Application Of A 'Whole-Of-Catchment' Model To The Port Phillip Bay Catchment, Australia

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EXTENDED ABSTRACT

The quality of water travelling through the catchment of, and entering, Port Phillip and Western Port Bays is of considerable interest from ecological and management perspectives. Management agencies for the Port Phillip catchment have to plan for a target reduction of 1000 tonne of nitrogen entering the Bay by 2006, and reduction in sediment loads in Western Port are of similar concern. There are a variety of methods by which nutrient and sediment reduction can be achieved, ranging from direct intervention at point sources, to reductions in and filtering of diffuse loads.

This paper reports on development of a coarse whole-of-catchment model for the Port Phillip and Western Port catchments using the E2 catchment modelling system. A monthly modelling system was used, generating runoff from 68 sub-catchments, 37 of which have outlets with coincident water flow and quality data (Figure 1).

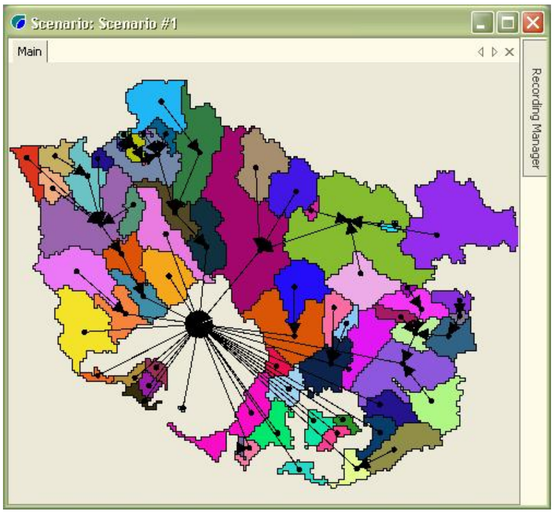


Figure 1. Sub-catchments of Port Phillip and Western Port E2 model

Sub-catchment functional units (FUs) were defined by landuse, with basic landuses being nature conservation, 'protected', minimal use, grazing, forestry, dryland, irrigated, built urban and water bodies.

The AWBM catchment runoff model was calibrated both by sub-catchment, with lumped landuses, and by landuse across all sub-catchments. The sub-catchment basis was found to give more accurate results, due somewhat to the system used for calculation of landuse based flows from multi-landuse catchments. Twenty years of monthly flow were simulated. Flow was found to be reasonably well predicted, with Nash-Sutcliff criteria (Coefficient of Efficiency) values varying from 0.16 to 0.85, with a median across 37 gauged catchments of 0.60.

Water quality estimation was confounded by the requirement to combine generation and filtering to match loads calculated at monitoring stations, as well as by the selection of techniques for estimating monitored load. Appropriate selection of generation and filtering values allowed load estimates to match those of previous studies.

Despite some limitations in information retrieval and reporting, the E2 framework was found to provide a flexible and expandable approach to catchment modelling that should provide good service to future catchment decision making needs in the Port Phillip and Western Port catchments.

1. INTRODUCTION

The catchments (watersheds) of Port Phillip and Western Port Bays (Victoria, Australia) contain a range of landuses that produce varying loads of water quality constituents into both the catchment waterways and the bay receiving waters. Landuses include native forest, farmland, urban areas (including the greater Melbourne metropolitan area) and industrial activity, and competition for space and resources, e.g. for population growth, are putting increasing pressure on these.

Investigation of the water quality of Port Phillip Bay (Harris *et al.*, 1996) revealed processes that threatened the future water quality of catchment waterways and the Bay, and resulted in the adoption by the Government of Victoria (Government of Victoria, 1997) of legislation to develop a Port Phillip Bay Environmental Management Plan, encompassing a nutrient reduction plan, identifying that:

> "..the nutrient reduction plan will aim to reduce the annual load of Nitrogen discharged from the catchment to the Bay by 1000 tonne by 2006"

In recent years attention has also turned to the neighbouring Western Port Bay, with investigation of catchment processes, including sediment movement and smothering of sea-grass beds in receiving waters (Wallbrink and Hancock, 2003).

Along with these investigations, there has also been development of the roles of various agencies and authorities in protecting and managing the catchments of Port Phillip and Western Port Bays. These include Melbourne Water Corporation (MWC), the Department of Sustainability and Environment, the Environment Protection Authority, and the Port Phillip & Westernport Catchment Management Authority. These agencies are now working together to understand and manage the water quality threats that occur within the catchments and waterways.

Over recent years the larger, more identifiable and more easily controlled 'low hanging fruit' load contributors, such as sewage treatment plants and leaking septic systems, have been targetted for action, and reductions in water quality loads have been noted. Attention is now turning increasingly to control of catchment-scale actions and diffuse load contributors.

In focussing on these contributors, and possible management interventions to reduce their contributions, the questions of accurately predicting from where loads are arising, and how management may affect these, has become increasingly important. Modelling of catchment processes, sources, loads, and management intervention effects is part of this assessment and prediction process.

The modelling requirements for these, and many other catchment management processes, are generally along the following lines:

- Discrimination between different contributing 'landuses'
- Spatial representation of contributed sources
- Temporal operation of the modelling, allowing examination of variable climate and dynamic adoption practices
- Assessment of concentration and load at various points within catchments, and to receiving water bodies
- Ability to examine the likely effects of a range of management interventions applied in a range of ways, such as for all of a particular land use across the catchments, particular landuses in specific areas, or other interventions that alter the generation or transportation of constituents (e.g. wetlands, improved management practices, treatment options)

A range of catchment modelling tools have been developed by the former Cooperative Research Centre for Catchment Hydrology (CRCCH) over the past few years. These often build upon previous experience of CRCCH researchers in development of tools such as the Catchment Simulation Shell (Argent and Grayson, 2003), Tarsier (Watson and Rahman, 2004) and ICMS (Cuddy *et al.*, 2002). Building upon experience with these, the CRCCH recently produced E2, a whole-of-catchment modelling system, now available from the Catchment Modelling Toolkit at www.toolkit.net.au.

Development of 'whole-of-catchment' modelling requires considerable testing and application to real-life situations, so as to identify problems in conceptual structure, technical application, data availability and system knowledge.

The research reported here aimed to i) apply the E2 catchment modelling software to the Port Phillip and Western Port Bay catchments, ii) develop a base catchment model for initial assessment of water quality loads and effects of management actions, iii) assess the needs for data and modelling to better meet future system planning and policy development in the Port Phillip and Western Port areas, and iv) assess and inform the development of E2 to better meet the needs of users.

2. E2 – WHOLE OF CATCHMENT MODELLING SOFTWARE

E2 provides a new approach to catchment management modelling that is built around providing both a flexible approach and an expandable modelling system (Argent *et al.*, 2005a; Argent *et al.*, 2005b; Perraud *et al.*, 2005) (Figure 2). Flexibility is provided by allowing users to select from a range of available models for particular catchment processes, with selection ideally being based upon available knowledge, data and the problem being addressed. Extensibility is provided through the use of plug-in models that increase both the depth (i.e more models of particular types) and breadth (i.e. different models) of the models that are available for use.

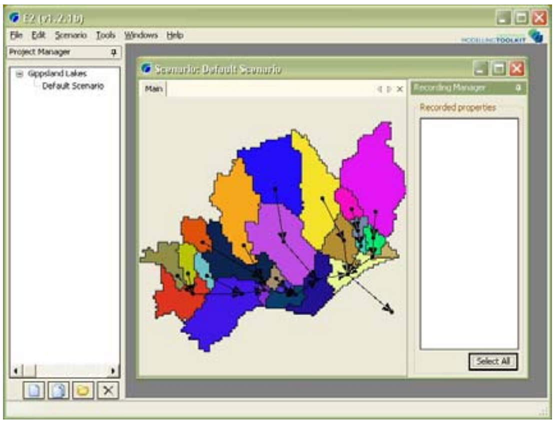


Figure 2. E2 with a scenario loaded

E2 uses a component-based approach to modelling, where alternative models are provided as libraries of components from which desired models can be selected. The architecture and software construction of the E2 system also uses a component-based approach, that supports re-use of software components, such as graphing and analysis windows.

The conceptual structure of E2 combines both sub-catchment processes and node-link transporting and transformation of water and materials. Sub-catchments form the basic unit for representing landscape behaviour and also denote the level of 'lumping' of processes within catchments. Within sub-catchment variability and representation of processes in provided through the concept of Functional Units (FUs) – areas that function in similar ways, such as areas of similar land use or hydrology.

For each FU within a sub-catchment three basic processes can be defined:

- Runoff generation
- Constituent generation
- Filtering of flow and constituents

A range of component models are available for representing these processes, and processes are deemed to act in series. Thus, for a given FU (e.g. forest) within a given sub-catchment, users can select and calibrate a rainfall-runoff model (e.g. AWBM), select and calibrate a constituent generation model (e.g. TSS generation via Effective Mean Concentration) and implement a filtering process (e.g. sediment filtering by planting of riparian buffers). This is then done for each FU (e.g. forest, dryland agriculture, cropping, urban areas) in this, and every other, sub-catchment. The constituent loads being generated from all FUs in a sub-catchment arrive at the outlet node of the sub-catchment with no further processing (Figure 3). If within-sub-catchment transport and transformation processes from FU to FU are important, then a smaller sub-catchment size is selected, and this processing takes place through the node-link network.

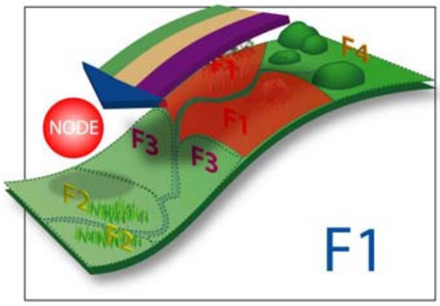


Figure 3. Flow and load from FU1 delivered to sub-catchment outlet. Other FUs are marked F2, F3 and F4.

Flow and loads delivered from sub-catchments to nodes are transported and transformed through a node-link network. Each link in the network can have assigned to it various routing and in-stream processing component models, which act to process the flow and load through the system. Dams are also treated as links, albeit with complex processing and routing. Nodes are also able to represent some required system behaviours, such as flow extraction and water demands.

3. THE E2 PORT PHILLIP MODEL

E2 was used in construction of a catchment flow and loads model for the Port Phillip and Western Port Bay catchments. The loads of interest were nitrogen (Total nitrogen, TN), phosphorus (Total phosphorus, TP) and sediment (Total Suspended sediment, TSS). Both bays were incorporated in the model as they are receiving waters of interest to management agencies.

3.1. Data Sets and Sources

Good catchment models generally require a large amount of data and information to work well. Time series data (e.g. rainfall and flow) of reasonable length and quality are required for calibration and validation. Elevation, topographic or catchment boundary data are used to accurately delineate catchments and flow paths. Data on controls, extractions and diversion of flows are useful for accurately representing flow processes. Land use and land cover data provide the basic spatial information for describing runoff and constituent generating processes.

In this study landuse, evapotranspiration and digital elevation data (DEM) were downloaded from the Australian Natural Resources Data Library (http://adl.brs.gov.au/ADLsearch/). Rainfall data were obtained from the Bureau of Meteorology. Monthly flow data were obtained from MWC. The model was based on a regular grid of model elements (cells) of 1 x 1 km^2 in the DEM, obtained by projecting a Port Phillip and Western Port catchment boundary map over the DEM.

There are two primary methods to delineate sub-catchments in E2. A quick way is to generate the sub-catchments automatically based on the DEM, and requires a hydrologically sound DEM, with no pits. This works with a user-specified stream catchment area threshold. E2 identifies all cells with catchment area above this threshold as 'stream cells', then sets sub-catchment boundaries based upon the confluence points of streams. Extra sub-catchment node points, such as stream gauges, can be added through importing a file list of node positions. Because of the coarse elevation resolution (1 km^2) of the DEM, the potential existed to have cells with inappropriate elevation values, in terms of resultant drainage direction, and so this approach was not used.

The other network delineation method uses manual loading of a sub-catchment map, which is a raster map where each cell has an integer value representing it's sub-catchment number. This approach has advantages in flat areas, where good DEMs are unavailable, in coastal areas with many flow outlets, and where infrastructure affects the natural flow lines. To create this sub-catchment map for the Port Phillip and Western Port catchments, a software tool (FlowEditor) was developed that makes a map based on analysis of drainage direction for each cell. In this case, drainage for a cell was based on D-8, steepest descent routing. Altogether 68 sub-catchments were generated, with 37 sub-catchment outlets being coincident with gauging stations (Figure 1). Gauged sub-catchments ranged in area from 6 to 2300 km^2, with a median of 147 km^2.

A Victorian 1996/97 Land Use Map was obtained, re-projected, re-sampled to 1 km^2, and mapped onto the catchment boundaries map. Nine landuse types were identified: nature conservation, protected, minimal use, grazing, forestry, dryland, irrigated, built urban and water bodies.

Rainfall data for each sub-catchment were selected from sites in or close to the sub-catchment. Twenty years of monthly rainfall data (1981-2000) was prepared, based on accumulation of daily rainfall data. Potential evapotranspiration data were based on ET_0 estimates obtained for Melbourne.

3.2. Component Model Selection

Once basic catchment data are obtained, the next step in setting up an E2 catchment model is selection of component models. These component models are used to represent the basic generation and filtering processes going on in each FU in each sub-catchment, and it is possible to select a range of alternative models for different FUs if knowledge and experience warrant this approach. For this exercise it was decided to select only one of each component model type, with AWBM (Boughton, 1993) being selected as the runoff generation model, and an EMC/DWC (effective mean concentration/ dry weather concentration) model being used for constituent generation. Initially, a 'percent removal' filtering model was selected, although this can be altered readily to reflect the requirements of various management interventions.

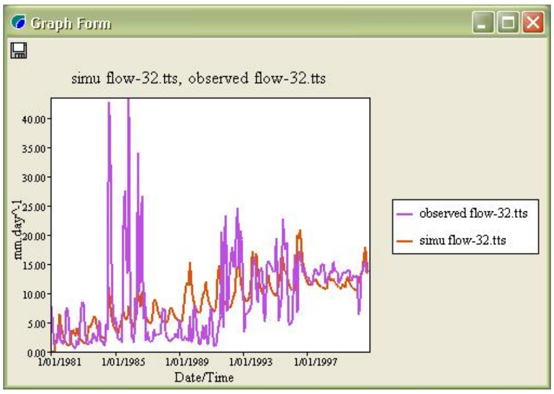
4. FLOW CALIBRATION

Flow model calibration was undertaken using the RRL (Rainfall Runoff Library), available from the

Catchment Modelling Toolkit, at www.toolkit.net.au. Although E2 has a calibration tool, the RRL has more features for optimisation of parameters, and parameter values were readily transferred to E2.

The first calibration approach used simple sub-catchment flow calibration, with Rosenbrock Single Start selected as the optimisation method, and the Nash-Sutcliffe Criterion used as the objective for calibration. The Coefficient of Efficiency (E) values varied from 0.16 to 0.85, with a median across the 37 gauges of 0.60. Figure 4 shown two of the sub-catchment flow calibration results.

Overall the flow modelling was regarded as acceptable, with good agreement with both peaks and low flow periods, except in situations where the runoff appeared to be affected by non-stationary processes (Figure 4).



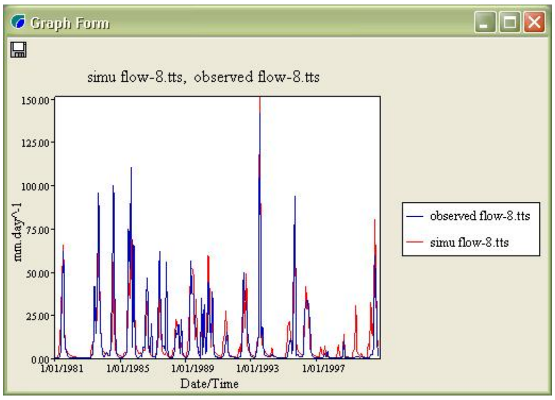


Figure 4. Calibrated and simulated flow for sub-catchments 32 (E = 0.23) and 8 (E = 0.81)

As E2 offers the opportunity to apply different models or different parameter sets to models within each FU, the option of landuse-based calibration was also undertaken. This approach is possibly more problematic than sub-catchment based calibration, as the Port Phillip and Western Port region has a strong east-west rainfall gradient and it is possible that the dominant runoff producing processes may differ across the catchment.

The RRL calibration tool was used for landuse-based calibration by starting calibration in single-landuse (ie FU) sub-catchments, then transferring the resulting parameters to models for that FU, within other catchments. The FU flows thereby estimated were subtracted from the total sub-catchment flow, giving a flow amount arising from the remaining FUs in the sub-catchment. This technique resulted in a much wider range of E values, from -5.67 to 0.85, with some of these results reflecting negative flows arising from the subtraction process.

Although this latter techniques offers some promise for situations with significantly different landuse types (eg. forest v. non-forest), the sub-catchment based approach was used in subsequent analysis.

5. WATER QUALITY ESTIMATION AND CALIBRATION

Assuming that reasonable flow, water quality and landuse data are available, water quality load modelling and calibration using a system such as E2 has three primary issues that need to be addressed:

1. Estimation and parameterisation of the load generated from various land uses,
2. Estimation of the filtering of load that takes place between the generation point or area, and the position in the receiving waters where water quality is monitored, and
3. Calculation of the load against which the model will be calibrated, using a combination of period flow and aperiodic water quality sampling.

The first of these is normally dealt with by use of values obtained from either plot-scale field investigations or from catchment-scale measurements where the catchment has a single or highly dominant landuse. If the latter approach is used, then this combines generation and filtering into a lumped measure of generation.

If adequate field-scale values of generation from key landuses are available, then filtering is essentially used as the calibration process, with filter model parameters being adjusted so that generated loads match those at monitoring points. For a simple filtering model, such as a 'percentage removal' filter, all filters for FUs in a given sub-catchment are given the same value unless there are good reasons to do otherwise. An example of this might be an urban area, where the loads are regarded as directly entering waterways, with zero percent removal, while other FUs, more remote from the notional sub-catchment node, may have very high precent removal of generated load. The adequacy of the generation rates is a key problem with this approach, and modellers must be aware of the range of likely generation values that can arise from various landuse at various time and space scales.

The third point above is one that is often overlooked in stream pollutant modelling. There are over 20 techniques for estimation of water quality load from periodic flow and aperiodic water quality sampling (Letcher *et al.*, 2002). Selection of a technique is dependent on the nature of the monitoring record, the parameter being measured, and also the required result.

For the E2 model of Port Phillip and Western Port bays, these problems were addressed by using values from previous studies (Harris *et al.*, 1996; Argent and Mitchell, 2003), and calibrating the filter parameters to produce the estimated average annual loads of 240, 2600, and 57000 t/yr of TP, TN and TSS, respectively. Comparing the modelled results from individual sub-catchments with estimated loads offers little information, as the filtering values are tuned match the former with the latter.

6. DISCUSSION

The main aims in developing and applying the E2 Port Phillip model were to provide a basic model for further development, provide some assessment of and input to the E2 software, and to assess the needs for data and modelling for future management in the Port Phillip and Western Port areas.

The basic model meets all the requirements specified earlier, in that it allows representation of different contributing landuses, provides temporal run-time analysis, has a spatially distributed generation network, provides flow and concentration values at points across the catchment, and supports investigation of the effects of management interventions.

One of the shortcoming of E2, however, is that it does not analyse the contributions of various landuse (FU) types to the total simulated flows and loads. Thus, it does not support the design of management scenarios where landuse change can be linked to specific changes in resultant loads. It does, however, allow different runoff, constituent and filtering parameters to be applied to all FUs of a type across one, many or all sub-catchments. Thus, catchment-wide application of management interventions can be represented. The 'reality' of the filtering method that is selected for application is dependent upon available data, the capability of the selected filter model to represent appropriate processes at the select scale, and the consequential parameterisation of the filtering model.

A range of other features related to examination of system state, and the recording and reporting of results in various ways and a range of units, have been reported to the E2 development team, and are planned for inclusion in future versions. Improvements to calibration, with inclusion of optimisation functions, would also be a useful tool, and indicator of good practice, to stream pollutant modellers.

E2 also provides a reasonable basis for future modelling in Port Phillip and Western Port Bays, and has recently been adopted there for Decision Support tool development as part of a multi-agency investigation. To improve the quality of the modelling, the key areas lacking information at present are the local generation rates for a range of land uses, and better information on the changes to generation and filtering arising from planned management interventions. By developing monitoring strategies to address these gaps, relevant agencies could contribute significantly to improvement of the stream pollutant modelling of Port Phillip and Western Port Bays.

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