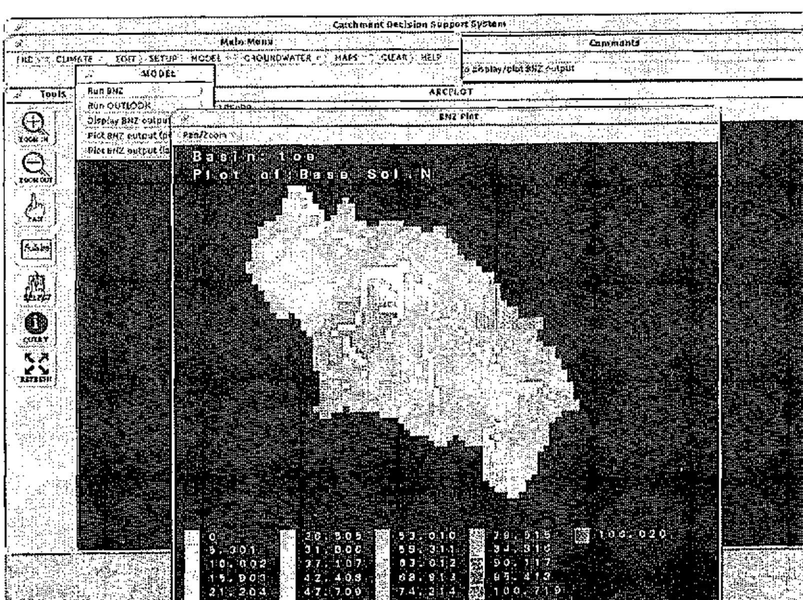


**Fig. 5** The CDSS user interface showing a map of BNZ nitrate leaching predictions for the Toenepi.

## Improved basin simulations

Further BNZ simulations for the Toenepi basin are currently underway using the CDSS. More detailed climate data is now available, including rainfall data for two raingauges located within the basin. The spatial routines within the CDSS enable a much finer grid cell resolution, and as the generation of the required model input data is now so rapid, a number of simulations can be undertaken to assess the accuracy of using different cell sizes. Simulations for the Toenepi using 1, 2, 5, 10, and 20 ha cells are proposed. In addition the reduction of the time taken to format the model input data has allowed more detailed land use information to be used. Instead of dividing each farm into one of six land use classes, as with the initial model simulations, a different land use classification is possible for each farm. This will give a much more accurate input in terms of fertilizer applied and stocking density.

## Further developments to the CDSS

One important feature of the CDSS is that it can easily accommodate new models and additional changes to the system. Since its initial development two further modifications to the CDSS have seen the incorporation of a routine to predict nitrate leaching to groundwater and an agricultural economics model. One of the main limitations of the BNZ model is that it only considers surface water and not groundwater quality. Surface water simulations for the Toenepi basin were adequate since it is not underlain by any aquifers, but in other regions of New Zealand the leaching of contaminants (nitrate in particular) is a major problem (Burden, 1982). Work in association with Freiburg University led to the development of a new routine to predict the percolation, nitrate concentration and nitrate load to groundwater (Rodda, 1997). This routine was based on combining the cell by cell output from BNZ in terms of percolation and nitrate leaching with a map of the spatial extent of the aquifer for a selected basin. This routine was tested for the Dreisam basin in southern Germany which is partially underlain by the Zartener Becken aquifer. Although the routine does not predict the concentration of nitrate present in the groundwater, but the concentration of nitrate in percolation to groundwater, the results for model simulations over the period 1988–1993 are very close to measured borehole data collected by Rolke *et al.* (1996).

The agricultural economics model, OUTLOOK (Metherel *et al.*, 1995) was introduced to the CDSS because it was seen as equally important to consider proposed land use management options to improve water quality in terms of a financial cost to the farmer, as well as a cleaner environment. Also OUTLOOK was largely based on land use and soil parameters which were already present as input parameters to BNZ. Outputs from OUTLOOK can also be displayed in the form of catchment maps and provide further decision support information to managers and policy makers.

## CONCLUSIONS

The development of the CDSS has made a significant contribution to water quality modelling in New Zealand. It has dramatically reduced the time involved in generating input data for BNZ and also improved the accuracy of this data and allowed a number of consecutive model simulations to be run using different grid cell sizes or different soil type and land use combinations. The system is currently being used for water quality modelling studies in the Toenepi, Oteramika and Ngongotaha basins in New Zealand and the Dreisam basin in Germany. Recent work has also illustrated the potential for improving the system by incorporating groundwater models. It is foreseen that the CDSS will be continually modified as new basin scale hydrological and water quality models become available. More rigorous groundwater modelling for example can be achieved by linking a groundwater transport model such as MODFLOW (McDonald & Harbaugh, 1988) into the CDSS.

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