Using Source to model the Goulburn River between Lake Eildon and Goulburn Weir

Northern Victoria Application Project
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1 Executive Summary

1.1 Background

This research is part of the “Northern Victoria Focus Catchments (Goulburn and Ovens)” eWater CRC application project. The project is investigating how flow scenarios and the management of environmental flows can influence river and floodplain ecology.

The work presented in this technical report summarises the hydrological modelling component of the Northern Victoria application project for the unregulated catchments along the Goulburn River between Lake Eildon and the Goulburn Weir. The main aims of the work were to:

- Compare two methods for deriving rainfall runoff parameters (Rainfall Runoff Library (RRL) and the Parameter Estimation Tool PEST) to a Source for catchments model, using different objective functions to achieve the best parameterisation of the model.
- Develop a hydrological model of the unregulated tributaries which feed into the Goulburn River between Lake Eildon and the Goulburn Weir.
- Link the Source for catchments model of the unregulated tributaries with the Source for rivers model of the Goulburn River and compare the Source for catchments and Source for rivers derived modelled flows.

1.2 Key Outcomes

eWater Source for catchments model of the Goulburn Study Area was set up to estimate flow from the unregulated tributaries of the Goulburn River between Lake Eildon and the Goulburn Weir. The model consisted of 32 sub-catchments, a time-series input into the Goulburn River downstream of Lake Eildon (405203 – Goulburn River @ Eildon), a daily rainfall/runoff model (SIMHYD) and two one-day lags along the Goulburn River (upstream of Trawool and Seymour). The model run period was from 1975 – 2005. Parameter estimation was conducted using PEST over a 20 year period (1976-1995), which incorporated a series of average-wet rainfall periods based on residual rainfall graphs. The validation period (1996-2005) was generally drier than average based on long term rainfall averages and the daily residual rainfall graphs.

Model Performance

In general the Goulburn Base Source for catchments model provided a good prediction of streamflow from the unregulated tributaries between Lake Eildon and the Goulburn Weir. Model performance was generally acceptable throughout the catchment during both the parameterisation (1975-1995) with over 90% of catchments having a CoE\textsubscript{Daily} > 0.6 and validation (1996-2005) with approximately 50% of catchments having a CoE\textsubscript{Daily} > 0.6. While the Goulburn Base SC Model provided a good prediction of observed streamflow in the Goulburn River, this relied on the use of observed outflows from Lake Eildon as an input at
the top of the system. Whilst Source for catchments has the capability of including simple
dam release models, the outflows from Lake Eildon are quite complex, linked to irrigation
demand and town water supply. As such, to investigate the impacts of the unregulated
tributaries on the Goulburn River under future scenarios including climate change and
altered river management regimes it was necessary to link the results from the Source for
catchments Model to the Source for rivers Model of the Goulburn system.

Rainfall Runoff Calibration

An additional aim of the work presented in this report was to investigate the application of
several calibration tools to a Source for catchments model. While PEST and RRL provided
similar parameterisation and fit to the flow data, RRL was limited due to the ability to only
parameterise a single catchment at a time and the requirement to manually load stream
gauge and climate data for each catchment and then manually update the parameter sets
within Source for catchments. On the other hand the linking of PEST to Source for
catchments (using e2commandline) provided a powerful tool for parameterising the model.
While the initial setup of the PEST files was complex, an automated process was developed
to generate the required PEST files, run PEST and extract the results for analysis. This
automation, combined with the power of PEST as a parameterisation tool which also allows
parameter sensitivity and uncertainty to be assessed, was a key result from this work and we
will continue to utilise PEST with Source for catchments into the future.

Linking the Source for rivers and Source for catchments

Linking the Source for rivers and Source for catchments models was an important step in
investigating and testing the functionality of Source as well as providing a model of the
Goulburn River that predicted contributions from the unregulated tributaries as well as the
regulated Goulburn River. The two models were easily linked within Source through
changing the inflows in the Source for rivers model. Combining the two models provided
reasonable agreement in predicted streamflow along the Goulburn River between the
Source for rivers and Source for rivers-Catchments models which were a result of
differences in the predicted inflows used for each model. Importantly the combined Source
for rivers-Catchments model could easily be used to investigate the impacts of unregulated
tributaries on flows in the Goulburn River during future climate scenarios, by simply updating
the climate files used by the Goulburn Base Source for catchments model.

1.3 Recommendations

- **Parallel development of e2commandline and Source for catchments.** PEST
  linked to Source for catchments provided a powerful tool that can simultaneously
  optimise hundreds of Rainfall-Runoff models whilst accounting for stream routing, dam
  releases and extractions. It is unlikely that we would use Source for catchments
  without PEST in the future. Therefore it is imperative the development of
e2commandline is kept inline with Source for catchments so that future functionality
  within Source for catchments can be utilised while still allowing the use of PEST.

- **Source for catchments Plugin to fully automate the link to PEST.** It is our view
  that PEST should be incorporated as a standard tool within Source for catchments.
The current tools within the PEST plugin go a long way to meeting this however further development would be required to fully automate the process.

- **Develop the ability to copy scenarios between different files.** Having the ability to copy a scenario between files would allow a Source for catchments and Source for rivers model developed separately in different files (potentially by different groups) to easily be incorporated into a single unit without having to build one of the models from the start. This is an important consideration given the potential complexity within model scenarios.
2 Introduction

One of the significant challenges faced in the management of water resources is balancing water use to maintain healthy water resources that support growing communities and a thriving economy now and into the future. Climate change and land use change impacts on these water resources represents an additional challenge in their management. By utilising a range of modelling tools this project contributes to our understanding and management of water resources in Victoria. Specifically this project will contribute to the delivery of the “Northern Victoria Focus Catchments (Goulburn and Ovens)” eWater CRC Application project.

2.1 Background - The Northern Victoria Application Project

The Ovens and Goulburn rivers contribute significantly to the water resources of the Murray-Darling Basin. These two rivers are similar in many ways in terms of their geomorphology, land use, and vegetation communities, but the Ovens River is largely unregulated while the Goulburn is highly regulated. Both rivers have high environmental value and natural biodiversity. Irrigated and dryland agriculture are very important in both catchments, and contribute significantly to the Victorian and National economies.

In their natural state, the off-channel floodplain wetlands, red gum forests, and other ecosystems of both rivers would be strongly influenced by seasonal flooding. Although the Ovens River still floods frequently, the Goulburn River, regulated by Eildon Dam, does not. This project is investigating how changing landscapes and climates potentially impact on flow, and how these processes combined with the management of environmental flows could affect river and floodplain ecology.

The key outcomes for the application project in order of priority were:

- A better capacity, utilising the eWater models, to manage the provision of water between environmental and consumptive uses, and to take into account future climate scenarios in planning and management.
- More effective planning of environmental outcomes (whilst meeting consumptive needs) arising from optimisation across storage management, water delivery, environmental flows, changing irrigation industries, and river restoration works.
- More effective day-to-day (operational) management of environmental water reserves across full climatic range.
- Greater capacity for integrated surface and groundwater management.

The key areas of activity to achieve the outcomes are summarised in Figure 1 which presents a conceptual model of the major activity areas for the Northern Victoria application project. From the perspective of DPI Victoria one of the key outcomes from the project is the increased understanding of the role that land management and landscape complexity have in influencing the water resources, which in turn affects ecological and environmental assets.
The work presented in this technical report is focused on the hydrological component of the Northern Victoria application project and will investigate the surface water resources from the unregulated catchments along the Goulburn River between Lake Eildon and the Goulburn Weir. This report presents the first step towards understanding how changing land use and climatic conditions in these unregulated tributaries may affect the Goulburn River and the ecological resources within the catchment.

2.2 The target catchment

The Goulburn River catchment in central Victoria covers 16,192 km² and extends from the Great Dividing Range near Woods Point, to the Murray River in the north-west near Echuca. Agriculture in the catchment is diverse, ranging from hardwood timber production in the south-east to dairying and fruit production in the north. The Lake Eildon environs produce sheep for wool, and beef and dairy cattle. Further along the Goulburn Valley, sheep and cropping are important in dryland and irrigated areas.

Streamflow along the Goulburn River has been modified by two major features, Lake Eildon and the Goulburn Weir. Lake Eildon, just below the junction of the Goulburn and Delatite rivers, has a capacity of 3300GL. On average 91% of the water released from Lake Eildon is used for irrigation purposes. Operation of the Eildon Reservoir has reduced the July to September flows passing Eildon to 33 percent of the mean seasonal flow, allowing an increase of the January to March flows of 23 percent. The Goulburn Weir near Nagambie and associated diversion channels to the east and west of the river, serving the Goulburn-Murray Irrigation District, have reduced the average annual down river flow to less than half the pre-regulated flow.

The highly regulated nature of the Goulburn River, downstream of Lake Eildon, means that environmental flows are required to manage the environmental resources within the catchments, particularly wetlands and floodplains. Understanding the inflows from the unregulated tributaries of the Goulburn River downstream of Lake Eildon is important in providing the maximum benefit from environmental releases. The ability to maximise the impact of environmental releases by coinciding them with peak flows from the unregulated
tributaries requires the ability to accurately predict peak flows from the unregulated tributaries. Modelling will enable us to improve our predictions.

Figure 2 The Yea River within the study area on the Goulburn River between Lake Eildon and Goulburn Weir in Victoria (image supplied by the Goulburn Broken CMA).

2.3 Source for catchments

Source for catchments is the modelling framework used in this report. It is a water quality and quantity modelling framework that supports decision-making and a whole-of-catchment management approach. It allows you to model the amounts of water and contaminants flowing through a regulated and unregulated catchment and into major rivers, wetlands, lakes, or estuaries. This software gives access to a collection of models, data and knowledge that simulate the effects of climatic characteristics (like rainfall and evaporation) and catchment characteristics (like land-use or vegetation cover) on runoff and contaminant loads from unregulated catchments. The node based integrated model usually operate at daily time steps and can produce reports at varying temporal scales (from daily to annual) and spatial scales (from a single sub-catchment to whole of catchment).

2.4 Source for rivers

Source for rivers (previously known as River Manager) is designed as a complete river systems modelling package for river management organisations across Australia. It is designed to support planning and operational aspects of river system management at a range of spatial and temporal scales. Source for rivers can be used to:

- Investigate the impact of changes in management, land-use and climate on river behaviour and water availability. Including the combined impacts of various drivers
(e.g., environment, climate, land use, farm dams, irrigation, water savings, water trade and groundwater development).

• Assess the impacts of land use and water management on water quality.
• Model the supply, demand and use of water at a range of time scales.
• Simulate complex management rules, such as continuous sharing.

2.5 Aims

The main aims of the work presented in this technical report were to:

• Compare two methods for deriving rainfall runoff parameters (Rainfall Runoff Library(RRL) and the Parameter Estimation Tool PEST) for a Source for catchments model, using different objective functions to achieve the best parameterisation of the model.
• Develop a hydrological model of the unregulated tributaries which feed into the Goulburn River between Lake Eildon and the Goulburn Weir.
• Link the Source for catchments model of the unregulated tributaries with the Source for rivers model of the Goulburn River.

It was anticipated that:

• Source for catchments would provide a base model from which to build and develop water flow and water quality scenarios associated with climate and land use change.
• Linking Source Catchment flows into the Source River model of the Goulburn would provide a base model to allow the impacts of climate scenarios in the unregulated reaches to be investigated along the highly regulated Ovens River.
3 Goulburn Base Source for catchments Model

This section of the report details the data, methods and results of developing a Source for catchments (SC) model of the unregulated tributaries of the Goulburn River between Lake Eildon and the Goulburn Weir.

3.1 Catchment Overview

The extent of the study area for the Goulburn Source for catchments model is shown in Figure 3, namely the Goulburn River and its tributaries between Lake Eildon and the Goulburn Weir.
Land use was mapped using the Australia Land Use Mapping (ALUM) classification Version 5 (BRS 2001). By broadly grouping these land uses, their distribution throughout the catchment can be seen (Figure 4) from native and plantation forests in the south-east through cropping dominated systems in the middle of the catchment and grazing in the north-west.

**Figure 4** Spatial map of land uses for the Goulburn study area in Victoria.

### 3.2 Methods: Goulburn Base SC Model

This section outlines the data and methods used in the development and application of the Source for catchments model. Source for catchments works with information that is commensurate with publicly available data. Some spatial data layers have been created or modified to suit the particular needs of the project. Such modifications have been explained within each layer description below.

**Topographical Data**

Digital Elevation Models (DEMs) are a raster representation of the earth’s surface (Figure 5). The DEM used was a 100m×100m grid sourced from the Victorian Governments Spatial Information Infrastructure Group.
Figure 5  Spatial map of digital elevation for the Goulburn study area in Victoria.

The DEM was used to build a sub-catchment map for the study area using 2CSalt (1.0.8 Prototype, eWater Toolkit), with regions merged using ArcMap (v9.3, ESRI inc.) to ensure that the sub-catchments matched the gauge network. Sub-catchments for each of the tributaries were defined to their junction with the Goulburn River. Three additional sub-catchments were created along the main branch of the Goulburn River between Lake Eildon and the Goulburn Weir. This was done so that a streamflow lag could be applied between these nodes, consistent with the REALM model of the Goulburn River (SKM 2004).
Climate Data

The Goulburn Source for catchments model used the SIMHYD rainfall runoff model as the method of generating streamflow at the gauge points. SIMHYD is a daily conceptual rainfall-runoff model that estimates daily streamflow using just two key inputs daily rainfall and potential evapotranspiration data. Morton’s wet environment evapotranspiration (mwet) estimates were used to describe the upper constraint on evapotranspiration in the model, as it is only dependent on atmospheric variables and is the estimate of evapotranspiration that would occur when water supply is not limiting. Therefore it is conceptually a reasonable representation of the maximum potential evapotranspiration (Chiew and McMahon 1991).

The climate data used for the Goulburn model (1975-2005) was the 5km gridded data sourced from Queensland Department of Natural Resources and Environment’s SILO service. The gridded data was derived by interpolating the Bureau of Meteorology’s station records using splining and kriging techniques described in Jeffrey et al. (2001). The gridded rainfall and mwet data was loaded into Source for catchments (eWater CRC, Australia 2010) and spatially averaged over each sub-catchment, with the mean annual rainfall and mwet shown in Figure 7 and Figure 8 respectively.
Figure 7 Mean Annual SILO derived Rainfall (1975-2005) in each of the sub-catchments for the Goulburn study area in Victoria.

Figure 8 Mean Annual SILO derived mWET (1975-2005) in each of the sub-catchments for the Goulburn study area in Victoria.
Stream flow

Stream flow data was needed for the calibration of the rainfall runoff model used within Source for catchments. Stream flow data were obtained from the Victorian Water Resource Data Warehouse (VWQMN 2009) up to 2009 for 21 gauges: (Figure 9 and Table 1). Missing stream data was ignored in the parameterisation of the model, therefore no infilling of the stream traces was conducted. Graphical analysis was conducted for all of the stream gauges to ensure data quality.

Figure 9  Stream gauge location for the Goulburn study area in Victoria
### Table 1 Years of stream flow measurement for each gauge in the Goulburn study area in Victoria

<table>
<thead>
<tr>
<th>Gauge No</th>
<th>Gauge Name</th>
<th>Streamflow Start Date</th>
<th>Streamflow End Date</th>
<th>Years of Flow data</th>
<th>Missing Data (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>405201</td>
<td>Goulburn River @ Trawool</td>
<td>06-Dec-74</td>
<td>13-Sep-09</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>405202</td>
<td>Goulburn River @ Seymour</td>
<td>12-Jun-75</td>
<td>14-Sep-09</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>405203</td>
<td>Goulburn River @ Eildon</td>
<td>02-Dec-74</td>
<td>17-Nov-09</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>405205</td>
<td>Murrindindi River @ Murrindindi above Colwells</td>
<td>09-Jun-75</td>
<td>18-Nov-09</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>405209</td>
<td>Acheron River @ Taggerty</td>
<td>13-Dec-73</td>
<td>18-Nov-09</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>405212</td>
<td>Sunday Creek @ Tallarook</td>
<td>04-Feb-61</td>
<td>14-Sep-09</td>
<td>49</td>
<td>0</td>
</tr>
<tr>
<td>405217</td>
<td>Yea River @ Devlin’s Bridge</td>
<td>18-Mar-75</td>
<td>18-Nov-09</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>405228</td>
<td>Hughes Creek @ Tarcombe Road</td>
<td>16-May-75</td>
<td>19-Nov-09</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>405231</td>
<td>King Parrot Creek @ Flowerdale</td>
<td>31-Dec-74</td>
<td>18-Nov-09</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>405238</td>
<td>Mollison Creek @ Pyalong</td>
<td>09-Dec-72</td>
<td>15-Sep-09</td>
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<td>0</td>
</tr>
<tr>
<td>405240</td>
<td>Sugarloaf Creek @ Ash Bridge</td>
<td>09-Dec-72</td>
<td>14-Sep-09</td>
<td>37</td>
<td>0</td>
</tr>
<tr>
<td>405241</td>
<td>Rubicon River @ Rubicon</td>
<td>13-Dec-73</td>
<td>17-Nov-09</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>405248</td>
<td>Major Creek @ Graytown</td>
<td>20-Apr-71</td>
<td>15-Sep-09</td>
<td>38</td>
<td>0</td>
</tr>
<tr>
<td>405257</td>
<td>Snobs Creek @ Snobs Creek Hatchery</td>
<td>13-Mar-74</td>
<td>25-Jun-87</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>405261</td>
<td>Spring Creek @ Fawcett</td>
<td>19-May-73</td>
<td>03-Jun-87</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>405265</td>
<td>Mill Creek @ Tallarook</td>
<td>14-Jun-75</td>
<td>06-Oct-82</td>
<td>7</td>
<td>5</td>
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<tr>
<td>405274</td>
<td>Home Creek @ Yarck</td>
<td>10-Jun-77</td>
<td>16-Nov-09</td>
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<td>0</td>
</tr>
<tr>
<td>405281</td>
<td>Compton Creek @ Graytown</td>
<td>28-Mar-81</td>
<td>21-May-86</td>
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<td>5</td>
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<td>405290</td>
<td>Pine Creek @ Broadford</td>
<td>20-Sep-88</td>
<td>15-Sep-09</td>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>405291</td>
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<td>16-Sep-88</td>
<td>19-Nov-09</td>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>405309</td>
<td>Hughes Creek @ Goulburn Valley Hwy</td>
<td>01-Oct-98</td>
<td>01-Jul-01</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

### Base Source for catchments Model structure

The Source for catchments model of the Goulburn Study Area was set up to estimate flow from the unregulated tributaries of the Goulburn River. The main features of the model (Figure 11) included:

- 32 sub-catchments based on gauge location.
- A time-series input into the Goulburn River at the top of the Catchment based on daily stream gauge data from immediately downstream of Lake Eildon (405203 – Goulburn River @ Eildon). This meant that daily water releases from Lake Eildon did not need to be modelled.
- Rainfall runoff was modelled using SIMHYD. SIMHYD was chosen as it represents a simple lumped conceptual daily rainfall-runoff model, with relatively few parameters. SIMHYD has been extensively used, with applications including the Murray Darling Basin Sustainable Yields project which utilised SIMHYD across the entire Murray Darling Basin (CSIRO 2008).
• Parameterisation of the model was conducted using PEST (Watermark Numerical Computing, Australia 2010) and the Rainfall Runoff Library (CRC Catchment Hydrology, Australia). For the purposes of parameterising the model, the sub-catchments were regionalised based on gauge points. Tributaries to the Goulburn with only a single gauge point, had a single calibration and parameter set applied for the whole tributary. Where tributaries had multiple gauge points the downstream sub-catchments were regionalised with the greatest upstream contributing area for the purpose of parameterisation (Figure 12).

• No node models, routing or extractions were used in the unregulated tributaries.

• Two one-day lags were applied in the model along the length of the Goulburn River between Lake Eildon and the Goulburn Weir, consistent with the REALM model of the Goulburn River (SKM 2004).

• The model was built in Source for catchments (v1.0.2b) and parameterisation was run using the e2commandline version.

Figure 10  Releases from Lake Eildon at the top of the study catchment were incorporated as an historic time series.

Figure 11  Network diagram of the Source for catchments model.
Using Source to model the Goulburn River between Lake Eildon and Goulburn Weir.

Figure 12 Regionalisation of SIMHYD parameters in the Source for catchments model.

Hydrologic Parameter Estimation

The SIMHYD rainfall-runoff model parameters applied in Source for catchments were derived using PEST, a model-independent parameter estimation program (Watermark Numerical Computing, Australia 2010). PEST is similar to existing nonlinear parameter estimation software (it uses a powerful, yet robust, estimation technique that has been extensively tested on a wide range of problem types), however it can be wrapped around an existing model such as Source for catchments (using e2commandline). PEST adjusts model parameters until the fit between model outputs and laboratory or field observations is optimised in the weighted least squares sense.

Regionalised parameters were optimised in PEST using the default objective function; the squared sum of residuals between the observed and a predicted time-series. In this project PEST was applied to individual sub-catchments providing independent parameter sets for each gauged sub-catchment. The optimised parameters were then applied based on the regionalisation shown in Figure 12. Parameter estimation was conducted over the period 1975-1995 as it provided the best available stream gauge data across all of the gauges.

A detailed assessment of calibration performance as a function of calibration period and flow-weighting was conducted for the Acheron catchment (Appendix 1). Based on these findings the Goulburn model was parameterised using the 1976-1995 parameterisation period derived from an objective function using non-weighted flow. The Goulburn catchment was calibrated and parameterised in a systematic fashion which allowed all of the upper catchments to be parameterised and fixed before the downstream catchments were calibrated and parameterised, with PEST parameterising a single catchment at a time. For example, the catchment upstream of gauge 405290 (Figure 12) was calibrated with PEST,
once a parameter set for this catchment had been determined they would be locked into the model and the catchment between the gauges 405212 and 405290 would then be calibrated and parameterised. This processing method was chosen as it was significantly quicker than optimising all parameters simultaneously and was found to result in the best model fit at each gauge point. Simultaneous optimisation of parameters across all sub-catchments would only be of benefit if there was some evidence that parameters or catchment attributes could be linked across different sub-catchments.

**Automation of PEST calibration**

An automated process (Figure 13) was developed in MATLAB utilising PEST, e2_commandline (Source for catchments v1.0.2b) and four files from the Source for catchments PEST plugin (parameters.dat, param_groups.dat, parval.dat and config_template.tpl). The process was designed to allow the user to specify an order for optimising catchments. For example, one could specify to simultaneously optimise all upstream catchments then hold these parameter sets fixed and proceed to optimise the routing for these catchments. The aim was to achieve better calibration by limiting the number of parameters for any given optimisation process and to alleviate issues around the correlation of parameters between different sub-catchments and the rainfall-runoff and stream-routing models.
Create PEST input files:
- tsproc.dat
- E2PEST.pst
- E2Config.txt
- modelrun.bat
- parameters.bat

Run PEST

Select $i^{th}$ set of parameters

Create PEST input files:
- tsproc.dat
- E2PEST.pst
- E2Config.txt
- modelrun.bat
- parameters.bat

Load calibrated parameters into Source Catchments and save scenario

Run PEST

Run Source Catchments over calibration and validation period

Format Outputs

Figure 13 Automated PEST calibration allowing the user to specify an order to optimise catchments.

To investigate the Source for catchments model performance the PEST output files were used along with a number of statistical functions to assess model fit:

1. The Nash Sutcliffe Coefficient of Efficiency was used to assess the predictive power of hydrological models. It is defined as:

$$CoE = 1 - \frac{\sum_{t=1}^{T} \left(Q_{o}^{t} - Q_{m}^{t}\right)^2}{\sum_{t=1}^{T} \left(Q_{o}^{t} - \bar{Q}_{o}\right)^2}$$

where $Q_{o}$ is observed daily discharge, and $Q_{m}$ is daily modelled discharge. $Q_{o}^{t}$ is observed daily discharge at time $t$ (Nash and Sutcliffe 1970). Nash–Sutcliffe efficiencies can range from $-\infty$ to 1, where:

- an efficiency of 1 ($E = 1$) corresponded to a perfect match of modelled discharge to the observed data,
- an efficiency of 0 ($E = 0$) indicated that the model predictions are as accurate as the mean of the observed data, and
• an efficiency less than zero (E < 0) occurred when the observed mean was a better predictor than the model.

• While a CoEDaily of 0.6 was viewed as satisfactory, a CoEDaily of 0.8 or higher was believed to provide a good representation of streamflow at the gauge.

The Nash Sutcliffe CoEDaily was also calculated on the natural log of stream flow data, to reduce the bias of high flow events and provide an indication of how well the model is capturing the baseflow/low flow events.

\[
CoE(\ln) = 1 - \frac{\sum_{t=1}^{T} [\ln(Q'_t) - \ln(Q''_t)]^2}{\sum_{t=1}^{T} [\ln(Q'_t) - \ln(Q''_t)]}
\]

Cumulative flow: Cumulative daily flow was calculated on dates where measured data was available, so while it may not reflect the full model period it was not adversely affected by missing data in the observed data series.

\[
CumFlow\% = \left(1 - \frac{\sum_{t=1}^{T} Q'_t}{\sum_{t=1}^{T} Q''_t}\right) \times 100
\]

Model validation

Model validation was conducted over a 10 year period (1996-2005) for the majority of stream gauges. Where stream gauge data did not extend into the validation period (405257, 405261, 405265 and 405281) the decision was made to continue with a consistent parameterisation period and to have no validation period for these gauges. The same statistical measures were used to investigate model performance in both the parameterisation and the validation periods.
3.3 Results and Discussion: Goulburn Base SC Model

The Goulburn Base Source for catchments model used a regional parameterisation for SIMHYD combined with observed releases from Lake Eildon. Overall the Base Model resulted in a good CoEDaily and prediction of cumulative flow across most of the catchments during the parameterisation period (Figure 15). Of the 20 gauge points in the Goulburn Study Area only 5 gauges had a CoEDaily of less than 0.7 during the parameterisation period and 2 gauges had a CoEDaily of less than 0.6. The two worst gauges (in terms of CoEDaily) were both upland catchments (405290 and 405265) with approximately 6 years data during the parameterisation period and ephemeral flow; Figure 14 shows the observed and modelled streamflow for both gauges.

The 405265 gauge measures flow from a small sub-catchment of 28.6km², the PEST parameterisation resulted in a CoEDaily of 0.57 during the parameterisation period and a cumulative difference in flow of approximately 50%. This is an ephemeral stream and while SIMHYD generally captures the main trends in the data (Figure 14) it is over predicting the low and no-flow periods, due to the sensitivity of the SIMHYD model to any rainfall events. It is worth noting that the mean annual rainfall in this sub-catchment (Figure 7) is higher than the surrounding sub-catchments which may also influence the results.

The 405290 gauge was also poorly represented by the model with a CoEDaily of less than zero during the parameterisation period. Further analysis of this gauge has shown that the upstream catchment area for this gauge has been incorrectly defined, explaining the poor performance of the model at this point. The model as shown in Figure 15 has an upstream catchment area of 10260ha, almost fourteen times the actual area that flows into the Pine Creek 405290 gauge (738ha).

![Figure 14](image)

*Figure 14 Measured and predicted flow for the Goulburn base model results for stream gauge 405265 from 1975-1982*
Figure 15 (a) The Nash Sutcliffe CoE_daily and (b) % difference in cumulative flow predicted for the catchments across the Goulburn River study area during the parameterisation period (1976 – 1995).
Figure 16 Spatial map showing the CoEDaily across catchments in (a) validation period and (b) over the full 30 years.
Across the Goulburn study area, the CoE\textsubscript{Daily} during the validation period was generally less than the parameterisation period, similar to the results for the Acheron Catchment (405209) (Appendix 1). This was not a surprising result given the shift in rainfall from average-wet during the parameterisation period to dry over the validation period. Despite this, the model and PEST parameterisation appeared to give a reasonable prediction of flow in the majority of the unregulated tributaries.

Flow in the Goulburn River downstream of Lake Eildon was generally dominated by the releases from Lake Eildon during the irrigation season (Figure 17a). However, over the winter and early spring period releases from Lake Eildon are low and flow is dominated by the inflows from the unregulated tributaries (Figure 17a). Two gauges along the river 405201 and 405202 were used to assess the overall performance of the Goulburn Base Source for catchments Model. Both gauges had a CoE\textsubscript{Daily} of greater than 0.9 for the parameterisation period and greater than 0.8 for the validation period with a cumulative difference in flow of less than 3% in both the parameterisation and validation periods.

The first stream gauge along the Goulburn is located at Trawool (405201), Figure 17 shows the observed and modelled streamflow at Trawool as well as the time series input of measured flow at Eildon (downstream of Lake Eildon). The results highlight the importance of the unregulated tributaries in generating peak flow events and in determining flow during the winter-spring periods outside of the irrigation season. The second stream gauge along the Goulburn was located at Seymour (405202) with similar results observed at the second stream gauge (Figure 18).
Using Source to model the Goulburn River between Lake Eildon and Goulburn Weir.

Figure 17 SIMHYD model results for the Goulburn river at Trawool (gauge 405201); (a) streamflow from 1986-1995, and (b) cumulative flow from 1976-2005.
Figure 18 SIMHYD model results for the Goulburn river at Seymour (gauge 405202): 
(a) streamflow from 1986-1995, and 
(b) cumulative flow from 1976-2005.
3.4 Conclusions: Goulburn Base SC Model

The Goulburn Base SC Model provided a good prediction of streamflow from the unregulated tributaries between Lake Eildon and the Goulburn Weir. Model performance was generally acceptable throughout the catchment during both the parameterisation (1975-1995) with over 90% of catchments having a CoE\text{Daily} > 0.6 and validation (1996-2005) periods with approximately 50% of catchments having a CoE\text{Daily} > 0.6. This Goulburn Base SC Model could be used to investigate different future scenarios. In particular, future climate change scenarios could be simply investigated by loading in new climate data (rainfall/evaporation).

While the Goulburn Base SC Model provided a good prediction of observed streamflow in the Goulburn River, this relied on the use of observed outflows from Lake Eildon as an input at the top of the system. In order to investigate the impacts of unregulated tributaries on the Goulburn River under future scenarios including climate change and altered river management regimes, it is necessary to link the results from the Source for catchments Model to the Source for rivers Model of the Goulburn system.

Goulburn Base SC Model (Source v2.10.1)

An important step in linking the Goulburn Base SC Model to Source for rivers was to re-build and validate the model in a more recent version of Source (v2.10.1.34 prototype) which contains both the Source for catchments and Source for rivers functionality which would enable more direct integration of the two models.

The Goulburn Base SC Model was initially built in Source (v1.0.2b). This model was rebuilt in (v2.10.1.34) by manually defining the stream network from a sub-catchment boundary layer to ensure identical catchment boundaries and node positions. The optimised parameter sets for each sub-catchment initially developed in the Goulburn Base SC Model were converted into a “csv” file for each parameter region (Figure 12), with the appropriate file being imported through the “Configure-RainfallRunoff-Parameters” tool. While a fully automated process for uploading these parameter sets would be fantastic (from a single file) the ability to use “csv” files meant that the parameters files were created and uploaded in less than 15 minutes.

Once the model was rebuilt it was run in Source (v2.10.1.34) with downstream flow from every link compared between the original and rebuilt models. The predicted streamflows at every link were essentially identical with CoE\text{Daily} = 1, percentage difference in cumulative flow < 0.001%. This meant that we had a Source for catchments model which was ready and able to be linked to the Source for rivers model of the Goulburn.
4 Goulburn Source for rivers-Catchments Model

Traditionally river management and river operations models have estimated flows and water quality measures from upland sub-catchments by combining observed gauging station data with simple point-scale rainfall-runoff models and linear regression models. As such models are node-based they cannot readily incorporate the spatial component of climate, topography and land-use and the interaction that they have on stream flow and water quality. Linking Source for catchments to the Source for rivers models allows for increased complexity in the way that we conceptualise contributing flows from sub-catchments to stream and allows us to explore scenarios of land-use change, climate change and other factors such as water quality that can only be considered in a spatial context. It is not however a one-way interaction. To fully calibrate and test a Source for catchments model it is often necessary to account for stream dynamics such as irrigation, town extractions and dam releases. Often these systems are quite complex, as in the Goulburn River, and it becomes difficult to incorporate them into a Source for catchments model. Linking to a Source for rivers scenario which can provide a dynamic model of stream extractions and in-stream processes can overcome this problem.

As an example, one aim of the Source for rivers component of the Application project was to test the ability of Source for rivers to simulate the impacts and effectiveness of various flow release triggers and rules in enhancing flooding in the lower Goulburn River. Source for rivers was selected for this trial because of its flow routing capabilities and because it had previously been used to build and calibrate a daily time step model of the Goulburn River, from Lake Eildon to the River Murray. This daily time step model, developed by Sinclair Knight Merz Pty Ltd (SKM) incorporated modelled historic spills and pre-releases from Lake Eildon, tributary inflows, flow routing, the major diversions at Goulburn Weir and inflow from the Broken River. As the out-of-bank flows were not during irrigation periods, irrigation allocations and management were not modelled. Rather, the model required accurate inflows from upland tributaries along the Goulburn River to simulate winter and spring flows.

A daily Source for rivers planning model of the Goulburn River from Lake Eildon to the River Murray, built by SKM was used to link with the Goulburn Base SC Model with the aim of:

- Investigating the ease with which Source for catchments and Rivers scenarios can be linked, and
- Providing a Base Source for rivers Model which uses Source for catchments to predict flows from the unregulated tributaries.
4.1 Methods: Source for rivers–Catchments Model linking

The Source for rivers model

The Source for rivers model was provided by SKM. The model (Figure 19) was built in Source (v2.10.1) using time series inflows and demands for the period 1891-2006.

Figure 19. Schematic representation of the Source for rivers model developed by Sinclair Knight Merz Pty Ltd, where blue circles with arrows represent inflows into the Goulburn River and the large red circles represent gauge points along the Goulburn.
Linking the Source for catchments & Rivers models

Linking the flows from the Source for catchments model to the Source for rivers model was achieved in two steps. First, the Source for catchments model was run recording the appropriate catchment flows and downstream links. Once the Source for catchments model was built the flows as detailed in Table 2 were linked to the inflow nodes for the Source for rivers model. This was done by selecting each inflow node and setting the source of the data as the Source for catchments scenario.

Table 2. Summary of the Source for catchments output locations linked as input to the Source for rivers model between Lake Eildon and the Goulburn Weir.

<table>
<thead>
<tr>
<th>Source for rivers Inflows</th>
<th>Source for catchments Flows</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubicon River</td>
<td>Downstream flow from Link 41d</td>
<td></td>
</tr>
<tr>
<td>Acheron River</td>
<td>Downstream flow from Link 09d</td>
<td></td>
</tr>
<tr>
<td>Ungauged Eildon to Site 1</td>
<td>Downstream flow from Link 57</td>
<td></td>
</tr>
<tr>
<td>Spring Creek</td>
<td>Downstream flow from Link 61d</td>
<td></td>
</tr>
<tr>
<td>Home Creek</td>
<td>Downstream flow from Link 74d</td>
<td></td>
</tr>
<tr>
<td>Murrindindi River</td>
<td>Downstream flow from Link 05</td>
<td></td>
</tr>
<tr>
<td>Yea River</td>
<td>Downstream flow from Link 17</td>
<td></td>
</tr>
<tr>
<td>Ungauged Site 1 to Site 2</td>
<td>Outflow from Catchment 17d</td>
<td></td>
</tr>
<tr>
<td>King Parrot Creek</td>
<td>Downstream flow from Link 31d</td>
<td></td>
</tr>
<tr>
<td>Ungauged Site 2 to Trawool</td>
<td>Outflow from Catchment g01</td>
<td></td>
</tr>
<tr>
<td>Sunday Creek</td>
<td>Downstream flow from Link 12</td>
<td></td>
</tr>
<tr>
<td>Sugarloaf Creek</td>
<td>Downstream flow from Link 40d</td>
<td></td>
</tr>
<tr>
<td>Ungauged Trawool to Site 3</td>
<td>Downstream flow from Link 65d</td>
<td></td>
</tr>
<tr>
<td>New Inflow</td>
<td>Outflow from Catchment g02</td>
<td></td>
</tr>
<tr>
<td>Whiteheads Creek</td>
<td>Downstream flow from Link 91d</td>
<td></td>
</tr>
<tr>
<td>Hughes Creek</td>
<td>Downstream flow from Link 309</td>
<td></td>
</tr>
<tr>
<td>Major Creek</td>
<td>Downstream flow from Link 48d</td>
<td></td>
</tr>
<tr>
<td>Ungauged Site 3 to Goulburn Weir</td>
<td>Outflow from Catchment gk2</td>
<td></td>
</tr>
</tbody>
</table>
Measuring the performance of the combined model

To investigate the Source for catchments & Rivers model performance the PEST output files were used along with a number of statistical functions to assess model fit including:

1. The Nash Sutcliffe Coefficient of Efficiency calculated using daily flows, and
2. Percentage Difference in Cumulative flow

4.2 Results: Source for rivers-Catchments Model Linking

Comparison of the modelled inflow data

The first step in linking the Source for rivers and Source for catchments model was to compare the modelled inflows from Source for rivers (SR) model and the Source for catchments (SC) model. A comparison was made between the Source for rivers and Source for catchments modelled flows for the period 1975-2005 (Table 5 and Figure 20). This was achieved by calculating the CoE Daily and the percentage difference in cumulative flow between the modelled flows of the SC and SR models (Table 3). The CoE Daily’s between SC and SR models were generally greater than 0.4 (Table 5) and the differences in cumulative flow, less than 20% suggesting that whilst there was some scope to improve inflows, the Source Catchment results could be used to feed into the Source for rivers model. It is likely that one of the reasons that the flows between the two catchments are not highly correlated is that when the Source for catchments model was established, the location of the ungauged sites 1-3 was not known, and the contribution to these was the best fit of the existing sub-catchments within the Source for catchments model. Realignment of the sub-catchments within the Source for catchments model could potentially lead to improved correlation between the SC and SR inflows.

Table 3. Comparison between the Source for catchments (SC), Gauge and Source for rivers (SR) SKM flows and observed flow at selected stream Gauges in the tributaries of the Goulburn River between Lake Eildon and the Goulburn Weir (1975-2005).

<table>
<thead>
<tr>
<th>Gauge</th>
<th>SC:SR</th>
<th>%DiffCumFlow</th>
</tr>
</thead>
<tbody>
<tr>
<td>405241</td>
<td>0.41</td>
<td>15.3</td>
</tr>
<tr>
<td>405209</td>
<td>0.74</td>
<td>7</td>
</tr>
<tr>
<td>405205</td>
<td>0.45</td>
<td>8</td>
</tr>
<tr>
<td>405217</td>
<td>0.46</td>
<td>-1</td>
</tr>
<tr>
<td>405231</td>
<td>0.2</td>
<td>-14</td>
</tr>
<tr>
<td>405212</td>
<td>0.34</td>
<td>-16</td>
</tr>
<tr>
<td>405248</td>
<td>&lt;0</td>
<td>-54</td>
</tr>
</tbody>
</table>
Figure 20. Comparison between Source for rivers Inflow and Source for catchments predicted flow at stream gauge 405209 on the Acheron River.

**Comparison of Source for rivers Stream Gauge predictions**

The Goulburn Source for rivers model has five stream gauge points along the Goulburn River between Lake Eildon and the Goulburn Weir (large red circles in Figure 19). This analysis compares the flow predicted by Source for rivers at these 5 gauge points using the inflows initially provided in the Source for rivers model developed by SKM and the Source for rivers-Catchments combined model.

Overall the CoE\textsubscript{Daily} between the Source for rivers and the Source for rivers-Catchments models was acceptable (>0.6), with the exception of one Source for rivers Gauge (Table 4). Importantly, there was less than 3% difference in cumulative flow at any of the Source for rivers Gauge points over 30 years (Table 4). While at the top of the Goulburn (Downstream Acheron Gauge - Figure 21a) there was good agreement between the timing and magnitude of flow, by Goulburn Weir a number of peak flows in the Source for rivers model were not captured by the Source for rivers-Catchments model and there was a significantly greater spread of data in the XY plot of modelled values.
Table 4. Comparison between the original Source for rivers and the Source for rivers-Catchments models for selected Source for rivers Gauges on the Goulburn River between Lake Eildon and the Goulburn Weir (1975-2005).

<table>
<thead>
<tr>
<th>Source for rivers Stream Gauge Points??</th>
<th>CoE Daily</th>
<th>% Diff Cum Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downstream Acheron</td>
<td>0.97</td>
<td>-2</td>
</tr>
<tr>
<td>Downstream Yea</td>
<td>0.85</td>
<td>-3</td>
</tr>
<tr>
<td>Trawool</td>
<td>0.75</td>
<td>-3</td>
</tr>
<tr>
<td>Downstream Whiteheads</td>
<td>0.54</td>
<td>-1</td>
</tr>
<tr>
<td>Upstream Goulburn Weir</td>
<td>0.67</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 21. Time Series and XY graph of the Source for rivers and Source for rivers-Catchments flow at (a) the Downstream of Acheron Gauge and (b) the Upstream of Goulburn Weir Gauge.
4.3 Conclusions: The Source for rivers-Catchments Model

Linking the Source for rivers-Catchments models was an important step in investigating and testing the functionality of Source as well as providing a model of the Goulburn River that predicted contributions from the unregulated tributaries as well as the regulated Goulburn River. Some general observations and conclusions from the combination of the two models were that:

- The two models were easily linked within Source through changing the inflows in the Source for rivers Model.

- There was reasonable agreement in predicted streamflow along the Goulburn River between the Source for rivers and Source for rivers-Catchments models which were a result of differences in the predicted inflows used for each model.

- The comparison was only run over the 1975-2005 period due to limited input data within the Source for catchments model; this could easily be increased by loading a longer time series of the silo gridded data into the Source for catchments model.

- Linking the two models would have been easier if the location of the ungauged sites along the Goulburn used in the River Manager model were known when the Source for catchments model was established so there was a direct relationship between the ungauged sub-catchment areas in the two models.

- The Source for rivers-Catchments model could easily be used to investigate the impacts of unregulated tributaries on flows in the Goulburn River during future climate scenarios, by simply updating the climate files used by the Goulburn Base Source for catchments model.
5 Conclusions

The main aims of the work presented in this technical report were (1) to develop a hydrological model of the unregulated tributaries which feed into the Goulburn River between Lake Eildon and the Goulburn Weir using Source for catchments, and (2) to link the Source for catchments model of the unregulated tributaries with the Source for rivers model of the Goulburn River and undertake a comparison between SC and SR derived modelled flows.

In general the Goulburn Base Source for catchments model provided a good prediction of streamflow from the unregulated tributaries between Lake Eildon and the Goulburn Weir. Model performance was generally acceptable throughout the catchment during both the parameterisation (1975-1995) with over 90% of catchments having a CoE Daily > 0.6 and validation (1996-2005) periods with approximately 50% of catchments having a CoE Daily > 0.6. While the Goulburn Base SC Model provided a good prediction of observed streamflow in the Goulburn River, this relied on the use of observed outflows from Lake Eildon as an input at the top of the system. In order to investigate the impacts of unregulated tributaries on the Goulburn River under future scenarios including climate change and alter river management regimes it was necessary to link the results from the Source for catchments Model to the Source for rivers Model of the Goulburn system.

Linking the Source for rivers-Catchments models was an important step in investigating and testing the functionality of Source as well as providing a model of the Goulburn River that predicted contributions from the unregulated tributaries as well as the regulated Goulburn River. The two models were easily linked within Source through changing the inflows in the Source for rivers Model. Combining the two models provided reasonable agreement in predicted streamflow along the Goulburn River between the Source for rivers and Source for rivers-Catchments models with CoE Daily’s generally greater than 0.4. Importantly the combined Source for rivers-Catchments model could easily be used to investigate the impacts of unregulated tributaries on flows in the Goulburn River during future climate scenarios, by simply updating the climate files used by the Goulburn Base Source for catchments model.

An additional aim of the work presented in this report was to investigate the application of two calibration tools to a Source for catchments model. While PEST and RRL provided similar parameterisation and fit to the flow data, RRL was limited due to the ability to only parameterise a single catchment at a time and the requirement to manually load stream gauge and climate data for each catchment and then manually update the parameter sets within Source for catchments. On the other hand the linking of PEST to Source for catchments (using e2commandline) provided a powerful tool for calibrating and parameterising the model. While the initial setup of the PEST files was complex, an automated process was developed to generate the required PEST files, run PEST and extract the results for analysis. This automation, combined with the power of PEST as a parameterisation tool which also allows parameter sensitivity and uncertainty to be assessed, was a key result from this work and we will continue to utilise PEST with Source for catchments into the future.
5.1 Recommendations

- **Parallel development of e2commandline and Source for catchments.** PEST linked to Source for catchments provided an amazingly powerful tool that can simultaneously optimise hundreds of Rainfall-Runoff models whilst accounting for stream routing, dam releases and extractions. It is unlikely that we would use Source for catchments without PEST, as such it is imperative the development of e2commandline is kept inline with Source for catchments so that future functionality within Source for catchments can be utilised while still allowing the use of PEST.

- **Source for catchments Plugin to fully automate the link to PEST.** It is our view that PEST should be incorporated as a standard tool within Source for catchments. The current tools within the PEST plugin go a long way to meeting this however further development would be required to fully automate the process.

- **Develop the ability to copy scenarios between different files.** While it would not have helped in this application because the Source for catchments model was developed in a significantly older version of Source than the Source for rivers model. The ability to copy a scenario between files would allow a Source for catchments and Source for rivers model developed separately in different files (potentially be different groups) to easily be incorporated into a single unit without having to build one of the models from scratch. This is an important consideration given the potential complexity within model scenarios.
6 Acknowledgements

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- Robin Ellis from the Queensland Department of Environment and Resource Management for his help in developing the ability to use PEST with Source for catchments, as well as his input into discussions of parameterisation approaches.

- The Goulburn Broken Catchment Management Authority (particularly Meegan Judd), Goulburn Murray Water (particularly Lydia Mattner), and Goulburn Valley Water (particularly Brady Schmidt); for their support and data collection which has been invaluable.

- The Catchment and Climate team (particularly David Waters and Alex Miller) for the support in the application of Source for catchments.
7 References

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When this work commenced Source for catchments did not contain a parameter estimation tool within the model. This meant that in order to parameterise a model the user had to access external parameterisation tools. The Rainfall Runoff Library (eWater toolkit) was one available method, however it required data for each sub-catchment (size, rainfall, evaporation and observed streamflow) to be manually input into the program. The Rainfall Runoff Library is limited to parameterising a single catchment at a time and is really only designed for upstream catchments. In contrast PEST is a parameter estimation tool which can be linked to any model and which has the ability to optimise complex multi-catchment models simultaneously.

### 8.1 Methods

A step wise approach to parameter estimation was used to investigate the performance of PEST as a parameter estimation tool within the Goulburn Source for catchments model and to determine the most effective method for parameter estimation.

The exploration of parameter estimation using RRL and PEST focussed on a single catchment on the Acheron River upstream of Taggerty (Gauge 405209). The 603km² catchment was dominated by forestry (85%) and cropping (12%), with elevation ranging from 200 to 1470m and mean annual rainfall of 1331mm averaged across the catchment. The stream gauge (405209) had over 35 years of flow data, with no missing data and no zero flow periods.

The following steps were used to investigate the application of PEST to Source for catchments:

1. Rainfall Runoff Library (eWater Toolkit) was run by importing the rainfall, mWet and observed flow data and optimising the SIMHYD parameters to provide a calibrated model.
2. PEST was run to optimise the SIMHYD parameters within Source for catchments using the sum of squared residuals objective function. This provided a single parameter for the catchment.
3. PEST was run using a the sum residual squared objective function which was calculated on the natural log of measured and predicted flow data to provide a parameter estimation which was weighted towards the base flow in the catchment.
4. PEST was run with the higher flows weighted to bias the sum of residual squared objective function towards the peak flows. Three weightings were used:
   - top 5th percentile weighted at 10,
   - top 5th percentile weighted at 100, and
   - top 10th percentile weighted at 10.
To investigate the performance of different parameter estimation approaches the PEST output files were used along with a number of statistical functions to assess model fit achieved by running PEST on a daily basis.

1. The Nash Sutcliffe Coefficient of Efficiency

2. The Nash Sutcliffe CoEDaily calculated on the natural log of stream flow data, to reduce the bias of high flow events and provide an indication of how well the model is capturing the baseflow/low flow events.

3. Percentage Difference in Cumulative flow

The analysis was conducted over a 30 year period 1/1/1976 - 31/12/2005, with parameterisation over the period the first 20 years of measured data and validation over the remaining period.

8.2 Results: Investigation of parameterisation techniques

Both PEST and the Rainfall Runoff Library (RRL) were able to provide acceptable parameterisation of the SIMHYD model in catchment 405209. The results in terms of CoEDaily and cumulative flow are presented for both the parameterisation and validation periods.

RRL - sum of residuals squared objective function

The first parameter estimation approach used on the 405209 catchment was to optimise the model through the rainfall runoff library (RRL v1.1.0a). The genetic algorithm method within the RRL was used, with sum of residuals squared as the primary objective function to be consistent with the objective function used by PEST.

In general the RRL parameterisation provided a good fit with the measured flow data (Table 5 and Figure 22). With a CoEDaily of 0.86 during the parameterisation period and 0.82 during the validation period and less than 6% difference in cumulative flow over the parameterisation and entire period the model fit was generally acceptable although the difference in cumulative flow in the validation period was 17%. In general SIMHYD provided a very reactive and peaky response to rainfall. While it didn’t seem to capture a number of the peak flows it appeared to provide a reasonable representation of baseflow conditions. In mid 1994 there was a large flow event observed at the gauge which occurred over an eight day period, this flow was not associated with a high rainfall event within the SILO gridded climate data, suggesting that it may have been associated with localised storms within the catchment or that it may represent a problem with the gauge over that period.

While the RRL provided a good fit to the data very quickly, the main limitation of RRL was the need to manually export input data from Source for catchments, the ability to only include a single functional unit, the fact that it can only run one catchment at a time and RRL can’t be run on nested catchments. Because PEST can run on the Source for catchments model using e2commandline a number of these problems are overcome.
Table 5  Parameter estimation and statistics determined using the RRL (sum of residuals squared) for the Acheron Catchment (gauge 405209).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseflow Coefficient</td>
<td>0.07</td>
</tr>
<tr>
<td>Impervious Threshold</td>
<td>3.70</td>
</tr>
<tr>
<td>Infiltration Coefficient</td>
<td>105</td>
</tr>
<tr>
<td>Infiltration Shape</td>
<td>0.40</td>
</tr>
<tr>
<td>Interflow Coefficient</td>
<td>0.08</td>
</tr>
<tr>
<td>Pervious Factor</td>
<td>1.0</td>
</tr>
<tr>
<td>Rainfall Interception Storage Capacity</td>
<td>3.9</td>
</tr>
<tr>
<td>Recharge Coefficient</td>
<td>0.69</td>
</tr>
<tr>
<td>Soil Moisture Storage Capacity</td>
<td>453</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>CoEDaily</td>
<td>0.86</td>
<td>0.82</td>
<td>0.85</td>
</tr>
<tr>
<td>CoEDaily (ln)*</td>
<td>0.59</td>
<td>0.32</td>
<td>0.52</td>
</tr>
<tr>
<td>CumFlow%</td>
<td>0.9</td>
<td>16.8</td>
<td>5.2</td>
</tr>
</tbody>
</table>

* CoEDaily calculated using the natural log of observed and predicted flow
Figure 22 RRL (sum of residuals squared) - SIMHYD model results for the Acheron Catchment (gauge 405209); (a) streamflow from 1986-1995, and (b) cumulative flow from 1976-2005.
PEST1 - sum of residuals squared objective function

The next step in investigating the parameterisation of the Goulburn Source for catchments model was to use PEST with the same structure and starting conditions that were used in the RRL. This initial PEST run produced similar results to the RRL in terms of the fit between modelled and observed flows. In general the PEST parameterisation provided a good fit with the measured flow data (Table 6 and Figure 23a) during the parameterisation period. PEST resulted in a CoE\textsubscript{Daily} of 0.87 and less than 2.5% difference in cumulative flow during the parameterisation period. However, during the validation period despite a CoE\textsubscript{Daily} of 0.84 the cumulative error in flow was greater than 20% which was not acceptable.

In terms of the climate over the parameterisation and validation periods, the cumulative daily rainfall residual from 1975 to 2005, suggests that 1975 to 1985 was relatively stable with no extended wetting or drying periods (as shown by trends in the residual plot), 1986-1995 was a period of above average rainfall with a consistent increase in cumulative residuals, while 1996-2005 was a drying period. The parameterisation period was chosen for two main reasons: firstly to ensure that all gauges had a significant time series (> 5 years) of stream gauge data within the parameterisation period, and to investigate how well SIMHYD performs over a dry period when it has been parameterised over an average to wet period.

Parameterisation of SIMHYD using RRL or PEST both showed that stream flow was under predicted during the validation period. This raised the question of whether this was a response to the change in rainfall patterns between the parameterisation and validation periods, or whether it was due to insufficient rainfall within the catchment to generate the streamflow.

To further investigate this, PEST was re-run on the Acheron catchment using 1996-2005 as the parameterisation period. With the 1996-2005 parameterisation, the SIMHYD storage parameters were reduced as well as the infiltration and recharge coefficients (Table 6). The results (Table 6 and Figure 23) show that there was sufficient rainfall to generate the observed flow within the 1996-2005 period, with a CoE\textsubscript{Daily} of 0.89 and a difference in cumulative flow of 7%. However, with the 1996-2005 parameterisation period flow is significantly over predicted between 1976-1995 (Table 6 and Figure 24). This suggests that the SIMHYD parameterisation is sensitive to the rainfall conditions and climate sequence used.

While, changing the parameterisation period resulted in improved CoE\textsubscript{Daily}’s and cumulative flow during the relatively dry 1996-2005, the distribution of flow suggests that using either parameterisation period resulted in an under prediction of low flow events and a very reactive and peaky response to rainfall which didn’t seem to capture the peak flows events. While the two parameterisation periods result in a similar prediction of the low flow events (generally less than the observed flows), it was the higher flows that appeared to be elevated by the change in parameterisation (Figure 25). It was possible that modifying the objective function to try an improve the prediction of baseflow and peak flow conditions, could also result in greater consistency in model performance between the selected parameterisation and calibration periods.
Table 6  Parameter estimation and statistics determined using PEST1(\text{sum of residuals squared}) for the Acheron Catchment (gauge 405209), with the results presented for the 1976-1995 parameterisation period as well as the second parameterisation using 1996-2005.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseflow Coefficient</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Impervious Threshold</td>
<td>3.70</td>
<td>5.0</td>
<td>2.2</td>
</tr>
<tr>
<td>Infiltration Coefficient</td>
<td>105</td>
<td>400</td>
<td>336</td>
</tr>
<tr>
<td>Infiltration Shape</td>
<td>0.40</td>
<td>1.98</td>
<td>1.84</td>
</tr>
<tr>
<td>Interflow Coefficient</td>
<td>0.08</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>Pervious Factor</td>
<td>1.0</td>
<td>0.99</td>
<td>1.0</td>
</tr>
<tr>
<td>Rainfall Interception Storage Capacity</td>
<td>3.9</td>
<td>5.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Recharge Coefficient</td>
<td>0.69</td>
<td>0.61</td>
<td>0.53</td>
</tr>
<tr>
<td>Soil Moisture Storage Capacity</td>
<td>453</td>
<td>424</td>
<td>294</td>
</tr>
</tbody>
</table>

Statistics

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CoEDaily (1976-1995)</td>
<td>0.86</td>
<td>0.87</td>
<td>0.72</td>
</tr>
<tr>
<td>CoEDaily (1996-2005)</td>
<td>0.82</td>
<td>0.84</td>
<td>0.89</td>
</tr>
<tr>
<td>CoEDaily (ln)(1976-1995)</td>
<td>0.59</td>
<td>0.61</td>
<td>0.46</td>
</tr>
<tr>
<td>CoEDaily (ln) (1996-2005)</td>
<td>0.32</td>
<td>0.30</td>
<td>0.13</td>
</tr>
<tr>
<td>CumFlow% (1976-1995)</td>
<td>0.9</td>
<td>2.3</td>
<td>11.6</td>
</tr>
<tr>
<td>CumFlow% (1996-2005)</td>
<td>16.8</td>
<td>21.5</td>
<td>6.8</td>
</tr>
</tbody>
</table>

On the basis of the PEST and RRL results for the Acheron Catchment where the pervious fraction coefficient was always pushed to 1.0 it was decided to hold this parameter fixed. This means that there is no impervious runoff; therefore the impervious threshold parameter has no affect on the SIMHYD results and was also fixed at the default value of 1.0.

To try and improve the prediction of SIMHYD, PEST was run using (1) an objective function calculated using natural log of observed and predicted flow to bias the parameterisation towards the low flow periods; and (2) by weighting the top 5-20th percentiles of flow to bias the parameterisation towards the peak flow events. This analysis was conducted using the original parameterisation (1976-1995) and validation periods (1996-2005) which were chosen to not only test model performance but also based on the available data for parameterisation across the entire study area.
Figure 23 PEST1 (sum of residuals squared) - SIMHYD model results for the Acheron Catchment (gauge 405209): (a) parameterised over 1976-1995, and (b) parameterised over 1996-2005.
Figure 24 PEST1 sum of residuals squared Cumulative flow 1976-2005 using
(a) 1976-1995 parameterisation period, and
(b) 1996-2005 parameterisation period.
Figure 25 PEST1 (sum of residuals squared) distribution of flow (percentiles) between
(a) 1976-1995 parameterisation period, and
(b) 1996-2005 parameterisation period.
PEST2 - sum of residuals squared using natural log of flow

The next step in investigating the parameterisation of the Goulburn Source for catchments model was to use PEST with the same structure and starting conditions that were used in the previous PEST runs, but an objective function of the sum of residuals squared calculated on the natural log of the observed and predicted flow.

In general the PEST parameterisation using the natural log objective function provided a poor description of streamflow from the Acheron Catchment. While the $\text{CoE}_{\text{Daily}}(\ln)$ was greater than 0.7 for the parameterisation and validation periods the $\text{CoE}_{\text{Daily}}$ was less than 0.5 in both periods (Table 7). Cumulative flow varied by 1% in the parameterisation period and 18% in the validation period. In general while the use of natural log data in the objective function did improve the prediction of baseflow flow, it resulted in very high peak flow rates throughout the period (Figure 26). The difference in predicted flow using observed (PEST 1) or the natural log of observed (PEST 2) data in the objective function was highlighted in Figure 27, with Figure 27a showing predicted flow on a log scale and Figure 27b showing the distribution of flow from the 10th-90th percentiles.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial</th>
<th>RRL</th>
<th>PEST1</th>
<th>PEST2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseflow Coefficient</td>
<td>0.3</td>
<td>0.07</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>Impervious Threshold</td>
<td>1.0</td>
<td>3.70</td>
<td>5.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Infiltration Coefficient</td>
<td>200</td>
<td>105</td>
<td>400</td>
<td>251</td>
</tr>
<tr>
<td>Infiltration Shape</td>
<td>3</td>
<td>0.40</td>
<td>1.98</td>
<td>2.5</td>
</tr>
<tr>
<td>Interflow Coefficient</td>
<td>0.1</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>Pervious Factor</td>
<td>0.9</td>
<td>1.0</td>
<td>0.99</td>
<td>1.0</td>
</tr>
<tr>
<td>Rainfall Interception Storage Capacity</td>
<td>1.5</td>
<td>3.9</td>
<td>5.0</td>
<td>0</td>
</tr>
<tr>
<td>Recharge Coefficient</td>
<td>0.2</td>
<td>0.69</td>
<td>0.61</td>
<td>0.46</td>
</tr>
<tr>
<td>Soil Moisture Storage Capacity</td>
<td>200</td>
<td>453</td>
<td>424</td>
<td>447</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>$\text{CoE}_{\text{Daily}}$</td>
<td>0.46</td>
<td>0.15</td>
<td>0.38</td>
</tr>
<tr>
<td>$\text{CoE}_{\text{Daily}}(\ln)$</td>
<td>0.86</td>
<td>0.73</td>
<td>0.83</td>
</tr>
<tr>
<td>CumFlow%</td>
<td>1.0</td>
<td>18.2</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Figure 26 PEST2 (sum of residuals squared-natural log of flow) - SIMHYD model results for the Acheron Catchment (gauge 405209); (a) streamflow from 1986-1995, and (b) cumulative flow from 1976-2005.
Figure 27 Comparison of predicted flow with PEST parameterisation using observed (PEST1(sum of residuals squared)) and natural log of observed (PEST2(sum of residuals squared-natural log of flow)) flow data to calculate the objective function,

(a) observed and predicted flow graphed on a log scale, and

(b) The 10th-90th percentile flow (1976-1995) comparing the observed and predicted flow distributions.
PEST3 - sum of residuals squared-weighted to high flows

While using natural log data in the calculation of the objective function improved the prediction of baseflow conditions, the peak flows were still not captured by the model. The next step in investigating the parameterisation of the Goulburn Source for catchments model was to try and improve the prediction of peak flows by the SIMHYD model by weighting the higher flows, thus biasing the objective function towards high flows. In the previous PEST runs all daily flows were weighted as 1, three different weighting approaches were trialled to bias the objective function towards the high flows, namely:

- top 5th percentile of daily flows were weighted at 10,
- top 5th percentile of daily flows were weighted at 100, and
- top 10th percentile of daily flows were weighted at 10.

Weighting the top 5th percentile of flows by either 10 or 100, resulted in poor prediction of flow, with soil storage parameters pushed down resulting in a significant increase in predicted flow over the entire 30 year period. The CoEDaily for these two parameterisations were between 0 and 0.5 while the cumulative difference in flow ranged between 24-47%. Weighting the top 10th percentile of flows by 10 provided a better fit to the observed data than weighting just the top 5th percentile. Cumulative differences in flow were less than 7% in both the parameterisation and validation periods (Table 8), although flow was consistently over predicted. The CoEDaily was 0.78 during the parameterisation period but only 0.44 during the validation period (Table 8).

In general the PEST parameterisation using the weighted flows in the objective function provided a reasonable description of streamflow from the Acheron Catchment. In general the use of weighted high flows in the objective function resulted in minimal change in the prediction of baseflow flow conditions, but a notable increase in predicted flow from the 30th percentile (Figure 29a and b).

### Table 8
Parameter estimation and statistics determined using PEST3 (sum of residuals squared-weighted to high flows) with the top 10th percentile weighted by a factor of 10, for the Acheron Catchment (gauge 405209).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial</th>
<th>RRL</th>
<th>PEST1</th>
<th>PEST2</th>
<th>PEST3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseflow Coefficient</td>
<td>0.3</td>
<td>0.07</td>
<td>0.06</td>
<td>0.04</td>
<td>0.07</td>
</tr>
<tr>
<td>Impervious Threshold</td>
<td>1.0</td>
<td>3.70</td>
<td>5.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Infiltration Coefficient</td>
<td>200</td>
<td>105</td>
<td>400</td>
<td>251</td>
<td>86.6</td>
</tr>
<tr>
<td>Infiltration Shape</td>
<td>3</td>
<td>0.40</td>
<td>1.98</td>
<td>2.5</td>
<td>0.79</td>
</tr>
<tr>
<td>Interflow Coefficient</td>
<td>0.1</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
<td>0.11</td>
</tr>
<tr>
<td>Pervious Factor</td>
<td>0.9</td>
<td>1.0</td>
<td>0.99</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Rainfall Interception Storage Capacity</td>
<td>1.5</td>
<td>3.9</td>
<td>5.0</td>
<td>0</td>
<td>5.0</td>
</tr>
<tr>
<td>Recharge Coefficient</td>
<td>0.2</td>
<td>0.69</td>
<td>0.61</td>
<td>0.46</td>
<td>0.89</td>
</tr>
<tr>
<td>Soil Moisture Storage Capacity</td>
<td>200</td>
<td>453</td>
<td>424</td>
<td>447</td>
<td>500</td>
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<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>CoEDaily</td>
<td>0.78</td>
<td>0.44</td>
<td>0.68</td>
</tr>
<tr>
<td>CoEDaily (ln)</td>
<td>0.58</td>
<td>0.39</td>
<td>0.53</td>
</tr>
<tr>
<td>CumFlow%</td>
<td>6.9</td>
<td>6.0</td>
<td>3.4</td>
</tr>
</tbody>
</table>
Figure 28 PEST3 (sum of residuals squared-weighted to high flows) with the top 10th percentile weighted by a factor of 10 - SIMHYD model results for the Acheron Catchment (gauge 405209); (a) streamflow from 1986-1995, and (b) cumulative flow from 1976-2005.
Figure 29 Comparison of predicted flow with PEST parameterisation using observed (PEST1(sum of residuals squared)) and weighted (PEST3(sum of residuals squared-weighted to high flows)) flow data to calculate the objective function,
(a) observed and predicted flow graphed on a log scale, and
(b) The 10th-90th percentile flow comparing the observed and predicted flow distributions.
8.3 Conclusion: Investigation of parameterisation techniques

Based on the results from the Acheron catchment presented it was decided that the full Goulburn model would be parameterised using the 1976-1995 parameterisation period and an objective function using non-weighted flow.

PEST linked to Source for catchments provided an amazingly powerful tool to optimise Rainfall-Runoff models within Source for catchments. Whilst initially setting up the links between Source for catchments and PEST was time consuming it is unlikely that we would use Source for catchments without PEST.
Using Source to model the Goulburn River between Lake Eildon and Goulburn Weir.