E2 - A Flexible Framework for Catchment Modelling

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EXTENDED ABSTRACT

Catchment management requires modelling for compliance, investigation, understanding, knowledge capture, and informing decisions. The nature of the problems is variable, ranging across scales both temporally and spatially, including discrete events, long term averages, daily and seasonal dynamics, point and spatial estimates and total catchment outputs. These requirements have spawned a variety of models over the years. Difficulties in model use are created when the problem situation changes, and a different question is being asked of a given model. Models with fixed algorithms and structures are not good at providing the flexibility that is often required as management needs change. To address this, a flexible modelling framework has been created, named E2. E2 is part of the Catchment Modelling Toolkit. It uses a robust conceptualisation of catchment processes, based around the notion of a catchment, made up of sub-catchments, wherein component models of different natural processes are positioned and linked to form a whole-of-catchment model (Figure 1)

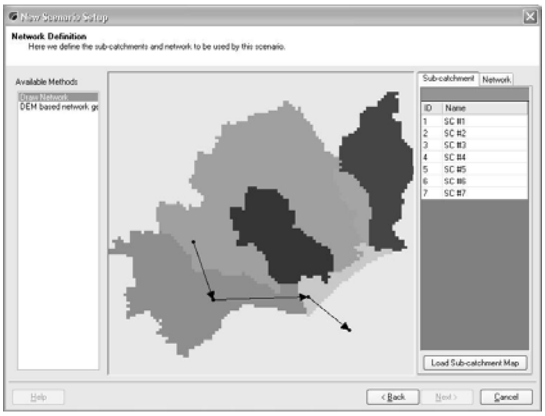

Figure 1. E2 Sub-catchment network

The conceptual structure underlying E2 starts with Functional Units – physically separated areas in a catchment that have similar natural processes that function in a similar manner. Sub-catchments contain numbers of functional units, and each functional unit can have attached to it component models representing processes of runoff generation, constituent generation and filtering, where filtering includes transformation processes between source and outlet. The combined effect of the processes occurring in all functional units in a sub-catchment are directed to a sub-catchment outlet, represented by a node. The nodes of various sub-catchments are joined together by links, along which the flow of water and constituents can be modified through routing, storage, decay, enrichment, sources and sinks. E2 uses a project-based approach, with each project containing one or more scenarios. Scenarios are constructed by stepping through the process shown in Figure 2.

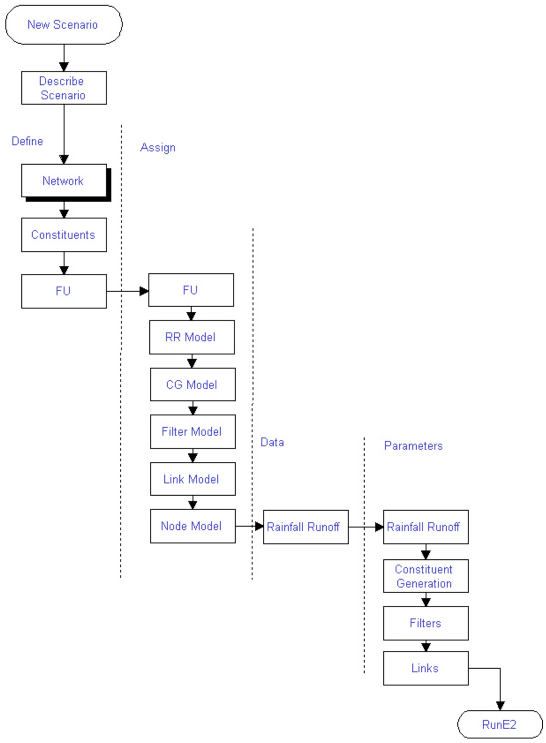

Figure 2. E2 scenario building process

By selection of appropriate system network geometry and component models, and re-use of basic data, E2 can be used to create whole-of-catchment models of varying complexity.

1. INTRODUCTION

Catchment management has become a considerable industry in Australia over recent years, with increasing interest and activity across a wide range of public and private sectors. During this time the industry has also become increasingly sophisticated in the use of technology, as more and increasingly complex problems are addressed, more stakeholders become involved, and requirements for certainty and accountability increase. Modelling has played a key role in this increasing sophistication.

The nature of the problems addressed by catchment managers is diverse, ranging across scales both temporally and spatially, including discrete events, long term averages, daily and seasonal dynamics, point and spatial estimates and total catchment outputs. These requirements have spawned a variety of models over the years, and modelling has been used within catchment management for compliance, investigation, understanding, knowledge capture, and informing decisions.

A short list of models used in catchment management over recent years includes (Marston *et al.*, 2002):

- AgET, APSIM, AQUALM-XP, AQUIFEM-N, AWBM, DATAGEN, FEFLOW, FLOW2D, FLOWTUBE, GLEAMS, HYDROLOG, IHACRES, IMSOP, IQQM, LASCAM, MACAQUE, MIKE-11, MODFLOW, MODHYDROLOG, NEX-1, PERFECT, RAFTS, REALM, RORB, SMF2D, SWAGMAN, SWAT, THALES, TOPOG, URBS, WAVES, WEC-C, WSIBal

These examples provide a considerable range of function, and form, that meet the needs of catchment managers, and those working for them, to varying degrees. Enormous resources have gone into modelling using these and other models over the years, a large proportion of which has gone towards data collection, collation and manipulation.

Difficulties in model use are created when the problem situation changes, and a different question is being asked of a given model than that for which the model was designed or parameterised. Models with fixed algorithms and structures are often not good at providing the flexibility required as management needs change. Over recent years, familiarity with modelling and user-focussed tool development has spawned greater requirements for flexibility in catchment modelling than is provided by many current tools.

During a similar period to that over which catchment management and modelling needs have progressed there have been significant, and relevant, developments in the areas of software engineering and computer science. These have included new theories, methods and tools, such as pattern-based design (Gamma *et al.*, 1995), object-oriented development and integrated development environments.

When coupled with recently trained (or re-trained) expert developers, these theories, methods and tools can go together to provide for many of the needs for flexible and adaptive software. In catchment management the basic modelling needs are spatio-temporal operation, flexible spatial discretisation, variable temporal resolution, and the ability to generate, route and manage flow and materials through a catchment system.

To address the general modelling needs in the catchment management area, a flexible modelling framework has been created, named E2. The software for E2 has been under development since early 2004, with the first public release in February 2005. The heart of E2 is, however, a robust conceptual structure around which the functioning software was built.

2. E2 – THE CONCEPTUAL STRUCTURE

The conceptual structure for E2 is a mix of new and old approaches and ideas. The experience of the first three authors (Argent, Grayson, Podger) in modelling and software systems over (too) many years was combined with recent experiences and knowledge of the latter three authors (Rahman, Seaton, Perraud) with the Tarsier modelling system and a catchment model called the EMSS.

E2 uses a robust conceptualisation of catchment processes, based around the notion of a catchment, made up of sub-catchments, wherein component models of different natural processes are positioned and linked to form a whole-of-catchment model. The fundamental structure of E2 uses sub-catchments, nodes and links.

Sub-catchments define the spatial context, so that processes and management actions can be positioned in space. The combined effect of the processes occurring in a sub-catchment are directed to a sub-catchment outlet, represented by a node. Nodes and links provide for the movement of flow and material through the system, and provide for routing and transformation of material in-stream.

A fundamental concept in E2 is the selection and combination of *component* models – models that represent *fundamental processes*, such as runoff generation or routing, at a consistent level of detail or granularity. By selection of appropriate component models and specification of system network geometry, E2 can be used to create a range of whole-of-catchment models that differ in complexity but which use the same sets of input data.

3. SUB-CATCHMENT PROCESSES

Within sub-catchments the requirements for sub-area variability are accounted for through use of *functional units* (FUs). FUs are areas within sub-catchments that are deemed to function in a similar manner, and so be represented by particular models with particular parameters. This is similar to HRUs (Leavesley and Stannard, 1995) and Geomorphic units, but can be used to represent any function of interest (e.g. presence/absence) provided that the areas of these can be defined, and add up to 100% of sub-catchment area. This FU conceptualisation can be extended to represent unusual behaviour by having areas of sub-catchments that are either defined not to function (ie no component models), or which work in different ways.

The effects of processes operating within a sub-catchment are deemed to act at the sub-catchment outlet node - ie there is no direct processing of material or flow from one FU to the next within a sub-catchment. If such processing is required due to the nature of the problem situation, then a finer definition of sub-catchments can be made. In this way, E2 is scalable, being able to represent systems from backyards to continents.

Within sub-catchments each FU can have assigned to it *component models* representing processes of:

- runoff generation,
- constituent generation, and
- filtering, where filtering includes transformation processes between source and sub-catchment outlet.

These processes act in series and can be represented by a range of available component models.

3.1. Runoff Generation

E2 works by transporting flow and materials through the system. As a catchment modelling system, E2 commonly uses the generation of flow as a starting point. Each FU can have assigned to it a rainfall-runoff model. The currently available rainfall-runoff component models are:

- AWBM (Boughton, 1993)
- Baseflow Separation (Nathan and McMahon, 1990)
- Observed flow
- SimHyd (Chiew and Mcmahon, 1991)
- Sacramento (Burnash *et al.*, 1973)
- SMAR (Nash and Barsi, 1983; Tan and O'Connor, 1996)

Four of these models (AWBM, SimHyd, Sacramento, SMAR) share similarities in conceptual structure. The 'Observed flow' model replaces modelled flow with an input flow sequence, and 'baseflow separation' separates an input flow series into base (slow) and surface (quick) flow. E2 generates both 'slow' and 'quick' flow from each FU, allowing for the use of more complex component models that provide these two fluxes.

The rainfall-runoff models mentioned above are generally run on a daily basis, although E2 supports any time step that is required by a model. Recent examples of this capability have included the addition of a single store 'leaking bucket' rainfall-runoff model, appropriate for monthly modelling in some situations.

Once flow has been generated from the FUs in a sub-catchment it is able to have associated with it material or constituent concentrations, to represent load generation.

3.2. Constituent Generation

In E2 constituent generation is the process of flow gathering material that is then transported into the catchment network. The term *constituents* is used in preference to contaminants, pollutants or material, to avoid any negative or positive connotations. Typical constituents are sediment, nitrogen or phosphorous, although a constituent can be any material (e.g. litter) for which generation, transport and management processes can be represented algorithmically.

Constituents are represented in terms of either concentration, if the constituent is going to be combined with flow to form a load, or directly as load if no flow modelling is done. Similar to flow, two streams of 'slow' and 'quick' load are modelled, allowing representation of, for example, different ground- and surface-water source concentrations of nitrogen.

The available constituent generation models are:

- Event Mean Concentration/ Dry Weather Concentration (EMC/DWC) wherein slow flow is accorded the DWC and quick flow events are accorded the EMC. This model can also be used as an Effective Mean Concentration by setting EMC and DWC to equivalent values
- Export rate model, which uses a single total export value for load
- Observed Concentration, which allows an external concentration time series to be loaded.

Prior to passing the generated load from a FU to the sub-catchment outlet node, a filtering process can also be imposed.

3.3. Filtering

Filtering is used primarily to represent transformation processes between generation and sub-catchment outlet. Filtering provides a way to represent management interventions that may not directly affect the generation of constituents, but rather act in some non-pathway specific way that may ameliorate, enhance or enrich the constituents.

Filters component models in E2 include:

- Percent removal, where a direct proportion of load is removed
- k-C* first order decay
- Load-based sediment and nutrient delivery ratios
- Riparian denitrification

This last is a plug-in model that represents complex riparian water storage relationships and requires considerable data and parameterisation.

Filtering provides a flexible approach to the application of management actions because filters, like other sub-catchment component models, can be applied to one FU in one sub-catchment, all FUs in a sub-catchment, all FUs of a given type across all sub-catchments, or globally to all FUs. By flexibly applying filters of various levels across the catchment it is possible to reflect implementation of quite complex sets of management actions.

Once generated and filtered, loads then pass to the sub-catchment outlet node where they enter the catchment node-link network.

4. NODES AND LINKS

The outlet nodes of various sub-catchments are joined by links, along which the flow of water and constituents can be modified through routing, the effects of sources and sinks, and in-stream processing such as storage, decay, and enrichment.

There are a small number of behaviours represented at nodes, namely extraction and the representation of water demands. E2 has a number of simple demand models, such as a monthly demand pattern, that can be linked to an upstream dam, from which the required demand will be passed if available.

Links are able to have both routing and processing models assigned to them. There are a range of routing models currently available, such as simple lags, Laurenson non-linear models (Laurenson and Mein, 1997) and Muskingum-Cunge routing (Miller and Cunge, 1975). In-stream processing models are currently limited to exponential decay, and sediment and nutrient deposition.

Due to link-like behaviour, such as storage and routing of flow and constituents, dams are treated as special types of link models. E2 has an elegant dam model available that has a depth-volume-area relationship, losses, and minimum and maximum release curves. Reasonably complex release structure behaviour, such as multi-level off-takes, can be represented through this release curve approach.

5. E2 – THE SOFTWARE

E2 is part of a suite of catchment modelling tools developed by or in conjunction with the former Cooperative Research Centre for Catchment Hydrology, and available from the Catchment Modelling Toolkit at www.toolkit.net.au.

E2 is a 32-bit Windows™ application based upon TIME, the invisible modelling environment (Rahman *et al.*, 2003; Rahman *et al.*, 2004), which is model development system that relies heavily on the use of metadata and which has a component-based approach to software construction. TIME has been under development for some three years, and has a developer base of over 30 developers across Australia.

One of the key design aspects of E2 is that it is build for extensibility and flexibility, providing a core capability for a wide range of catchment modelling problems. E2 is also extensible through a plug-in based approach, where specialist functionality, such as new models, analysis and reporting routines, can be plugged-in to the core framework. The architecture of E2 is discussed in a companion paper (Perraud *et al.*, 2005). Provided they are appropriately coded, new component models are recognised by E2 and can be loaded into E2 through a plug-in menu.

The E2 application opens with an empty user interface (Figure 3), within which users can either load an existing E2 project, create a new project, or undertake analysis of external data using the range of analysis tools within E2.

The basic operation of E2 uses *projects*, which are able to contain one or more *scenarios*. Projects are defined by the catchment network that is being used, and scenarios within a project must be based on the network of the underlying project to ensure that scenario comparisons, such as sub-catchment load comparison, are valid.

Scenarios are built through a wizard that steps users through the processes of specification, model assignment, data attachment and parameterisation (Table 1).

Table 1. Tasks in setting up an E2 Scenario

Step	Task	
1	Specify	Network
2		Constituents
3		Functional Units
4	Assign Model	Functional Units
5		Rainfall Runoff (RR)
6		Constituent Generation (CG)
7		Filter
8		Link
9		Node
10	Data Input	RR
11	Parameterise	RR
12		CG
13		Filter
14		Links

The first, and one of the main, steps in setting up an E2 project is specification of the catchment network. There are a range of methods to undertake this, with the primary two methods being network calculation from a Digital Elevation Model (DEM) and manual network configuration (Figure 4).

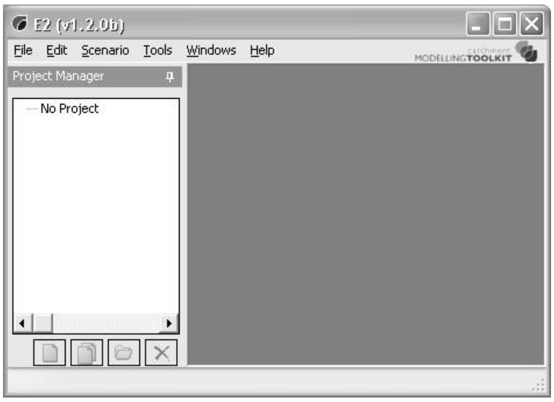

Figure 3. User interface for E2

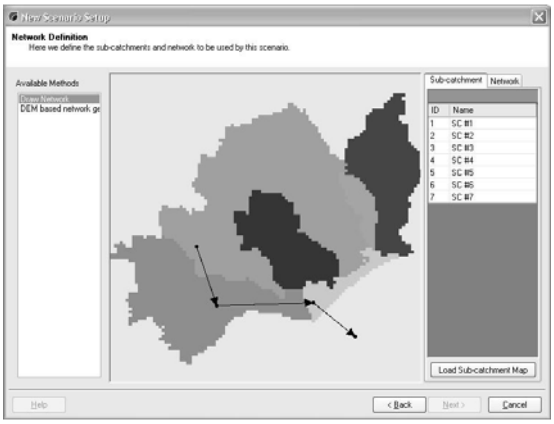

Figure 4. Manual network configuration

Similar to the network specification, E2 offers a range of options for most of the steps in setting up E2 projects and scenarios. These are commonly listed under "Available Methods" to the left of the screen upon which the task is being done.

For network definition, the DEM method required a pit-filled and hydrologically connected DEM for the catchment of interest. A stream network is first calculated via a user-specified areal stream threshold setting, then sub-catchments are automatically created for areas above any junction in the resulting stream network. For coarser or finer networks, and less or mode sub-catchments, the 'stream threshold' value is simply changed up or down. Extra sub-catchment nodes, such as to represent gauging points, can be added by loading a file of node positions.

Manual network definition uses a mouse click-and-drag approach to connect sub-catchments, and is useful in areas where the surface topography does not accurately reflect the drainage network, or where DEMs are not readily available.

Another example where the flexibility of E2 is evident is in the area of data input for rainfall runoff models. Figure 5 lists 4 methods for data input, i) grid-based manual data entry (shown), ii) Import climate data from grids, iii) importing potential evapotranspiration data from maps, and iv) importing SILO (gridded spatio-temporal) rainfall data. For the grid based option, the tab control on the right (figure 5) shows "Table" and "Map" options. The map option shows a map of sub-catchments which can be selected in groups to support attachment of input data files to multiple models across sub-catchments.

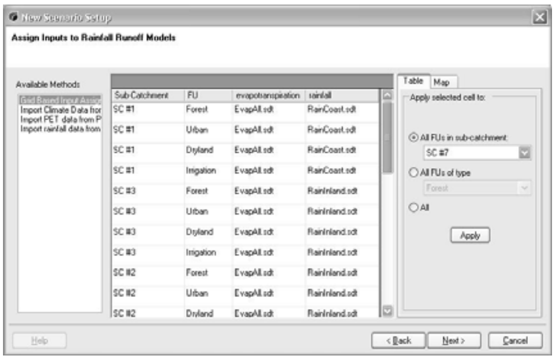

Figure 5 Input data assignment for rainfall runoff models showing multiple available methods

6. CALIBRATION TOOL

One of the significant tasks in development of E2 was creation of a flexible calibration tool to support calibration of flow from both sub-catchments, and sub-networks - consisting of a small group of sub-catchments, nodes and links (Figure 6).

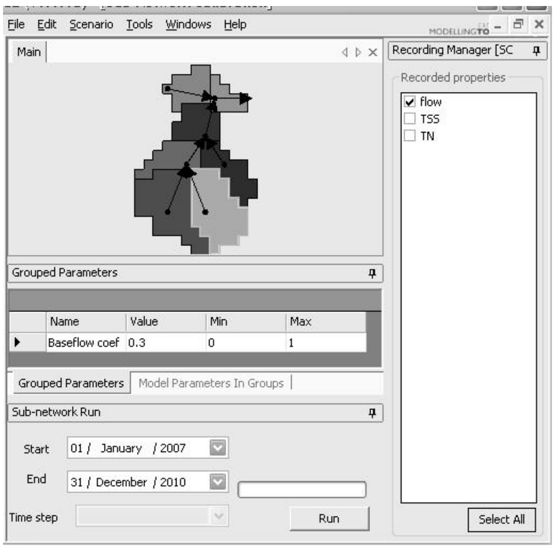

Figure 6 Sub-network calibration tool allowing alteration of multiple model parameters

The calibration tool works through a 'wizard', built using the same software components as the scenario wizard, that steps users through sub-catchment or sub-network selection, parameter grouping and scaling, and model running. The key aspect of the calibration tool is the capability to manually group and scale parameters for multiple sub-catchments. For example, if farmland soil moisture stores are 70% of forest soil moisture stores for a simple rainfall-runoff model, then this ratio of farm:forest can be fixed for the models in all or some sub-catchments. This ratio will then be retained as the manual calibration process scales the relevant variables (eg Maximum Soil Store) up and down during calibration. A range of efficiency criteria, inherited from TIME, are available and new methods can be added as required.

7. OUTPUT ANALYSIS

E2 offers a range of tools for analysis of output from a model run. These include graphs, statistics, computation (eg concentration, from the quotient of load and flow), unit conversion, and maps. Most of the analysis windows operate using a common drag-and-drop approach, so model results can be, for example, dragged from a unit conversion window to a statistics window. Figure 7 shows an example of a thematic map output of mean sub-catchment TSS load.

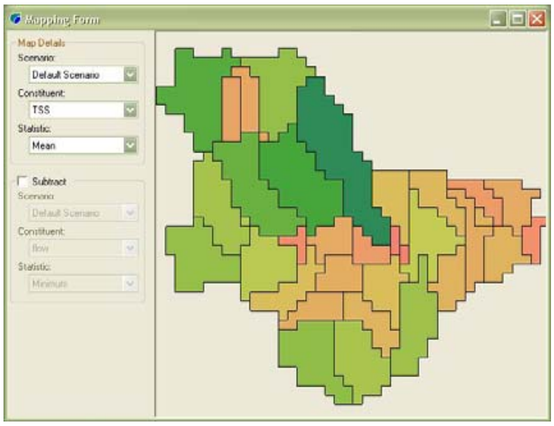

Figure 7 Thematic output map of sub-catchment loads

8. PLUG INS

Plug-ins provide the capability for E2 features to expand beyond the basic catchment flow and constituent modelling to include a range of input, manipulation or output tools. For common processes, such as rainfall-runoff modelling, E2 automatically recognises models of the appropriate type (ie. rainfall-runoff model) and makes them available for assignment. This allows users with specific needs to have custom built component models added to E2.

Connection and integrated operation of E2 with other models is also handled through plug-ins. E2 model integration currently operates with the 2CSalt model, via input loading and replacement in the E2 network, SedNet, via loading of the SedNet network file, and IQQM, via passing of model operation from E2 to IQQM, and back again.

Other plug-ins are drawn from general and specific sources that provide a range of functions, from a raster and time-series data calculator to incorporation of the River Analysis Package (RAP) routines for Hydraulic Analysis and Time Series Analysis.

9. CONCLUSIONS

The above is a short introduction and overview of the E2 catchment modelling software. This software has been created to be flexible and extensible to enable support for a wide and increasing range of catchment software applications. Over coming years the E2 capability and features will expand in response to both the needs of E2 users and the production of catchment science outcomes in E2 compatible component models.

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