Supplementary Material

A bricolage-style exploratory scenario analysis to manage uncertainty in socio-environmental systems modeling: investigating integrated water management options

A. The integrated model

The integrated model was developed to enable analysis of the ecological and economic impacts of climate, technology, markets, and policy (Figure A1). A daily hydrological model interacts with models of annual farmer decisions, water policy, and ecology.

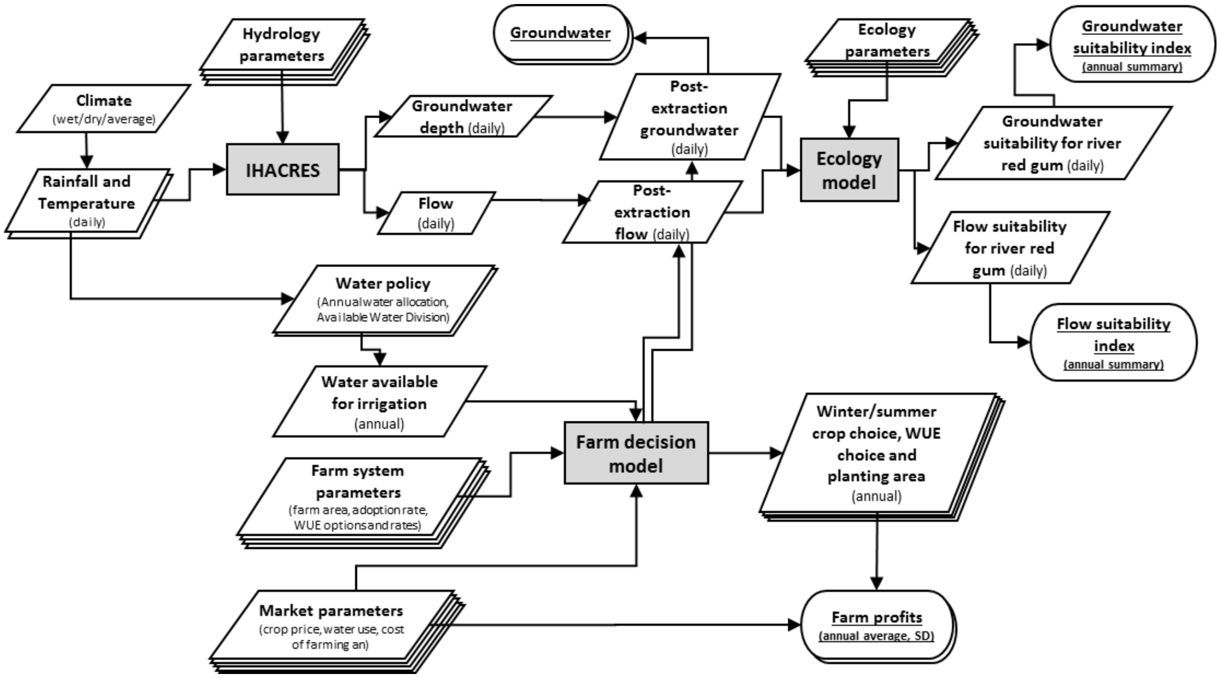

Figure A1: Conceptual diagram of the integrated model

Hydrology and groundwater (IHACRES)

The hydrological model takes daily extraction and climate time series and predicts daily stream flow and groundwater levels. Several parameters have been calibrated using historical stream flow and groundwater level data. It is based upon a groundwater extension of the IHACRES model (Jakeman & Hornberger, 1993; Jakeman, Littlewood, & Whitehead, 1990). Effective rainfall is calculated from climate data using the catchment moisture deficit model of Croke and Jakeman (2004).

$$M_t = \begin{cases} M_{t-1}\exp\left(-\frac{P_t}{d}\right), & M_{t-1} < d \\ M_{t-1}\exp\left(-\frac{P_t - M_{t-1} + d}{d}\right), & M_{t-1} < d + P_t \\ M_{t-1} - P_t, & d + P_t < M_{t-1} \end{cases} \qquad \text{Eq. 1}$$

$$\boldsymbol{E_t} = \begin{cases} \boldsymbol{0},\ \boldsymbol{T_t < 0} \\ \boldsymbol{eT_t},\ \boldsymbol{M_t < f\ and\ 0 < T_t} \\ \boldsymbol{eT_t \exp(2\left(1 - \frac{M_t}{f}\right))},\ \boldsymbol{f\ \leq M_t\ and\ 0 < T_t} \end{cases} \qquad \text{Eq. 2}$$

$$\boldsymbol{M_t = M_t + E_t} \qquad \text{Eq. 3}$$

$$\boldsymbol{U_t = P_t + M_t - M_{t-1}} \qquad \text{Eq. 4}$$

P_t, E_t, M_t and T_t are precipitation, evapotranspiration, moisture deficit and temperature for time step *t*, and *d*, *e*, and *f* are constants.

Effective rainfall is partitioned into recharge and inflow into streams. As in Jakeman and Hornberger (1993), stream flow, q_t, at time, *t*, is given as a transfer function

$$\boldsymbol{q_t = \alpha q_t + (1 - v_s)\beta A u_t} \qquad \text{Eq. 5}$$

where u_t is effective rainfall, *A* the catchment area, v_s is the fraction of effective rainfall entering groundwater as recharge, and *α* and *β* are constants.

Following Ivkovic, Croke, Letcher, and Evans (2005) and Blakers, Croke, and Jakeman (2011), groundwater infiltration *I* is given

$$\boldsymbol{I_t} = \begin{cases} \boldsymbol{aG_t},\ \boldsymbol{G_t > 0} \\ \boldsymbol{0},\ \boldsymbol{G_t \leq 0} \end{cases} \qquad \text{Eq. 6}$$

where G_t is the volume of groundwater storage and *α* is the storage coefficient. Groundwater storage changes according to

$$\boldsymbol{G_t = G_{t-1} - I_t + v_s A u_t - E_t - L_t} \qquad \text{Eq. 7}$$

where E_t is extraction and L_t a parameter representing further loss. Equations (6) and (7) are solved simultaneously.

Water Policy

The water policy model is loosely based on licensing in Australia. A farm owns separate surface and groundwater licenses in megalitres. Surface water allocations for a particular year are given as a percentage of these licenses based on the recent climate according to

$$\boldsymbol{W} = \begin{cases} \boldsymbol{\frac{R - R_{\min}}{R_{max} - R_{min}} \times 100\%},\ \boldsymbol{R < R_{90}} \\ \boldsymbol{100\%},\ \boldsymbol{R \geq R_{90}} \end{cases} \qquad \text{Eq. 8}$$

where *W* is the annual water allocation rate (%), *R* is this year's annual rainfall, R_{min}, R_{max} and R_{90} are minimum, maximum and 90th percentile of the annual rainfall.

By default, the groundwater allocation rate is a constant 100%. However, more policy options are explored and specifications are described in Supplementary Material B. An improved water policy would seek to maintain surface and groundwater at levels determined to be appropriate by the community and stakeholders. Such policy would incorporate current levels as well as the state of dependent ecosystems and economies.

Ecology model

The ecology model estimates the suitability of groundwater and surface water regimes for the maintenance of river red gum at the riparian areas, as in Fu and Guillaume (2014). The daily groundwater index is calculated based on groundwater depth below ground.

$$I = G(\textit{groundwater level}) \qquad \text{Eq. 9}$$

where I denotes the groundwater suitability index; G is a function of groundwater level which estimates groundwater suitability index.

The surface water index is calculated from a flow time series based on flood events, which are continuous periods with flow above the commence-to-flood (CTF) thresholds. The surface water index is calculated based on a weighted average of the duration, flood timing, and inter-flood dry period.

$$S = w_d D(\textit{flood duration}) + w_t T(\textit{flood timing}) + w_f F(\textit{inter-flood dry period}) \qquad \text{Eq. 10}$$

where S is the surface water suitability index; D, T, F are respectively a function of flood duration which produces a flood duration index, a function of flood timing which produces a flood timing index, and a function of inter-flood dry period which produces an inter-flood dry period index; and w_d, w_t and w_f are weights for duration, timing and inter-flood dry period respectively.

Farm Decision model

The farm decision model is based on the annual selection of crop areas to maximize farm profit. As in Letcher et al. Letcher, Jakeman, and Croke (2004), this is achieved using a linear programming solution to

$$\mathbf{arg}\min_{\boldsymbol{a_c}} \sum_c \boldsymbol{a_c y_c p_c} \qquad \text{Eq. 11}$$

subject to the constraints: $\sum_c a_c \leq A$ and $\sum_c a_c w_c \leq WL$

Where for each crop, c, a_c is the area planted in hectares, y_c the yield in units per hectare, p_c the price in dollars per unit, and w_c the water use in megalitres per hectare. A is the maximum area in hectares, W is the annual water allocation rate and L is water license in megalitres.

B. Selection of scenarios

B.1 Scenarios in system variables

Scenarios in system variables are associated with uncertainties relating to external and uncontrollable drivers of the environmental and economic outcomes or limitations in our knowledge. Variables and corresponding themes were selected based on the authors' prior knowledge of potentially important sources of uncertainties in model assumptions. In this case study, we focused on the extreme cases when possible, intending to span a broad range of future scenarios, including some that would be considered unlikely, but not impossible.

Climate

Two climate scenarios were selected to investigate the impact of climate condition. The dry climate scenario uses a 10-year daily climate input time series for the period which has the lowest historical 10-year mean annual rainfall in the study area. The whole period of record available is 112 years (1 Jan 1899 to 27 Dec 2011). Similarly, the wet climate scenario uses climate data for the period with highest 10-year mean annual rainfall in the area.

Crop market

Two market scenarios were selected to investigate the impacts of crop market uncertainty. The "down" market scenario assumes that crop prices for all the crops drop 20% over a full 10-year period. The "up" market scenario assumes crop prices increase by 20% over a 10-year period.

Hydrological modeling

There are many parameters in the hydrology model, some of which are correlated. Instead of selecting individual hydrological parameters, we modified the hydrological model output (i.e. daily flow) to represent uncertainty in overestimating or underestimating flows. Two scenarios were selected representing the upper and lower bounds of the flow. The lower bound flow scenario reduces modeled flow by 50%, while the higher bound flow scenario increases the modeled flow by 50%. The extent of the upper and lower bounds were informed by the hydrologist who developed the model for this case study.

Hydrogeological modeling

Similar to the hydrological modeling scenarios, two scenarios were selected to account for uncertainty in the groundwater model. The shallower and deeper groundwater scenarios respectively reduce and increase modeled groundwater depth by 20%. The extent of the upper and lower bounds were informed by the hydrogeologist who developed the groundwater model for this case study.

Requirements of flood duration for river red gum

Two key literature sources were identified that specify requirements of flood duration for healthy growth of river red gum in the Murray-Darling Basin, where the case study is located: Rogers and Ralph (2010) and Roberts and Marston (2011). The specified requirements were not identical, representing uncertainty in ecological knowledge and natural variability. Therefore, we test the impact of the knowledge uncertainty using two scenario themes: Roberts scenario uses information on flood duration requirements from Roberts and Marston (2011) and Rogers scenario uses those from Rogers and Ralph (2010) (Figure B1).

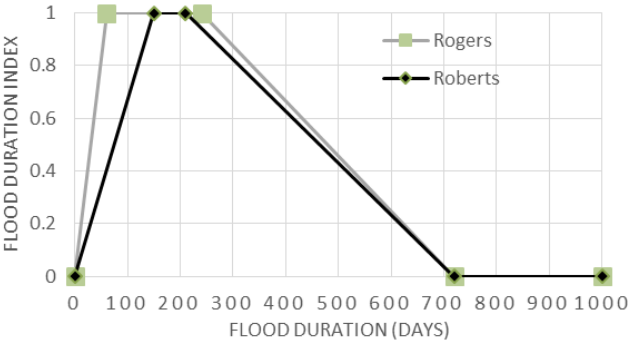

Figure B1: Inputs for two flood duration scenarios. An index of 1 indicates highly suitable flood duration to sustain river red gum, while an index of 0 indicates not suitable.

Relative importance of flood attributes

As shown in Eq.10, we used weights to capture the relative importance of different flood attributes for the maintenance of river red gum. However, there is no consensus on their relative importance (i.e. weights), although flood duration is considered more important than timing and inter-flood dry period. Two scenario themes were included in analysis. The “best guess” weight scenario uses weights of 0.5, 0.2 and 0.3 for duration, timing and inter-flood dry period, respectively. The “favor duration” scenario uses weights of 0.9, 0.05 and 0.05 for duration, timing and dry period instead. The latter scenario reflects the view that the river red gum is a perennial tree and providing sufficient soil moisture at any time would be desirable to maintain growth.

Requirements of groundwater depth for river red gum

The scenario themes in this variable reflect uncertainty in our knowledge in terms of how deep/shallow the groundwater needs to be to sustain the river red gum. Two scenarios were selected. One is the “best guess” groundwater depth scenario, which considers 12m below ground to be the maximum depth that a river red gum can access (Figure 1). The “deep roots” scenario relaxes that rule and considers groundwater above 15m below ground to be accessible by river red gums, although the deeper the groundwater, the less suitable it is.

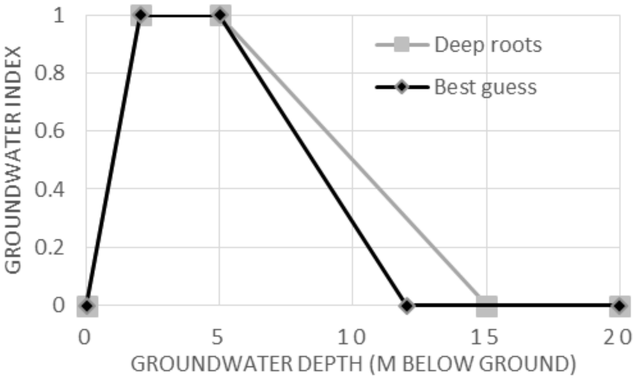

Figure 1: Inputs for two groundwater depth scenarios. An index of 1 indicates highly suitable groundwater depth to sustain river red gum, while an index of 0 indicates not suitable.

A2.2 Scenarios in management options

Scenarios in management options relate to interventions within the scope of control in order to make changes to the system, either by water managers in terms of modifying water allocation rules, or by farmers in terms of improving irrigation water use efficiency and adoption of new technology.

Maximum surface water allocation

The maximum surface water allocation represents the maximum proportion of surface water entitlement that can be used for irrigation. We selected two scenarios to capture extreme cases: 1) a maximum surface water allocation rate of 50% over the model period (10 years), indicating a situation when the irrigation water is dramatically reduced; and 2) a maximum surface water allocation rate of 200%, indicating a doubling of the maximum water allocation compared to the current level. Note that the actual annual allocation is then calculated based on the level of annual rainfall relative to maximum annual rainfall, and these allocation rates (Eq. 8).

Maximum groundwater allocation

Similar to the maximum surface water allocation scenarios, we tested two scenarios on groundwater allocation: 1) a maximum groundwater allocation rate of 50% indicating a much tighter restriction on groundwater pumping; and 2) a maximum groundwater allocation rate of 200% indicating a more relaxed groundwater pumping rule. The actual annual groundwater allocation is determined depending on the conjunctive use options as specified below.

Conjunctive use options

The conjunctive use options specify how the actual groundwater allocation rate is determined. We tested four options:

- By rain: similar to surface water allocation, the groundwater allocation is linearly related to rainfall, and ranges between 0% and the specified maximum groundwater allocation rate. This captures the idea that the water used should depend on the volume available.
- Constant: groundwater allocation rate is a constant (=100%), corresponding to a policy built on a single long term sustainable aquifer yield.
- Force fix: within a 5-year cycle, when surface water allocation is less than 100%, allow over-extraction of groundwater (up to 130% allocation) to compensate for surface water loss, but forcefully reduce groundwater allocation in the 5th year to meet the 5-year average groundwater allocation of 100%, after which the 5-year count is restarted. This type of partial rollover of groundwater allocations has never been implemented but is part of the new ideas being explored by stakeholders, allowing conjunctive use of surface and groundwater, in this case with groundwater to be used as a backup water source in dry years.
- Opportunistic and force fix: when surface water allocation is less than 100%, allow over-extraction of

groundwater, but recover the allocation when either 1) surface water allocation is high (>90%, i.e. in wet years), after which the 5-year count is restarted, or 2) forcefully reduce groundwater allocation in the 5th year to meet the 5-year average groundwater allocation of 100%, after which the 5-year count is restarted. Recharge events in wet years are assumed to allow more aggressive use of groundwater as a backup water source in dry years.

Flood irrigation efficiency

Depending on technology used and management practices, different levels of water use efficiency can be achieved for flood irrigation. Based on earlier studies (Ticehurst & Curtis, 2015), we selected the minimum (50% efficiency) and maximum (80% efficiency) flood irrigation efficiency for the scenarios.

Spray irrigation efficiency

Similar to flood irrigation efficiency, we selected two spray irrigation efficiency scenarios: 70% and 90% which represent the minimum and maximum spray irrigation efficiency in the area.

Adoption of spray irrigation technology

This looks at the percentage of flood and spray irrigation techniques that could be adopted in the study area. Based on an earlier study (Ticehurst & Curtis, 2015), the spray irrigation adoption rates by the farmers are between 0.5% and 16.9%, with the rest of the areas being flood irrigation. Therefore, we selected 0.5% and 16.9% spray irrigation (and subsequently 99.5% and 83.9% of flood irrigation) area as the two scenarios in adoption of irrigation technique. The former scenario representing the domination of a more traditional irrigation method, while the latter representing the shift towards more modern irrigation technology that may achieve higher water use efficiency.

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