Hydro Planner – a linked modelling system for water quantity and quality simulation of total water cycle

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EXTENDED ABSTRACT

This paper describes a software tool called *Hydro Planner*, being developed as part of CSIRO's Water for a Healthy Country National Research Flagship Program. The main purpose of Hydro Planner is to enable urban water planners and managers to adopt a systems approach to obtain an improved understanding of how water, wastewater and stormwater systems interact with each other and with natural water systems in terms of water, contaminant and nutrient flows at city and regional scale. Hydro Planner can assist development of regional water allocation, river management, land development and urban water supply/demand strategies by allowing practitioners to assess implications of a variety of water management and land development options by considering the influence of factors such as climate change, population growth and technological changes. The aim of this paper is to describe conceptual design and implementation aspects of Hydro Planner.

The modelling approach adopted in Hydro Planner utilises E2 model integration framework (www.toolkit.net.au/e2) to link models that can simulate various components of total water cycle in an urban context. The component models included in Hydro Planner support continuous simulation of runoff and constituent generation from water supply and urbanised catchments, urban and environmental water needs, supply system behaviour such as reservoir storage levels and demand shortfalls and routing of both flows and constituents through a stream network down to the tidal limits in estuaries. Hydro Planner is being developed with a view toward generic integration of these components. Our aim is to provide an integrated modelling system of the total water cycle in any given urban area through linking of component models of a complexity appropriate to the questions being addressed and the available data and knowledge.

Hydro Planner consists of seven modules: (1) *catchment module* - supports linking of models that can simulate constituent and runoff generation processes from supply catchments; (2) *water supply module* – supports linking of models that can simulate water supply system behaviour; (3) *consumption module* - supports linking of models that can simulate urban water consumption; (4) *stormwater module* – supports linking of models that can simulate stormwater and associated constituent generation and routing process; (5) *wastewater module* - supports linking of models that can simulate wastewater and associated constituent generation and routing processes; (6) *receiving water module*- supports linking of models that can simulate flow and constituent routing through a stream network; and (7) *integration module* - supports translation and computation of input/output data between modules and the Graphical User Interface.

The E2 framework contains component models needed for the catchment and receiving water modules. Hydro Planner adds models to support the remaining modules. Implementation of Hydro Planner is currently in progress. At present, catchment, water consumption, water supply and receiving water modules are nearing completion. The water consumption module provides functionalities to access Water Services Association's End Use Model and the water supply module provides functionalities to communicate with the REALM model. The catchment module supports a number of rainfall/runoff models and constituent generation models. The receiving water module supports a number of routing models.

Currently, a case study is underway using Benalla water supply system, to test functionalities of catchment, water consumption, water supply and receiving water modules of Hydro Planner. The test case study is used to assess: potential impacts of 2030 climate change scenarios; and the potential impacts of changing end water use behaviours. The test case considers the effect of climate change, population growth and various demand and supply side management options on the supply system performance such as system yield and the quality of water in Ryans Creek.

1. INTRODUCTION

As the focus of urban water management moves from fully meeting all urban water needs and protecting public health to providing a service that advances well being of the environment, community and the economy, practitioners need a good understanding of the interrelationships between the urban water system and the environment, community and the economy to ensure that the urban water service provision is ecologically sustainable. This paper describes a software tool being developed as part of CSIRO's Water for a Healthy Country National Research Flagship Program, called *Hydro Planner.* It aids analysis of the urban water system to understand how water, wastewater and stormwater systems interact with each other and with natural water systems in terms of water, contaminant and nutrient flows at city and regional scale. The aim of this paper is to describe conceptual design and implementation aspects of Hydro Planner. Currently a case study is in progress to demonstrate and test functionalities provided by Hydro Planner. We provide a brief description of the test case study as part of this paper.

2. PURPOSE AND TARGET AUDIENCE

Hydro Planner adopts a *systems approach* to provide an automated method to explore interactions between components of the urban water system in terms of water and *constituent* flows at city and regional level (note: throughout this paper we use the term *constituents* to describe sediments, nutrients, contaminants, pathogens, etc.) under both natural influences (e.g. climate) and human influences (e.g. planning and management decisions related to water management and land development) within the urban water context. Figure 1 shows components of the water cycle included in Hydro Planner. Arrows shown in Figure 1 indicate interactions between components.

The *systems approach* allows seeing interrelationships rather than things, and seeing patterns of change rather than static 'snapshots' (Sustainable Development Update, 2004). An application of this systems approach to urban water system means consideration of the urban water system as a group of interacting, interrelated and interdependent components that form a complex and unified whole. It also means that changes happening in a particular system component may have an impact on other components, which may not be obvious or intended, but can cause a significant impact to the surrounding environment. Understanding and where possible, internalising of these unintended impacts within the decision making process can improve the way in which urban water services being provided in sustainability terms.

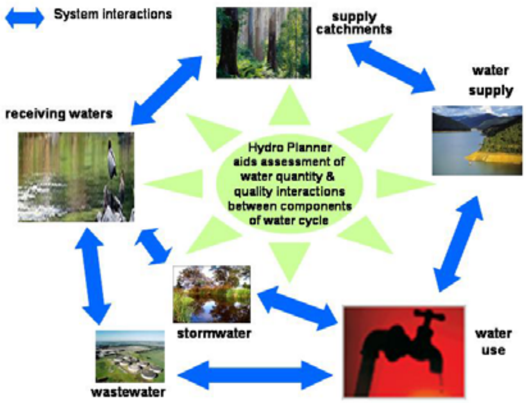

Figure 1 Components of water cycle included within Hydro Planner

Therefore, the main purpose of Hydro Planner is to enable urban water planners and managers to adopt a systems approach for the assessment of physical interactions in an urban water system in terms of water quantity and quality.

The ability to perform system-wide assessment will help decision-makers understand and account for flow-on impacts of management and planning decisions. This is somewhat different to the concept adopted in the traditional urban water management practice in which the main focus is managing its constituent components in a rather fragmented manner, where, for example, segregated management is adopted for water, wastewater and stormwater without giving much consideration to interrelationships between them. A lack of systems knowledge with regard to urban water service provision can lead to the provision of solutions that can be seen as appropriate at local level and in the short term, but may cause undesirable impacts at a regional level and in the longer term.

Practitioners can use Hydro Planner to assist development of regional water allocation, river management and urban water supply/demand and land development strategies. Hydro Planner can be applied within such strategy development context to the following specific areas of analysis:

(1) Water availability analysis: that is, to identify and quantify the temporal and spatial distribution

of existing and potential water sources (e.g. surface water, stormwater, wastewater).

(2) Water balance/allocation analysis: that is, to link supply-side analysis with demand-side analysis on a daily, monthly or annual basis to understand the overall impact of various supply and demand options on system yield and flow-on implications such as health of waterways.

(3) Constituent balance analysis: that is, to identify and quantify sources and sinks (i.e. destinations) of constituents

(4) Flow and constituent routing analysis: that is, to understand transportation aspects of constituents. This type of analysis is required to identify reaches of waterways and rivers that are likely to be *stressed* (i.e. not meeting water quality compliance standards).

3. MODELLING APROACH

When selecting a modelling approach to develop Hydro Planner, the following aspects have been taken into account:

(1) The purpose of Hydro Planner is to provide an automated method for exploring system-wide interactions among various components of the urban water cycle, rather than modelling of a particular component of the urban water cycle. This implies a requirement for adopting a *model integration approach*. Model integration is an emerging approach for model development particularly in the area of environmental modelling (Argent, 2004).

(2) Adopting a model integration approach can avoid 'reinventing-the-wheel', which implies where applicable Hydro Planner can use already available models of various components of the urban water cycle and focus on quantifying interactions without reinventing models to represent processes occurring in each and every component of the water cycle.

(3) Hydro Planner must be extendable to enable linking of component models of urban water cycle that are appropriate for application study being considered, research questions being addressed and more importantly availability of data for component model calibration and validation.

Consideration of the above aspects led to selection of E2 catchment modelling framework (Argent et al, 2005) as the starting point of Hydro Planner development. The E2 framework is based on TIME (The Invisible Modelling Environment), which is a software development framework available for creating, testing and delivering environmental simulation models (Rahman et al, 2003). TIME allows integration of component models particularly in the water domain and provides support for the representation, management and visualisation of a variety of data types, as well as support for testing, integrating and calibrating component models. Since E2 is based on TIME, it inherits the capabilities of TIME. E2 adds functionality to link models to simulate runoff and constituent generation from sub-catchments and routing of both flows and constituents through a stream network down to the tidal limits in estuaries.

E2's modelling approach provides a 'node-link' structure to represent a stream/river network and associated sub-catchments. Sub-catchments feed runoff and constituents into nodes. Runoff and constituents are routed along links. Sub-catchment processes are modelled using three types of processes: runoff generation, constituent generation and filtering (Argent et al, 2005). A library of models/algorithms is available and can be associated with each of these processes and the routing process in links. The user can select models/algorithms for these processes depending on factors such as availability of data and spatial and temporal scale appropriate to an application study.

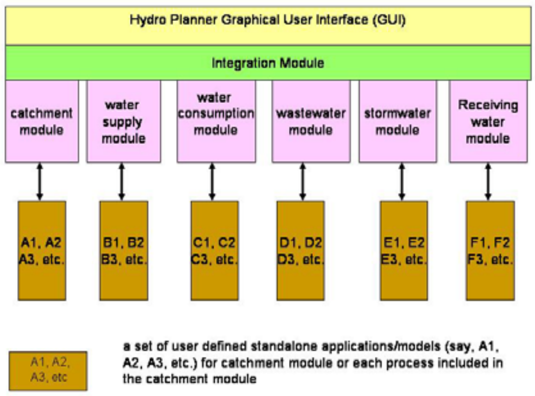

Figure 2 Hydro Planner modelling approach

Hydro Planner augments E2 to incorporate urban water supply, urban water use and wastewater and stormwater systems. That is, simulation of water supply sources and bulk water transfer, urban water consumption; stormwater and associated constituent generation processes; wastewater and associated constituent generation processes. Similar to E2's flexible model linking approach, Hydro Planner is being developed with a view toward generic integration of these urban components. That is, our aim is to provide an integrated modelling system of the total water cycle in any given urban area through linking of component models of a complexity appropriate to the questions being addressed and the available data and knowledge.

The conceptual structure of Hydro Planner, as seen in Figure 2, consists of seven modules:

(1) C*atchment module* - supports linking of models that can simulate constituent and runoff generation processes from supply catchments

(2) *Water supply module* – supports linking of models that can simulate behaviour of the bulk water supply system (i.e. water sources and major transfer system)

(3) *Consumption module* - supports linking of models that can simulate urban water consumption

(4) *Stormwater module* - supports linking of models that can simulate stormwater and associated constituent generation and routing processes through major drainage and waterway system

(5) *Wastewater module* - supports linking of models that can simulate wastewater and associated constituent generation and routing processes through major trunk sewer system

(5) *Receiving water module* – supports linking of models that can simulate constituent routing through a natural stream network and in-stream processes

(7) *Integration module* – provides a layer between the above six modules and the graphical user interface (GUI). This layer helps make the GUI independent of the particular models chosen within each of the modules. It also translates data representations form a general user input format into the structures specific for the individual component models. Furthermore, it provides functionality to support computation inputs to and outputs from modules to quantify interaction between systems components.

Each module provides a set of functionalities depending on the component being modelled and a set of models/standalone applications that it supports. The user can select the model/standalone application from that defined set. In Figure 2, these standalone applications/models are shown as A1, A2, B1, B2, etc.

The models in E2 form the basis of the catchment module and the receiving water module. Hydro Planner adds models to support the remaining modules. Implementation aspects of Hydro Planner are described in the next section.

4. IMPLEMENTATION

Implementation of Hydro Planner involves the adding of component models to E2 to support modules #2 to #5, module #7 and development of a GUI that is specific to Hydro Planner.

Implementation is being carried out in two stages: stage 1 - development of catchment, water consumption, water supply and receiving water modules (say, *Hydro Planner - stage 1*), and stage 2 - development of stormwater, wastewater and integration modules and development of a *preliminary* GUI that is specific to Hydro Planner. It should be noted that E2's Graphical User Interface (GUI) is currently utilised during the development phase of Hydro Planner.

Since E2 provides functionalities to support catchment and receiving water modules, these modules simply migrate to Hydro Planner. Thus stage 1 implementation involves development of the water consumption and water supply modules. Currently stage 1 development is almost complete. Implementation of the modelling structure shown in Figure 2 (i.e. both stage 1 and 2) will be completed by June 2006.

Implementation aspects of the water consumption and water supply modules are described below. Structure of the catchment and receiving water modules and the component models included in these modules can be found in Murray et al (2005).

4.1. Water consumption module

The water consumption module is illustrated in Figure 3. It provides functionality to link Water Services Association of Australia's (i.e. WSSA) (2004) End Use Model (EUM).

The EUM can forecast mean annual water demand by taking into account factors that influence sectoral water use (e.g. residential, commercial, and unaccounted for water) and the end uses of water in each sector (e.g. residential showers or commercial cooling towers). These factors include appliance stock (e.g. washing machines with a Triple-A water use efficiency rating), uptake rates of appliances and demographics. The output of EUM consists of water consumption values for each end use in each sector on an annual basis for defined spatial regions. The EUM also allows options targeted at reducing water consumption by specific end uses to be modelled.

The EUM has two distinct parts, the user interface and the persistent data store. The user interface component is implemented in Microsoft Excel™, which supports data entry, calculation of results and visualisation. Data storage is in a MS Access™ relational database.

The water consumption module supports functionality to query EUM's MS Access™ relational database, *process* the *query results* and configure EUM's interface such as changing parameters and adding scenarios. The *query results* include a spatially implicit annual time series of water consumption for each end use. *Processing* involves temporal and spatial disaggregation of query results into a form suitable for use within the Water Supply Module. The query results dataset lists the individual uses and corresponding volume for each time step, currently yearly.

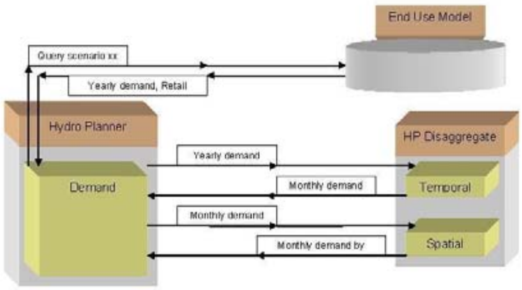

Figure 3 Functionalities provided in the Water Consumption Module to support linking with WSAA's End Use Model

Currently, the Water Supply module requires monthly time series of water consumption for defined areas, so the Water Consumption module uses a user-defined set of factors for spatial disaggregation and an algorithm based on monthly evaporation, rainfall and mean temperature for disaggregation of annual water consumption values to monthly values.

4.2. Water Supply Module

Currently the water supply module supports functionality to link REALM (Resource Allocation Model) (Victoria University and Department of Sustainability and Environment, 2004) with Hydro Planner.

REALM is a water supply system simulation model. It is used by some water authorities in Australia to determine the impact of a variety of options (e.g. new operating rules and physical system modifications) on the behaviour of the supply system (e.g. reservoir storage levels and demand shortfalls). REALM represents the water system as a network of nodes and links. Nodes represent demand centres and supply sources while links represent water supply trunk mains, waterways and rivers. It uses a network linear programming algorithm to optimise water allocation, to specified rules, within the network, for each time step of the simulation. REALM typically operates on a monthly time step and requires monthly time series of inflow, rainfall and evaporation at source nodes, monthly time series of demand at demand nodes, capacities of links and operating rules as input data.

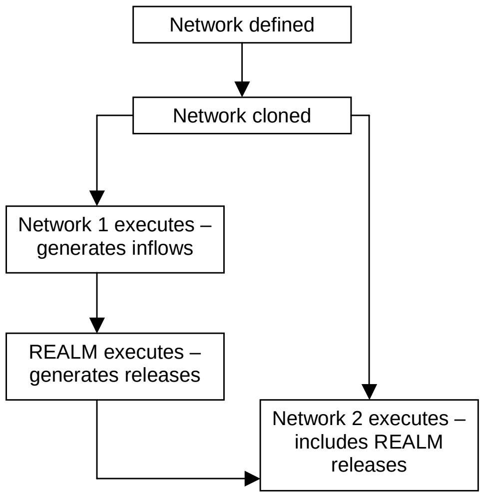

Figure 4 E2 and REALM integration process

Inclusion of REALM as a component model within water supply module led to a need for establishing a two-way data exchange between REALM and E2. That is, E2 to provide REALM with catchment inflows and REALM to provide E2 with information on both controlled and uncontrolled water releases and environmental flow releases from reservoirs. To provide this two-way data exchange, firstly, Hydro Planner executes E2 to estimate catchment inflows and simplified channel flows. Then the Water Consumption module is executed to estimate demand data. This data is fed to REALM to provide it with input describing the inflow of water to storages and demands on these storages. Secondly, Hydro Planner executes REALM, which provides both controlled and uncontrolled water releases and environmental flow releases from reservoirs to the stream network. This data is fed to E2 to provide it with input describing the release of water from E2 storages. This process is illustrated in Figure 4.

A daily time step has been chosen for modelling the quality of water in urban waterways. This means monthly releases provided by REALM need to be disaggregated to daily values. Currently disaggregation simply involves division of the monthly release value by the number of days in the month. A more complex disaggregation algorithm probably using a configurable disaggregation curve is expected to replace this approach.

The Water Supply Module also incorporates functionality to run the (non-interactive) REALM executable and utilities for writing out REALM demand and inflow files and reading REALM release files. To provide information to facilitate data exchanges between E2 and REALM correspondences between related REALM and E2 entities (e.g. reservoirs) are identified by a series of mapping objects. These mappings objects are configured, by the user, in an XML file prior to execution.

An important aspect of REALM and E2 integration is to ensure that the state of the REALM network at any time in the simulation mirrors the state of the E2 network at the same time. If the states are not similar the two systems will deviate and the integration will not provide sensible outcomes. Such deviations can be minimised by ensuring that the evaporation models, loss models, and release disaggregation used within the E2 framework are carefully calibrated to correspond with the representation of those factors in the REALM network. A mechanism is proposed that will compare E2 and REALM storage levels at the end of the simulation as measure of system divergence.

5. MODEL INTEGRATION ISSUES

In this section, we highlight some of the various integration difficulties that have been encountered in our work so far and these include:

(1) Differences in temporal scale of component models included in various modules. For example, the constituent modelling performed in E2 operates at a daily time-step; REALM operates at a monthly time-step; and EUM produces annual demand values. Therefore, work has been required to design appropriate disaggregation/aggregation of inputs/outputs, according to various assumptions. For example, at present, we use climate-based algorithm to disaggregate annual to monthly water consumption to integrate REALM and EUM component models.

(2) Hydro Planner is being designed as a spatially explicit modelling system that can represent spatial data at sub-catchment level, which is defined by the user. However, not all component models operate at a same sub-catchment level. Furthermore, some of the models are not spatially explicit, e.g. EUM and REALM. Thus differences in spatial representations of component models included in the various modules pose a significant challenge when translating spatially explicit data defined via GUI to inputs of various component models or *vice-versa*. At present, we are in the process of designing 'integration module' to handle this spatial aspect of the Hydro Planner.

(3) Incompatible assumptions of various component models. However, this has not been encountered during this stage of Hydro Planner development. It could occur if a model did not include some process needed for a subsequent model.

(4) How well various component models lend themselves to integration, i.e. being run under control of some other program, rather than an interactive user. Two possible integration modes of component models are 'batch mode' and 'macro mode'. The batch mode was used in REALM integration, where we generated input data files; read and processed output files; and, run REALM under Hydro Planner control. Under the macro model, a component model is executed and inputs/outputs can be sent/received via a command without needing to write data files. This mode will be utilised to enhance integration of EUM.

At present, we are in the process of generalising the knowledge gained from the current integration work to permit different component models to be selected and used within the Hydro Planner system in particular within consumption, water supply, stormwater and wastewater modules.

6. TEST CASE STUDY

We are currently in the process of testing functionalities of *Hydro Planner – stage 1* using Benalla water supply system as a case study. A schematic diagram of the Benalla water supply system is shown in Figure 5. Benalla lies some 200 km from Melbourne in North East Victoria on the banks of Ryans Creek. The following data and information have been processed to apply Hydro Planner to Benalla:

1. An EUM for Benalla is not available. However, observed daily water consumption data is available for the period 1 July 1995 to 30 June 1999. Using this data and assuming an annual growth rate of 1% and a population of 9000 in 2000/01, EUM for Benalla has been developed. The total water consumption has been disaggregated to end uses based on typical values.

2. Sub-catchments have been delineated from digital elevation models. The AWBM model

(Boughton, 2004) has been used for modelling of sub-catchment inflows. The model has been calibrated using observed data of catchment rainfall, evaporation and streamflow for the period from January 1998 to June 1999.

3. A calibrated REALM model of the Benalla supply system has been obtained from the Department of Sustainability and Environment of Victoria.

4. Constituent data is not available. Therefore, assumptions have been made with regard to land uses, constituent generation rates and flow routing processes.

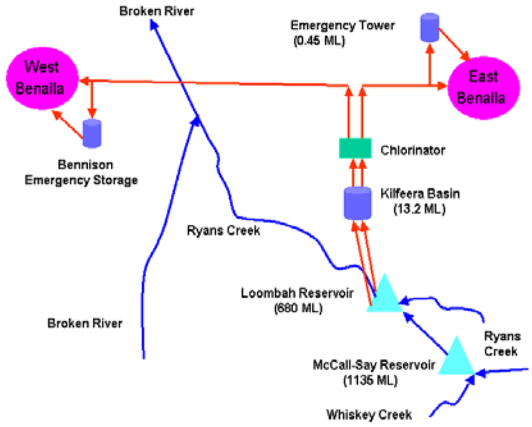

Figure 5 Benalla water supply system

The test case study will be used to assess: (1) impacts of 2030 climate change scenario on catchment inflows, water consumption, system yield and the quality of water in Ryans Creek, and (2) impacts of changing end water use behaviours on the supply system performance and the quality of water in Ryans Creek. Outcomes of this scenario assessment work will demonstrate how Hydro Planner can be used to assess supply system yield by accounting for likely changes in climate and population and management interventions such as various demand management measures and some source diversification options.

7. CONCLUSIONS

Hydro Planner enables water managers and planners to adopt systems approach to explore how water, wastewater and stormwater systems interact with each other and with natural systems. The modelling approach adopted in Hydro Planner allows practitioners to develop an integrated modelling system of the total water cycle in any given urban area through linking of component models of a complexity appropriate to the questions being addressed and the available data. The current version of Hydro Planner combines models of managed water releases and demand with a model of natural hydrology that provides a high temporal resolution and detailed simulation of water quantity and quality.

8. ACKNOWLEDGMENTS

Data provided by North East Regional Water Authority for carrying out the climate change impact study for Benalla have been used for the case study described in this paper. Thanks to Jean-Michel Perraud, Andrew Grant and Carol Howe of CSIRO for their valuable contributions.

9. REFERENCES

Argent, R. M., Podger, G., Grayson, R. and Fowler, K. (2005), E2 catchment modelling software – user guide, CRC for Catchment Hydrology, www.toolkit.net.au/e2, Australia.

Argent, R. M. (2004), An overview of model integration for environmental applications – components, frameworks and semantics, Environmental Modelling and Software, 19 (2004) 219-234.

Boughton, W. (2004) The Australian water balance model, Environmental Modelling and Software, 19 (2004) 943-956.

Murray, M., Perraud, J-M, Podger, G. and Argent, R. M. (2005) E2 catchment modelling software – component models, CRC for Catchment Hydrology, www.toolkit.net.au/e2, Australia.

Rahman, J. M., Seaton, S. P., Perraud, J-M, Hotham, H., Verrelli, D. I. and Coleman, J. R. (2003), It's TIME for a New Environmental Modelling Framework. Proceedings of MODSIM 2004 International Congress on Modelling and Simulation, Townsville, Australia, 14-17 July 2003. Modelling and Simulation Society of Australia and New Zealand Inc., Vol 4, pp 1727-1732

Sustainable Development Update (2004) Issue 1, Vol 4, pp 2-3, www.albaeco.com/sdu/.

Victoria University of Technology and Department of Natural Resources and Environment, Victoria. REALM Users Manual, Jun. 2001b.

Water Services Association of Australia (2004), The End Use Model – User Manual.