CLUES CATCHMENT MODELLING
- LESSONS FROM RECENT APPLICATIONS

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Abstract

CLUES (Catchment Land Use for Environmental Sustainability) is a GIS-based catchment model for predicting water quality and socio-economic indicators as a function of land use in New Zealand. The model has been applied recently in several catchment studies in New Zealand, for purposes of identifying critical source areas, the relative contaminant contribution of various land uses, effect of land use change, and the effect of mitigation measures for reducing nutrients. This paper summarises these applications and documents strengths and weaknesses identified and areas where CLUES can be improved. Strengths of the model include: the ability to import land use layers to reflect local data and land-use scenarios developed externally to CLUES; rapid assessment of mitigation measures through interactive tools; flexibility of results display through use of standard GIS software; and flexible assessment of mitigation measures and land use intensification through data import facilities. We identified the need to check data inputs such as point sources as they were sometimes inaccurate or out of date. Considerable discrepancies between model predictions occurred in some cases, particularly for concentrations. This partly reflects the underlying variability and uncertainty in parameter estimates, with local values of yields for uniform land uses differing from national values used in CLUES. Also, the assumptions used in the simplified versions of leaching models used in CLUES were sometimes inappropriate. The flows used to convert loads to concentrations sometimes differed from measured values, leading to errors in the predicted concentration. In other cases, there were clear interactions with groundwater that were not captured by the model. Some of the parameters in the standard CLUES model have been modified as a result of these experiences. In other cases, we adjusted the local values of CLUES parameters to reduce consistent regional biases, either by altering the parameter files or applying mitigation factors. We conclude that CLUES predictions should be used with due regard to local influences and knowledge of the catchment, and that re-calibration should be considered to improve model performance if suitable data is available. In the future, we plan to incorporate more regional council monitoring data into the calibration of the national model to capture more regional variability.
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Description of the model

CLUES is a modelling system for assessing the effects of land use change on water quality and socio-economic factors at catchment, regional and national scale. CLUES simulates water quality variables relevant to managing ecosystem health (annual average loads, concentrations and yields of TN and TP, and loads of sediment and *E. coli*) thus indicating how they respond to land use change. CLUES runs on a GIS-platform (ArcGIS) and links a number of models and geo-spatial databases together into one software package (**Error! Reference source not found.**). The combination of water quality modelling, an easy-to-use interface, tools for creating land use change and land management scenarios and GIS functionality means that CLUES is a powerful model which allows geo-visualisation and spatial analysis of simulation results.

The development of CLUES was initiated in 2004 by the Ministry of Agriculture and Forestry (MAF) in association with the Ministry for the Environment (MfE), led by NIWA and in collaboration with Lincoln Ventures, Harris Consulting, AgResearch, Plant and Food Research, and Landcare Research. Subsequent development has been funded by an Envirolink Tools project sponsored by Environment Waikato, and Pasture21 funding. Recent changes include the ability to add mitigation measures (as mitigation factor) and stock intensification, improved management of scenarios, and new and updated socio-economic components.

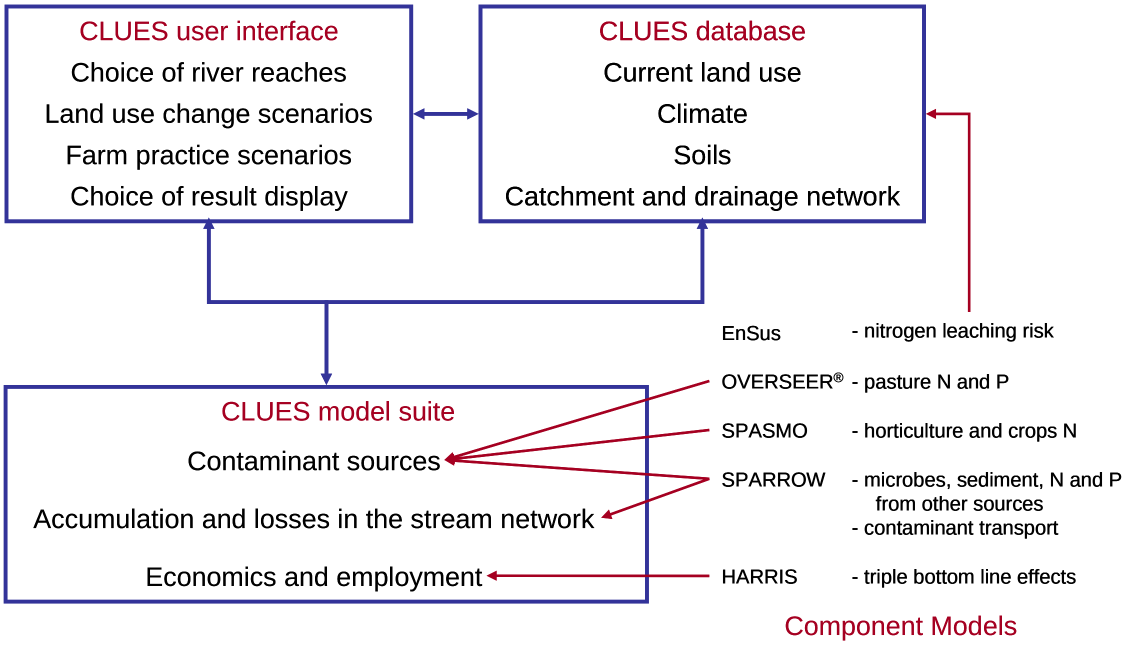

Figure 1: CLUES modelling framework (from Semadeni-Davies et al., 2011)

CLUES models annual average Total Nitrogen, Total Phosphorus, E. coli and sediment loads in streams nationally (576,000 stream reaches, sub-catchments of 0.5 km^2 on average) and predicts a range of socio economic indicators such as farm employment and associated GDP. CLUES also predicts concentrations of Total Nitrogen and Total Phosphorus. Land-use maps are provided, these were created with extensive reference to the LCDB2 (Land Cover Database), AgriBase (AsureQuality Ltd), and LENZ (Land Environments of New Zealand) land use geo-databases and represent current (as of 2002) land use.. Users can create new land use scenarios by modifying the land use interactively or importing a new land-use layer. Mitigation (and stock reduction / intensification) scenarios can also be created. The combination of water quality modelling, an easy-to-use interface, land use change and farm practice scenarios, and GIS functionality means that CLUES is a powerful model which allows geo-visualisation and spatial analysis of simulation results.

Further details on the modelling framework can be found in (Woods *et al.*, 2006) and in the user manual (Semadeni-Davies *et al.*, 2011). CLUES software is freely available for download (ftp://ftp.niwa.co.nz/clues) and reports including user manuals can be found at the MAF website. CLUES training courses are run by NIWA according to demand and have been funded using Envirolink small advice grants.

An example of an output from CLUES, the median TN concentration in stream nationally, was used to give a national-scale perspective on nutrient concentrations (Figure 2) to the Land and Water Forum.

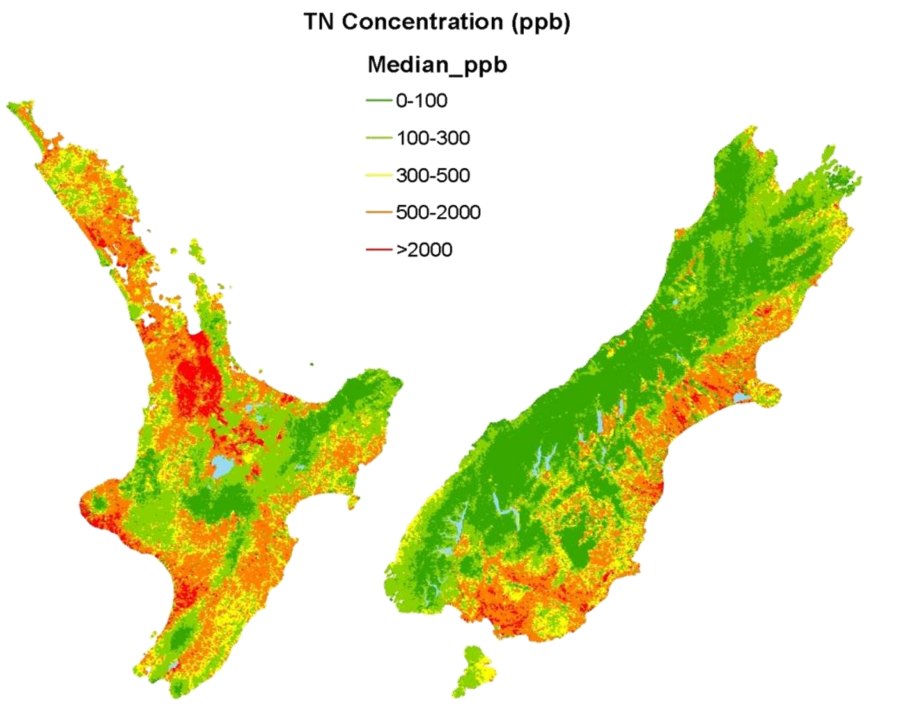

Figure 2. Predicted median TN concentrations nationally.

The model was calibrated to sites in the National Rivers Water Quality Network. Errors in model calibration (Figure 3) are less for TN than for TP (this applies also to R^2 and log-rmse measures of error as well as the error factors). Generally, loads are predicted better than concentrations, because the concentrations are calculated from the loads, introducing compounding error sources such as errors in mean annual flow. Some of these errors may seem large in relation the range of changes expected from interventions in the catchment. However, as with many catchment models, the error in relative change with respect to some baseline is expected to be less than the absolute error in the prediction. For example, if some error in concentration in baseline prediction at a site is due to an error in the flow rate, that same flow rate would likely apply for the future scenario, so that the percentage change in concentration will be more reliable than the absolute value of the new concentration.

Applications

The CLUES model has been applied in several applications (Table 1). Key points from selected applications are presented below. The selected applications illustrate the benefits of using CLUES but also highlight areas where difficulties were encountered, leading to model modifications, development of different ways to apply the model, or identification of areas where the model needs to be refined. In this paper we have tended accentuate difficulties and weaknesses encountered in the model, with the danger of alarming potential users. The intention, however, is not only to give readers and appreciation of errors and difficulties that might be encountered, but also to demonstrate how many of these difficulties have been overcome by model modifications, adjusting parameters, or devising different ways of using the model, and also where current research is addressing remaining difficulties.

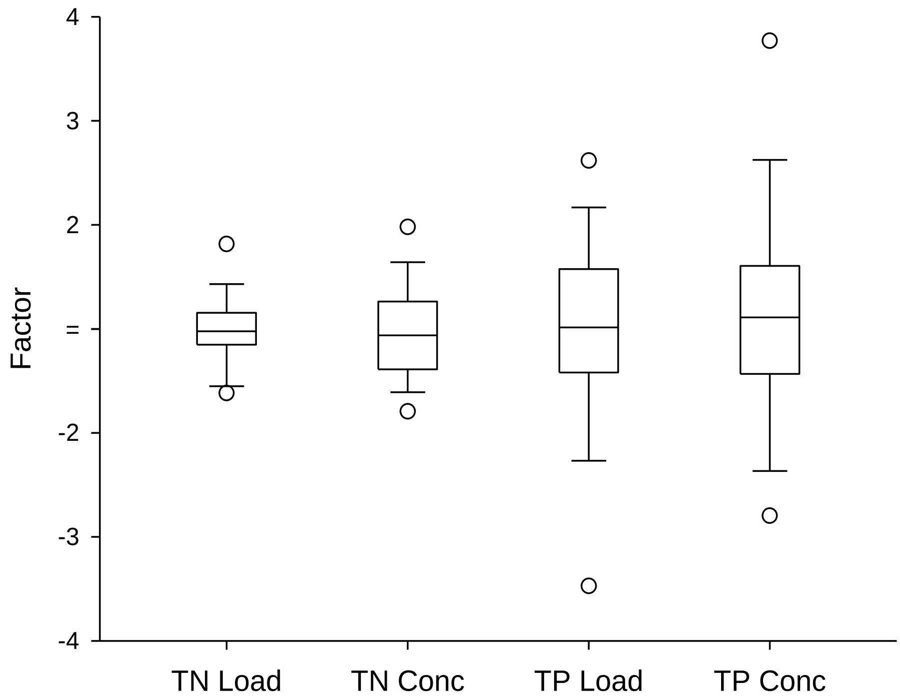

Figure 3. Error factors for TN and TP concentration and load predictions, evaluated at the National River Water Quality Network sites used in calibration. A positive factor indicates over-prediction, while a negative factor indicates under-prediction. The boxes show inter-quartile range, the whiskers 10 and 90 percentiles, and the circles 5 and 95 percentiles.

Dairy Best Practice Catchments

In a relatively early application (Parshotam and Elliott, 2009a), CLUES was applied to the five Dairy Best Practice Catchments, which are discussed elsewhere in this proceedings. One finding was that the version of CLUES used at that stage consistently under-predicted the P load. This led to re-calibration of the national model by allowing an additional P term beyond that provided by OVERSEER, and this term has been incorporated into the current version of CLUES. The stream attenuation term was reduced so that at larger scales, similar results were obtained. The addition of the term was justified in broad terms, because the version of OVERSEER used in CLUES does not account for diary effluent discharges, direct deposition into streams, and bank erosion sources of P. This result highlights the value of data from sites with fairly uniform land use, especially for catchment scales smaller than those from the NRWQN. A danger of employing the additional term, however, accrues from its blanket application to all dairy areas, whereas in reality the addition source terms will depend on local conditions and farm management. This points to the need to be aware of the extra term and if necessary to modify it for local conditions; ultimately, it would be preferable to incorporate more spatially –specific information on additional P sources, either through the use of a more refined version of OVERSEER or via adjustment of mitigation measures.

One of the outputs of the application was a map of generated yield of P per sub-catchment. In the case of the Toenepi catchment (Waikato), the map showed quite a uniform yield, whereas in reality we expect more spatial variation. For example, we know that some farms are disposing of treated dairy effluent directly into streams, and that this would be likely to give rise to large P yields, yet this is was not taken into account. As another example, it is known that there are localised areas of poorly-drained soils in the catchment. While the OVERSEER component of CLUES takes variations of soil drainage into account, the values input to OVERSEER are average over a sub-catchment, losing the spatial detail and also the non-linear response of P loss to drainage conditions. Losses can be adjusted using adjustment/mitigation factors imported into CLUES, but this would be a fairly blunt instrument for addressing the limited spatial resolution. These findings point to the desirability of improving the spatial detail in CLUES, and current efforts under MSI funding are addressing this need.

This application also pointed to complications associated with groundwater. In the Pigeon Creek catchment (near Inchbonnie, West Coast) the predicted N yield was larger than measured, but was comparable to the yield at larger scales. The flow rate was also over-predicted. These features suggest and influence of groundwater (subsurface diversion out of the catchment, exchange with aquifers fed by less-contaminated water), which is not included in the model. Currently, there is no funding to add a groundwater component to CLUES, although this is clearly desirable. An impediment in this regard is the lack of information on the location and properties of groundwater reservoirs nationally, which hampered earlier efforts to include groundwater. This suggests that in future it may be more appropriate to provide a groundwater component in CLUES that is only activated if groundwater information is available.

In the Dairy Best Practice Catchments application it was also found that in some locations, stocking rates differed significantly from the regional defaults used in CLUES. A new feature has now been developed whereby stocking rates can be adjusted locally if suitable input data are available, and this is available in the current version (CLUES 3.1).

Waikato 'Critical Catchments'

Under the Pasture 21 programme, CLUES was applied to the Waikato River catchment with the aim of determining stream and locations that are 'sensitive' or 'critical' (Semadeni-Davies et al., 2009; Semadeni-Davies et al., 2010). An example output (Figure 5) demonstrates how CLUES can be used to identify streams that might become impacted (exceed EW thresholds for TN concentration) and their associated catchment areas under a hypothetical land use change scenario, and the changes in generated nutrient yield or hot-spots.

This left the obvious question: what to do about the anticipated increases in concentrations given that nutrient sources may be located far upstream. Such questions prompted the inclusion of a new farm mitigation measures feature into CLUES, whereby the effect of mitigations is input to CLUES for each sub-catchment. Mitigation is simulated by applying a percentage change or mitigation factors to the nutrient, sediment and *E. coli* yields generated by stock, i.e., dairy, sheep and beef and deer farming. Each stock type can have its own mitigation factors.

This feature is being used in recent and current CLUES applications. What has still not been addressed is more demanding questions such as: which are the best locations for implementing or restricting land use change while maintaining socio-economic benefits and where is mitigation likely to be most effective? At present, these more complex questions can only be addressed in an iterative scenario-based approach.

Table 1. Listing of applications of CLUES.

Location	**Organisation and reference or contact**	**Purpose**
Dairy Best Practice Catchments	Pasture 21. (Parshotam and Elliott, 2009a)	Testing CLUES nutrient predictions for five Dairy Best Practice catchments.
Waikato (Waipapa, whole catchment)	Environment Waikato (Contact: Reece Hill)	Effect of land use conversions in Waipapa, tailored land-use approach in the Waikato catchment
Manawatu	NIWA for Envirolink. (Parshotam and Elliott, 2009b)	Comparison with nutrient measurements, identification of contribution from different sources
Bay of Islands	LINZ, Northland Regional Council. (MacDiarmid, 2009, pp 57-72)	Assessment of nutrient loads to the Bay of Islands, part of an Oceans Survey 2020 project.
Waikato	Pasture 21. (Semadeni-Davies *et al.*, 2009; Semadeni-Davies *et al.*, 2010)	Identification of hot-spots of nutrient generation, reaches that exceed concentration criteria under various land-uses, and the associated catchments.
NZ estuaries	NIWA. CLUES-ACER (John Zeldis)	Estuary water quality model ACER linked to CLUES.
Waikato	Waikato River Independent Scoping Study. (Anon., 2010, Appendix 10)	Effects of land use change and interventions on *E. coli*. Separate model used for current concentration predictions. Changes in loading from CLUES used to infer changes in concentration.
Oreti (Southland)	Environment Southland. (Monaghan *et al.*, 2010)	Effect of hypothetical mitigation measures on nutrient loads.
National	Department of Conservation. (Leathwick *et al.*, 2007)	Freshwater Environments of NZ (FENZ) biodiversity predictor.
Lake Rotorua	Environment BOP (David Hamilton, University of Waikato)	Assessment of effect of land use and mitigation measures on P loading to Lake Rotorua (current project in March 2011).
Hurunui, Canterbury	Pasture 21. (Lilburne *et al.*, 2011)	Effect of scenarios of land-use change and intensification and mitigation measures on nutrient loads and concentrations.
Mataura, Southland	Environment Southland. (Semadeni-Davies and Elliott, 2011)	Effect of scenarios of land use change scenarios associated with intensification, and net effect after mitigation measures applied (current project in March 2011).

Another finding from the Waikato application is that poor concentration predictions were produced in some locations (Figure 6). While some unexplained variability is expected (Figure 3), the errors in the Waikato application were larger than expected. One high measured value was associated with ammonia in a geothermal discharge. As this significant source is not included in CLUES, it is not surprising that CLUES did not capture its effects on downstream water quality. Other difficulties arose with shallow lakes. In the Waikato, there are several shallow lakes where the removal efficiency is less than expected based on the lake area, because wind activity re-mobilises bed sediments. Hence the concentration in the streams downstream of such lakes is under-predicted. Re-calibrating the model to reduce the effective settling velocity would help resolve this problem. In some locations, the flow predictions were poor, probably as a result of groundwater interactions, and this influenced the concentration predictions (that use flow values). Finally, in some locations, the stream concentrations have not yet adjusted to historical land use changes, due to long groundwater residence times, and the concentration was over-predicted as a consequence.

Waikato River Independent Scoping Study

One of the analyses conducted for the WRISS study, conducted to inform Crown-Iwi co-management of the Waikato Rivers (Anon., 2010, Appendix 10) was to identify the effect of various river 'clean-up' activities on *E. coli* concentrations. CLUES provides only load predictions for *E. coli*, not concentrations. Therefore, a separate empirical estimate model was used for estimating concentrations (Unwin *et al.*, 2010) under the current land was used in conjunction with CLUES load predictions to derive estimates of future concentrations. The basic assumption was that if the load is reduced by some factor in the future (as derived from CLUES modelling) then the median concentration will also be reduced by this same factor. This approach obviously ignores complexities associated with timing of microbial delivery, and how the reduction for high-flow concentrations could be different from the reduction under normal flows. Nevertheless, the hybrid approach used in this study provides a pragmatic solution in the absence of a dynamic model.

An example of the output of this approach is that mitigation measures would result in a significant increase in the fraction of streams meeting EW criteria, especially in the Waipa catchment (Figure 7).

Hurunui

As part of the Hurunui Land Use and Water Quality Study, CLUES was applied to predict the effect of future land use change (associated with irrigation development) and the effectiveness of mitigation measures (Lilburne et al., 2011). One of the requirements of this application was to use nitrogen leaching rates from lookup tables recently derived for the Canterbury region. To accommodate this, CLUES was modified to be able to import nitrogen leaching rates from an input map, rather than using values calculated from Overseer. In the future, the lookup tables could be incorporated within CLUES, although this may also entail some extension of the land use types in CLUES.

The nitrogen loads in the main stem were predicted within reasonable bounds (and this could have been improved by adjusting stream attenuation rates). However, there were considerable errors in N predictions in the tributaries in the lower catchment. There are significant exchanges with groundwater in these tributaries (as evidenced by losing and gaining reaches), and transfer of water between tributary catchments via the large Culverden aquifer. CLUES does not currently account for such transfers and there is no ready work-around, so that incorporation of a groundwater component in CLUES would be required to achieve more reliable predictions in the tributaries.

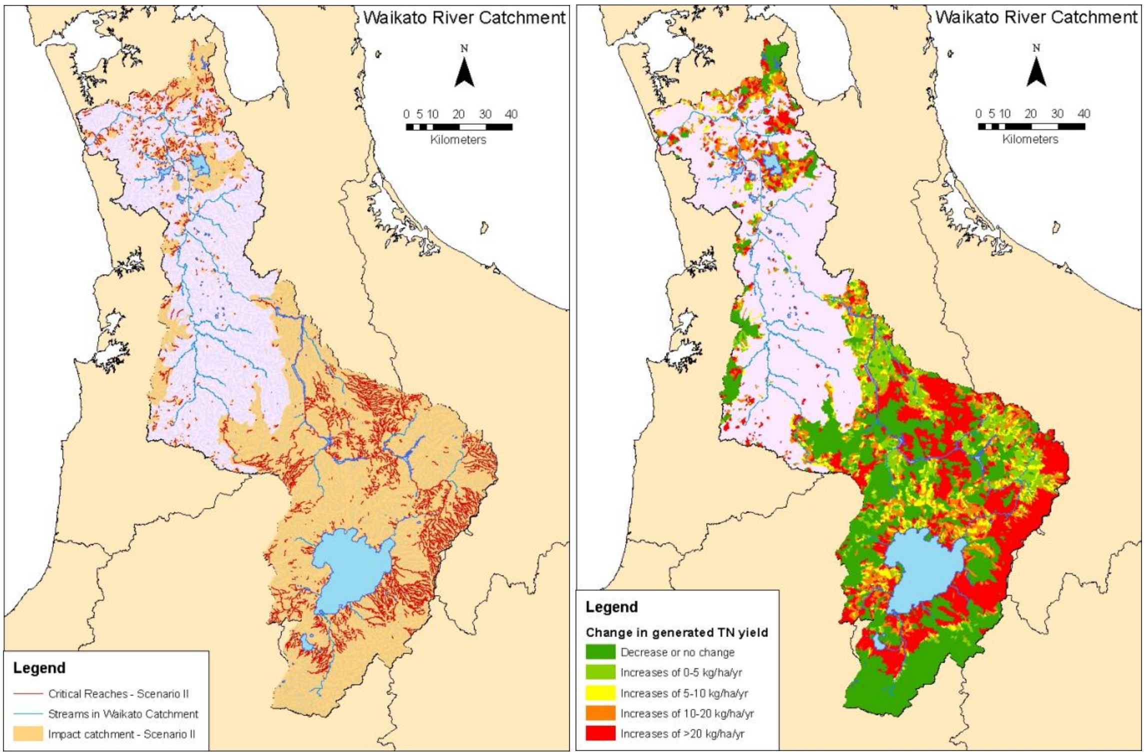

Figure 2: TN concentration change impact catchments for Scenario II (conversion of land in low LUC classes to dairying) showing location of new critical reaches and the associated catchment areas (left) and changes in generated TN yield (right) (from Semadeni-Davies et al., 2009)

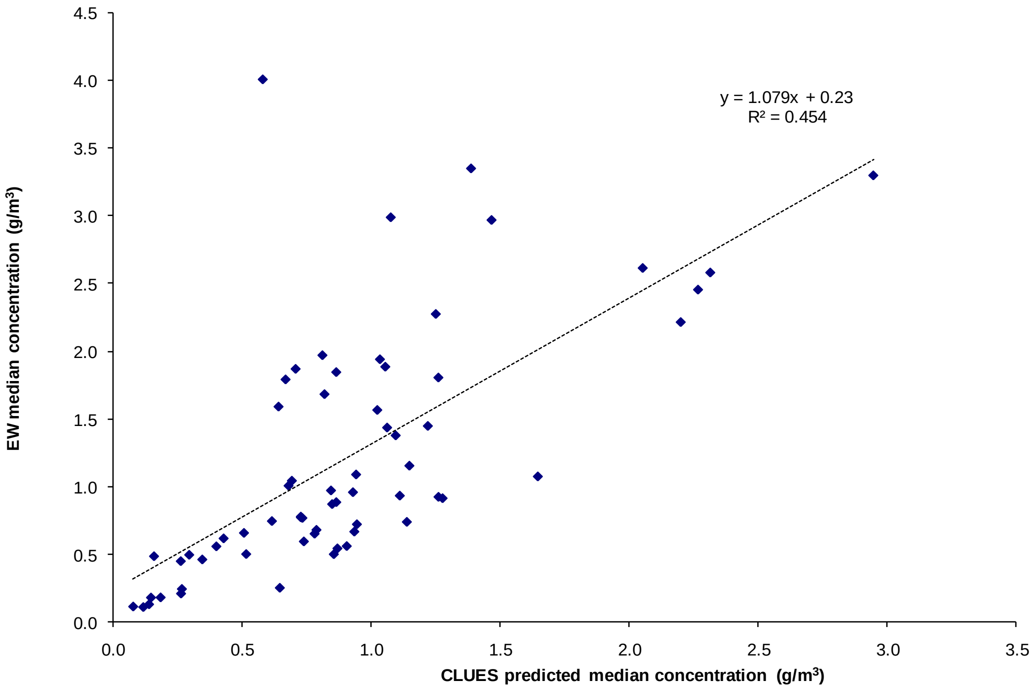

Figure 6. Comparison of measured and predicted TN concentrations in the Waikato catchment (from Semadeni-Davies et al., 2009)

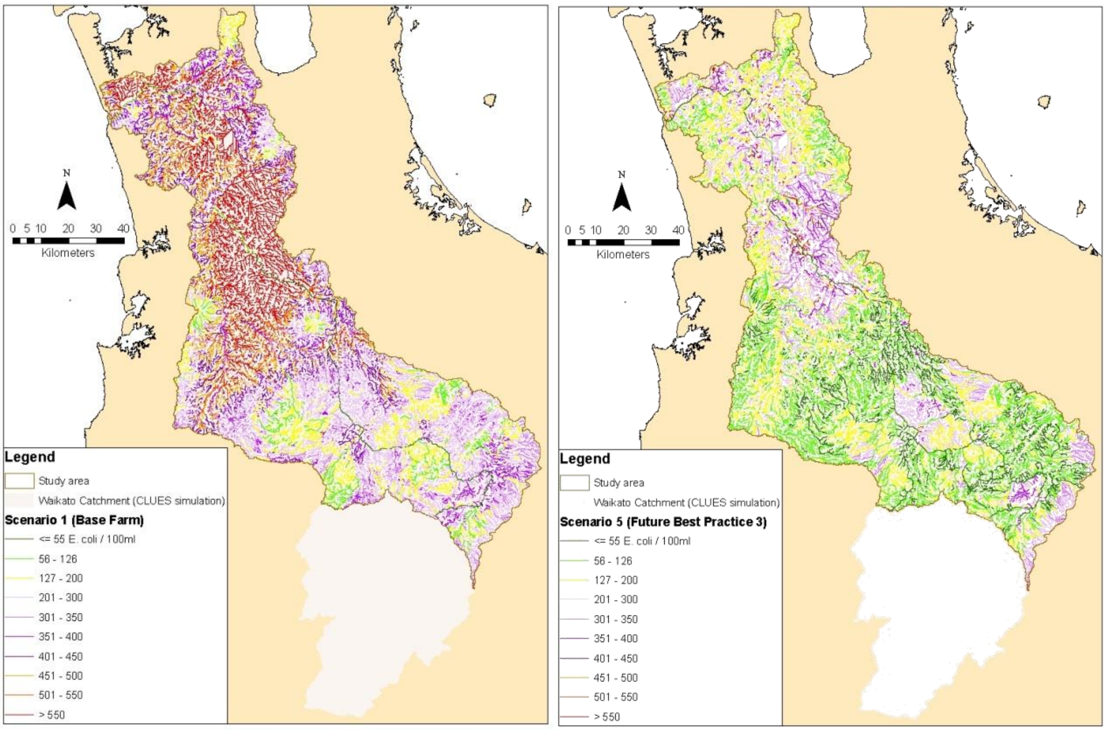

Figure 7. Predicted *E. coli* concentrations (per 100 mL) before and after mitigation measures are applied. Red stream reaches have a predicted median concentration greater than 500 per 100 mL, while green reaches have a concentration less than 126 per 100 mL, and other colours are for intermediate concentration values. Figure abstracted from (Anon., 2010, Appendix 10)**.**

The P predictions also proved to be difficult in this catchment. In the upper catchment, there is a large component of predicted P derived from mass erosion, and this gives rise to a large component of the P load being delivered in infrequent storms. In this study, the management of P concentrations based on load reduction was being investigated, so that storm erosion sources were less relevant. Hence, the P contribution from mass erosion was removed from CLUES. From independent information about the nature of dairying in this catchment, it was considered that the additional P loading from dairying (as discussed in the section on Diary Best Practice Catchments above) was too high, so it was reduced. The P loads were then too low overall (event for non-dairy catchments), so the stream attenuation was reduced. Despite these modifications for local conditions, the model predictions departed significantly from measurements in some tributaries, especially for the concentrations. A further complication was that the P load from plantation forestry was probably over-estimated because there is little information on forest loads in low-rainfall areas in the original calibration dataset. As a consequence, a scenario with reversion to forestry provided unrealistically high P loading. Overall, this application of CLUES represents an extreme condition relative to calibration dataset, and consequently the results proved to be less satisfactory than might be expected in more usual conditions. A challenge is to improve the model performance for these conditions, because they land use intensification by means of irrigation development is often under these conditions (dry, with shallow soils).

On the positive side, this CLUES application demonstrated the potential to offset the effects of land use intensification with a suite of mitigation measures at the catchment scale. The net effects of mitigation and land use change have also been addressed in recent studies in the Mataura (Semadeni-Davies and Elliott, 2011) and Oreti (Monaghan et al. 2010) catchments in Southland.

Conclusions

Applications of CLUES have been growing rapidly and a number of these have been presented in this paper. They demonstrate the use of the model for identifying the relative contribution of different sources, hot spots of generation, stream reaches exceeding thresholds and their associated catchments, the effect of land-use change, and the effect of land-use intensification and mitigation measures at catchment scale.

CLUES predictions entail errors, which can be considerable in some cases. When used to assess the relative changes (such as percentage increases) resulting from scenarios, such errors will be less severe. If local data are available, adjustment of model parameters can be used to improve the alignment of predictions and measurements. Current research is also incorporating more Regional Council data into the calibration of CLUES. Incidentally, more rigorous cross-validation methods will be used in this work.

Information needs and model weaknesses identified in the applications of CLUES have led to model improvements and refinements in a continuous improvement process, which will improve the reliability and usefulness of the model in future applications.

It would be desirable to incorporate more spatial detail into the model, both to improve model predictive performance and to provide more meaningful information on critical source areas. Current research is investigating the incorporation of more spatial detail into the models underlying CLUES. Similarly, it would be desirable to be able to manipulate more OVERSEER inputs.

Difficulties remain in application of the model in areas with strong surface-groundwater interactions. Further research is required in this area. Realistically, it may be possible to include such interactions only in locations where there is good knowledge of aquifer characteristics. A further area for improvement is in characterising the influence of irrigation on nutrient losses.

Acknowledgements

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