Overview of Project Methods

A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project

September 2007

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Background

Australia is the driest inhabited continent on Earth, and in many parts of the country – including the Murray-Darling Basin – water resources for rural and urban use is comparatively scarce. Into the future, climate change and other risks (including catchment development) are likely to exacerbate this situation and hence improved water resource data, understanding and planning and management are of high priority for Australian communities, industries and governments.

On 7 November, 2006, the Prime Minister of Australia met with the First Ministers of Victoria, New South Wales, South Australia and Queensland at a water summit focussed primarily on the future of the Murray-Darling Basin (MDB). As an outcome of the Summit on the Southern Murray-Darling Basin, a joint communiqué called for "CSIRO to report progressively by the end of 2007 on sustainable yields of surface and groundwater systems within the MDB, including an examination of assumptions about sustainable yield in light of changes in climate and other issues."

The subsequent terms of reference for what became the Murray-Darling Basin Sustainable Yields Project specifically asked CSIRO to

- estimate current and likely future water availability in each catchment and aquifer in the MDB considering:
  - climate change and other risks,
  - surface-groundwater interactions, and
- compare the estimated current and future water availability to that required to meet the current levels of extractive use.

The MDB Sustainable Yields Project is reporting progressively on each of 18 contiguous regions that comprise the entire MDB. These regions are primarily the drainage basins of the Murray and the Darling rivers – Australia's longest inland rivers, and their tributaries. The Darling flows southwards from southern Queensland into New South Wales west of the Great Dividing Range into the Murray River in southern New South Wales. At the South Australian border the Murray turns south-westerly eventually winding to the mouth below the Lower Lakes and the Coorong. The regions for which the project assessments are being undertaken and reported are the Paroo, Warrego, Condamine-Balonne, Moonie, Border Rivers, Gwydir, Namoi, Macquarie-Castlereagh, Barwon-Darling, Lachlan, Murrumbidgee, Murray, Ovens, Goulburn-Broken, Campaspe, Loddon-Avoca, Wimmera and Eastern Mount Lofty Ranges (see map).

> Travelling irrigator, Cowl Cowl Station, near Hillston, NSW.

Acknowledgments
Prepared by CSIRO for the Australian Government under the Raising National Water Standards Program of the National Water Commission. Important aspects of the work were undertaken by Sinclair Knight Merz; Resource, Environmental Management Pty Ltd; Department of Water and Energy (New South Wales); Department of Natural Resources and Water (Queensland); Murray-Darling Basin Commission; Department of Water Land and Biodiversity Conservation (South Australia); Bureau of Rural Sciences; Salient Solutions Australia Pty Ltd; eWater Cooperative Research Centre; University of Melbourne; Webb, McKeown and Associates Pty Ltd; and several individual sub-contractors.

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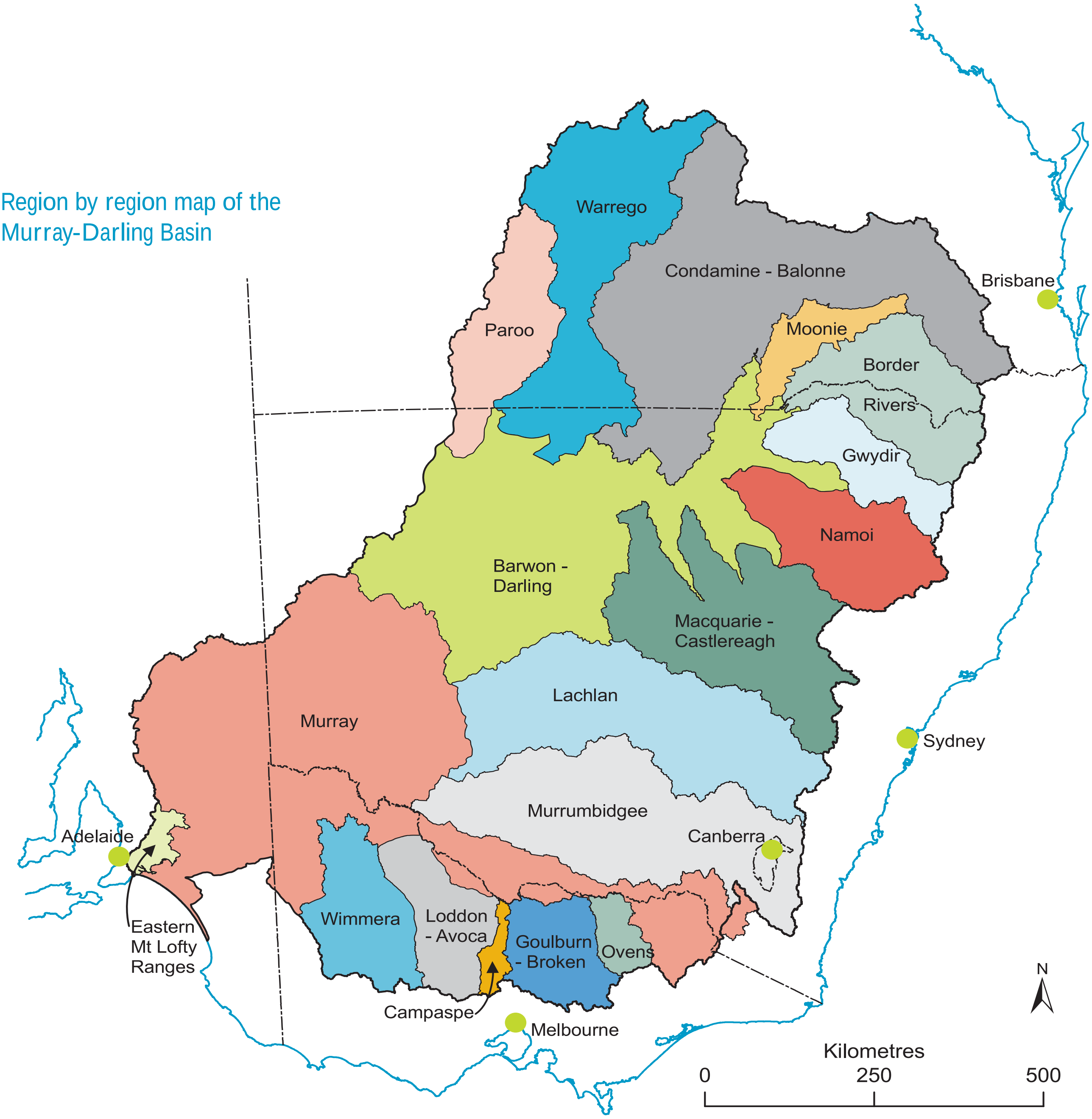
Region by region map of the Murray-Darling Basin



The MDB Sustainable Yields Project will be the most comprehensive Basin-wide assessment of water availability undertaken to-date. For the first time:

- daily rainfall-runoff modelling has been undertaken at high spatial resolution for a range of climate change and development scenarios in a consistent manner for the entire Basin,
- the hydrologic subcatchments required for detailed modelling have been precisely defined across the entire Basin,
- the hydrologic implications for water users and the environment by 2030 of the latest Intergovernmental Panel on Climate Change climate projections, the likely increases in farm dams and commercial forestry plantations and the expected increases in groundwater extraction have been assessed in detail (using all existing river system and groundwater models as well as new models developed within the project),
- river system modelling has included full consideration of the downstream implications of upstream changes between multiple models and between different States, and quantification of the volumes of surface-groundwater exchange, and
- detailed analyses of monthly water balances for the last ten to twenty years have been undertaken using available streamflow and diversion data together with additional modelling including estimates of wetland evapotranspiration and irrigation water use based on remote sensing imagery (to provide an independent cross-check on the performance of river system models).

The successful completion of these outcomes, among many others, relies heavily on a focussed collaborative and team-oriented approach between CSIRO, State government natural resource management agencies, the Murray-Darling Basin Commission, the Bureau of Rural Sciences, and leading consulting firms – each bringing their specialist knowledge and expertise on the Murray-Darling Basin to the project.

> Barmah Forest billabong, Vic.

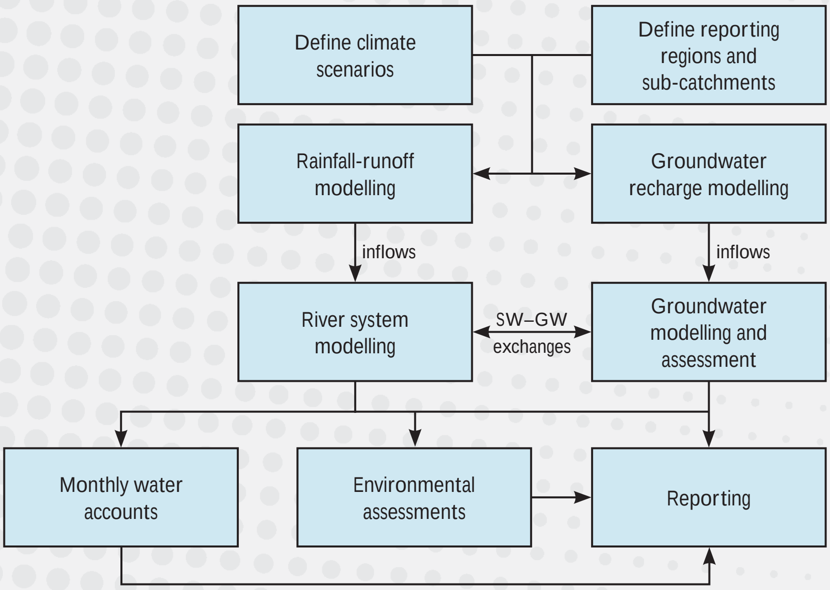
Project framework

> Peel River, NSW.

The framework for the project is shown in the diagram below. The first steps in the sequence of the project are definition of the reporting regions and their composite subcatchments, and definition of the climate and development scenarios to be assessed (including generation of the time series of climate data that describe these scenarios). The second steps are rainfall-runoff modelling and rainfall-recharge modelling for which the inputs are the climate data for the different scenarios. Catchment development scenarios for farm dams and commercial forestry plantations are modifiers of the modelled runoff time series.

Next, the runoff implications are propagated through river system models and the recharge implications propagated through groundwater models – for the major groundwater resources – or considered in simpler assessments for minor groundwater resources. The connectivity of surface and groundwater is assessed and the actual volumes of surface-groundwater exchange under current and likely future groundwater extraction are quantified. Uncertainty levels of the river system models are then assessed based on monthly water accounting.

Framework for the Murray-Darling Basin Sustainable Yields Project



> Murray River downstream from Berri, SA.

The results of scenario outputs from the river system model are used to make limited hydrological assessments of ecological relevance to key environmental assets. Finally, the implications of the scenarios for water availability and water use under current water sharing arrangements are assessed, synthesised and reported.

> Murray River near Cobdogla, SA.

> Chaffey Dam, near Tamworth, NSW.

Climate and development scenarios

The project is assessing the following four scenarios of historical and future climate and current and future development, all of which are defined by daily time series of climate variables based on different scalings of the 1895–2006 climate:

1. historical climate and current development
2. recent climate and current development
3. future climate and current development
4. future climate and future development

These scenarios are described in some detail below with full details provided in [1].

Historical climate and current development

Historical climate and current development is the baseline against which other climate and development scenarios are compared. The historical daily rainfall time series data that are used are taken from the 'SILO Data Drill' of the Queensland Department of Natural Resources and Water which provides data for a 0.05^o x 0.05^o (5 km x 5 km) grid across the continent [2,3]. Areal potential evapotranspiration (PET) data are calculated from the SILO climate surface using Morton's wet environment evapotranspiration algorithms [4,5].

Current development for the rainfall-runoff modelling is the average of 1975 to 2005 land use and small farm dam conditions. Current development for the river system modelling is the dams, weirs and license entitlements in the latest State agency models, updated to 2005 levels of large farm dams. Current development for groundwater models is 2004–2005 levels of license entitlements. Surface–groundwater exchanges in the river and groundwater models represent an equilibrium condition for the above levels of surface and groundwater development.

Recent climate and current development

Recent climate and current development is used for assessing future water availability should the climate in the future prove to be similar to that of the last ten years. Climate data for 1997–2006 is used to generate stochastic replicates of 112-year daily climate sequences. The replicate which best produces a mean annual runoff value closest to the mean annual runoff for the period 1997–2006 is selected to define this scenario.

Future climate and current development

Future climate and current development is used to assess the range of likely climate conditions around the year 2030. Three global warming scenarios are analysed in 15 global climate models (GCM) to provide a spectrum of 45 climate variants for 2030. The scenario variants are derived from the latest modelling for the fourth assessment report of the Intergovernmental Panel on Climate Change [6].

Two types of uncertainties in climate change projections are therefore taken into account: uncertainty in global warming mainly due to projections of greenhouse gas emissions and global climate sensitivity to the projections; and uncertainty in GCM modelling of climate over the MDB. Results from each GCM are analysed separately to estimate the change per degree global warming in rainfall and other climate variables required to calculate PET. The change per degree global warming is then scaled by a high, medium and low global warming by 2030 relative to 1990 to obtain the changes in the climate variables for the high, medium and low global warming scenarios. The future climate and current development scenario considerations are therefore for 112-year rainfall and PET series for a greenhouse enhanced climate around 2030 relative to 1990 and not for a forecast climate at 2030.

The method used to obtain the future climate and current development scenario climate series also takes into account different changes in each of the four seasons as well as changes in the daily rainfall distribution. The consideration of changes in the daily rainfall distribution is important because many GCMs indicate that extreme rainfall in an enhanced greenhouse climate is likely to be more intense, even in some regions where projections indicate a decrease in mean seasonal or annual rainfall. As the high rainfall events generate large runoff, the use of traditional methods that assumes the entire rainfall distribution to change in the same way would lead to an underestimation of mean annual runoff in regions where there is an increase, and an overestimation of the decrease in mean annual runoff where there is a decrease [7].

All 45 future climate and current development scenario variants are used in rainfall-runoff modelling; however, three variants – a 'dry', a 'mid' (best estimate –median) and a 'wet' variant – are presented in more detail and are used in river and groundwater modelling.

Future climate and future development

Future climate and future development considers the 'dry, 'mid' and 'wet' climate variants from the future climate and current development scenario together with likely expansions in farm dams and commercial forestry plantations and the changes in groundwater extractions anticipated under existing groundwater plans.

Farm dams here refer only to dams with their own water supply catchment, not those that store water diverted from a nearby river, as the latter require licenses and are usually already included within existing river system models. A 2030 farm dam development scenario for the MDB has been developed by considering current distribution and policy controls and trends in farm dam expansion. The increase in farm dams in each subcatchment is estimated using simple regression models that consider current farm dam distribution, trends in farm dam [8] or population growth [9,10] and current policy controls [11–14]. Data on the current extent of farm dams is taken from the 2007 Geosciences Australia 'Man-made Hydrology' GIS coverage and from the 2006 VicMap 1:25,000 topographic GIS coverage. The former covers the eastern region of the Queensland MDB and the north-eastern and southern regions of the New South Wales MDB. The latter data covers the entire Victorian MDB.

A 2030 scenario for commercial forestry plantations for the MDB has been developed using regional projections from the Bureau of Rural Sciences which takes into account trends, policies and industry feedbacks. The increase in commercial forestry plantations is then distributed to areas adjacent to existing plantations (that are not natural forest land use) that have the highest biomass productivity estimated using the PROMOD model [15].

Growth in groundwater extractions has been considered in the context of existing groundwater planning and sharing arrangements and in consultation with State agencies. For groundwater the following issues have been considered:

- growth in groundwater extraction rates up to full allocation,
- improvements in water use efficiency due to on-farm changes and lining of channels, and
- water buy-backs.

Rainfall-runoff modelling

The adopted approach provides a consistent way of modelling historical runoff across the MDB and assessing the potential impacts of climate change and development on future runoff.

The lumped conceptual daily rainfall-runoff model, SIMHYD with a Muskingum routing method [16,17] is used to estimate daily runoff on 0.05º grids (~ 5 km x 5 km) across the entire MDB for the four scenarios.

The model is calibrated against 1975–2006 streamflow data from about 200 unregulated catchments of 50–2000 km^2 across the MDB (calibration catchments). Although unregulated, streamflow in these catchments for the calibration period may reflect low levels of water diversion and will include the effects of historical land use change. The calibration period is a compromise between a shorter period that would better represent current development and a longer period that would better account for climatic variability. In the model calibration, the six parameters in SIMHYD are optimised to maximise an objective function that incorporates the Nash-Sutcliffe efficiency [18] of monthly runoff and daily flow duration curve, together with a constraint to ensure that the total modelled runoff over the calibration period is within five percent of the total recorded runoff. The resulting optimised model parameters are therefore identical for all cells within a calibration catchment.

The runoff for non-calibration catchments is modelled using optimised parameter values from the geographically closest calibration catchment, provided there is a calibration catchment within 250 km. Once again the parameter values for each grid cell within a non-calibration catchment are identical. For catchments more than 250 km from a calibration catchment default parameter values are used. The default parameter values are identical across the entire Basin and are chosen to ensure a realistic runoff gradient across the drier parts of the MDB. The places these default values are used are therefore all areas of very low runoff.

As the parameter values come from calibration against streamflow from 50–2000 km^2 catchments, the runoff defined here is different, and can be much higher than streamflow recorded over very large catchments where there can be significant transmission losses (particularly in the western and north-western parts of the MDB). Almost all of the catchments available for model calibration are in the higher runoff areas in the eastern and southern parts of the MDB. Runoff estimates are therefore generally good in the eastern and southern parts of the MDB and are comparatively poor elsewhere.

The same model parameter values are used for all the simulations. The future climate scenario simulations therefore do not take into account the effect on forest water use of global warming and enhanced atmospheric CO_2 concentrations. There are compensating positive and negative global warming impacts on forest water use, and it is difficult to estimate the net effect because of the complex climate-biosphere-atmosphere interactions and feedbacks [19,20].

Bushfire frequency is also likely to increase under the future climate scenario. In local areas where bushfires occur, runoff would reduce significantly as forests regrow. However, the impact on runoff averaged over an entire region is unlikely to be significant [20].

For the future climate and future development scenario the impact of additional farm dams on runoff is modelled using the CHEAT model [21] which takes into account rainfall, evaporation, demands, inflows and spills. The impact of additional plantations on runoff is modelled using the FCFC model (Forest Cover Flow Change) [22,23].

The modelling approach and results (model calibration, cross-verification, regionalisation and climate change impact simulation with the SIMHYD and Sacramento rainfall-runoff models, and farm dam and commercial forestry plantation modelling) across the MDB are described in detail in [20].

\> Forestry area near Tumut, NSW.

\> Farm dam near Boorowa, NSW.

River system modelling

The project is using river system models that encapsulate descriptions of current infrastructure, water demands, and water management and sharing rules to assess the implications of the changes in inflows described above on the reliability of water supply to users. Given the time constraints of the project and the need to link the assessments to State water planning processes, it is necessary to use the river system models currently used by State agencies, the Murray-Darling Basin Commission and Snowy Hydro Ltd. The main models in use are IQQM, REALM, MSM-Bigmod, WaterCress and a model of the Snowy Mountains Hydro-electric Scheme.

The modelled runoff series from SIMHYD are not used directly as subcatchment inflows in these river system models because this would violate the calibrations of the river system models already undertaken by State agencies to different runoff series. Instead, the relative differences between the daily flow duration curves of the historical climate scenario and the remaining scenarios (respectively) are used to modify the existing inflows series in the river system models. All the scenario inflow series for the river system modelling therefore have the same daily sequences – but different amounts.

A few areas of the MDB have not previously been modelled and hence some new IQQM or REALM models have been implemented. In some cases ancillary models are used to estimate aspects of water demands of use in the river system model. An example is the PRIDE model used to estimate irrigation for Victorian REALM models.

River systems that do not receive inflows or transfers from upstream or adjacent river systems are modelled independently. This is the case for most of the river systems in the Basin and for these rivers the modelling steps are:

- model configuration,
- model warm-up to set initial values for all storages in the model, including public and private dams and tanks, river reaches and soil moisture in irrigation areas,
- using scenario climate and inflow time series, run the river model for all climate and development scenarios,
- where relevant, extract initial estimates of surface-groundwater exchanges and provide this to the groundwater model, and
- where relevant, use revised estimates of surface-groundwater exchanges from groundwater models and re-run the river model for all scenarios.

For river systems that receive inflows or transfers from upstream or adjacent river systems, model inputs for each scenario were taken from the upstream models. In a few cases several iterations were required between upstream and downstream models because of the complexities of the water management arrangements. An example is the connections between the Murray, Murrumbidgee and Goulburn regions and the Snowy Mountains Hydro-electric Scheme.

River system models in the Murray-Darling Basin

Model	Description	Rivers modelled
IQQM	Integrated Quantity-Quality Model: hydrologic modelling tool developed by the NSW Government for use in planning and evaluating water resource management policies.	Paroo, Warrego, Condamine-Balonne (Upper, Mid, Lower), Nebine, Moonie, Border Rivers, Gwydir, Peel, Namoi, Castlereagh, Macquarie, Marthaguy, Bogan, Lachlan, Murrumbidgee, Barwon-Darling
REALM	Resource Allocation Model: water supply system simulation tool package for modelling water supply systems configured as a network of nodes and carriers representing reservoirs, demand centres, waterways, pipes, etc.	Ovens (Upper, Lower), Goulburn, Wimmera, Avoca, ACT water supply.
MSM-BigMod	Murray Simulation Model and the daily forecasting model BigMod: purpose-built by the Murray-Darling Basin Commission to manage the Murray River system. MSM is a monthly model that includes the complex Murray accounting rules. The outputs from MSM form the inputs to BigMod, which is the daily routing engine that simulates the movement of water.	Murray
WaterCress	Water Community Resource Evaluation and Simulation System: PC-based water management platform incorporating generic and specific hydrological models and functionalities for use in assessing water resources and designing and evaluating water management systems.	Eastern Mt Lofty Ranges (six separate catchments)
SMHS	Snowy Mountains Hydro-electric Scheme model: purpose built by Snowy Hydro Ltd to guide the planning and operation of the SMHS.	Snowy Mountains Hydro-electric Scheme

Surface-groundwater interactions

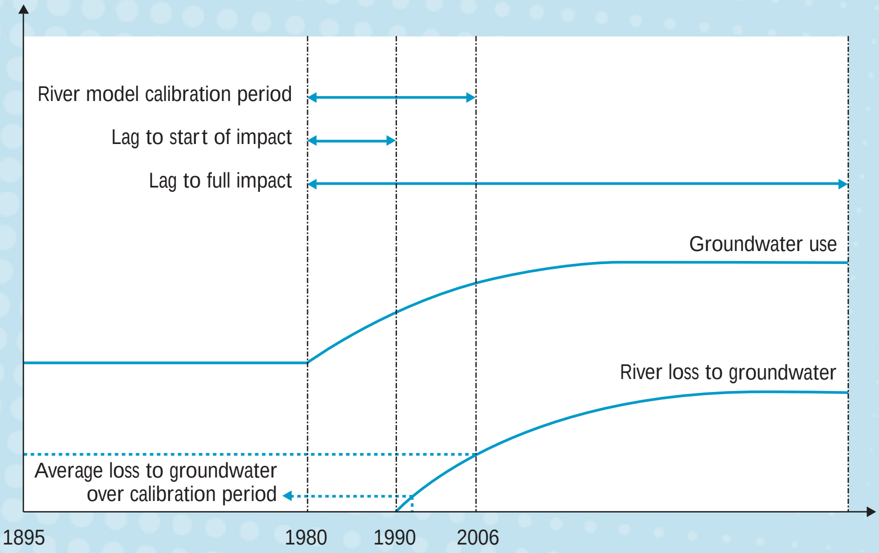
The project is explicitly considering and quantifying the water exchanges between rivers and groundwater systems. The approaches used are described below.

The river models used by State agencies have in turn typically been calibrated by State agencies to achieve mass balance within calibration reaches over relatively short time periods. When the models are run for extended periods the relationships derived during calibration are assumed to hold for the full modelling period. In many cases however, the calibration period is a period of changing groundwater extraction and a period of changing impact of this extraction on the river system. That is, the calibration period is often one of changing hydrologic relationships, a period where the river and groundwater systems have not fully adjusted to the current level of groundwater development. To provide a consistent equilibrium basis for scenario comparisons it is necessary to determine the equilibrium conditions of surface and groundwater systems considering their interactions and the considerable lag times involved in reaching equilibrium.

The diagram below shows a notional timeline of groundwater use, impact on river, how this has typically been treated in river model calibration, and what the ultimate equilibrium impact on the river would be. By running the groundwater models until a 'dynamic equilibrium' is reached, a reasonable estimate of the ultimate impact on the river of current groundwater use is obtained. A similar approach is used to determine the ultimate impact of future groundwater use.

For some groundwater management units – particularly fractured rock aquifers – there is significant groundwater extraction but no model available for assessment. In these cases there is the potential for considerable impacts on streamflow. At equilibrium, the volume of water extracted must equal the inflows to the aquifer from diffuse recharge, lateral flows and flows from overlying rivers. The fraction that comes from the overlying rivers is determined using a 'connectivity factor' that is estimated from the difference in levels between the groundwater adjacent to the river and the river itself, the conductance between the groundwater pump and the river and the hydrogeological setting. Given the errors inherent in this method, significant impacts are deemed to be those about 2 GL/yr for a subcatchment, which given typical connectivity factors translates to groundwater extraction rates of around 4 GL/yr for a subcatchment.

Notional timeline of groundwater use and resultant impact on river



> Murrumbidgee Irrigation Area, Griffith, NSW.

Monthly water accounts

Monthly water accounts provide an independent set of the different water balance components by river reach and by month. The water accounting differs from the river modelling in a number of key aspects:

- The period of accounting extends to 2006 where possible, which is typically more recent than the calibration and evaluation periods of the river models assessed. This means that a comparison can produce new insights about the performance and assumptions in the river model, as for example associated with recent water resources development or the recent drought in parts of the MDB.
- The accounting is specifically intended to estimate, as best as possible, historical water balance patterns, and use observed rather than modelled data wherever possible (including recorded diversions, dam releases and other operations). This reduces the uncertainty associated with error propagation and assumptions in the river model that were not necessarily intended to reproduce historical patterns (e.g. differences in actual historical and potential future degree of entitlement use).
- The accounting uses independent, additional observations and estimates on water balance components not used before, such as actual water use estimates derived from remote sensing observations and SIMHYD estimates of local runoff generation. This can help to constrain the water balance with greater certainty.

Despite these advantages, it is emphasised that the water accounting methodology invokes models and indirect estimates of water balance components where direct measurements are not available. Because of this, these water accounts are not an absolute point of truth. Rather, they provide an estimate of the degree to which the river water balance is understood and gauged, and a comparison between river model and water account water balances provides one of several lines of evidence to inform our (inevitably partially subjective) assessment of model uncertainty and its implications for the confidence in the findings. The water accounting is based on existing methods [24, 25] and is described in detail in [26].

Wetland and irrigation water use

An important component of the accounting is an estimate of actual water use based on remote sensing observations. Spatial time series of monthly net water use from irrigation areas, rivers and wetlands are estimated using interpolated station observations of rainfall and climate combined with remote sensing observations of surface wetness, greenness and temperature. Net water use of surface water resources is calculated as the difference between monthly rainfall and monthly actual evapotranspiration (AET).

AET estimates are based on a combination of two methods. The first method uses surface temperature remotely sensed by the AVHRR series of satellite instruments for the period 1990–2006 and combines this with spatially interpolated climate variables to estimate AET from the surface energy balance [27]. The second method loosely follows the FAO56 'crop factor' approach and scales interpolated potential evaporation estimates using observations of surface greenness and wetness by the MODIS satellite instrument [25]. The two methods are constrained using direct on-ground AET measurements at seven study sites and catchment stream flow observations from more than 200 catchments across Australia. Both methods provide AET estimates at 1 km resolution.

The spatial estimates of net water use are aggregated for each reach and separately for all areas classified as either irrigation area or floodplains and wetlands. The following digital data sources are used:

- land use grids for 2000/2001 and 2001/02 from the Bureau of Rural Sciences [28],
- NSW wetlands maps from the NSW Department of Environment and Conservation,
- hydrography maps, including various types of water bodies and periodically inundated areas, from Geoscience Australia (GA maps; Topo250K Series 3),
- long-term rainfall and AET grids derived as outlined above, and
- LANDSAT satellite imagery for the years 1998 to 2004.

The reach-by-reach estimates of net water use from irrigation areas and from floodplains and wetlands are subject to the following limitations:

- Partial validation of the estimates suggest an average accuracy in AET estimation within 15 percent, but probably decreasing with the area over which estimates are averaged. Uncertainty in spatial estimates originates from the interpolated climate and rainfall data as well as from the satellite observations and the method applied.
- Errors in classification of irrigation and floodplain/wetland areas may add an unknown uncertainty to the overall estimates, particularly where subcatchment definition is uncertain or wetland and irrigation areas are difficult to discern.
- Estimated net water use cannot be assumed to have been derived from surface water in all cases as vegetation may also have access to groundwater use, either directly or through groundwater pumping.
- Estimated net water use can be considered as an estimate of water demand that apparently is met over the long-term. Storage processes, both in irrigation storages and wetlands, need to be simulated to translate these estimates in monthly (net) losses from the river main stem.

Therefore, the AET and net water use estimates are used internally to conceptual water balance models of wetland and irrigation water use that include a simulated storage as considered appropriate based on ancillary information.

> Warrego River, north of Cunnamulla, Qld (QNDRW).

Calculation and attribution of apparent ungauged gains and losses

In a river reach, ungauged gains or losses are the difference between the sum of gauged main stem and tributary inflows, and the sum of main stem and distributary outflows and diversions. The net sum of all gauged gains and losses provides an estimate of ungauged apparent gains and losses. There may be differences between apparent and real gains and losses for the following reasons:

- Apparent ungauged gains and losses will also include any error in discharge data that may originate from errors in stage gauging or from the rating curves used to convert stage height to discharge.
- Ungauged gains and losses can be compensating and so appear smaller than in reality. This is more likely to occur for longer time scales. For this reason water accounting was done on a monthly time scale.
- Changes in water storage in the river reach, connected reservoirs, or wetlands, can lead to apparent gains and losses that become more important as the time scale of analysis decreases. A monthly time scale has been chosen to reduce storage change effects, but they can still occur.

The monthly pattern of apparent ungauged gains and losses is evaluated for each reach in an attempt to attribute them to real components of water gain or loss. The following techniques are used in sequence:

- Analysis of normal (parametric) and ranked (non-parametric) correlation between apparent ungauged gains and losses on one hand, and gauged and estimated water balance components on the other hand. Estimated components included SIMHYD estimates of monthly local inflows and remote sensing-based estimates of wetland and irrigation net water use.
- Visual data exploration: assessment of temporal correlations in apparent ungauged gains and losses to assess trends or storage effects, and comparison of apparent ungauged gains and losses and a comparison with time series of estimated water balance components.

Based on the above information, apparent gains and losses are attributed to the most likely process, and an appropriate method is chosen to estimate the ungauged gain or loss using gauged or estimated data. The water accounting model includes the following components:

- A conceptual floodplain and wetland running a water balance model that estimates net gains and losses as a function of remote sensing-based estimates of net water use and main stem discharge observations.
- A conceptual irrigation area running a water balance model that estimates (net) total diversions as a function of any recorded diversions, remote sensing-based estimates of irrigated area and net crop water use, and estimates of direct evaporation from storages and channels.
- A routing model that allows for the effect of temporary water storage in the river system and its associated water bodies and direct open water evaporation.
- A local runoff model that transforms SIMHYD estimates of local runoff to match ungauged gains.

These model components are described in greater detail in [26] and are only used where data or ancillary information suggest their relevance. Each component has a small number of unconstrained or partially constrained parameters that need to be estimated. A combination of direct estimation as well as step-wise or simultaneous automated optimisation is used, with the goal of attributing the largest possible fraction of apparent ungauged gains and losses. Any large residual losses and gains suggest error in the model or its input data.

Groundwater modelling

Groundwater assessment, including groundwater recharge modelling, is undertaken to assess the implications of the climate and development scenarios on groundwater management units (GMUs) across the Basin. A range of methods are used appropriate to the size and importance of different GMUs. There are over 100 GMUs in the Murray-Darling Basin, and the choice of methods is based on an objective classification of the GMUs as high, medium or low priority.

Rainfall-recharge modelling is undertaken for all GMUs. For dryland areas, daily recharge is assessed using a model that considers plant physiology, water use and soil physics to determine vertical water flow in the unsaturated zone of the soil profile at a single location. This model is run at multiple locations across the MDB in considering the range of soil types and land uses to determine scaling factors for different soil and land use conditions. These scaling factors are then used to scale recharge for given changes in rainfall for all GMUs according to local soil types and land uses.

For many of the higher priority GMUs, recharge is largely from irrigation seepage. In New South Wales this recharge has been embedded in the groundwater models as a percentage of the applied water. For irrigation recharge, information has been collated for different crop types, irrigation systems and soil types, and is used for the scenario modelling.

For high priority GMUs numerical groundwater models are being used. In most cases these already exist but often require improvement. In some cases new models are being developed. Although the groundwater models have seen less effort invested in their calibration than the existing river models, the project is investing considerable effort in model calibration and various cross-checks to increase the level of confidence in the groundwater modelling.

For each groundwater model, each scenario is run using river heights as provided from the appropriate river system model. For recent and future climate scenarios, adjusted recharge values are also used, and for future development the 2030 groundwater extractions levels are used. The models are run for two consecutive 111-year periods. The average surface-groundwater flux values for the second 111-year period are passed back to the river models as the equilibrium flux. The model outputs are used to assess indicators of groundwater use and reliability.

For lower priority GMUs no models are available and the assessments are limited to simple estimates of recharge, estimates of current and future extraction, allocation based on State data, and estimates of the current and future impacts of extraction on streamflow where important.

> Murrumbidgee River near Jugiong, NSW.

Environmental assessment

The environmental assessments of the project are considering the environmental assets already identified by State governments or the Australian Government that are listed in the Directory of Important Wetlands in Australia [29] or the updated on-line database of the directory. From this directory environmental assets are selected for which there exists sufficient publicly available information on hydrological indicators (such as commence-to-fill levels) which relate to ecological responses such as bird breeding events.

Information sources include published research papers and reports, accessible unpublished technical reports, or advice from experts currently conducting research on specific environmental assets. In all cases the source of the information on the hydrological indicators used in each assessment is cited. The selection of the assets for assessment and hydrologic indicators was undertaken in consultation with State governments and the Australian Government through direct discussions and through reviews by the formal internal governance and guidance structures of the project.

The Directory of Important Wetlands in Australia lists over 200 wetlands in the MDB. Information on hydrological indicators of ecological response adequate for assessing scenario changes only exists for around one-tenth of these. More comprehensive environmental assessments are beyond the terms of reference for the project. The Australian Department of Environment and Water Resources has separately commissioned a compilation of all available information on the water requirements of wetlands in the MDB that are listed in the Directory of Important Wetlands in Australia.

> Wetlands near Kerang, Vic.

For regions where the above selection criteria identify no environmental assets, the river channel itself is considered as an asset and ecologically-relevant hydrologic assessments are reported for the channel. The locations for which these assessments are provided are guided by prior studies. In the Victorian regions for example, detailed environmental flow studies have been undertaken which have identified environmental assets at multiple river locations with associated hydrological indicators. In these cases a reduced set of locations and indicators has been selected in direct consultation with the Victorian Department of Sustainability and Environment. In regions where less information is available, hydrological indicators may be limited to those that report on the water sharing targets that are identified in water planning policy or legislation.

Because the environmental assessments are a relatively small component of the project, a minimal set of hydrological indicators are used in assessments. In most cases this minimum set includes change in the average period between events and change in the maximum period between events as defined by the indicator.

A quality assurance process is applied to the results for the indicators obtained from the river system models which includes checking the consistency of the results with other river system model results, comparing the results to other published data and with the asset descriptions, and ensuring that the river system model is providing realistic estimates of the flows required to evaluate the particular indicators.

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