# Integrating Biophysical and Economic Data to Support Water Allocations in the Murray Basin, Australia

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**Abstract:** Economic analysis of policies aimed at sustainable use and management of natural resources requires information about the biophysical and economic aspects of alternative options. Since these biophysical and economic aspects are inter-related and inter-dependent, it is essential that these data are integrated. However, existing biophysical and economic monitoring networks and studies tend to observe, collect and report biophysical and economic data at different scales. Consequently, much of these data are spatially incompatible and require significant effort in manipulating and scaling for a comprehensive economic analysis. In the current study, the key steps in overcoming spatial incompatibilities between biophysical and economic data in an integrated model to examine the impacts of climate change scenarios and water resources management policies in the Murray Basin of Australia are presented.

***Keywords***: Water allocation; land use; biophysical-economic modelling; spatial incompatibilities.

## 1. INTRODUCTION

Water scarcity, overallocation and environmental degradation are major water resources management problems in many irrigation areas of Australia. The Murray-Darling Basin (MDB) which is the major irrigation area of Australia, has faced overallocation compounded by severe drought. Further, there is the potential for climate change to exacerbate these impacts across the MDB.

Integrated biophysical and economic modelling is becoming a common approach for assessing policy scenarios across watersheds or other scales (Jakeman and Letcher, 2003). The approach has gained momentum with the introduction of integrated catchment management policies (MDBMC, 2001) and legal requirements for water resources management in the MDB. Attempting to carry out an integrated assessment is a major challenge because the approach requires establishing links between different disciplines and integrating the various discipline specific methodological approaches. Further, the existing biophysical and economic monitoring networks and studies tend to observe, collect and report biophysical (such as, rainfall, runoff, water available, crop yield) and economic (such as, cost of inputs of agricultural products and prices of commodities) data at different scales and time periods. This problem of 'incompatible' spatial data has been encountered in several fields of study, such as by Gotway and Young (2002).

Our aim in this paper is to consider the problem of constructing an integrated biophysical and economic model to aid in the assessment of policy questions such as water overallocation in the MDB. We describe the key biophysical and economic data needed for an economic analysis and the challenges and difficulties faced in integrating them for a baseline description. We identify the steps taken in overcoming these difficulties and building an integrated biophysical and economic model for scenario and policy analyses. A brief discussion of the nature of the conclusions that result and the key benefits from the approach completes the paper.

## 2. STUDY AREA – THE MURRAY-DARLING BASIN

The MDB is Australia's most significant river system. The MDB accounts for around 41% of the Australia's gross value of agricultural production and around 70% of all water used for agriculture in Australia is used in the MDB (ABS, 1997). Water scarcity has become a significant issue in recent years when water available for irrigation diversion has been significantly lower than the licensed entitlements in most regulated river valleys. Scarcity has been driven by significant expansion in the area of irrigated agricultural activities over the last 20 years (CSIRO, 2008) compounded by reduced rainfall and water allocations due to drought and climate change. Increased water scarcity has resulted in greater competition between irrigation and non-irrigation water users (Qureshi et al., 2010). In this environment linking biophysical and economic models is necessary to assess relevant scenarios and policies and to help resource managers and policy makers in achieving sustainable water resource management objectives in the MDB.

## 3. METHODOLOGY FOR CONSTRUCTING APPROPRIATE DATA SETS

The best starting point in any overall modelling strategy is generating a baseline description of the particular system being studied at a scale relevant to the policy questions to be addressed. The policy questions for which input is required influence the type of model to be used, the range of data collected and the analyses performed. The end use of the model also raises 'scale' issues, including system boundaries and temporal limits, and necessarily is limited by the problems caused by mismatches in the temporal and spatial scales at which natural resources, institutions and human communities operate (Turner, 2000).

The choice of an appropriate scale for the study is considered important because mechanisms vital to the spatial dynamics of a process at one scale may be unimportant or inappropriate to another. Further, relationships between variables at one scale might be obscured or distorted when viewed from another scale. Nevertheless, spatial aggregation is necessary to create meaningful units for analysis (Gotway and Young, 2002). The data and information needed include the area of land use by each agricultural activity (crop) across regions, regional water allocation and its quality (salinity), crop evapotranspiration and water requirements, crop yield, contribution of rainfall and irrigation water, irrigation efficiency, costs of all crop production inputs, and prices of agricultural products or commodities.

In this study, we consider the sub-catchment level be the most appropriate scale. This is because most sub-catchments are small enough to limit variation in climate and crop viability and have relatively uniform rules governing entitlements and allocations but are large enough to minimise the total data required and for aggregated analysis of economic impacts. The sub-catchment scale analysis is also the most useful for resource management policy analysis, including impact of water reallocation, trading and infrastructure development. For the purposes of this model we focus on the southern MDB. The model includes the eight major agricultural activities undertaken in irrigated areas across the region, namely: cereals, rice, pasture for dairy, beef and sheep (pDairy), vegetables (represented by potatoes), citrus fruits (cFruits), deciduous fruits (dFruits), stone fruits (sFruits) and vines (grapes). Dairy represents areas of the all the pasture related activities including sheep and beef.  The detail of integrating and utilising land and water data for each catchment is provided by Qureshi et al. (working paper) and a summary is given in the following sections.

### 3.1 Mapping catchments and water availability

Water use data are required for both past use and to explore future contingencies such as climate change. The CSIRO carried out a detailed basin scale assessment of the anticipated impacts of climate change on the availability and use of water resources in the MDB (CSIRO Sustainable Yield (SY) project, particularly CSIRO, 2008). Four scenarios were developed for analysis by CSIRO:

a) base case scenario of historical development and historical climate change;
b) historical development and future climate change dry scenario;
c) historical development and future climate change median scenario; and
d) historical development and future climate change wet scenario.

The simulated runoff and consequent water diversion data accounted for existing water sharing plans and rules and water available for irrigation (CSIRO, 2008). The CSIRO SY study reported average water diversion data for each sub-catchment. However, these catchments were not aligned with the natural resources management (NRM) regions or ABS SLA or SD (Statistical Division) levels. For example, in the SY project, the Murray catchment was considered as a single catchment which crossed over three states; New South Wales (NSW), Victoria (Vic) and South Australia (SA). Given the differences in water entitlements and allocation rules and management regimes across the jurisdictions, it was essential to split the Murray catchment into three separate sub-catchments. Alignment of these catchments with NRM regions and for ABS SLAs was also critical for linking biophysical and economic information and for scenario and policy analysis. This process resulted into 12 catchments, eight in Vic (Goulburn & Broken - GB, Campaspe - Campas, Loddon & Avoca - LodAvo, Murray Riverina Vic - MRivVic, Mallee Vic - MalleeVic, Upper Murray and Kiewa - UMurrayK, Ovens and Wimmera & Avon - WimAvon),, two in NSW (Murrumbidgee – Murrum and Murray Riverina NSW - MRivNSW), and one in South Australia (Lower Murray SA -LMurraySA).

Simulated water diversion data files (including for irrigation, urban, domestic and other uses from different river reaches and conveyance losses) were obtained and adjusted to these sub-catchments for four climate scenarios from CSIRO Sustainable Yield research project for 111 years (personal communication, Mainuddin 2008). The data accounted for uncertainty in future rainfall, runoff and available water for diversion. The data were aggregated or distributed to each study catchment depending on the location of the diversion point.

To represent the variability in supply in each of the CSIRO scenarios, the data was broken into four distinct categories or, states of nature. A very dry state of nature represents the 12% of driest years, a dry state of nature represents the next 38% of dry years, a wet state of nature represents the next 38% of relative wet years, and a very wet state of nature represents the 12% of the wettest years in the 111 year simulation. This gave a final set of 16 different potential stats of nature according to climate change and long-run variability in rainfall. Thus, the level of allocation associated with each state of nature is dependent on the base case and each of three climate change scenarios. For example, low water allocation years become more common as the climate moves from no change to severe change. The estimated impacts of climate change on irrigation water allocations and the associated reliability for four scenarios are presented in Qureshi et al. (2010). For dry and medium scenarios across the basin there was an overall reduction in allocations by 23% and 4%, respectively.

### 3.2 Agricultural activities across regions

Land use data were obtained from the Australian Bureau of Statistics (ABS) agricultural statistics. Data were collected at Statistical Local Area (or SLA) level and were disaggregated across watershed (catchment) boundaries in order to estimate the agricultural activity occurring within the reporting catchments. The Bureau of Rural Sciences (BRS) land use grid (BRS, 2004) was used to determine what proportion of a broad land use category occurring in a given SLA fell into a given reporting catchment. A schematic representation of the steps involved in land use data scaling in southern connected MDB is shown in Qureshi et al. (2010).

Agricultural commodities in the ABS AgStats data were categorised according to the SPREAD land use categories represented in the BRS land use grid.[1] For example, the ABS category 'wheat' was mapped to the SPREAD class 'cereals excluding rice'; while 'apricot' was mapped to the 'stone fruit' class. For specific tree crops, ABS AgStats reports tree numbers rather than hectares at the commodity level (e.g. number of orange trees, number of lemon trees).[2] For the above disaggregation process, tree numbers were converted to hectares based on the orchard tree density estimates used in the 2001 National Land and Water Resources Audit. However, the ABS does report some aggregate areal statistics for tree crops (e.g. 'total citrus – area' which was used to cross check commodity level tree crop areas derived from tree numbers. ABS AgStats does not report livestock areas but rather numbers of dairy cattle, beef cattle and sheep per SLA. Also, while the land use grid spatially depicts pasture areas, it does not specify livestock types. To address the issue of dairy, beef and sheep pasture areas, the ABS areal statistic 'total grazing land' was disaggregated within that SLA across dairy cattle, beef cattle and sheep pasture based on the dry sheep equivalent proportions of livestock numbers reported for the SLA.[3] These derived SLA based livestock areas were then distributed to catchments as described above for the crop and horticulture commodities.

The aforementioned method for re-scaling SLA level agricultural commodity statistics to catchments resulted in total area of a crop but does not distinguish which crops are irrigated. The ABS does not comprehensively report irrigation area by commodity type at the SLA level. Instead, it reports irrigation areas within aggregated land use classes at the larger scale NRM boundaries; potentially to avoid individual establishment boundaries being identified. Again, a classification and spatial disaggregation method was used to derive the areas of irrigated commodities by catchment. The NRM level ABS data was used to determine what proportion of a given aggregate land use class was irrigated in a given NRM region. A summary of irrigated land use area (hectares) by each crop across the catchments is provided in Qureshi et al. (2010).

### 3.3 Scaling land and water use

There was a mismatch between historical land use and simulated water diverted or historical water allocation proportions in most catchments. Figure 1 shows land and water use proportions based on ABS 2005-06 estimated land use, CSIRO's climate base case scenario expected mean water diversion, and Murray-Darling Basin Authority (MDBA) estimated 2005-06 water use in the MDB. The mismatch between land and water use was caused by a mismatch in irrigated land use data and water diversions and allocations. For example, in Murrumbidgee, the actual land use was 36% of the total irrigated land use in the basin but according to the climate base case scenario, its expected mean water diversion was 26%. On the contrary, for MRivNSW, the actual land use based on ABS estimates was less than 15% but based on the climate base scenario water allocation it was about 20%. This could be due to an under/overestimation of land use or water diversion data calculated

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[1] SPREAD (Spatial REallocation of Aggregated Data) procedure used by BRS http://adl.brs.gov.au/mapserv/landuse/index.cfm?fa=app.nationalMappingTechnicalSpecifications

[2] AgStats ABS http://abs.gov.au/AUSSTATS/abs

[3] The DSE rates used to standardise livestock to reflect differential pasture stocking rates are as follows. Dairy cattle = 10 DSE, Beef cattle = 8 DSE and Sheep = 1.5 DSE.

for each catchment (i.e. inclusion and exclusion of more spatial area in Murrumbidgee and MRivNSW, respectively) or due to not accounting for groundwater use, especially in Murrumbidgee where groundwater proportion is more than 10% of total water use. A comparison of the proportions of land use data for year 2005-06 with the MDBA estimated historical water use data also found mismatches across most of the catchments (shown in Figure 1).

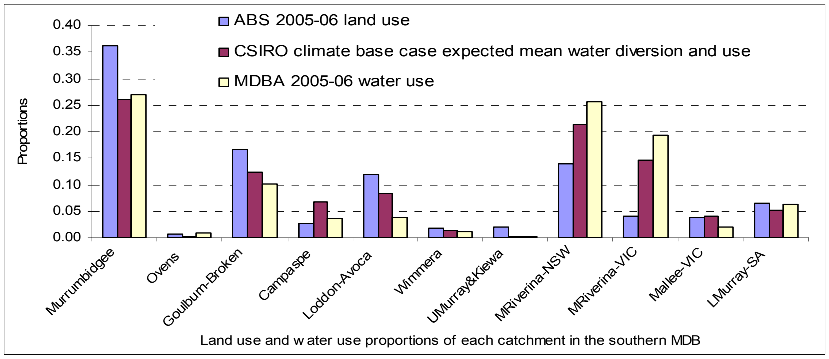


Figure 1. Catchment land and water use proportions – 8 major catchments

Alignment of the land use data with regional the base case or initial water allocations data was critical for a number of reasons, including: understanding irrigation water usage by crops and its economic value across the catchments; the impact of reduction in water allocations due to drought and climate change; and for assessing cost to irrigators and regions of acquiring water for environmental flows. Accurate data can help government in bringing any policy change such as infrastructure investment, structural adjustment packages or developing and implementing new water sharing plans.

Assuming water use can reflect land use in each catchment, we obtained historical water allocations data (i.e. base water entitlements multiplied by the largest announced percentage allocation in the season) of the last 11 years to cross check and identify and remove any inconsistency in each catchment's water allocation data across the MDB. We used the proportions of water used to adjust the irrigated crop land use in each catchment (by arbitrarily increasing and decreasing land use area in respective catchments) for better representation of land use activities for each catchment across the basin.

### 3.4 Water salinity data acquisition

Agricultural productivity of water is impacted by its salt content which in turn is impacted by climate change. CSIRO sustainable study did not provide any information and data about water salinity. We used MDB MSM-BIGMOD to provide information regarding the climate change impact and reduced flows on River Murray salinity across catchments in the southern MDB.[4] MSM-BIGMOD simulates the River Murray system by dividing the river into a number of river reaches. The salinity of the inlet channel is dependent on the history of flow. The model maintains a salt balance even when a reach ceases to flow and the dead storage evaporates (MDBC, 1999). Estimating weekly/monthly/annual river salinity under the different climatic conditions is in Elmahdi *et al.*, (2008) and a summary of salinity (EC) data of different states of nature for different catchments is presented in Qureshi et al. (2010). These salinity values for each scenario along with the concentration levels have been used as inputs into the economic model to estimate the impact of salinity on crop water use requirements to maintain per hectare productivity and associated costs across sub-catchments in the Southern MDB.

[4] MSM-Bigmod- http://www2.mdbc.gov.au/livingmurray/mfat/popups/bigmod.htm

### 3.5 Estimation of actual crop evapotranspiration, effective rainfall and irrigation requirements

We have estimated actual crop evapotranspiration ($ET_a$), effective rainfall and net irrigation requirements of different crops grown in the southern MDB using a soil water balance simulation model. The model is based on an FAO study (Allen et al., 1998), and is similar to that of the CROPWAT model developed by FAO. The model has been used previously to estimate $ET_a$ and irrigation water requirements for a range of crops grown in the MDB (Qureshi et al., 2007; Mainuddin and Kirby, 2009). We have used spatial average historical and future climate scenario rainfall and potential evapotranspiration (PET) data available from the MDB SY study (Chiew et al., 2008). Maximum crop water requirements (in millimetres) for eight major agricultural activities are estimated for each scenario and state of nature to use in the analysis. The detail of the data including ET and effective rainfall under each scenario and state of nature and potential maximum crop yield is given in Qureshi et al. (2010).

### 3.6 Economic data collection procedure

The key economic data are commodity and input prices. To deal with temporal variation in commodity prices, historical prices of individual commodities were obtained from ABARE and ABS and other publications (ABARE, 2007; ABS, 2006) as well as from state agricultural departments. Water prices relate to the security of water applied. Irrigators of horticulture generally rely on more reliable high security water entitlements. In contrast, annual activities generally rely on general security water entitlements or purchase water in a temporary market and incur cost on each unit of water usage. However, for simplicity in the current analysis no distinction is made between low security and high security water entitlements and an average water pumping charge of $20/ML is used for each activity.

## 4. INTEGRATED MODEL – CONSTRUCTION, VALIDITY, RESULTS AND DISCUSSION

### 4.1 Integrated biophysical and economic model

An integrated biophysical and economic optimisation model has been developed based on the information described in the previous sections. All the hydrologic, agronomic and economic data were linked in GAMS (General Algebraic Modelling System) (Brooke *et al*. 2004). The objective of the model is to maximise profit after accounting for establishment costs, fixed costs, and operating/variable costs subject to land and water constraints. A non linear programming structure is used to deal with the crop water, salinity, and crop production functions. Optimisation proceeds via a two-step process. The first stage of the model determines the level of investment and allocation of land to individual annual and perennial agricultural activities and irrigation systems without knowing how much water is allocated. The second stage determines the optimal area for irrigation for each activity in each region. The model is described in detail in Qureshi et al. (2010).

### 4.2 Model validation

The different sources and scales of data sources (e.g. spatially explicit Basin-wide cropping data were available only for 2000-01 and 2005-06) it is only possible to compare the validity of the model crop allocation and economic outcomes in these two years (only 2005-06 is reported for brevity below). Modelled land use was compared to southern MDB land and crop water use for 2005-06. The results, shown in Figure 2, indicate that by taking the steps (mentioned above) and calibrating landuse data to actual water use data of 2005-06, conditions are reproduced with reasonable accuracy, except the area of cereals and pasture. The model estimated about half of the land used by cereals and about 15% more than the land used by pasture related activities. In cereals case, this could be due to the possibility of cereals using rainfall as the primary water source with only limited supplementary irrigation and a consequent under-estimate of area within the model. Also, different farmers have differences in their farming objectives (including risk management) and may choose strategies other than pure profit maximisation.

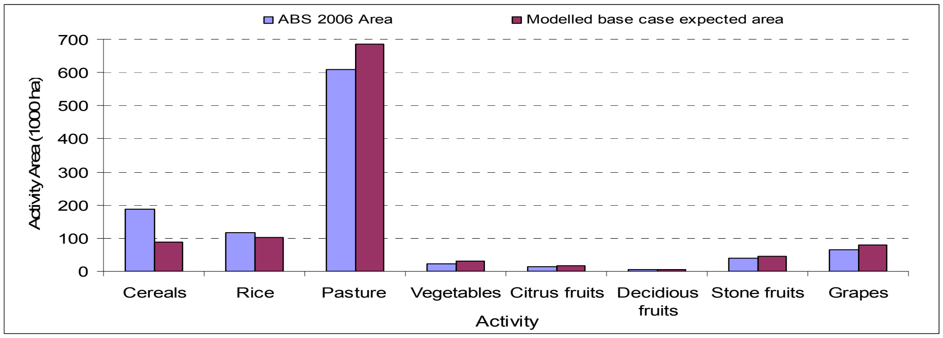


Figure 2. Comparison of actual and modelled land uses by activity

Model validity can also be assessed by comparing modelled water allocations against actual allocations. For example, a key consideration in the model is future water availability under climate change at the study catchment scale. For the purpose of validity checking we identified equivalent annual data to two of the policy scenarios developed earlier: a base case scenario representing mean allocation of water in the last decade; and a single year of data equivalent to the climate dry, very dry year scenario. We found that the model water use was similar to the actual water use for the relevant scenarios. As a point of interest, the climate dry scenario represents a future with approximately 12% of water allocations being delivered (2246 GL), a reasonable correspondence to allocations (2700 GL) in a very dry year of 2007-08.

Checking the validity of the economic estimates from the model is difficult because no other study has carried out analysis at a similar scale. The ABS has however estimated irrigated areas and associated gross value at NRM region and statistical division level for 2005-06 which are effectively an aggregated set of the sub-catchments used in the model. Some NRM catchments may have more than one study/modelled catchments but others are smaller. For example, Mallee catchment has areas of Mallee (Vic) and Loddon Avoca NRM regions. Irrigated areas and associated gross values of NRM catchments and estimated gross values of the model's climate base case scenario are provided in Qureshi et al. (2010) indicating that the model behaves reasonably well, especially when impacts of water reduction across the whole basin is desirable.

### 4.3 Discussion of preliminary model results

The model has been constructed with the objective of examining the economic impacts of a range of specific impacts and policy responses such as the economic implications of future climate scenarios on the irrigation values. A particular area of interest is the economic impact of water markets and trading (Qureshi et al., 2010). To illustrate the nature of the results a preliminary set of aggregate gross values for the four climate scenarios and four states of nature described earlier in the paper are shown in Figure 7. These estimates allow for intra regional trade but no trade across regions. The results clearly indicate the degree of variability in gross value under different climate scenarios and the importance of this type of modelling for policy analysis. The reduction in economic returns is obvious, especially in very dry years. Further analysis (not shown in Figure 7) shows that interregional water markets markedly reduce the economic cost of climate change, even in very dry years under the very dry climate scenario.

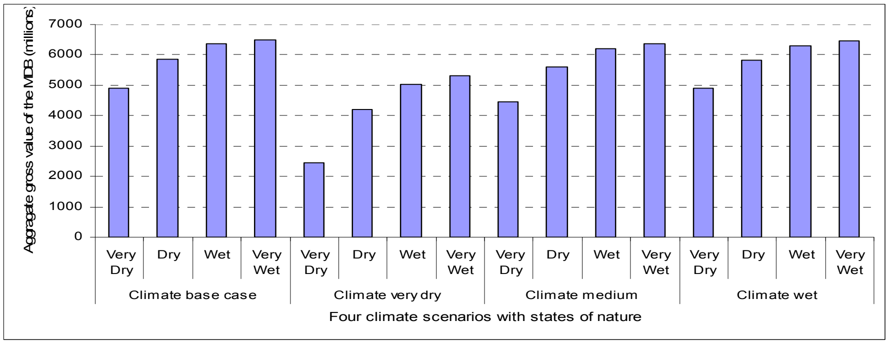


Figure 7. Southern MDB aggregate gross value under alternate climate futures

## 5. CONCLUSIONS

Sustainable use and allocation of water resources requires understanding the biophysical (environmental) and economic linkages and the economic implications of future climate scenarios and potential policy implications. This paper discusses the difficulties and challenges environmental-economic modellers face in integrating biophysical and economic aspects for economic analyses. The model described in this paper has been constructed based on these objectives to inform the consideration of policy mechanisms in the southern MDB in Australia. Several key steps are necessary to address data incompatibility and scaling issues and in calibrating the model. For example, land use data had to be aligned with water allocation data in order to describe the economic returns from irrigation water use across catchments, examine the impact of reduced water allocations, and for assessing cost of reallocating water to environmental flows.

Accurate assessment of a region's allocation can help governments in evaluating climate impacts, developing and implementing policy such as regional water sharing plans. The preliminary results presented in this paper suggest the usefulness of integrated environmental and economic modelling for such policy. The inclusion of a two-step estimation procedure was an important advance that allowed a significant improvement in model performance in describing relatively short run responses to climate variability. Finally, the inclusion of integrated crop water use and irrigation water salinity components substantially enhance the accuracy of economic return estimates from the model, especially under hotter and dryer climate scenarios.

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