Integrated, dynamic economic – hydrology model of the Murray-Darling Basin

Mac Kirby[1*], Mohammed Mainuddin[1], Lei Gao[2], Jeff Connor[3], Mobin-ud-Din Ahmad[1]
[1] CSIRO Water for a Healthy Country, GPO Box 1666, Canberra ACT 2601, Australia
[2] CSIRO Land and Water, PMB 2, Glen Osmond SA 5064, Australia
[3] CSIRO Ecosystem Sciences, PMB 2, Glen Osmond SA 5064, Australia

Contributed paper prepared for presentation at the 56th AARES annual conference, Fremantle, Western Australia, February7-10, 2012

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[3] CSIRO Ecosystem Sciences, PMB 2, Glen Osmond SA 5064, Australia

Summary

We aim to model the impact of variability in and changes to water availability in the Murray-Darling Basin on flows available to the environment and irrigation, and impact on the value of irrigated agricultural production. Our objective is to understand the opportunities for changed management of the basin, how they are constrained by climate change and other factors, and how they might affect the returns to irrigation and flows for the environment, so that we may provide information to help plan for the future. In this paper we describe the model: in other papers in this conference we describe analyses of water availability and use in the basin based on this model.

The hydrology component of the model is based on a simple, monthly water balance stocks and flows model of the basin, subdivided into 58 catchments. In each catchment, the rainfall and potential evapotranspiration are used to partition the rain between actual evapotranspiration and runoff. Runoff accumulates in the rivers, and flows downstream; it is stored in dams, fills lakes and wetlands from which it evaporates, spills onto and is partly consumed on the floodplains, is diverted for irrigation, eventually (if enough water remains) flowing out of the mouth. This hydrology part of the model is calibrated against observations of flow at the downstream flow gauge of the 58 catchments (the records of which vary from a few years to the full 114 years of our typical simulation period from 1895-2009). It simulates reasonably well the full range of flows, and the development of dams and irrigation diversions.

The economics part of the model is based on regressions with dependent variables: the observed areas, production, water use and gross value of production of irrigated agriculture. Each dependent variable is estimated as functions of water available, evaporation and rainfall, and crop prices, for ten major commodity groups. The regressions are based on data for 17 regions and four recent years during the drought: they cover a wide range of water uses, water availability, rainfall, evaporation and commodity price circumstances observed during the drought. We report separately in this conference on this statistical analysis (Connor et al, 2012a.

In the integrated model, the hydrology model first determines the availability of water for irrigation in the 58 catchments and also calculates the flows, on a monthly cycle. Once per year, the water availability values are aggregated to the 17 economic regions, and the economic model determines the irrigation outcome in terms of areas under each commodity group in each region and the gross value of production.

The integrated model has some unique features in comparison to existing MDB economics models: the coupling of economics with detailed hydrology; the ability to simulate active management of environmental flows and the resulting consumptive water use economic impacts; and, the ability to simulate the dynamics of the water balance and economic impact over 114 year historical and simulated future climate sequences.

1 Introduction

The Murray-Darling Basin has a complex hydrology with highly variable flows, combined with a complex system of water use primarily for irrigated agricultural production. It is currently subject to great change in water availability and use, partly because of the recently released proposed Murray-Darling Basin Plan (MDBA, 2011), partly because of other factors like climate change (CSIRO, 2008), and partly because of other changes such as rise of water trading (eg. Kirby et al, 2012).

Models that combine hydrology with economics are common. Examples elsewhere in the world include the model by Cai et al. (2003) of the Syr Darya River Basin in Central Asia, that by Ward et al. (2006) of the Rio Grande in North America, and that by Ringler (2001) of the Mekong. The Murray-Darling Basin is also the subject of several hydrology – economic models such as those of Adamson et al. (2007) and Grafton and Jiang (2011), and Grafton et al. (2011). Generally the hydrology is based on average flows, or flows representing a single state (such as a drought), at few locations. Dynamic effects, including storages, are not represented.

The limited representation of hydrology in such models is perhaps not surprising. Only one hydrology model of any complexity, other than that described here, has been developed for the Murray-Darling Basin. The model described by CSIRO (2008) links many catchment models developed and maintained by the State authorities responsible for different regions. The individual models have different underlying conceptual bases (some are daily, some weekly models, for example, with different rainfall-runoff models and so on), is large and comprehensive, and embodies the water sharing rules and entitlement classes referred to above. It takes several hours to run. It is difficult to use, is too cumbersome to link to optimisation, and is not well suited to the rapid exploration or linking to economic models. Thus, as far as we know, there is no hydrology model that fulfils our purpose.

Here, we describe an integrated hydrology model of the whole basin. The hydrology part is a dynamic, monthly time-stepping model of flow, storage and diversion of water in the basin. It is based on a subdivision of the basin into 58 catchments. In each catchment, the monthly runoff, river flow and irrigation demand are modelled as lumped processes. The model runs for a 114 year period, based on climate records for 1895-2009; a single run takes about 1 s. The economics part, based on an econometrics analysis of irrigation described elsewhere in this conference, uses the water availability from the hydrology part of the model, and thence predicts irrigation water use and gross value of production.

2 Hydrology sub-model

We divide the Murray-Darling Basin into 58 major catchments and apply a simple water balance to each (Figure 1). The catchments are aggregates of the rainfall-runoff sub-catchments used in the Murray-Darling Basin Sustainable Yields project (CSIRO 2008). The outlets of the 58 catchments are all at river gauging points; 15 of the gauging points are of particular interest for assessing environmental flows (MDBA 2010).

Figure 1 . The Murray-Darling Basin and the 58 sub-catchments used in the hydrology sub-model.

For each catchment, we assume that a simple, conceptual, mass balance model applies, depicted schematically in Figure 2. The three main components of the schema are a rainfall – runoff component, river flow and storage, and an irrigation water demand component. Not all features appear in every catchment: for example, catchments in basin headwaters have no inflow from upstream, and some catchments lack irrigation.

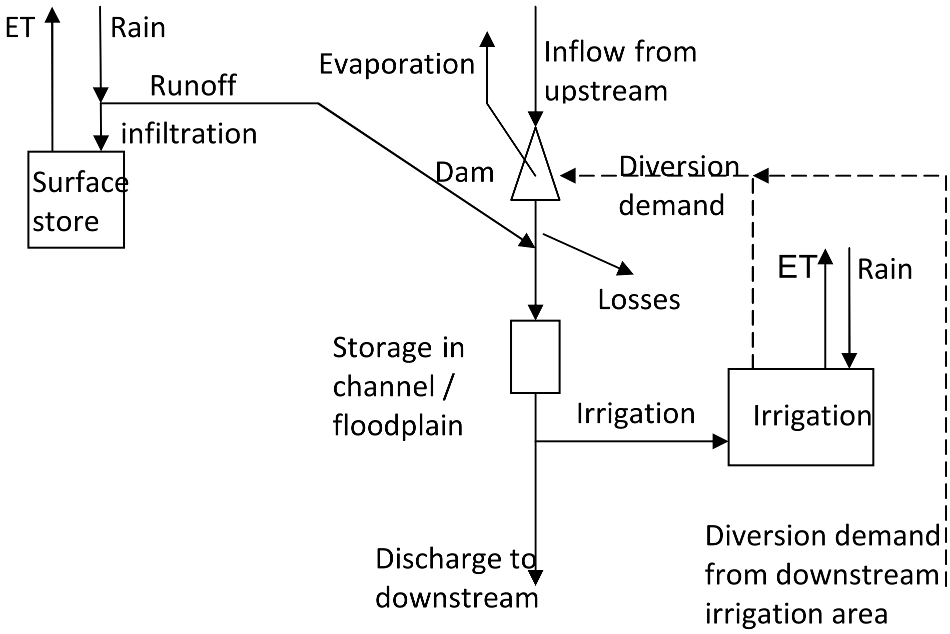

Figure 2. Conceptual model of a single catchment.

Any element within the water account, whether it is a dam, a river, a catchment, or the whole basin must obey basic mass balance given by:

$$\sum Inflows - \sum Outflows - \sum \Delta storages = 0 \qquad (1)$$

Rainfall, Evapotranspiration and Runoff

We derive partitioning of rainfall using the reasoning of Budyko (1974), which applies to average annual runoff, with the addition of a storage that varies from month to month; the monthly extension is based on Zhang et al. (2008). We firstly partition rainfall, P, at the land surface into runoff, R_o, and infiltration, I, where conservation of mass must be observed. The infiltration component, I, is an addition to a generalized surface store, which could include temporary free water such as puddles, as well as actual infiltration into the soil. Evapotranspiration from the generalized surface store will be dealt with separately after calculating the infiltration. Thus:

$$P - I - R_o = 0 \qquad (2)$$

Rainfall is the supply limit, whereas the unfilled portion of a generalized surface storage, ΔS_{smax}, is the capacity limit governing the partition and includes soil storage and small surface stores. We use a Budyko-like equation to smooth the transition from the supply limit to the capacity limit:

$$\frac{I}{\Delta S_{s\max}} = \left(\frac{\left(P/\Delta S_{s\max}\right)^{a_1}}{1+\left(P/\Delta S_{s\max}\right)^{a_1}} \right)^{1/a_1} \qquad (3)$$

where a_1 is a parameter.

The evapotranspiration depends on the potential evapotranspiration, ET_{pot} (the capacity limit), and the surface storage, S_s (the supply limit). Although we do not differentiate between soil and other surface stores, the implication is that evaporation occurs from small ponds, puddles, and the soil surface, in contrast to transpiration, which comes from deeper soil storage. An equation similar to equation (3) above, with a second adjustable parameter, a_2, is used to smooth the transition from the supply limit to the capacity limit:

$$\frac{ET}{ET_{pot}} = \left(\frac{\left(S_s^{t-\Delta t} / ET_{pot}\right)^{a_2}}{1+\left(S_s^{t-\Delta t} / ET_{pot}\right)^{a_2}} \right)^{1/a_2} \tag{4}$$

Infiltration increases the water stored in the generalized surface store, while it is decreased by evapotranspiration:

$$S_s^t = S_s^{t-\Delta t} + I - ET \tag{5}$$

where t is time and Δ_t is the time step (one month).

River Flow and Storage

We model river flow through a series of reaches, maintaining mass balance between them. Many rivers have a large difference between the high and low flows, which implies considerable storage within the river channels. Furthermore, floods also imply considerable storage, particularly in reaches further downstream.

Thus, the outflow of a reach, Q_o, is given by the inflow, Q_i, plus any tributary flows, Q_t, plus the runoff from the adjacent catchment, R_o (as calculated above), less any diversion (for urban or agricultural use), D, less any losses (evaporation, seepage), L, plus the change in reach storage ΔS_r:

$$Q_o = Q_i + Q_t + R_o - D - L + \Delta S_r \tag{6}$$

Inflow is generally 0 in a headwater catchment but, to simulate the inflows from the Snowy scheme, the model allows for a constant inflow to be added. The diversions are generally calculated as those required for irrigation, described below in section 3.5. To simulate the diversions to Adelaide and South Australia country towns, the model allows for a constant outflow to be subtracted.

The outflows, Q_o, cannot be negative. The terms on the right hand side are all calculated in other equations and, in principle, their sum could be negative. When this occurs, the change in reach storage, ΔS_r, is adjusted such that Q_o is zero.

Losses are calculated as a function of inflow:

$$L = Q_i\left(1 - c_{loss}\right) \tag{7}$$

where c_{loss} is a parameter with value $0 \le c_{loss} \le 1$.

The reach storage is also a function of the inflow:

$$S_r = c_1 Q_i \tag{8}$$

where c_1 is a parameter.

The change in reach storage is the difference between reach storage at two time steps:

$$\Delta S_r = S_r^t - S_r^{t-\Delta t} \tag{9}$$

A river recovers storage in a reach as flow when the levels of the river fall. Outflow from one reach becomes inflow to the next reach. Where tributaries join a reach, the inflow is the sum of the outflows of the tributaries plus the main river inflow to the reach to which they join. As described above, to prevent Q_o from becoming negative ΔS_r, may be adjusted. When this is done, the storage term evaluated in equation (9) is adjusted to maintain balance.

We assume storages in lakes and reservoirs, S_D, fill and empty according to:

$$S_D^t = \mathrm{MIN}\left(S_{D\max}, \left(S_D^{t-\Delta t} + c_6 Q_i - L - E - c_7 D_j\right)\right) \tag{10}$$

The minimum function gives the capacity limit of the storages. The inflows, Q_i, are multiplied by a constant, c_6 ($0 \le c_6 \le 1$), which, if it is less than 1, allows for some of the inflows to pass through the dam and contribute to an environmental flow. The diversions are those calculated below as D_j in equation (21), the total for all the irrigation areas that the dam serves, multiplied by a constant, c_7 ($0 \le c_7 \le 1$), which allows for losses between the dam and diversion point. This simple assumption is used to mimic the many and complex rules of water sharing in the basin. The diversion term is absent for lakes that do not supply water for irrigation. Evaporation is given by:

$$E = c_4 \, ET_{pot} \, S_D^{c_5} \tag{11}$$

The term c_4 ET_{pot} accounts for evaporation demand from open water, and c_4 is often assumed to be about 0.7, although usually when pan evaporation rather than potential evapotranspiration is used, see Gippel (2006). The term $S_D^{c_5}$ is the conversion from storage volume to surface area and c_5 will often be around 2/3 (because volume is proportional to the cube of the depth, whereas the evaporating surface area is proportional to the square of depth). We do not explicitly consider evaporation from rivers, since it is implicit in the loss term, L, in equation (11).

The change in lake or reservoir storage is given by:

$$\Delta S_D = S_D^t - S_D^{t-\Delta t} \tag{12}$$

Irrigation Supply

Water is made available to irrigators in the Murray-Darling Basin in varying amounts from year to year depending on water available in storage and rules for release to the water, with both rules and storage levels varying from year to year and catchment to catchment. Our hydrology model does not use all of the actual rules but rather approximates the results of these rules with simplified algorthim that gives approximate temporally and spatially varying irrigation supply. In essence, available storage above a minimum reserve is released as supply to irrigation unless maximum potential crop water demand with all potentially irrigated land utilised is less than available storage.

We use a crop coefficient approach, in which a crop coefficient, K_C, is used to estimate the irrigation requirement of a crop as a proportion of potential evapotranspiration. K_C varies for different developmental stages of each crop ranging from 0 when there is no crop, to a value of about 0.8 to 1.2 when crop demand is maximum, the value depending on both the crop and its husbandry. Allen et al. (1998) explain the basis of this approach in detail. We assume here that crops are always well watered, and that the area cropped is reduced when water supply is limited. Thus, decreased crop water-use result from reduction in the area cropped, not reduced crop growth and yield.

The area under irrigation in any year is determined from the dam or reservoir storage in the month prior to the start of irrigation and the total mean annual irrigation demand for all irrigated crops.

The monthly irrigation demand per unit area, $\overline{Irr}_{Demandij}$, for crop *i* in month *j* is:

$$Irr_{Demandij} = \frac{\left(K_{cij}\, ET_{potj} - P_{eij}\right)}{IE_i} \tag{13}$$

where K_{Cij} is the crop coefficient for crop *i* in month *j*,

IE_i is the irrigation efficiency, and

P_{eij} and ET_{potj} are respectively the effective rainfall and potential evapotranspiration for month *j*.

If there is sufficient rain in a month, then $\overline{P}_{eij} > K_{Cij}\,\overline{ET}_{potj}$ and $\overline{Irr}_{Demandij} = 0$.

The mean monthly irrigation demand for each crop is summed for each month of the year to give a mean annual irrigation demand per unit area for the crop. The demand per unit area is used to calculate the area that can be irrigated from the water in storage. The area of irrigated crops in any year is, in each catchment, set to that which can be supplied by the water stored in the dams supplying that catchment. up to a maximum area which is taken as the largest measured area.

The total volume of irrigation, $Irr_{Demand\,Tj}$. required to satisfy the demand of *n* crops in any month *j* is:

$$Irr_{DemandTj} = \sum_{i=1,n}\left(Irr_{Demandij}\, A_{Ii}\right) \tag{14}$$

If there is adequate water storage in the dam, the total volume available for diversion to irrigate crops, D_J, is equal to the total irrigation demand. If the volume stored is less than the irrigation requirement, then the volume available for diversion is equal to the dam storage.

3 Irrigation economics sub-model

The economics component is a simulation model based on a regression analysis of irrigation during the drought, from 2006 to 2009. The regression analysis is described elsewhere in this conference by Connor et al, 2012a. The regression equations are applied to ten commodities some or all of which are produced in each of 17 Natural Resource Management regions for which water use and the gross value of irrigated agricultural production are reported by ABS (2010). Connor et al 2012b describe the use of the regression equations to predict the area of crops, the water use, and the gross value of irrigated agricultural production for major Basin crop and livestock commodities.

The crop area regression model is presented as equation 15.

$$A_{i,j,y} = \alpha_i^0 + \alpha_i^{wa} * wa_{i,j,y} + \alpha_i^p * p_{i,y} + \alpha_i^c * c_{i,j,y} + \alpha_i^n * n_j + e_{i,j,y} \cdots\cdots(15)$$

Where variables in all equations are reproduced in Table 1, α_i^0 is the regression intercept coefficient, and α_i^{wa}, α_i^p, and α_i^c are the regression coefficients for the water allocation, price and climate explanatory variables. α_i^c is the regression coefficient for the binary variable n_j included to account for distinct differences influencing land and water allocation and revenues from production in the northern Basin versus the southern basin that are not picked up in the other explanatory variable.

Water use per hectare for each crop i, W_i were estimated with the linear regression model

$$W_{i,j,y} = \beta_i^0 + \beta_i^{wa} * wa_{i,j,y} + \beta_i^p * p_{i,y} + \beta_i^c * c_{i,j,y} + \beta_i^n * n_j + e_{i,j,y} \cdots\cdots(16)$$

The explanatory variables (crop price, allocations available for irrigation, and net irrigation requirement) are as explained in Table 1 and in the land area regression explanation above; β_i^0 is the regression intercept coefficient, and β_i^{wa}, β_i^p, and β_i^c are the regression coefficients for the water allocation, price and climate explanatory variables.

Revenue or (gross value of irrigated production) regressions are as in equation 17 where Φ_i^0 is the regression intercept coefficient, and Φ_i^{wa}, Φ_i^p, and Φ_i^c are the regression coefficients for the predicted land area, price and climate explanatory variables. Rather than allocation as a dependent variable we found that predicted land area ($PA_{i,j,y}$) from equation 15 provided superior explanatory power.

$$R_{i,j,y} = \phi_i^0 + \phi_i^{wa} * PA_{i,j,y} + \phi_i^p * p_{i,y} + \phi_i^c * c_{i,j,y} + \phi_i^n * n_j + e_{i,j,y} \cdots\cdots(17)$$

Table 1 – Regression dependent and explanatory variables

Name	Description	Units
	Dependent variables	
$A_{i,j,y}$	Logits of land area (see equation 4)	Logits
$W_{i,j,y}$	Irrigation application rate per hectare	ML/Ha
$R_{i,j,y}$	Revenues from irrigated agricultural production	AU$*$10^6$
	Explanatory variables	
$wa_{j,y}$	Regional irrigation water allocation measured as the reported percentage of full regional entitlement	%
$p_{i,y}$	Commodity price	$/tonne
$c_{i,j,y}$	Variable measuring climatic influence on crop irrigation requirement calculated as crop potential evapo-transpiration	Mm

	less crop available rainfall	
n_j	Binary indicator variable, equals one for regions in the Darling and Lachlan catchments in the north of the basin and zero for other regions.	Binary
$PA_{i,j,y}$	Predicted land areas – result of regressions in equation 4 – used as an explanatory variable in revenue regressions.	Ha

Source: Connor et al., 2012a

As described in more detail in Connor et al. (2012a) regression had varying degrees of explanatory power with generally good results for GVIAP regression. Overall, allocations were the most consistently significant determinant of area in production, crop potential ET less crop available rainfall were the most consistently significant determinant of irrigation application rate, and predicted area was the most consistently significant determinant of GVIAP variation.

Irrigation adaptation and economic impact simulation involved determination of water supply with the hydrology sub-model. This involved calculating flow, storages and allocations each month. The allocations were then summed for a year and aggregated from the 58 hydrology catchments to the 17 economic regions shown in Figure 3. Then, once per year, equations 15 to 17, the economics sub-model, is applied in simulation mode to determine the area, water use and gross value of each commodity in each region. Variables rainfall, ET and water supply available vary each year as determined by the hydrology model, other variables (commodity prices) are held constant at the mean level in the data used to determine the regression coefficients.

The hydrology model is configured to simulate monthly flows and allocations in 114 year sequences, and so the economics model results in 114 year sequences of area, water use and gross value.

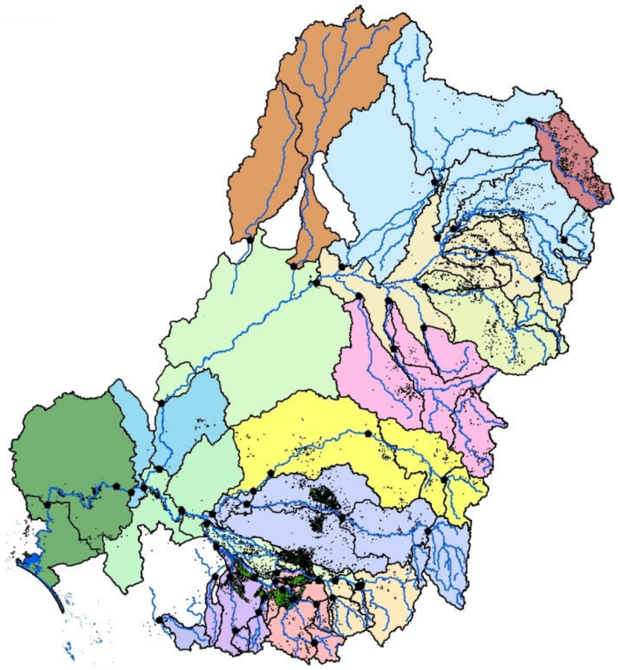

Figure 3 . The Murray-Darling Basin and the 17 regions used in the economics sub-model.

The crops for which the simulations are performed are rice, cereals, cotton, dairy, meat, grapes, tree crops (fruit and nuts), and vegetables. T

4 Results – calibration simulations

Elsewhere in this conference we discuss the use of this model to explore impacts of changes to water availability and options for planning. Here we present simulations of flow, diversion, area and gross value of production obtained from the hydrology and economics sub-models in calibration – that is, matching the simulated results to observed data.

Figure 4 and Figure 5 show the simulated monthly flows at Euston and Bourke. For comparison the measured monthly flows are also shown, and the period shown in each graph is only that of the measured record, not the full 114 year simulation period.

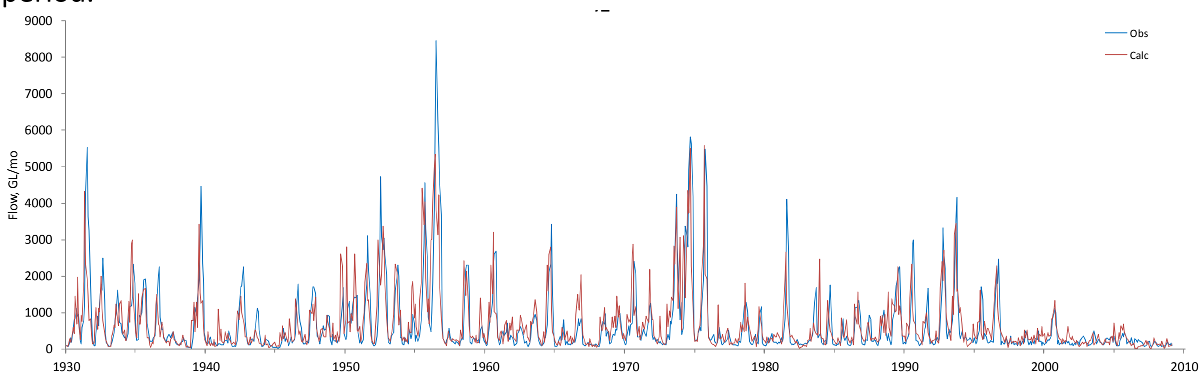

Figure 4. Observed and calculated flows in the Murray River at Euston.

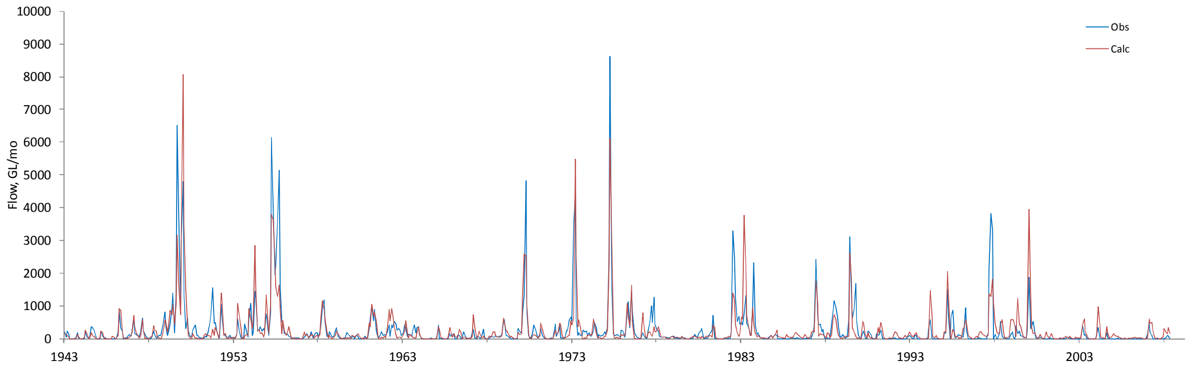

Figure 5. Observed and calculated flows in the Darling River at Bourke.

Figure 6 shows the simulated diversions for catchments aggregated to the catchments reported by the MDBA (2011) and, for comparison, shows the diversions reported for those catchments. (The reported diversions are in some catchments based on measured diversions and in some cases on estimates). The comparisons are reasonable except in the Condamine-Balonne and other Queensland catchments: there is reason to question the reported quantities in the Queensland regions, as in some years the apparent diversions are greater than the observed volume of water available for diversion.

The areas simulated by the economic sub-model are shown in Figure 7 along with the values reported in ABS (2010), and the gross values of irrigated agricultural production are shown in Figure 8 also with the values reported in ABS (2010). These results were obtained when the actual prices of commodities were used; the actual prices varied considerably from year to year (Kirby et al., 2012). For exploring policy and planning issues, it is more useful to hold prices constant, and the result of such a simulation is shown in Figure 9.

Figure 6. Observed and calculated diversions for the main regions in the Murray-Darling Basin. The Y axes are diversions in GL/year, and the X axes are years.

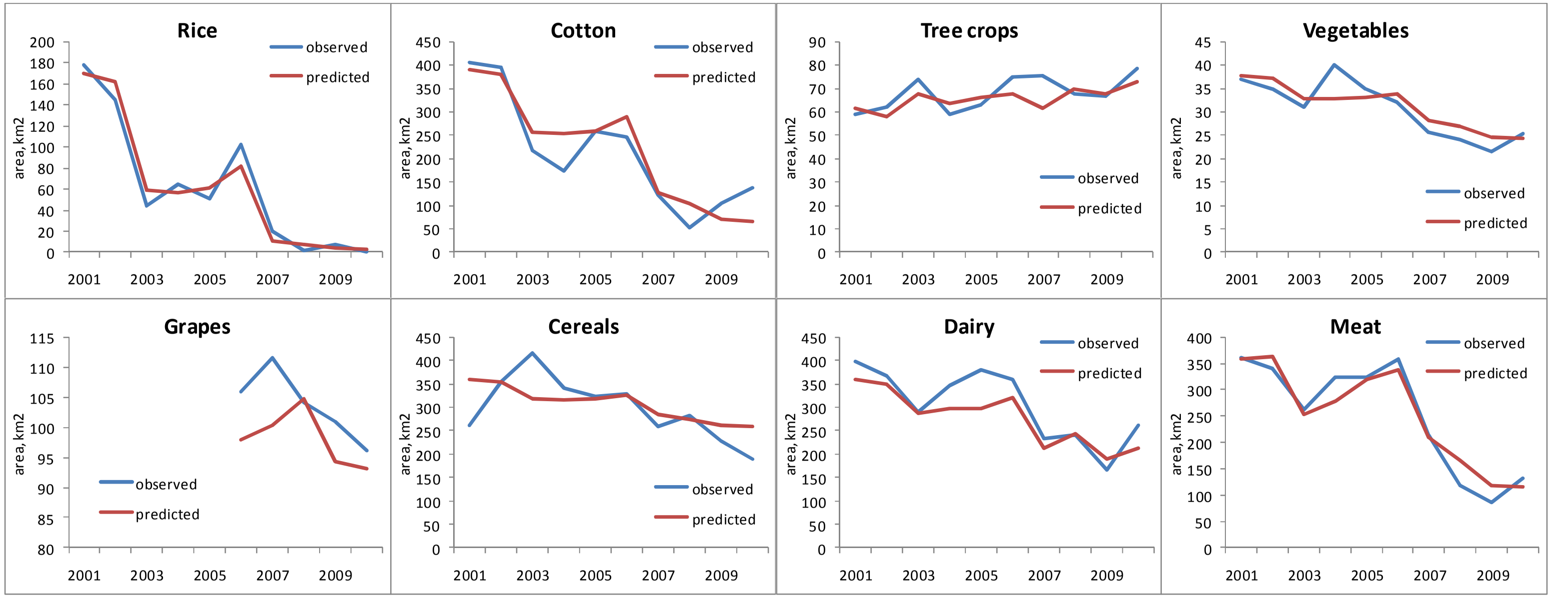

Figure 7. Observed and calculated areas for the main crops in the Murray-Darling Basin. The Y axes are areas in km^2.

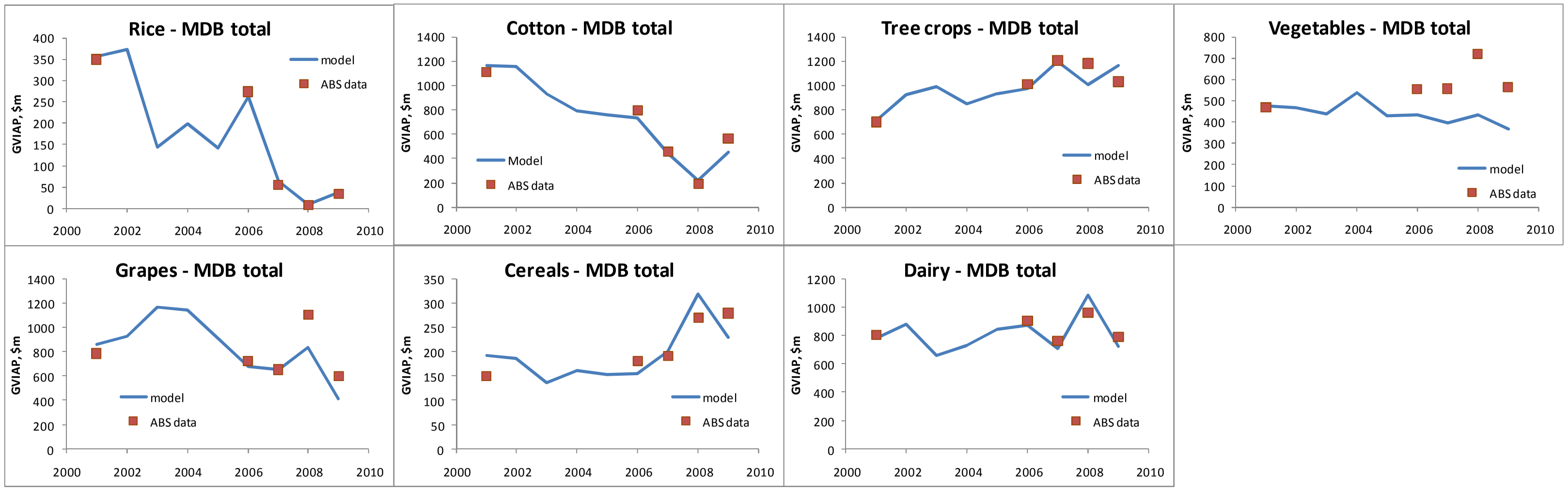

Figure 8. Observed and calculated gross value of irrigated agricultural production (GVIAP) for the main crops in the Murray-Darling Basin. The Y axes are GVIAP in $m.

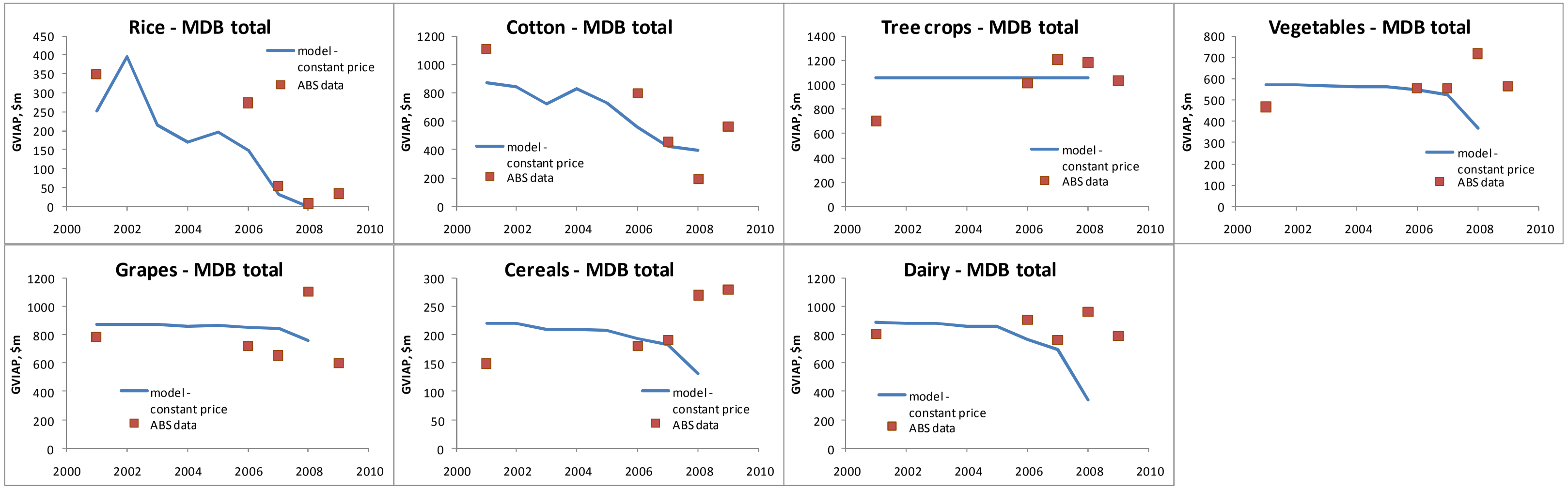

Figure 9. Observed and calculated gross value of irrigated agricultural production (GVIAP) for the main crops in the Murray-Darling Basin, using assumed constant prices. The Y axes are GVIAP in $m.

5 Discussion and conclusions

The integrated hydrology – economic model simulates flow, diversion, irrigation application rate, irrigated area and gross value of production for the Murray Darling Basin over 114 year sequences of climate, based on the historic climate of 1895 – 2009 and for climate change. The simulations match the observed values of the key hydrologic and irrigation and economic outcomes. Some metrics not described here, such as water storage and losses of water from the rivers to the environment are also calculated and can be reported as desired.

The basin water balance component is currently the only comprehensive hydrology model of the Murray-Darling Basin that is based on a single conceptual framework and is contained within a single program. The only other all of Basin water balance model is the somewhat more sophisticated and accurate, model resulting from linking many unlike river operations models used in the Murray Darling Basin Sustainable Yields Project (CSIRO, 2008). However, this involves complex linking of many river operations models, long run times and economics is done with model in a post processing as opposed to fully integrated mode.

The integrated hydrology – economic model is the only model representing the dynamics of inflows, water supply, irrigation sector adjustment, and economic impacts for the basin. Despite the comprehensive spatial and temporal coverage, based on statistically validated and integrated hydrology and economics, the model is implemented in a way that runs very fast, in something over 1 second for a 114 year simulation.

The model has the capability to explore issues such as:

- climate change impacts, by suitably varying the input climate data;
- limits to water availability imposed by policy, such as the proposed sustainable diversion limits;
- the management of water transferred to the environment; and,
- the trading of environmental water (which requires a modest extension to the model as here described). the impacts of policy changes (water availability changes) or environmental water management on the security profiles of irrigation for the various regions and crops in the basin.

From a hydrologic perspective, the model has limitations. It is a monthly model, and thus cannot simulate daily events such as floods or other flow peaks. It is not an operational model suitable for the detailed management of flows. It is also not an especially suitable model for assessing environmental flows, though it might be used to give pointers to some gross effects.

Other river models (such as those linked into an overall basin model by CSIRO, 2008) should be used to explore the details of river management. We think a sensible arrangement is to use our simple model for rapidly exploring a wide range of policy impacts and options, and then using the more comprehensive river models to assess the detailed management required to implement useful policy options.

The econometric simulation methodology used in the economics components has some advantages over competing mathematical programming models of the basin irrigation sector. Mainly greater ability to be calibrated to observed outcomes and to isolate confounding price, and weather impacts from impacts of changes in allocation. Still it is estimated with a limited time series and cross section of regional aggregate data. More accurate estimation would like be possible with additional years and less disaggregate data that may soon become available through ABARE surveys.

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