18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Hydrological modelling of coastal catchments in New South Wales

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Abstract: The New South Wales Government has developed the Natural Resource Monitoring, Evaluation and Reporting (MER) Strategy to report on State-wide targets for environmental outcomes. The purpose of MER Strategy is to inform decision-making on policy settings, investment programs and best practice management. The end-users of the MER program are State Government, Catchment Management Authorities, Local Councils, Landcare groups, landholders and all natural resource managers across NSW. Other objectives of the MER program include the integration of disparate monitoring programs, measure progress towards resource condition targets, inform NSW and Local Government State of Environment reports, supply data to Federal Agencies, provide open access to resource condition data and periodical formal reports evaluating the data.

Existing data sets and analyses are currently being integrated into catchment report cards. As part of the coastal estuarine health report cards, estimates of stream flow into coastal estuaries are required. The coastal report cards cover 198 catchments along the New South Wales coast. However, reliable data from the stream gauging network is only available for a small number of coastal catchments; only 78 stream gauging stations over 37 catchments. Hence, a modelling approach is required to provide estimates of stream flows from the ungauged catchments.

Traditionally, hydrological models are calibrated using measured stream flow data. Parameter sets can then be regionalised across multiple catchments to estimate flows in nearby ungauged catchments. However, the sensitivity of parameters and interactions between parameters can often lead to quite different sets of model parameters producing similar model outputs. Spurious results can occur especially if the calibration procedure varies across different catchments.

In this paper an alternative approach is presented. Stream flow was estimated using the 2Csalt model with no calibration of model parameters. Instead of attempting to regionalise model parameters, estimated flows from the uncalibrated model were compared to measured flow data for all 78 gauging stations. Scaling factors between the measured and estimated flows were calculated. These scaling factors were then regionalised and applied to adjust estimated flows from ungauged catchments.

The success of 2Csalt as an uncalibrated hydrological model exceeded prior expectations. This is likely due to its internal configuration where most hydrology parameters are calculated from terrain analyses and Groundwater Flow System mapping. The use of simple regionalised scaling factors considerably improved the prediction of stream flow for gauged catchments. This enhances the use of the model for estimating stream flows in nearby ungauged catchments.

The results presented in this paper are being combined with delivery ratios based on land use to estimate total suspended sediment, total nitrogen and total phosphorus for all catchments. Further work is using weather data downscaled from GCMs to estimate the effects of future climate scenarios on stream flow.

Keywords: *2Csalt, hydrological modelling, water quality modelling*

1. INTRODUCTION

In 2006, the New South Wales Government established the Natural Resource Monitoring, Evaluation and Reporting (MER) Strategy to report on State-wide targets for environmental outcomes. It is underpinned by the establishment of Standards and Targets that can be applied across all catchments. The MER program is designed to regularly report on indicators reflecting the health of catchments and progress towards achieving catchment health targets. For coastal estuaries, the target is that by 2015, there is an improvement in the condition of estuaries and coastal lakes ecosystems. Catchment health indicators to report on this target are being quantified using existing datasets, ongoing monitoring and analyses.

An integral component for reporting on the health of coastal catchments is information on stream flow. Stream flow or estuary inflow for the 198 catchments that have been delineated for reporting purposes is required. However, there are only 78 stream gauging stations within 37 catchments with reliable stream flow records. Consequently, 163 catchments or over 80% of all catchments have no or insufficient stream gauging. Therefore, a simulation approach is required to provide estimates of stream flow for all catchments. This paper provides an overview of the modelling undertaken to estimate stream flow across coastal catchments in New South Wales. Model testing and calibration is described and a summary of results is presented.

2. STUDY AREA AND DATA AVAILABILITY

The 198 catchments range in size from 0.3 km^2 to 22 100 km^2 and cover a total area of approximately 130 000 km^2 along coastal New South Wales (Figure 1). All areas draining eastwards into coastal streams and/or coastal estuaries are included. A number of key data sets were compiled for the hydrological modelling. Climate zones that reflect total rainfall and rainfall seasonality were defined by overlaying grids of average annual rainfall with proportion of average annual rainfall falling in winter months. For each of the 528 climate zones, daily weather data from 1956-2006 were extracted from the Queensland Department of Natural Resources Silo dataset. The climate file closest to the centroid of each climate zone was obtained. The period 1956-1974 was used as a model warm-up period and results were extracted for 1975-2007.

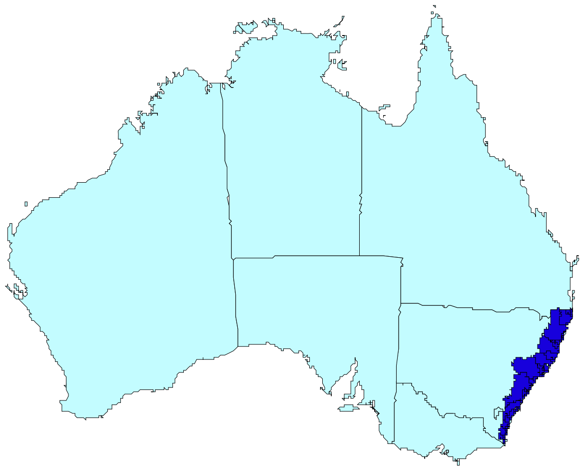

Figure 1. Location map of the 198 coastal catchments of New South Wales.

Soil mapping was compiled by splicing together the best available soil mapping. Detailed soil mapping was used where available and infilled with coarser land systems mapping for other areas. All soil units were attributed with a Great Soil Group (Stace *et al.* 1968). Soil hydraulic properties (water contents at air dry, wilting point, field capacity and saturation, and hydraulic conductivity) for each Great Soil Group were obtained from look up tables derived from a variety of sources including the Departmental soil databases, McKenzie *et al.* (2000) and the PAWCER pedotransfer software (Littleboy 1997).

Detailed land use mapping is available across all areas at a scale of 1:25 000. Each delineated land use unit has been attributed into one of many hundreds of land use types further split by specific details of land use and land management. Attributes from the land use mapping were simplified into 21 categories that better reflect hydrological response. For each land use type, potential plant water use (crop factors) were derived from a variety of sources including previous studies (e.g. Littleboy *et al*. 1992) and Allen *et al*. (1998).

Topography was defined using a 25m Digital Elevation Model (DEM). Based on previous modelling with 2CSalt (Littleboy 2005), the DEM was resampled to a 100m resolution as previous sensitivity analyses has shown that this coarser resolution provides almost identical model output.

There is no detailed Groundwater Flow System (GFS) mapping for coastal NSW. A simple GFS map was developed from 1:250 000 geology mapping. Attributes of aquifer depth, specific yield and hydraulic conductivity were added using simple lookup tables based on geological type.

3. SIMULATION METHODOLOGY

3.1. Description of 2Csalt

2CSalt (Stenson *et al*. 2005) was developed to provide water and salt inputs to regulated river models. It quantifies surface and subsurface contributions of salt and water export and predicts the impacts of land-use change on water and salt export at a catchment scale. It was designed to allow State agencies within eastern Australia to model upland unregulated catchments in a consistent manner across large areas. The 2CSalt model has been developed and extensively tested and applied within Australia's Murray-Darling Basin. It was designed to take advantage of existing data sets such as Groundwater Flow Systems (GFS) maps (Coram *et al*. 2000) and topography (digital elevation models). Outputs from 2CSalt include monthly predictions of water and salt movement across several water pathways with a hillslope and alluvial groundwater store, leading to water and salt contribution to streams.

2CSalt divides the modelled area into sub-catchments or Groundwater Response Units (GRUs), based on a user-identified threshold. These GRUs are the fundamental modelling unit within 2CSalt. Each GRU is then divided into 2 components: 1) hillslope; 2) flat "alluvial" area. This is done using the MRVBF terrain-analysis technique of Gallant and Dowling (2003). Water and salt generation from each of the GRUs is then summed to the area of interest (e.g. a gauging station).

2CSalt runs on a monthly time-step for all groundwater processes. For each GRU, maximum volumes and maximum fluxes between groundwater stores are independently calculated. Groundwater Flow Systems (GFS) mapping and terrain analysis are used to calculate and distribute these hydrogeological parameters across the catchment. This is in contrast to most other hydrological models where these types of parameters are often calibrated. The only 2Csalt parameters that can be calibrated are related to the discharge from different groundwater stores and control the shape of the storage-discharge relationship from each groundwater store.

Surface hydrology is derived from multiple runs of a daily time-series 1D water balance model summed to monthly totals. The PERFECT model (Littleboy *et al*., 1992) was used in this study. The output from 2CSalt is a monthly time series of water and salt generation to stream.

3.2. Hydrological model testing, calibration and application

Only the hydrological component of 2Csalt was parameterised and applied in this study. 2Csalt requires a number of model parameters but many of these parameters are derived from the input DEM or GFS mapping. There are only 6 hydrological parameters within 2Csalt that can be calibrated to adjust the output time series of estimated stream flow. These parameters are all groundwater based and in most cases will only affect estimated low flows (base flow) rather than large flow events from surface runoff.

Traditionally, hydrological models are parameterised by model calibration using measured stream flow data. Parameter sets across multiple catchments can then be regionalised to estimate flows in nearby ungauged catchments. However, the sensitivity of parameters and interactions between parameters can often lead to quite different sets of model parameters producing similar model outputs. Previous experience with 2Csalt in the New South Wales Murray-Darling Basin (Littleboy 2005) showed that the use of a set of standard parameters provided acceptable predictions of stream flow, stream salt loads and the flow: stream EC relationship. Stream flow for all catchments was estimated using these standard parameters. Instead of attempting to calibrate model parameters and then regionalising model parameters, estimated flows were scaled based on regionalised scaling factors. The procedure to develop scaling factors was:

1. For each of the 78 gauging stations, the ratio between the measured and uncalibrated modelled annual flows was calculated on an average annual basis.
2. The 78 ratios were grouped according to the river basin the gauging station was located in. These 14 river basins were Tweed, Brunswick, Richmond, Bellinger, Macleay, Hastings, Manning, Karuah, Shoalhaven, Clyde, Tuross, Bega and Towamba River basins and the Wollongong Coast Basin.
3. For each river basin, the mean ratio was calculated and applied as a scaling factor to linearly adjust estimated flows.

Two land use scenarios were simulated across all catchments; current land use and a pre-settlement land use (conservation areas assumed across all areas).

4. MODEL PERFORMANCE AND TESTING

Estimated and measured average annual stream flow for the 78 gauging stations is presented in Figure 2. Results are presented as both total flow in ML and flow in mm depth to remove the effects of catchment area from the assessment of model performance. Results are also presented as unscaled results and scaled results using the regionalised scaling factors. Figures 2a and 2c show the comparisons between measured and modelled stream flow from the uncalibrated model. Because no model calibration was undertaken, these comparisons quantify model performance for ungauged catchments. Prior to the application of the linear scaling factors, 2Csalt explained 87% of the variation in measured average annual stream flow (ML) and 64% of the variation of average annual flow (mm). The Nash Sutcliffe E coefficient for average annual flow (ML) is 0.853. There was a tendency for the model to underpredict stream flow on average as defined by the regression slope of 0.8159. After application of the regionalised scaling factors, 2Csalt explained 98% of the variation in average annual stream flow (ML) and 78% of the variation in average annual flow (mm) across all catchments with a Nash Sutcliffe coefficient of 0.977 for flow in ML. For flow in mm, model performance was poorer, probably because of the wide range of catchment area (0.3 km^2 to 22 100 km^2).

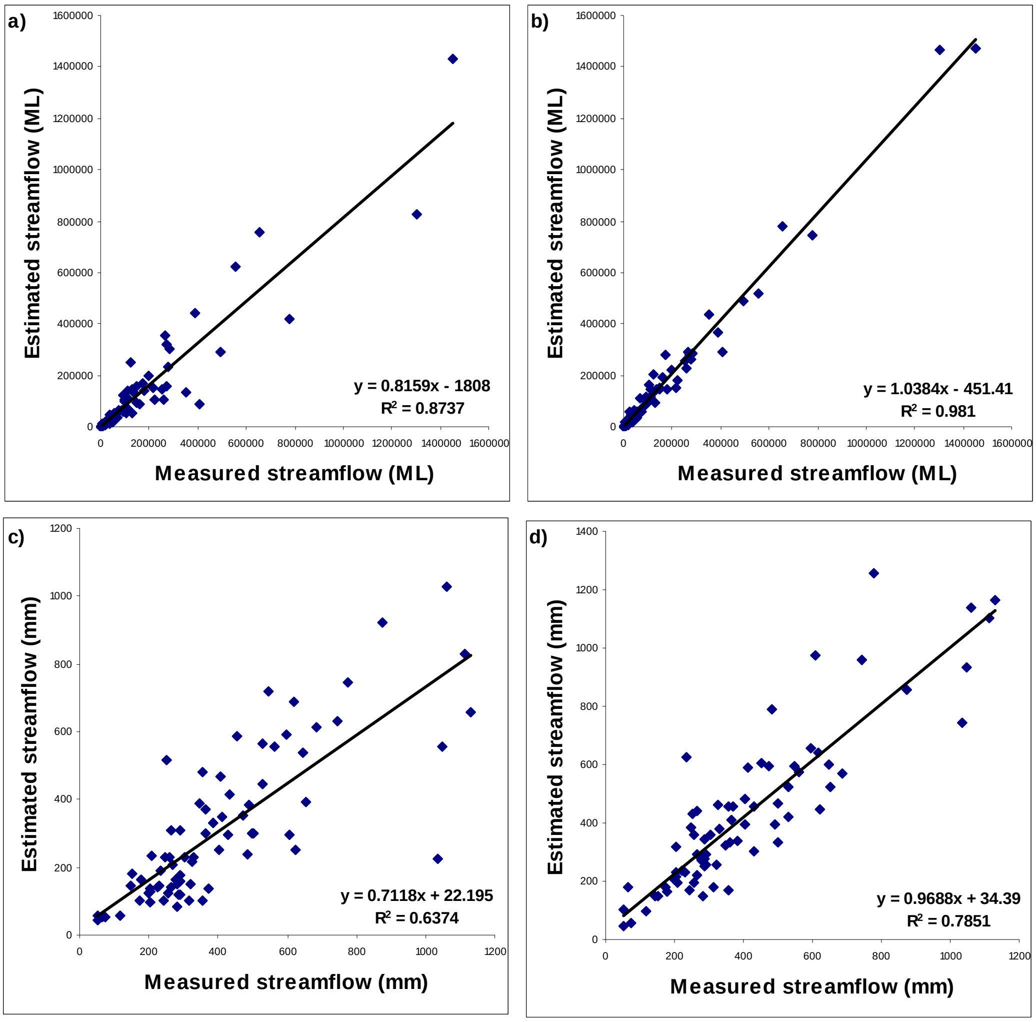

Figure 2. Comparison between mean annual measured and estimated streamflow. Results are presented for a) uncalibrated model in ML, b) uncalibrated model in ML after the application of regionalised scaling factors, c) uncalibrated model in mm, b) uncalibrated model in mm after the application of scaling factors.

Figure 3 shows the distribution of R^2 and Nash Sutcliffe E coefficients for the comparison between measured and modelled monthly stream flows (unscaled) for all catchments. For most catchments, the uncalibrated 2Csalt model explained between 75% and 95% of the variation in monthly stream flow. Since these results are for the model prior to any application of scaling, they represent model performance for ungauged catchments.

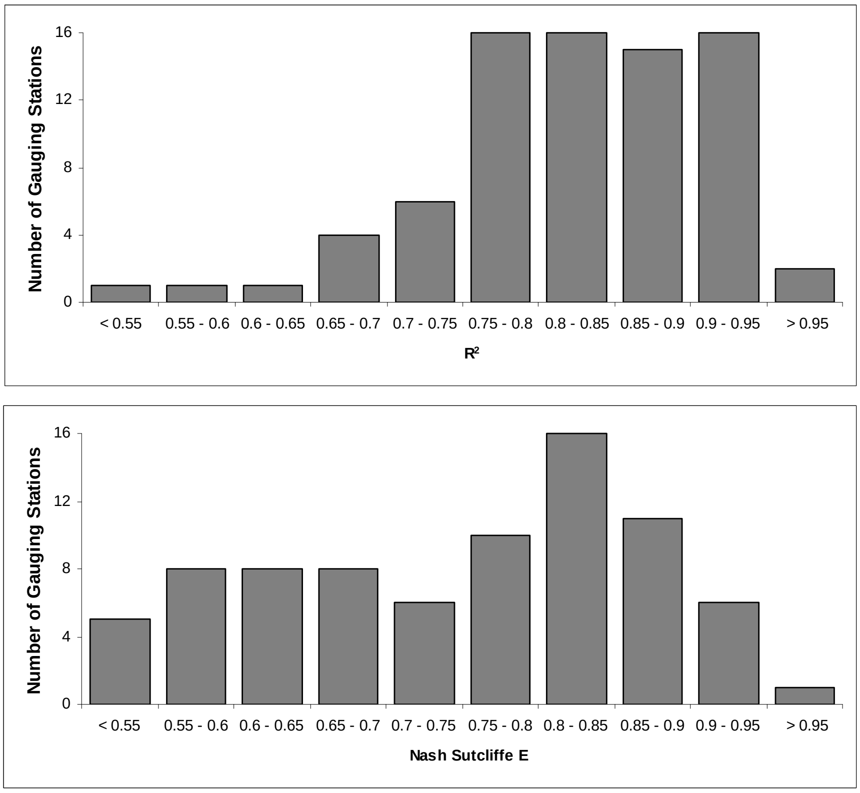

Figure 3. Distributions of the coefficients of determination (R^2) and Nash Sutcliffe (E) for the comparisons between estimated and measured monthly streamflow for all gauging stations. These results are for the uncalibrated model prior to applying regionalised scaling factors.

Since no model calibration was undertaken, the results from this model testing provide confidence in applying 2Csalt in adjacent ungauged catchments. The application of simple regionalised scaling factors further improved model performance.

5. MODEL APPLICATION

Maps showing estimated stream flow are presented in Figure 5 for a) current land use and b) pre-settlement land use. Percentage change in stream flow is also shown in Figure 5c. Increase in stream flow due to post-settlement land use changes ranges from zero to 142% with an average of 27%. The impacts of post-settlement clearing on base flow were larger ranging from zero to 920% with a mean of 95%.

To further explore the impacts of post-settlement clearing on stream flow, the percent changes in stream flow, surface flow and base flow is presented in Figure 6. Largest impacts were estimated for stream base flow (low flows) rather than surface flow (high flows). For example, post-settlement land use changes increased surface flow by >60% in <10% of all catchments. It is estimated that for approximately 15% of all catchments, total stream flow has increased by >60%. In contrast, base flow has increased by >60% in approximately half of all catchments. Base flow increased more than three-fold (200%) for >10% of all catchments. No catchments showed an increase in either total stream flow or surface flow by >200%.

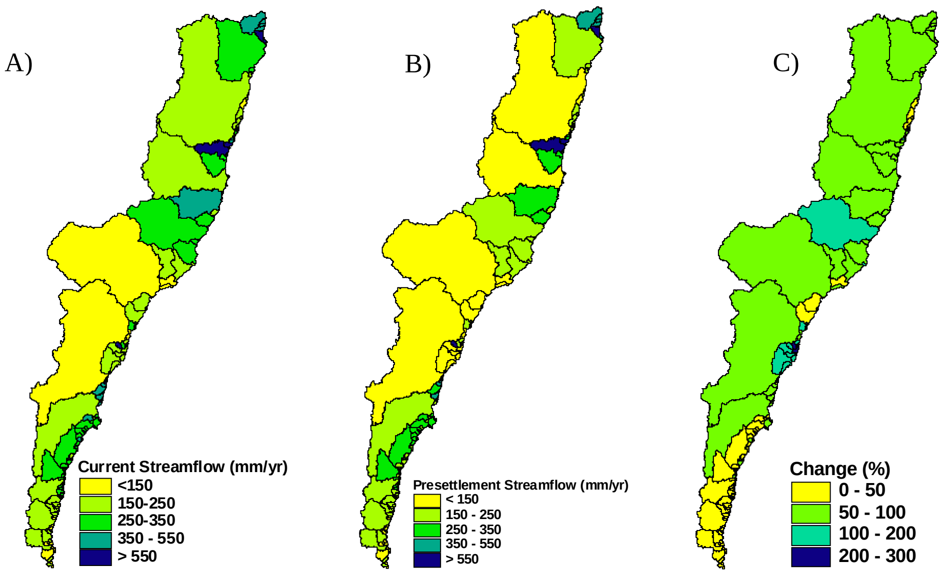

Figure 5. Total streamflow for a) current and b) pre-settlement land uses and c) the percent change in streamflow due to post-settlement clearing.

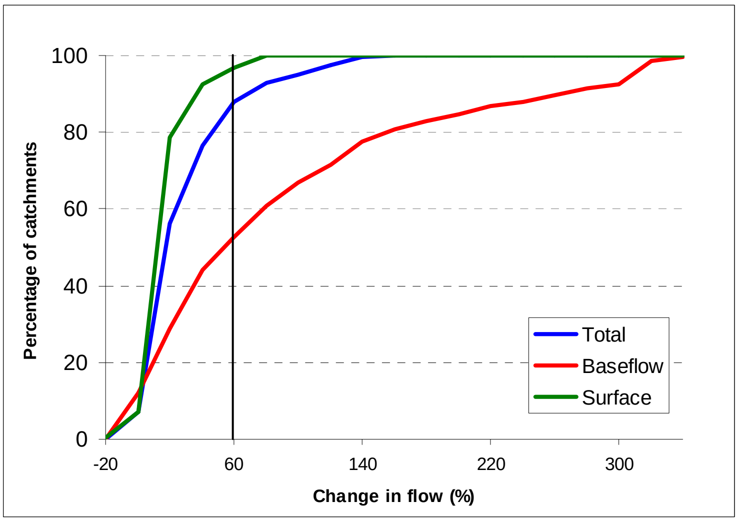

Figure 6. Change in total streamflow, surface flow and baseflow across all 200 catchments.

6. DISCUSSION AND CONCLUSIONS

The use of 2Csalt as a totally uncalibrated hydrological model was reasonably successful. The inclusion if simple regionalised scaling factors dramatically improved the estimation of stream flow. The success of applying 2Csalt as an uncalibrated model is likely due to its internal configuration where most groundwater parameters (volumes and maximum fluxes between groundwater stores) are calculated from terrain analyses and GFS mapping. In most hydrological models, these parameters are calibrated. The sensitivity of these parameters and interactions between parameters can lead to quite different sets of model parameters producing similar outputs. Spurious results can occur if the calibration procedure varies across different catchments. Many calibration procedures treat the hydrological model as a "black box". Under unconstrained calibration, many physically-based parameters can be assigned physically unrealistic values.

In most hydrology modelling activities, a subset of available gauging stations are selected for calibration with the remainder used for validation. Prior to the application of regionalised scaling factors, the modelled results in this paper are from a model with no calibration. In this way, all gauging stations are independent validations for modelling ungauged catchments. The use of simple regionalised scaling factors considerably improved the prediction of stream flow for gauged catchments. This enhances confidence in the use of the model for estimating stream flows in nearby ungauged catchments.

Further work is required to assess the validity of the regionalisation procedure. This will be undertaken by assessing model performance in estimating flow duration curves and by systematic removal of a subset of catchments from the regionalisation procedure to independently validate the scaling methodology. An assessment of the impacts of catchment area on model performance is also planned.

Results presented in this paper are being utilised with other modelling activities. For example, the estimates of surface flow are being combined with delivery ratios based on land use to estimate total suspended sediment, total nitrogen and total phosphorus for all catchments. Further work is running the 2Csalt model using weather data downscaled from GCMs to estimate the effects of future climate scenarios on stream flow.

ACKNOWLEDGMENTS

This work was undertaken as part of the New South Wales MER program coordinated by Tony Roper from Department of Environment and Climate Change. The support of Department of Environment and Climate Change management, in particular Greg Summerell and Peter Scanes is gratefully acknowledged. Warwick Hehir provided valuable GIS support in compiling the land use mapping used in this study.

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