Proceedings of the 2005 International Conference on Simulation and Modelling
V. Kachitvichyanukul, U. Purintrapiban, P. Utayopas, eds.

DETERMINING FUTURE DIRECTIONS IN CONTAMINANT CYCLE MODELLING THROUGH AN EVALUATION OF EXISTING MODELLING SYSTEMS

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ABSTRACT

An ability to describe and explore relationships between management activities and land and stream condition is often critical to maintaining and restoring the ecological health of stream and catchment systems. To achieve this, decision makers need robust and credible tools, and increasingly these tools are computer models embedded in decision support systems. These systems typically integrate an appropriate set of models which together describe the dominant processes under investigation. In this context, encapsulating our knowledge of contaminant cycle processes, and land management impacts upon them, presents a fundamental scientific challenge. This is compounded by the need to package this knowledge such that it is relevant to, and useable by, land managers, and policy and regulatory bodies. The aim of this paper is to guide future model development. The paper begins by describing the context of the development of catchment contaminant cycle models through a general discussion of end-user requirements. Following this is a description of three contaminant cycle models recently developed for Australian catchments – the Catchment-scale Modelling of Diffuse Sources modelling system (CatchMODS), the Environmental Management Support System (EMSS) and the Local Scale Environmental Management Support System (LEMSS). These modelling systems are evaluated and discussion is made of their capabilities and limitations in terms of meeting end-user requirements. Proposed directions for future contaminant model development activities are then discussed.

1 INTRODUCTION

Appropriately constructed contaminant cycle models have a key role in supporting efficient and effective catchment management. They can inform policy to address water quality and environmental degradation concerns, and support the prioritisation of investment in catchment remediation and development. They can improve the focus of management intervention and promote best practices. Importantly, their application increases both our understanding of contaminant cycle processes and our confidence in natural resource management decision making. Contaminant cycle models can also enable the simulation of the effects of management change and evaluation of their potential costs and benefits, a priori.

Several contaminant models have been used successfully to focus land management and inform policy debate. Examples include the Sediment River Network (SedNet) model (Prosser et al., 2001) which was applied as part of the Australian National Land and Water Resources Audit to determine critical sediment sources, the Catchment Management Support System (CMSS) (Davis and Farley 1997) which has been applied widely in Australian catchments as a planning tool for reducing nutrient loading and the MUSIC model (Wong et al., 2001) which has been used to predict how stormwater treatment can be used to manage sediment and nutrient loads from urban catchments.

With the success of such models, managers and policy makers are increasing their reliance on contaminant models not only as predictive tools but also as frameworks for communicating key aspects of catchment and stream management. This increased reliance on contaminant modelling results in the need for robust and credible tools.

The aim of this paper is to guide the ongoing development of contaminant cycle modelling. It begins by describing the context of the development of catchment contaminant cycle models through a synopsis of key contaminant model requirements. Three contaminant cycle models are described – the Catchment-Scale Modelling of Diffuse Sources (CatchMODS) model, the Environmental Management Support System (EMSS) and the Local Scale Environmental Management Support System (LEMSS). These models are evaluated in terms of meeting end-user requirements. Directions for future model development activities are then discussed and the paper summarised.

2 CONTAMINANT CYCLE MODEL REQUIREMENTS

To support effective catchment management there is a need for robust, credible and thoroughly tested modelling systems and underlying model components. To meet these needs we have collated the following general requirements for catchment contaminant modelling:

- adequate simulation of hydrologic and biogeochemical processes under current management conditions (Newham et al, 2004);
- identification of critical source areas that currently, or potentially, contribute high loads of contaminants to streams (Newham et al., 2004);
- adequate simulation of the impact of current and future land management practices on spatio-temporal outputs reaching surface waters;
- sensitivity to climate variability (Newham et al., 2004);
- adequate simulation of the impact of current and future instream management practices;
- use of modest and readily available data inputs;
- ability to represent inherent uncertainties in model outputs;
- clearly stated assumptions (Croke and Jakeman 2001);
- ability to be comprehensively tested;
- possessing of strong visualisation capabilities to enable results to be effectively communicated to users; and
- short model processing times.

This list is non-exhaustive and may change depending on the nature of the specific issue being addressed. These requirements should be considered in the following description and comparison of modelling approaches.

3 DESCRIPTION OF CONTAMINANT CYCLE MODELLING APPROACHES

This section describes the CatchMODS, EMSS and LEMSS modelling systems. These models were selected for evaluation in this paper for the following reasons. Firstly, all three models are applicable for widespread use to inform management decision making. Secondly, the models represent the current state of the art in modelling contaminant cycle processes in Australia. Finally, the models are sufficiently different in their scale and method of operation to enable useful comparison of their features as a guide to ongoing model development activities. The authors of this paper were heavily involved in the development of these three models and are now collaborating to build a composite modelling system that better addresses end-user needs.

3.1 Catchment-Scale Modelling of Diffuse Sources (CatchMODS)

The CatchMODS modelling system is designed to simulate existing conditions and the effects of management activities on the quality of receiving waters at catchment scales. The modelling system integrates hydrologic, sediment and nutrient export models and includes an economic component to evaluate the effects of management scenarios on nutrient and sediment delivery to receiving waters (Newham et al*.,* 2004). CatchMODS encapsulates the drivers of climate and associated hydrologic factors, the topography of a catchment, land use and riparian management practices and point sources of pollution. Through considering these drivers, the modelling system can be used to simulate the effects of management change.

CatchMODS is based on a series of linked river reaches (see Figure 1) and associated subcatchment areas. The modelling is lumped at these stream reach and subcatchment units and thus management prescription extends to the same scale (Newham et al*.,* 2004). There are six modelled contaminant inputs to an individual river reach in CatchMODS:

- upstream tributary inputs (except for first order streams);
- point source inputs;
- groundwater associated inputs;

- hillslope erosion;
- gully erosion; and
- streambank erosion.

The CatchMODS modelling system combines a modified version of the SedNet model and the IHACRES rainfall runoff model. The IHACRES model (Jakeman et al., 1990) is used to estimate both surface and sub-surface water discharge in the modelling network. Techniques to regionalise the parameters of the IHACRES model are applied in the model framework. Several hydrologic variables including mean annual flow, mean annual baseflow, median overbank discharge and bankfull streamflow are estimated for each reach in the stream network and are used as inputs to the sediment and nutrient models. CatchMODS addresses many of the limitations inherent in the SedNet model identified in Newham et al. (2003) and also includes basic nutrient export and economic costs components.

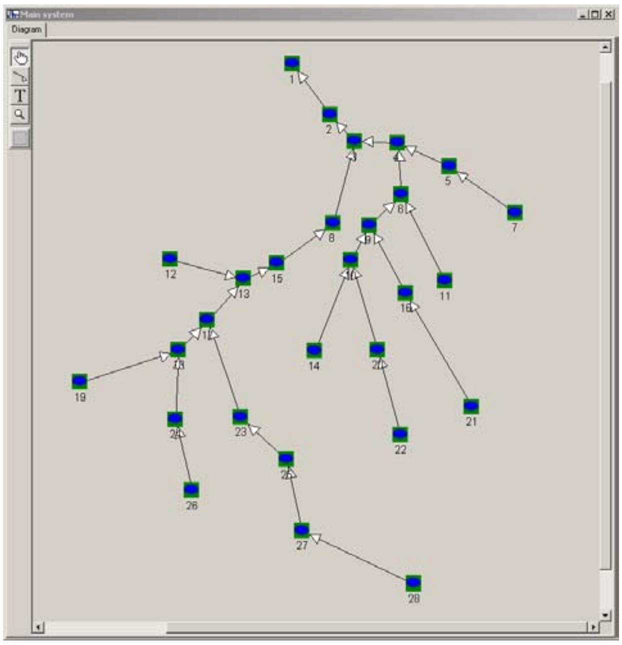

Figure 1. View of the spatial structure of CatchMODS for the Ben Chifley Dam catchment application. The numbers in the diagram denote the individual subcatchment/reach units.

The model estimates annual average loads of total suspended solids (TSS), total nitrogen (TN) and total phosphorous (TP) for each reach in a river network. The model is coded in the Interactive Component Modelling System (ICMS) (Reed et al*.,* 1997) and takes summary spatial data input produced in the ARCINFO GIS system.

CatchMODS was developed at the Australian National University for application in the Ben Chifley Dam Catchment (an upland catchment of the Murray-Darling Basin). Its development was assisted by the New South Wales Government through a grant from its Environmental Trust. The model was constructed and applied in collaboration with the Ben Chifley Catchment Steering Committee, the NSW Department of Environment and Conservation and several other public authorities.

3.2 Environmental Management Support System (EMSS)

The EMSS is a collection of lumped conceptual catchment-scale models used to estimate daily runoff and pollutant loads to receiving waters and to assess the impact of changes in land use and land management. The model is sensitive to changes in climate, reservoir operations, land use and land management practices (Vertessy et al*.,* 2001) and scenarios for implementing these changes can be included. EMSS is composed of three linked submodels - Colobus, Marmoset and Mandrill. Colobus is a runoff and pollutant export model, Marmoset is a streamflow and pollutant routing model and Mandrill is a reservoir model.

The Colobus submodel operates on individual subcatchments to provide daily estimates of streamflow, TSS, TP, TN and pathogens. Daily rainfall and potential evapotranspiration data are needed to estimate daily runoff, which is partitioned into event and baseflow components. These flow components are multiplied by user-specified loading factors (generation rates) to estimate daily loads. The rainfall-runoff component of Colobus originates from the SIMHYD model (Chiew et al*.,* 2002).

Like the spatial structure of SedNet and CatchMODS, EMSS subcatchments (see Figure 2) are linked using a node link system. The EMSS includes a reservoir submodel that simulates the regulation of river flows, traps pollutants and accounts for the evaporative losses from large reservoirs.

The EMSS was developed for application in the Brisbane River catchment of South East Queensland and is currently being applied in several other Australian catchments. The model is currently coded in the Tarsier framework (Watson et al., 2001) and is now being recoded in The Invisible Modelling Environment (TIME) (Rahman et al., 2003) currently under development at the Cooperative Research Centre for Catchment Hydrology (CRCCH).

3.3 Local Scale Environmental Management Support System (LEMSS)

The LEMSS is a model of catchment runoff, water quality and stream ecology (Watson and Vertessy, 2002). It was developed to provide a more detailed spatial representation than the EMSS. LEMSS predicts daily total sediment and nutrient loads as influenced by spatial patterns of land use, in-stream sediment and nutrient dynamics and climate variation. Like EMSS, the LEMSS uses a generation rates approach for estimating contaminant inputs. In addition to predicting runoff and pollutant fluxes through a river network, the LEMSS predicts some basic measures of aquatic ecosystem health for each segment of a river network represented in the model (Watson and Vertessy, 2002). Further discussion of the measures of aquatic health is made in the following section.

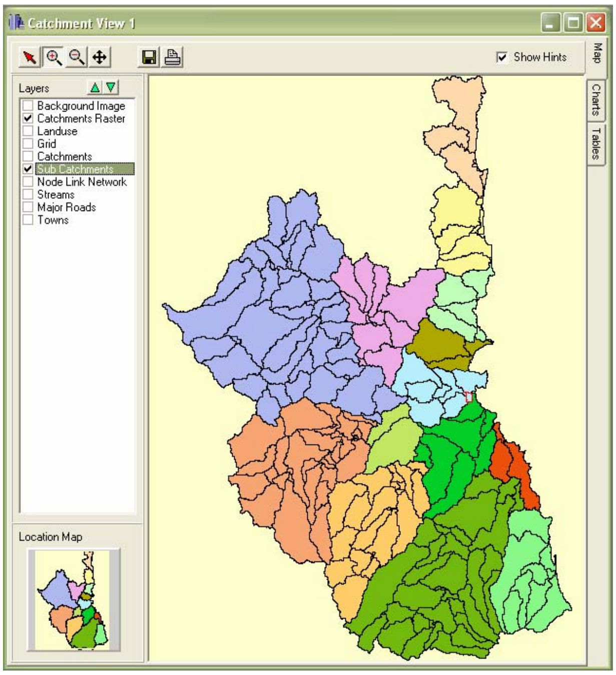

Figure 2. View of EMSS user interface showing the subcatchment boundaries of the South East Queensland application.

The link node spatial structure of the LEMSS differs from that used in CatchMODS and EMSS. A flexible clustering system is used to group grid cells into reasonably homogeneous spatial units based on landscape factors such as land use and topographic data (Watson and Vertessy, 2002). Typically, cells are clustered if they are adjacent, have identical land use (or some other selected attribute) and drain to the same point. These spatial units are connected by a network of links and nodes. Links represent flow pathways and nodes the places where links connect. The implementation of the model is scaled such that links typically represent stream channels and land units represent areas the size of first order catchments (Watson and Vertessy, 2002). This spatial representation of the model provides greater efficiency than modelling individual grid cells, while allowing greater discretisation than catchment-based approaches.

The LEMSS was constructed for application in the Pine Rivers region of South East Queensland as a predictive tool and as a framework for communicating key aspects of catchment and stream management. The LEMSS was developed by the CRCCH and was funded by the Moreton Bay Catchments and Waterways Partnership, The Pine Rivers Shire Council and The South East Queensland Water Corporation.

4 MODEL COMPARISON

Assessment of the strengths and limitations of the CatchMODS, EMSS and LEMSS modelling systems provides a good starting point for proposing future directions in catchment-scale contaminant cycle modelling. This section compares the various models based on the features described in the preceding section. These are listed in Table 1, with a comparative summary, and then discussed in some detail.

Table 1. Comparison of model features

Model Feature	CatchMODS	EMSS	LEMSS
Time interval	Steady state[1]	Daily	Daily
Spatial structure	Node-link	Node-link	Flexible node-link
Scenario investigation	Yes	Yes	Yes
Point sources	Yes	Yes	Yes
Reservoir deposition submodel	No	Yes	No
Management costs submodel	Yes	No	No
Instream ecological modelling	No	No	Yes
Embedded rainfall-runoff model	Yes	Yes	Yes
Embedded routing model	No	Yes	Yes
Ease of application in new catchments	Medium	Low	Low
Explicit uncertainty consideration	No	No	No

[1] The hydrologic submodel of CatchMODS operates at a daily timestep.

4.1 Time interval

Both the EMSS and the LEMSS provide daily estimates of contaminant fluxes whereas CatchMODS is limited to providing steady state estimates (reported as average annual loads). There are two main benefits to estimating contaminant fluxes on a daily time interval. Firstly, model outputs can generally be compared directly with measured contaminant concentration data and consequently ease assessment of model performance. Secondly, the ecological response to changing contaminant concentrations can be more easily estimated with information at daily time intervals. There are however several drawbacks associated with modelling contaminants at daily time intervals. These include firstly, raising the expectations of users with respect to the perceived predictive capabilities of contaminant models, secondly, significantly increasing the computing resources required to use these models, thirdly, having more onerous data requirements and finally, requiring additional interpretation of model outputs to communicate results.

4.2 Spatial structure

Each of the models discussed in this paper uses a node-link spatial structure for catchment discretisation. This structure allows for the effective routing of contaminants and reduces computing requirements over more distributed approaches (e.g. grid-based modelling). The disaggregation used in the EMSS and CatchMODS is based on specified area-based thresholds to define the structure of catchment drainage systems.

The LEMSS provides a more detailed spatial representation of catchments than the other two modelling systems. It is composed of smaller spatial elements, varying in size between a few to a few hundred cells of 25x25m (Watson and Vertessy, 2002). The LEMSS has a flexible spatial structure where disaggregation is based on a clustering system which is used to group grid cells into reasonably homogeneous spatial units. Spatial maps of virtually any landscape attribute (eg. soils, slope, land use, climate) or group of attributes can be used to generate the clusters. Because the flexible spatial structure of LEMSS is based on the clustering of attributes that may be changed in an user-constructed scenarios, different scenarios can result in changes to the spatial structure of the model between individual runs. Hence, any two users of the model would probably derive a different spatial structure owing to their choice of clustering strategy. To date, only minimal research has been carried out to assess the impact of alternate spatial structures on contaminant load prediction. Until more research is carried out, it is difficult to be certain that any change in model response is due to the scenario *per se*, rather than a technical artefact of the changed spatial structure (Watson and Vertessy, 2002). For this reason, we recommend that future contaminant modelling is undertaken using a fixed node-link spatial structure.

4.3 Scenario investigation

CatchMODS, EMSS and LEMSS all have the facility to generate scenarios of land use and management change. Table 2 summarises the management changes that can be simulated by each of the models.

Table 2. Management simulation capabilities of the CatchMODS, EMSS and LEMSS modelling systems.

Management change	**CatchMODS**	**EMSS**	**LEMSS**
Land use	Yes	Yes	Yes
Riparian revegetation	Yes	Yes	Yes
Gully management	Yes	No	No
Riparian buffer zones	No	Yes	Yes
Water allocation	No	No[1]	No
Point sources	Yes[2]	Yes[2]	Yes[2]
Climate scenarios	Yes	Yes	Yes

[1] Simple reservoir operation only, no extractions considered.
[2] Annual loads only.

Land use change can be simulated in all models. In the EMSS and LEMSS, users have the facility to build different spatial patterns of land use with embedded GIS style tools. In CatchMODS, land use changes are simulated by specifying the proportions of the different land uses at a subcatchment level. The latter approach has several advantages. Firstly, it enables construction of simpler user interfaces. Secondly, it reduces the perceived level of complexity for users. Finally, it manages expectations concerning model accuracy. The primary advantage of simulating spatially explicit land use changes is it enables improved representation of the effect of spatially dependent land use changes on contaminant process, for example, hillslope erosion and riparian buffering.

In general terms, the simulation of linear management changes, e.g. in gully and riparian zones, are not well simulated by the models described in this paper. Important riparian and gully management processes are modelled in a generally empirical manner. In CatchMODS, for example, increases in gully and riparian vegetation reduce contaminant source inputs by fixed proportions of base case estimates only and the contaminant trapping efficiency of near-stream vegetated areas is not explicitly considered. In the EMSS, assignment of a riparian zone to a length of stream reduces sediment and nutrient input in proportion to the loading rate (dynamic in time). In the LEMSS, assignment of riparian vegetation to a length of stream increases shading and decreases stream temperature, thus affecting in-stream ecosystem processes. Improving the simulation of linear management changes is an area of development suggested for future contaminant cycle modelling.

In the design of future contaminant modelling approaches consideration should be given to creating a method to express land use change that is model independent. This may include incorporating some of the drivers and limitations of land use change. One question that such research might address is how natural resource management policies can be incorporated to build more realistic land use change scenarios?

In all three models the effects of climate change can be examined. This is achieved by changing rainfall, temperature and/or evaporation inputs to the models (in most cases these are historic records). For ongoing development of contaminant models consideration needs to be given to improving how climate change scenarios are implemented. One potential method is to implement such changes via stochastic climate inputs. In such a case users can specify characteristics of the climate record with reference to predicted climate change scenarios such as are generated via global climate models.

The effects of changing water allocation and trading policies on stream hydrology is not explicitly considered in any of the models described in this paper. While this is a gap, it maintains the overall complexity of contaminant cycle models at a reasonable level. A possible way to consider the influence of different water allocation policies and management on contaminant fluxes explicitly, is to use outputs from water allocation models (e.g. Letcher, 2001 and Letcher and Jakeman, in press) as inputs to contaminant cycle models. In this instance careful consideration must also be made of the effect of water extractions on contaminant fluxes.

Each of the three models allow for user-specified point source contaminants inputs to be considered. This is a very useful feature and it should be retained in the structure of ongoing contaminant cycle model development. The three models also allow for the simulation of the effects of a variety of climate scenarios on contaminant loadings. Again this is a useful feature which should be retained and enhanced in future modelling.

4.4 Reservoir submodel

The EMSS includes a simple reservoir process model to estimate the influence of instream reservoirs. The CatchMODS and LEMSS do not presently incorporate reservoir modelling and as a result they have restricted application downstream of large reservoirs. There is however the potential for the outputs of contaminant cycle models to be coupled with reservoir process models.

4.5 Management costs submodel

Of the three models, only CatchMODS includes a simple costs component to enable limited evaluation and trade-off analysis of management scenarios. The fixed and ongoing costs of implementing various management changes can be estimated via the model. The inclusion of a similarly structured management costs component is suggested for future contaminant cycle models. Cost components such as that included in CatchMODS have relatively modest computational and data input demands and can be readily included in future modelling systems dependent on stakeholder needs.

4.6 Instream ecological modelling

Only the LEMSS includes any consideration of the ecological effects of changed pollutant loadings. This is achieved through estimation of three simple indices of stream health: physio-chemical, nutrient and ecosystem processes. Stream health indicators in LEMSS are estimated for each link in the stream network on a normalised (0-1) scale (Watson and Vertessy, 2002). All of the formulations used to estimate stream health are simple and warrant review as knowledge of aquatic ecosystem behaviour becomes more sophisticated (Watson and Vertessy, 2002).

Unfortunately our current understanding of aquatic ecosystem behaviour is generally limited to enable only qualitative modelling, such as the use of LEMSS style indices, for all but a few narrowly defined aspects of ecosystem behaviour (Young et al., 2000). In deciding what ecological models should be incorporated into future contaminant modelling systems it is important that, firstly, model outputs are matched to ongoing monitoring to ensure close links to management objectives (Young et al., 2000) and that, secondly, ecological modelling outputs provide a picture of the state of aquatic ecosystems in response to changing contaminant loadings.

4.7 Hydrologic modelling

Each of the models includes an embedded rainfall-runoff model in its structure. These models, Colobus (based on the SIMHYD rainfall-runoff model) for EMSS, a simple water balance model for LEMSS and the IHACRES rainfall-runoff model for CatchMODS, drive many of the contaminant processes that the contaminant models represent. To develop good pollutant load estimates, inputs of modelled streamflow data must reproduce both the total volume of streamflow and also the distribution of flow across the simulation period (Newham, 2003).

4.8 Ease of development

To broadly improve the focus of management intervention, contaminant models need to be easily applied in new catchments. The CatchMODS model has generally modest data inputs that can be easily imported for application in new catchments. As a result it is potentially more easily reapplied than the EMSS and LEMSS modelling systems. A second advantage of the CatchMODS modelling system is that it requires minimal software support and can be modified by non-expert programmers.

5 DIRECTIONS FOR CONTAMINANT CYCLE MODEL DEVELOPMENT

The three models described here meet, and in many instances exceed, the requirements of contaminant cycle models that were set out in the introduction in this paper. As such they collectively provide a strong basis for ongoing model development. A comparison of the strengths and limitations of the various model components of the modelling systems lead us to suggest that future development activities should aim toward providing models that, in addition to meeting the general model requirements outlined in Section 2, also have the following desirable characteristics:

- operate at a daily time interval to enable the modelling of aquatic systems;
- incorporate qualitative models to assess the response of aquatic ecosystems to changing contaminant loads;
- use a fixed node-link spatial structure;
- enable scenario generation and testing including an ability to simulate linear land management change;
- incorporate a simple reservoir process model;
- be easy to use and adapt for application in new catchments; and
- possess strong visualisation features to assist in communication of model outputs.

In addition to meeting the technical needs described above, it is critical that such models meet user needs and expectations. This paper has focussed on the technical aspects of contaminant cycle model development. While this is an important research challenge, an equally vital one is the need to construct the models such that they are relevant to the planning and decision-making environment. This requires close interaction with policy makers, analysts and catchment managers to establish how and when they may use such models and what features support and/or inhibit that use. Only then can the term ‘appropriate’ have meaning, both in terms of appropriate construction and appropriate use.

The work and recommendations described in this paper are complemented by a participative programme with the model user/beneficiary community. This programme, implemented as a series of workshops and surveys, will drive the appropriate construction of future model development and delivery.

6 CONCLUSIONS

Catchment managers and policy makers are increasing their reliance on the outputs from contaminant cycle models. Accordingly, the need for robust, credible and reliable tools is increasing. This paper has sought to guide the ongoing development of contaminant cycle models to ensure that future needs are well met. A comparison and evaluation of three catchment-scale models – CatchMODS, EMSS and LEMSS has been made. The three models described in the paper meet the necessary requirements for supporting catchment management activities and as such provide a useful basis for evaluating future directions in contaminant cycle modelling. The strengths and limitations of these models has been assessed and used to produce a series of recommendations for ongoing model development. In summary, it is suggested that development be directed towards scenario based assessment using models with node-link spatial structures, operating at daily time intervals and incorporating qualitative ecological models. Such models need to be easy to use and adapt for application in new catchments and possessing of strong visualisation features for effective application by, and communication to, end-users. The future development of such a model will provide a robust basis for improving land and water management outcomes.

7 ACKNOWLEDGEMENTS

This research is funded by Land and Water Australia and the Murray-Darling Basin Commission under a project titled Development of a Catchment Contaminant Cycle Model for Stakeholder Use. The project forms part of the National River Contaminants Program of Land and Water Australia (LWA, 2003).

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