A Regional Water Quality Model Designed for a Range of Users and for Retrofit and Re-use

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Abstract: We discuss the motivations for, and software design concepts underpinning, the development of a regional water quality model. The Environmental Management Support System (EMSS) was developed to predict daily fluxes of runoff, total suspended sediment, total nitrogen and total phosphorous through a large-scale river network. It was built using a custom environmental modelling framework called Tarsier, founded on the Borland C++ Builder rapid application development environment. Three autonomous models are integrated within the EMSS, but are loosely coupled so that alternative models could be retrofitted into the system if desired. The three models share common data handling and visualisation routines resident in the Tarsier modelling environment and used in other modelling applications. The EMSS was designed for use by a range of stakeholders with varying levels of computer and technical proficiency. To satisfy their varying needs, we built three different interfaces, suited to 'expert', 'intermediate' and 'basic' users. The interfaces for the latter two groups were developed using interface prototyping methods, resulting in software that suited the user requirements. The object-oriented design employed in the coding of the EMSS has enhanced the extendibility and re-useability of the software. The EMSS development was part of a larger hydrologic modelling initiative aimed at reducing duplication in model building and standardising approaches to model design and delivery. The lessons learned during development of the EMSS have informed our future model development strategy.
Keywords: Water quality model; Modelling frameworks; Tarsier; EMSS

1. INTRODUCTION

The streams and coastal waters of the South East Queensland (SEQ) region contain unique and complex ecosystems that support healthy populations of dugongs and turtles, migratory wading birds and major recreational and commercial fisheries. Since European settlement, these waterways have been degraded progressively by excessive loads of sediment and nutrients. The social response to this problem has been the formation of the South East Queensland Regional Water Quality Management Strategy (SEQRWQMS). This initiative involves participation by various councils, State government departments, private companies and community groups operating in the SEQ region. The aim of the Strategy is to generate knowledge and promote adoption of catchment management practices that will improve water quality and the integrity of the aquatic ecology in the region.

The SEQRWQMS has supported a range of research projects since 1993, dealing with topics as diverse as coastal zone hydrodynamics, catchment sediment sourcing and in-stream ecology. More recently, they commissioned the development of an Environmental Management Support System (EMSS) that could integrate knowledge emerging from these studies and incorporate it into predictive models that stakeholders could use. In the first instance we have developed a proof-of-concept system that contains a limited number of sub-models.

Version 1.1 of the EMSS is a regional water quality model. It predicts daily runoff, and daily loads of total suspended sediment (TSS), total nitrogen (TN) and total phosphorous (TP) from 176 different sub-catchments within the 22,670 km^2 region. The model predictions are sensitive to changes in climate inputs, reservoir storage operations, land use and land management practices, including point- and diffuse-source loadings and treatments. The EMSS is deployed in a GIS-like environment on a PC and has been designed for use by a range of stakeholders with varying levels of computer and technical proficiency. Vertessy et al. [2001], Cuddy et al. [2001], Watson et al. [2001] and Chiew et al. [2002] describe various facets of the current EMSS and its calibration.

In this paper, we focus on the various users of the EMSS and how they shaped the design of the software. We also discuss some of the higher-level software design concepts embedded within the EMSS and discuss how these promote *useability, extendibility* and *re-useability*. We begin however, by putting the EMSS development in a broader context of catchment modelling and some of the systemic problems that bedevil such pursuits.

2. THE ART OF CATCHMENT MODELLING

2.1 Systemic problems in catchment modelling

Relative to the recent advances in computing hardware and software, there has been only modest improvement in the utility of catchment modelling tools in the last decade. One of the reasons for this is that most catchment model development has been undertaken by environmental scientists and engineers with limited computer science training. The models they develop rarely make use of the power and efficiency of modern software engineering methods. Because of this, most catchment models are difficult to understand, use and adapt, leading to frustration amongst model users and developers [Argent et al., 2001].

Catchment models are usually built to perform a specific task, more often than not in an idiosyncratic fashion. They generally use unique input and output data formats and rarely link to standard databases. In most cases, the models cannot be linked to other models without significant code modifications. This rigidity is not only frustrating for model users and developers, but tends to promote poor model use. More often than not, model users adapt the problem to suit their model rather than endure the pain of adapting their model to suit the problem.

When consulted, most catchment managers, model users and model developers agree that a better suite of tools is needed to support catchment modelling activities. Surveys that we have conducted reveal that these groups identify many faults with current modelling tools and practice and that they are receptive to the introduction of new technologies that can overcome these problems [Marston et al., 2001]. This is in spite of the fact that many individuals have invested years in the development and application of their current modelling tools. The model users we surveyed expressed a desire for models that are more transparent, easier to adapt and provide better visualisation capabilities. Model developers sought tools that could simplify and speed-up the task of model building, and permit the re-use and interlinking of models.

2.2 Indicators of software quality

Meyer [1997] discusses several indicators of software quality, including *useability, extendibility* and *re-uesability*. The *useability* of modelling software is determined by the quality of the user interface, and the clarity of supporting documentation. Useability not only impacts on the user's sense of satisfaction at using a system, but also on the frequency and severity of operator errors. It will determine how difficult it is to learn the system, accomplish tasks, avoid mistakes and recover from mistakes. Modern development environments include power user interface design tools, greatly simplifying the technical aspects of user interface design, allowing developers to concentrate on their user's needs. *Extendibility* refers to the ability of software to be expanded to include new functionality. As much as 80% of development costs for software may be incurred during the post-deployment maintenance phase, when the need to be able to incorporate new functionality is critical [Meyer, 1997]. These costs can be significantly reduced if the software is easily modifiable. Extendibility is determined by a number of factors. For instance, does the integration of a new module, or modification of an existing one, require coding changes to be made in many parts of the software system? Object oriented programming languages support the development of extensible families of related modules. *Re-useability* refers to how easy it is to retrofit code written for one application into another. Re-useability is enhanced when a system is composed from small components, with simple, well defined, responsibilities. Object oriented techniques enhance re-useability by emphasising the allocation of responsibilities to individual components that are loosely coupled to other parts of a system.

Most catchment models would score rather poorly on these three indicators of software quality. Our view is that catchment modellers need to start designing and coding their models in a better way. In building the EMSS we have employed software engineering principles to promote these indicators.

2.3 The Catchment Modelling Toolkit

In response to the issues addressed above, we are collaborating with a large team within the Cooperative Research Centre for Catchment Hydrology to develop a new generation of catchment models and modelling support tools, integrated within a system of software called the Catchment Modelling Toolkit [see http://www.catchment.crc.org.au/toolkit]. A key feature of the Toolkit is a module-based programming approach, where models consist of interlinking modules, unified by a modelling 'framework' [Argent et al., 2001]. Currently, we are using two frameworks called 'Tarsier' and 'ICMS' for the development of models within the Toolkit [Rahman et al., 2001]. Both of these have high-level visualisation capabilities that enhance model transparency and stakeholder understanding of what catchment models do. We used Tarsier in the development of the EMSS because it is better suited to large computational problems.

Development of the Catchment Modelling Toolkit is a long-term objective, scheduled to end in 2006. We used the EMSS development as a test-bedding exercise to evaluate the utility of Tarsier in building a large modelling application that involved considerable stakeholder input.

2.4 The Tarsier modelling framework

The Tarsier modelling framework is founded on the Borland C++ Builder rapid application development environment [Watson et al., 2001]. Tarsier is a modular collection of components that enables fast and efficient development and deployment of environmental modeling software. It contains a variety of simulation models, data storage, manipulation and analysis tools, and visualization systems. Tarsier supports many structures for the organization of environmental data, including raster maps, networks, time series and lists of geographic locations. Upon these are built analytical tools that can be used for data interpolation, sampling and transformation, and statistical analysis. At the top level are modules that implement a variety of simulation models.

All models need to implement a certain amount of base-level functionality. Examples include code for opening, manipulating and saving data, for simulation control, and for the display of model results. Within Tarsier, most of these repetitive operations have been identified, encoded in general terms, and made available to model developers. Some of these are implemented within a central class hierarchy that is common to all Tarsier modules, whereas others are implemented as independent modules or classes. The availability of these leads to considerable time savings in model building and results in much more economic model code.

One of the strongest virtues of Tarsier is the ease of linking discrete models to one another; a vital requirement in integrated catchment modelling. The Tarsier kernel defines a number of parent classes that provide the common structure for models, the protocols for communication between models and the use of data by models. Models are implemented as a subclass of the core kernel class User, inheriting the common model structure and protocols. The Tarsier model structure and communication protocols are based on the 'observer' pattern of client-supplier computing [Gamma et al., 1994]. The observer pattern classifies objects as either *observers*, objects that are interested in the state of another object, or *subjects*, objects that can be observed. Observers register an interest in a subject by 'subscribing' to that object. When some property of the subject changes, such as a cell of a raster changing value, all observers subscribed to the subject are notified. Tarsier classifies classes as *Users* or *Usees*. Users are modules that rely on (use) other Tarsier modules, where Usees are modules that can be *used* by Users. Data types, such as *Raster* and *Time Series* represent Usees, while all models, visualisation tools and data analysts are Users. Users are themselves a specialised class of Usees, allowing models to be composed of sub-models, each of which uses data and other models. The observer pattern decouples a Usee from its Users and common Users from each other. For example, if a model manipulates a raster map, the model doesn't need knowledge of any visualisation tool accessing the map. The manipulation represents a change of some property of the map and triggers update notifications to all of the map's Users. Any visualisation of the map is notified and given the opportunity to redraw. This decoupling of models and visualisation facilitates dynamic visualization of all model results without overhead to the model developer.

Every functional module in Tarsier has a corresponding visual module that provides dynamic feedback on the state of its respective functional module. For instance, the rainfall-runoff model, *Colobus*, used in the EMSS, has a visual component that animates temporal changes in all of the hydrologic fluxes and stores. Building of the visual modules is aided by a suite of customised Tarsier components added to the Borland C++ Builder drag-and-drop design palette.

3. DEVELOPING THE EMSS

3.1 Description

The EMSS is composed of three linked models [Vertessy et al. 2001]. A runoff and pollutant export model (referred to as *Colobus*) operates on each sub-catchment, providing estimates of daily runoff (Q), and daily loads of total suspended sediment (TSS), total phosphorous (TP) and total nitrogen (TN). The sub-catchments are linked to one another using a 'node-link' system to represent the river network. Flow and pollutant loads from sub-catchments are conveyed down through the river network using a routing model (referred to as *Marmoset*). As many of the rivers in the region are regulated by storages, a storage model (referred to as *Mandrill*) has been included in the EMSS. This model regulates river flows, traps pollutants, and accounts for evaporative losses. The EMSS also handles the addition of point source loadings of TN and TP, and extractions of water from the river network. Flow and pollutant load predictions are output in a form that can be imported easily into a receiving water quality model. A schematic representation of the EMSS models and objects and how they are interlinked, is shown in Figure 1.

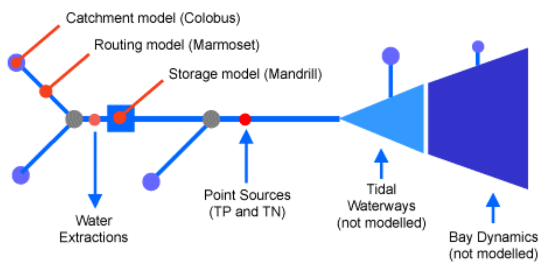

Figure 1: Schematic representation of the EMSS.

In the current configuration of the SEQ region EMSS there are 176 sub-catchments (and therefore 176 instances of the Colobus model), 2070 km of river network (represented as one instance of the Marmoset model) and 8 reservoir storages (and therefore 8 instances of the Mandrill model).

3.2 Scenarios

To simulate the efficacy of proposed water quality management actions, it is necessary to have some way of describing them in the EMSS. We refer to such descriptions as *scenarios*. The actions that underpin any particular scenario can include:

- Changing land use (this has an effect on runoff rate and pollutant loading rates)
- Changing best management practice (say, filtering pollutants via wetlands, constructed traps, and riparian vegetation)
- Changes in climate (say, comparing the behaviour of the system during wet and dry times)
- Addition or removal of major pollutant point sources or water extraction points

The current release of the EMSS contains three scenarios, representing past, current and future catchment conditions. Users can compare results from these three scenarios or modify any of these to form additional scenarios [Cuddy et al., 2001]. Future releases of the EMSS will contain alternative scenarios, with some of these built and 'accredited' in stakeholder workshops.

3.3 Useability

A hallmark of the South East Queensland Regional Water Quality Management Strategy (SEQRWQMS) has been the engagement of a large and broad stakeholder constituency. The individuals involved have widely varying levels of technical and computing proficiency. They range from professional scientists in consulting firms and natural resource management agencies, to landholders and concerned citizens with limited scientific training. As would be expected of any outcome-oriented natural resource management initiative, the SEQRWQMS is founded on a strong consensus building approach [Costanza and Ruth, 1998]. Indeed, they commissioned the EMSS to enhance this process, so the software had to be designed to engage this diverse audience. This presented a significant design challenge for the development team.

Our response was to build specific interfaces and operational features for *expert*, *intermediate* and *basic* users. *Expert* users run all parts of the software, starting with data input preparation, spatial discretisation of the catchment into sub-catchments and river networks, and the calibration and testing of the three component models. Such users need to be proficient in terrain analysis and hydrologic modelling and able to use various modelling support software resident in Tarsier. Most of the tools for expert users are accessed via the Tarsier shell that wraps around the EMSS interface. At the other end of the user spectrum, *basic* users simply examine model results from prerun scenarios, using custom data visualisation tools resident in the EMSS. These tools include tables, graphs, maps and statistical summaries of results. *Intermediate* users take a pre-calibrated version of the EMSS and create new scenarios framed around changes to climate, land use or catchment management practices. Such users do not necessarily require a technical appreciation of how the models work. A sophisticated graphical user interface makes it relatively easy for such users to set up and run a new scenario, then compare the output against a base case scenario.

In developing the user interfaces for basic and intermediate users, we adopted the *interface prototyping approach* advocated by Argent and Grayson [2001]. This entailed running several workshops in which the entire development team interacted with a cross-section of stakeholders. These workshops were conducted at various stages of the EMSS development, commencing at the early concept stage before any software had been encoded, and concluding with training workshops where last-minute modifications to the interfaces were implemented. The sophisticated GUI-building capability of the Borland C++ rapid application development environment and the strong visualisation features of Tarsier allowed us to quickly mock-up screens to elicit stakeholder reaction. Cuddy et al. [2001] describe some of the interface prototyping process we engaged in and discuss various design decisions that were made through the development process.

Another strategy we pursued to enhance the useability of the EMSS software was to build a complementary hypertext system called the EMSS Assistant. This contains background information on the SEQRWQMS, the EMSS developers, the SEQ region and the issues concerning stakeholders. It also includes detailed information on the models in the EMSS, presented in a hierarchical manner so that different stakeholders can get the appropriate level of information for their needs. Other sections deal with the input data used in the EMSS, detailing sources and levels of certainty attached to each data set used. All existing technical publications associated with the EMSS are bundled into this system as .pdf files, along with a user manual and set of tutorials. All sections of the EMSS Assistant are graphics-rich and are accessed via a web browser. The philosophy behind the design of the EMSS Assistant is to make the EMSS modelling system as transparent and as clear as possible, with all the necessary background information provided on-line in a visually appealing manner that entices stakeholders to explore it. Stakeholders have remarked that the EMSS Assistant significantly enhances the useability of the EMSS because the knowledge it conveys engenders trust in the assumptions and input data underpinning the model predictions.

3.4 Extendibility and Re-useability

Part of the design brief for the EMSS was that it be designed as a ‘living tool’ that can be used to harness and integrate new or alternative predictive models as they become available. This objective has been realised by using Tarsier as the supporting architecture for the EMSS. It is relatively simple for a programmer to add, subtract or substitute component models in the EMSS. Whilst a single rainfall-runoff model (Colobus) is used presently for each node in the system, it is possible to attach alternative models to some or all of the nodes, provided they use the same inputs and generate the same outputs as Colobus. Similarly, alternative storage models to Mandrill could be used in different parts of the catchment being modelled. As the model libraries in Tarsier grow, users of the EMSS will be able to select the models they feel fit the data and management questions best. Future versions of the EMSS will incorporate additional sub-models, including economic and ecologic ones. Adding these to the EMSS will require only minimal coding above that needed to encode the models themselves.

Some of the components used in the EMSS already existed within Tarsier, making development of the system easier. New ones that had to be developed not only satisfied requirements for the EMSS, but are now also accessible to other modelling applications resident in Tarsier. In so far as it was possible, the new components were encoded in a generic manner to promote their re-useability. Examples of such components include the Colobus and Marmoset models, an automated parameter optimisation module and a map viewer. Each of these modules has already been used in subsequent modelling projects with only minor re-coding required. Re-useability of model code is a core design philosophy underpinning the Catchment Modelling Toolkit initiative discussed earlier in this paper.

4. CONCLUSIONS

We have discussed the motivations for, and design principles underpinning, the development of a regional water quality model called the

Environmental Management Support System (EMSS). The development process was guided by two motivating forces. The first was a large and broad stakeholder group that wanted a highly useable modelling system that also had the flexibility to grow as their needs change. The second was a development team that wished to develop code that was both extendible and re-useable so that it would add value to a larger modelling initiative called the Catchment Modelling Toolkit project. Fortunately, these forces were not competitive, though it did raise a significant challenge for the development team to produce a modelling system that satisfied all of these qualities. Strong stakeholder involvement via an interface prototyping process was a vital ingredient in making the EMSS a useable tool. The use of the Tarsier modelling framework greatly aided development of a reasonably sophisticated modelling system that was composed of modules with a granularity that encouraged their extendibility and re-use.

5. ACKNOWLEDGEMENTS

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