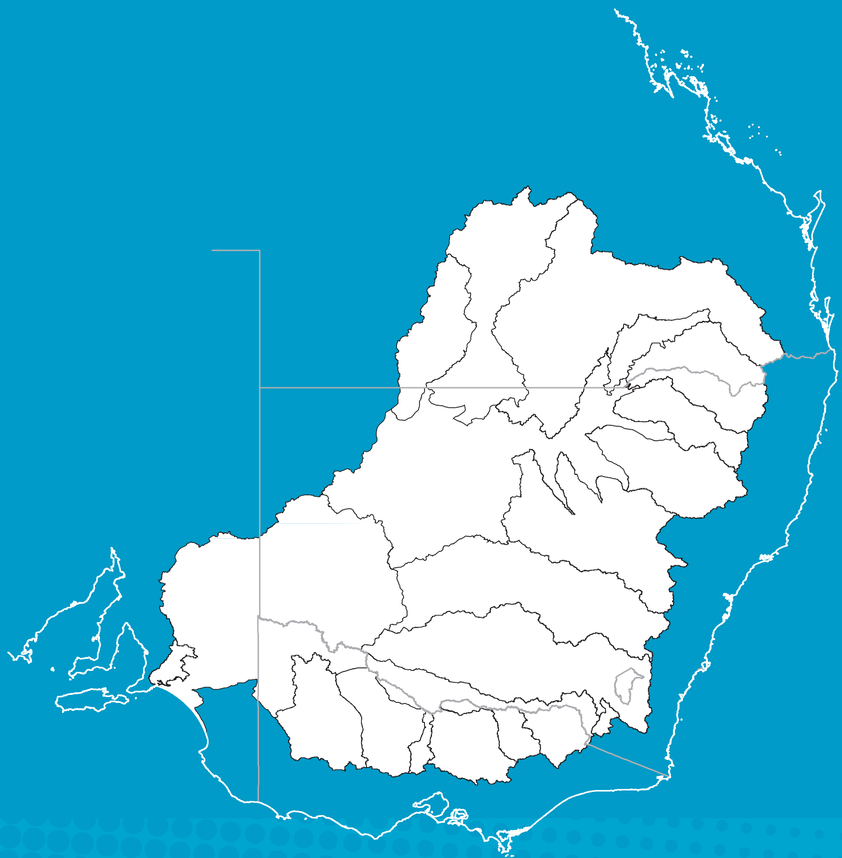

Recommendations for modelling surface–groundwater interactions based on lessons learnt from the Murray-Darling Basin Sustainable Yields Project

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

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Murray-Darling Basin Sustainable Yields Project acknowledgments

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Preface

This is a report to the Australian Government from CSIRO. It is an output of the Murray-Darling Basin Sustainable Yields Project which assessed current and potential future water availability in 18 regions across the Murray-Darling Basin (MDB) considering climate change and other risks to water resources. The project was commissioned following the Murray-Darling Basin Water Summit convened by the then Prime Minister of Australia in November 2006 to report progressively during the latter half of 2007. The reports for each of the 18 regions and for the entire MDB are supported by a series of technical reports detailing the modelling and assessment methods used in the project. This report is one of the supporting technical reports of the project. Project reports can be accessed at http://www.csiro.au/mdbsy.

Project findings are expected to inform the establishment of a new sustainable diversion limit for surface and groundwater in the MDB – one of the responsibilities of a new Murray-Darling Basin Authority in formulating a new Murray-Darling Basin Plan, as required under the Commonwealth Water Act 2007. These reforms are a component of the Australian Government's new national water plan 'Water for our Future'. Amongst other objectives, the national water plan seeks to (i) address over-allocation in the MDB, helping to put it back on a sustainable track, significantly improving the health of rivers and wetlands of the MDB and bringing substantial benefits to irrigators and the community; and (ii) facilitate the modernisation of Australian irrigation, helping to put it on a more sustainable footing against the background of declining water resources.

Executive summary

Background

At a summit held on 7 November 2006, the Prime Minister, the Premiers of New South Wales, Victoria and South Australia, and the Acting Premier of Queensland met to discuss the worsening drought and the impacts on water availability in the southern Murray-Darling Basin (MDB). One of the several agreements from this summit was to 'commission the 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'. This led to the Murray-Darling Basin Sustainable Yields Project, in which the security of surface water and groundwater allocations, as expressed in water sharing plans, has been examined and modelled under a range of climate and land use scenarios.

The large scale of the MDB analysis means that the whole system cannot be modelled as a single unit. The varying level of understanding of the component systems of the MDB means that different modelling methods need to be implemented based on availability of models and data. The project adopted a hierarchical system where high priority areas were investigated using complex numerical models and studies of low priority areas were restricted to connectivity mapping and partial water balances.

The project needed to build on pre-existing models and knowledge for two critical reasons: firstly due to the limited time available for delivery, and secondly to recognise the independent views and experiences of the relevant authorities in state government departments responsible for managing the groundwater resources.

Surface–groundwater interaction

A key component of the work in this project is the explicit consideration of the interactions between surface water and groundwater systems. Double accounting of water resources may occur when considering surface water and groundwater as separate entities. As such, quantification of their interaction is essential in order to examine the security of total water allocations.

At the scale of the MDB, there has been very little previous work done in the area of surface–groundwater interaction. This has required the adoption of a relatively new approach for this project, which we refer to as the 'dynamic equilibrium' approach. This report reviews the 'dynamic equilibrium' approach with a view that equivalent analyses will be required in future. The report provides guidelines for future analysis and recommendations for model development and data provision in the meantime that will aid such analyses.

This project uses two independent approaches for the assessment of surface–groundwater interaction. The first is connectivity mapping which provides an estimate of the flux of groundwater to or from surface water at a given time (Parsons et al., 2008). The second is modelling of impacts of groundwater extraction or surface water management on long-term reliability of total water allocation. This modelling estimates change from the original net flux. This second approach is the focus of this report.

Dynamic equilibrium approach

Linking groundwater models to existing river planning models is difficult because most of the river planning models in the MDB have unattributed ‘gains and losses’ terms. These gains/losses are used as part of river planning model calibration, and implicitly account for a range of fluxes to or from the surface water, including groundwater fluxes.

A ‘dynamic equilibrium’ approach has been developed to enable the groundwater analysis to synchronise with the surface water analysis. The approach was to run groundwater models where they existed for an initial 111 years of climatic data to allow the groundwater models to evolve to ‘dynamic equilibrium’, followed by another 111 years to estimate exchange fluxes to/from the surface water during varying climate and groundwater extraction. Then, the groundwater fluxes for a given state of groundwater extraction were compared to the fluxes during the calibration period of the river model, allowing the river fluxes in the river planning models to be modified accordingly. In areas where numerical groundwater models do not exist, a simple analytical approach was used to estimate impact of groundwater extraction under steady state conditions, and hence the likely impact on surface water.

Issues with the dynamic equilibrium approach

The experience gained within this project has highlighted some critical issues with the dynamic equilibrium approach that warrant further attention when similar modelling exercises are conducted in the future.

<u>The groundwater models may not reach ‘dynamic equilibrium’</u>, despite running for long time periods, thus nullifying this assumption. The most likely causes of this are that: (i) the spatial patterns of groundwater extraction are not sustainable, or (ii) increased recharge from surface water irrigation leads to long-term groundwater storage changes. In many cases, groundwater models are not set up to be run for long periods of time. Extended modelling runs may provide additional stresses on the models which have not been allowed for during calibration. In particular, if models have not been calibrated for steady state initial conditions, they may drift due to the calibration rather than actual physical drivers. Another example is that for the long time periods being considered, distant boundary conditions become more increasingly relevant and may artificially lead to high inflows.

<u>There may be existing stresses occurring on the groundwater system even before significant groundwater extraction</u>. The impact on surface water may therefore be caused by several groundwater factors perhaps operating over different time periods. These may include issues associated with surface water irrigation or land clearance (leading to increased recharge and rising groundwater levels) predating groundwater extraction. Where these occur in areas too saline for significant groundwater extraction, there may be a mix of falling watertables caused by groundwater extraction within the same groundwater management unit as rising watertables caused by surface water irrigation. In some cases, these may lead to processes such as evapotranspiration from shallow watertables that may not be built into the groundwater models. Some care needs to be taken in the ‘dynamic equilibrium’ approach so that the appropriate sharing plan is faithfully represented.

<u>There may be issues relating to using the calibration period of the river planning model as a reference</u>. This may lead to inconsistencies since: (i) the calibration periods for the surface and groundwater models may be different, (ii) the climate during these periods may not be typical of the longer time frame, and (iii) there may be substantive changes in groundwater development during the river model calibration period and changes to river management during the groundwater calibration period.

<u>The use of existing models and data can lead to problems</u>. Existing models may not have been designed to estimate fluxes to or from the river. Some processes within the riparian and floodplain zones are often not included in current models. Appropriate data, particularly on groundwater extraction, can be difficult to access. Availability and reliability of data is a prerequisite to any sound modelling exercise. The methodology for low-priority areas was simplistic and could be significantly improved.

Recommendations

The following recommendations for future modelling exercises are based on lessons learnt from the Murray-Darling Basin Sustainable Yields Project.

1. For a successful implementation of the dynamic equilibrium approach, the following guidelines are recommended:

1.1. Ensure that dynamic equilibrium is reached. This is achieved as follows:

- Calibrate groundwater models for steady state conditions, preferably from a without-development state. This ensures that the simulation is sufficiently stable in order to be able to be run over periods of 100 years in line with surface water planning models.
- Ensure that groundwater extractions are sustainable. This may require a shift to groundwater management models. Such models have rules similar to those of surface water planning models to ensure sustainable groundwater extraction. These rules may include trigger groundwater levels, water trading, irrigator response to changing watertables, river flows and climate variability and water quality changes.
- Simulate for a long enough time to ensure that the impacts of the imposed stresses are fully realised.

1.2. Models should have sufficiently large areas to ensure that the imposed boundary conditions are distant enough so that they do not lead to artificial inflows that may occur due to prolonged run times.

1.3. There needs to be consistent calibration periods for surface water and groundwater models where the impacts of groundwater development are accounted for in river model calibration and river management rules are accounted for in groundwater model calibration.

1.4. There is a need for greater automation of changing input and output files in both groundwater and surface water models. This includes dealing with floods in a predictive sense, changing flows into stage heights and interpolation between gauging stations and including changes in fluxes into loss and inflows to river models. This issue is particularly relevant for stochastic runs.

1.5. There is a need to obtain extraction data within GMUs and within subcatchments, showing distance from river and aquifer being used. There is great emphasis on the reliability and consistency of groundwater extraction data regarding both magnitude and spatial distribution.

1.6. There is a need to better handle areas with wide floodplains and shallow groundwater levels where the effects of evapotranspiration and flood recharge are taken into consideration.

2. A consistent methodology to evaluate surface–groundwater interactions in areas with no groundwater models needs to be established. Such areas might not have groundwater models since groundwater development is not high. However, the cumulative impacts of developments may still be significant in those areas.

3. Alternative approaches to the dynamic equilibrium approach should be considered in order to avoid some of the associated problems. Running river models for 20 to 30 years stochastically then statistically selecting representative head time series and importing them into groundwater models may overcome the problems associated with running the groundwater models for prolonged durations (over 100 years). It is also recommended that once the exchange fluxes are imported back to river models, they should be re-calibrated, with storages modified accordingly.

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1 Introduction

This report is one of a series of reports for the Murray-Darling Basin Sustainable Yields Project. It reviews the methodology used for estimating the impact of groundwater extraction on surface water flows and makes recommendations for further studies.

1.1 Murray-Darling Basin Sustainable Yields Project

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 are 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, 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
- current levels of extractive use.

The Murray-Darling Basin Sustainable Yields Project has reported 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 southwesterly 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 Figure 1).

The project focussed on climate change and its effects on water availability in the MDB. Four scenarios were considered. The first scenario (Scenario A) is based on the historical climate sequence. The second scenario (Scenario B) is a 'recent climate' scenario. It is based on stochastic 112-year (same length as Scenario A) climate series generated from rainfall, temperature and potential evapotranspiration characteristics in the past ten years (1997 to 2006). The third scenario (Scenario C) is a future climate and current development scenario. It is based on 112-year (same length as Scenario A) climate series derived from a range of global climate model (GCM) projections of ~2030 climate. The fourth scenario (Scenario D) is a future climate and future development scenario. It uses the same climate series as Scenario C, but system inflows will be modified to reflect catchment and groundwater development.

Examination of the security of surface and groundwater allocations (across all water use sectors including the environment) as expressed in existing water sharing plans requires a consideration of the interactions between surface and groundwater systems. The Murray-Darling Basin Sustainable Yields project is explicitly modelling the exchange fluxes between groundwater and surface water mainly to address the issue of double accounting and hence obtain a true estimate of sustainable yields of surface and groundwater systems within the MDB.

Figure 1-1. Region by region map of the Murray-Darling Basin

As part of the Terms of Reference, CSIRO was asked to provide guidance on surface and groundwater systems. This is being done in two parts:

- development and application of a methodology to each region
- development of recommendations for surface and groundwater interaction studies at this scale.

This report addresses the latter.

1.2 Why the modelling recommendations are required

The process of river modelling to support planning is well developed and is the basis of the assessment of surface water sharing plans in this project. While there remain several issues with calibration and estimation of surface water inflows, the application of these models to assessment of water sharing plans and hence surface water diversions is well understood. Groundwater fluxes are included implicitly in a general manner through unattributed gains and losses. These arise during the calibration and relate to the mass balance between two gauging stations that cannot otherwise be attributed. Surface water models are generally run for long periods of historical climate.

The process of groundwater modelling for assessment of groundwater sharing plans is also well developed. While there are very few examples of models that include management rules and also groundwater salinisation issues, the process of groundwater modelling is well understood. Models are generally run in a forecasting mode, projecting from the current groundwater status to decades into the future. Interactions with streams occur through:

- stream and flood recharge processes
- recharge from surface water irrigation

- stream discharge processes
- fluxes are estimated as part of the overall groundwater budget.

The issue of 'double accounting' arises when surface water assessments and groundwater assessments are conducted independently and a discrepancy may arise from the interactions between groundwater and surface water. In the context of this project, this appears to be mainly due to groundwater impacts on streams. To understand this, one needs to consider the different time periods:

- calibration period of the surface water model
- history of groundwater development
- assessment period
- time lag between groundwater development and the impact on streams to be realised.

An example from New South Wales may involve a calibration period for the IQQM river planning model from 1980 to 1995, a groundwater development occurring in the period from 1990 to 1995, an assessment period for water sharing plans occurring from 2014 to 2024, and a time lag of 15 years for half of the impact of the groundwater development to be realised. Thus, during the assessment period, about half of the groundwater impact on streams would have been realised but would not have been included in the IQQM river planning model. This can then lead to an over-assessment of the water availability.

Different river planning models are calibrated in different ways. In some cases, the unattributed gains and losses are not calculated using a constant relationship but reflect changing water balances. For example, the mass balances between gauging stations are calculated each year and this series of unattributed losses and gains are used in any planning scenarios. Thus, changes in groundwater fluxes may have been incorporated late in the sequence but largely ignored over the longer sequence. The application of the river planning model calibrated in this fashion can also lead to an over-assessment of the water availability.

There is a significant difference in the way groundwater models are run for the assessment of groundwater plans and river planning models are run for assessment of surface water plans. River planning models are often run for long sequences of historical climate data in order to better estimate long-term water availability. Groundwater models are run often for shorter periods (20 or so years). The response of groundwater systems to climatic variability tends to be more damped than that of surface water systems. Hence it is not so critical to run long sequences of climate data through groundwater models. On the other hand, the buffering in larger groundwater systems means that the initial state is important. Hence groundwater models are run in a forecasting mode extrapolating from the current state, while river planning models are run in a 'planning mode' over long climatic sequences.

Thus, it is not straightforward to provide integrated analyses of surface and groundwater. Integrated models exist but have not been used in this project. It becomes a significant exercise to develop models on a different platform.

It should be noted that groundwater models may only be available in an appropriate form for small sections of rivers, yet significant extraction might occur outside of these modelled areas. There are methods available for the assessment of the impacts of these extractions that do not involve complex numerical modelling. However, the time lags associated with the impacts of groundwater extractions on streams is sensitive to distance from stream and the hydrogeology in the vicinity of streams. Again, it is not straightforward to collate all such information.

The scale of the Murray-Darling Basin Sustainable Yields Project is unprecedented both on the national and international scales. One of the largest international studies of this sort was carried out in the Gulf Coastal Plain of the USA covering an area of about 600,000 km^2; the study provided a good understanding of pre- and post-development hydrologic budgets of the regional aquifer systems (Johnston, 1999). The Nebraska Department of Natural Resources has reported on the expected long-term availability of surface water supplies and hydrologically connected groundwater supplies of the Blue River basins, the Lower Niobrara River Basin, the Lower Platte River Basin, and the Missouri Tributary basins; the total area of the state of Nebraska is about 200,000 km^2. Many other studies have been conducted on a smaller scale. Jagelke and Barthel (2005) developed an integrated groundwater surface water model for the Neckar catchment located in south-west Germany covering an area of 14,000 km^2; the integrated model includes a groundwater model that interacts with a rainfall-runoff model and a water demand model. Sophocleous et al. (1999) couple the SWAT model to MODFLOW to investigate surface–groundwater interactions in the Rattle Creek basin in south-central Kansas, which covers an area of 3600 km^2. Harvey et al. (2006) modelled decadal timescale interactions between groundwater and surface water in the central Everglades, Florida, USA; the model covered an area of 430 km^2. Rodriguez et al. (2006)

developed a surface–groundwater interaction model for the Choele Choel Island in Patagonia, Argentina; they modelled the 340 km^2 study area using MODFLOW and the stream package. Werner et al. (2006) used MODHMS to model surface–groundwater interactions in the Sandy Creek Catchment of the Pioneer Valley, Australia; the study covered an area of 420 km^2. Ivkovic et al. (2005) conducted a comprehensive study of surface–groundwater interactions for the Namoi catchment located in the Murray-Darling Basin, Australia. The Murray-Darling Basin Sustainable Yields Project is a benchmark study that covers an area of about 1,000,000 km^2 and hence the need to document the experiences and the lessons learnt from it.

Given the large scale of the project, the whole system cannot be modelled as a single unit. Furthermore, the level of understanding of the system significantly varies across the MDB; this variation is closely related to data availability. Generally, areas with high groundwater usage have existing models and high data availability. A different modelling approach has to be adopted for data-poor low priority areas. The robustness of the existing models does vary a lot. The project had to build on pre-existing models and knowledge for two critical reasons: firstly, due to the limited time available for delivery, and secondly, to recognise the independent views and experiences of the relevant authorities in state government departments responsible for managing the groundwater resources in question.

Some of the pre-existing models have issues with their boundary conditions as well as their starting conditions. The calibration periods of river models are not consistent with those of the groundwater models, which complicates the issue of double accounting. Some critical processes such as flood recharge and evapotranspiration are either simplistically modelled or lacking altogether. Automation is a critical issue as existing river models had to be linked together and groundwater models had to be linked to river models. Using a long-term average surface–groundwater exchange flux may not be a very robust approach as the condition of dynamic equilibrium may sometimes not be achieved.

This report briefly describes how surface–groundwater interactions were modelled in the Murray-Darling Basin Sustainable Yields Project. It presents the various issues encountered in the modelling exercise, discusses the lessons learnt, and provides modelling recommendations for future studies.

2 Methodology for assessing surface–groundwater interactions

This section outlines the methodology adopted to assess the interaction between surface water and groundwater in the Murray-Darling Basin Sustainable Yields Project. It is structured into two sub-sections. Section 0 outlines the connectivity mapping, which is analysed in detail elsewhere (Parsons et al., 2008). This is an important task by itself but also informs the prioritisation process described in Section 2.1 whereby each groundwater management unit (GMU) in the MDB was assigned an assessment ranking depending on a number of criteria.

The basic criterion for assessing the type of interaction between a stream and the underlying groundwater aquifer relates to the saturation condition of the aquifer material in the close vicinity of the stream. The hydraulic connection between a stream and the underlying aquifer may be saturated or unsaturated, which greatly impacts the level of interaction between the two. The types of connections between surface water and groundwater are summarised in Table 2-1.

Table 2-1. Types of surface–groundwater interactions

Groundwater and streambed levels	Hydraulic connection	Type of connection	Flux
GWL above SBL*	Saturated	Gaining; stream gaining water (baseflow) from groundwater	Depends on head difference and streambed conductance
		Losing; stream losing water to groundwater	
GWL slightly below SBL	Saturated	Losing	Depends on thickness of clogging layer, relative conductivities of clogging layer and aquifer material, depth to watertable, and stream width; flux increases until it reaches a status of maximum loss
GWL below SBL	Unsaturated		
GWL well below SBL	Unsaturated, maximum loss flux		

*GWL=groundwater level; SBL=streambed level

The connectivity mapping provides a snapshot in time of the type of interaction between the surface water and groundwater where the flux is considered to be indicative of the level of the interaction. Therefore, the flux calculated in the connectivity mapping is not directly indicative of the pumping impacts. However, in areas where there is groundwater development it is built into the flux. Changes in the type of connection (from gaining to losing) can occur in areas with heavy groundwater development. As the connectivity map is a snapshot in time, it does not capture the lag times associated with groundwater pumping. An impact assessment of groundwater pumping complements the connectivity mapping and evaluates the proportion of surface–groundwater flux associated with pumping. Note that seasonal variations in both surface water and groundwater hydrology mean that the types of connections outlined in Table 2-1 vary in time. Excessive groundwater development might change a gaining stream to a losing stream, or change the type of connection under a stream from saturated to unsaturated. The large variability associated with the fluxes means that this is not a measurement exercise. Rather, it provides an insight into the type of connection between groundwater and surface water. It is a communication exercise between surface and groundwater modellers that may help them form a big-picture understanding of the interaction between the surface water and groundwater systems. This preliminary assessment tool provides a basis for assigning a complexity of assessment to each GMU. It also indicates the level of interaction between groundwater and surface water in areas where groundwater models are lacking. It also informs the conceptualisation process, which is critical for constructing new models for such areas. Furthermore, it provides a cross-check on the numerical modelling results.

2.1 Prioritisation process

There are over 100 GMUs in the MDB, ranging over two orders of magnitude in level of groundwater extraction and with different levels of threat. Seventeen of those GMUs account for about 78% of groundwater use within the entire MDB. A consistent assessment method would not do justice for the major units. The minimum assessment represents a longer term requirement, which could only be achieved beyond the life of this project. The GMUs were ranked according to the level of groundwater extraction, the fraction of groundwater allocation currently extracted, the fraction of sustainable yield currently extracted, potential growth in the GMU, and predicted future impact of groundwater extraction on surface water flow.

The following criteria were devised to facilitate the assessment process: (i) the complexity of the numerical models available and their capacity to model the relevant processes, (ii) the nature of the extraction data, (iii) the spatial and temporal distribution of data, (iv) the extent of connectivity between groundwater and surface water, and (v) the hydrogeological setting of the area. The outcome of the prioritisation process across the MDB is shown in Figure 2-1.

Accordingly, five assessment levels were identified: (i) 'very thorough' – this is the highest standard and requires a complex calibrated numerical model with explicit surface–groundwater interaction modelling where the two systems are well connected; (ii) 'thorough' – this level requires a numerical model but with poor quality groundwater data and low-confidence surface–groundwater interaction data where the extent of interaction is high; (iii) 'moderate' – in this category a numerical model may not be properly calibrated due to poor data availability and distribution or a model might be lacking altogether; (iv) 'simple' – these areas have no data, parameters have to be assumed, a numerical model cannot be built and a simple water balance approach is used; and (v) 'minimal' – in this category, only a description of the hydrogeological setting is presented and presentation of the extraction data where available.

The assessment in 10 of the top 20 GMUs did not meet the minimum assessment requirements due to a number of issues including: (i) poor model conceptualisation; (ii) poor quality groundwater data with poor spatial and temporal distribution that lead to poor calibration; (iii) unreliable extraction data especially in areas where surface water is highly connected to groundwater; and (iv) application of models outside the time scales of their predictive capacity. The general issue of data quality and availability seem to be the most crucial. The ranking of some GMUs was enhanced as new good-quality data emerged (e.g. Upper Murray, Cudgegong and Belubula), and in some cases it was downgraded to a lower ranking as the relevant groundwater models turned out be of inferior quality and not worthy of the initial high ranking of the GMU (e.g. Border Rivers).

This comprehensive modelling exercise has highlighted the need for a consistent modelling approach to be implemented across the entire MDB, which would enable a whole-of-MDB analysis to be carried out. The shortcomings that were identified in the groundwater models (which mainly related to data quality and availability) should inform monitoring and enable smart data acquisition systems to be devised to improve future modelling exercises.

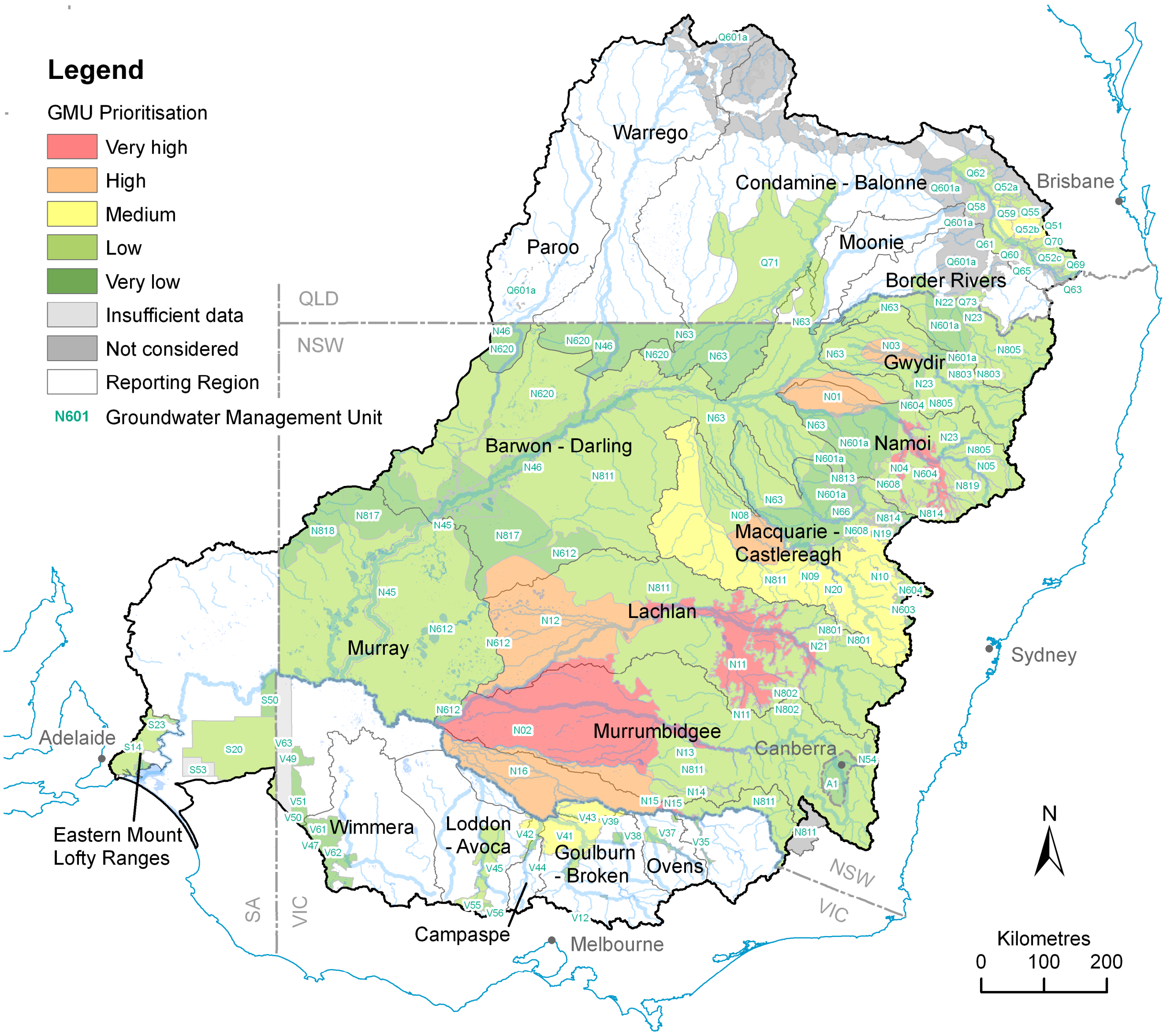

Figure 2-1. Location of groundwater management units in the Murray-Darling Basin

Table 2-2. Groundwater management unit prioritisation across the Murray-Darling Basin

Code	Name	Priority	Region
N01	Lower Namoi Alluvium	high	Namoi
N02	Lower Murrumbidgee Alluvium	very high	Murrumbidgee
N03	Lower Gwydir Alluvium	high	Gwydir
N04	Upper Namoi Alluvium	very high	Namoi
N08	Lower Macquarie Alluvium (downstream of Narromine)	high	Macquarie
N11	Upper Lachlan Alluvium	very high	Lachlan
N12	Lower Lachlan Alluvium	high	Lachlan
N13	Mid-Murrumbidgee Alluvium	very high	Murrumbidgee
N16	Lower Murrumbidgee Alluvium (downstream of Corowa)	high	Murrumbidgee
N819	Peel Valley Fractured Rock	low	Namoi
Q52b	Toowoomba South Basalt	medium	Condamine-Balonne
Q59	Condamine CGMA SA4	medium	Condamine-Balonne
V39	Katunga WSPA	medium	Goulburn-Broken
V42	Campaspe Deep Lead WSPA (CAM)	medium	Campaspe
V43	Shepparton WSPA	medium	Goulburn-Broken
V45	Mid-Loddon WSPA (LOD)	medium	Loddon-Avoca

2.1.1 Groundwater modelling and assessment

Two classes of analyses of varying levels of complexity were defined for the GMUs of the MDB. Firstly for low priority areas, a basic analysis is undertaken which comprises an overview of the hydrogeological setting, a water balance showing recharge and current/potential future levels of groundwater extraction, and surface–groundwater connectivity mapping including estimation of surface–groundwater exchange fluxes as a snapshot in time. Secondly for high priority areas, a more detailed analysis is adopted which involves coupling river management models and numerical groundwater models.

2.1.2 Methodology for low priority areas

The low priority areas are those that have low groundwater use and limited potential for groundwater to impact streamflow. The assessment for those areas was limited to the following:

- describe the hydrogeological setting of the area
- provide a water balance showing recharge and current/potential future levels of groundwater extraction
- map the connectivity between surface water and groundwater. The type of connection between a river and the underlying aquifer depends primarily on the difference between the water heads in the aquifer and the river. Rivers that gain water from the aquifer have by definition a saturated connection to the aquifer. Losing streams on the other hand may have a saturated or an unsaturated connection to the aquifer. The river loss flux continues to increase as the groundwater level declines until it reaches maximum loss term (beyond which no further increase in flux occurs). The connectivity mapping for the MDB is shown in Figure 2-2.
- determine the fluxes for a range of future groundwater developments and the unrealised impacts of past developments using analytical solutions for stream depletion. The detailed methodology is given in Appendix III. The impact of groundwater pumping on streams depends on the type of connection (identified in the connectivity mapping), the aquifer properties, and most importantly the distance between the pump and the river. The estimation for these low priority catchments simplifies these relationships.

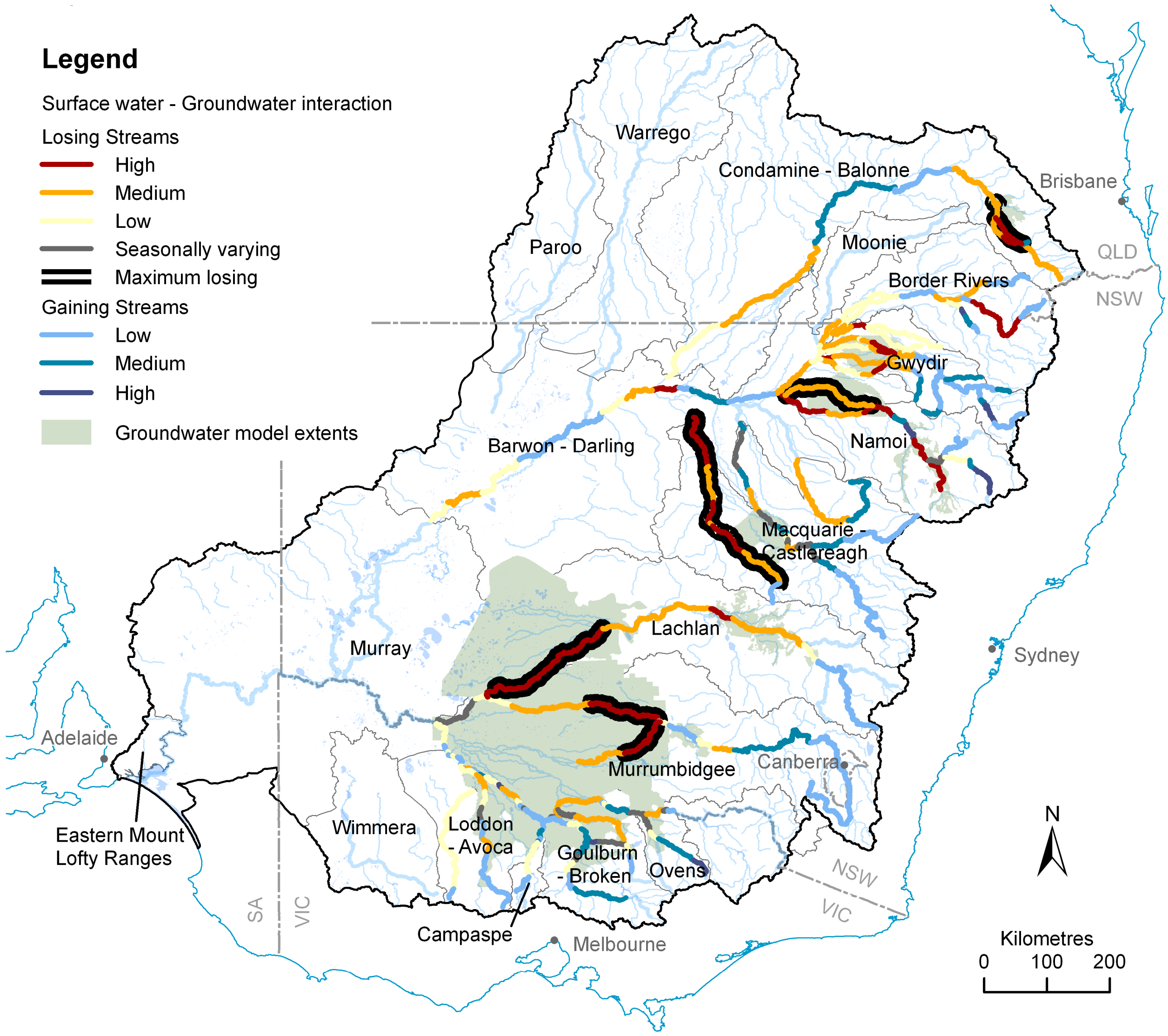

Figure 2-2. Surface–groundwater connectivity mapping for the Murray-Darling Basin

2.1.3 Methodology for high priority areas

High priority areas were characterised as either having existing numerical groundwater models (see Figure 2-2) or warranting the development of new numerical models. The numerical models (and hence the areas they were developed for) were subdivided into three subclasses depending on the level of confidence associated with their prediction capacity:

- Class 1 numerical models have been calibrated and have undergone thorough peer review. Such models have the capacity to produce high confidence predictions into the future (outside the calibration period).
- Class 2 models have been calibrated but have not undergone a peer review process. Such models might not produce high confidence results beyond the calibration period.
- Class 3 models are not calibrated or are poorly calibrated or conceptualised.

The methodology for assessing the interaction between groundwater and surface water for high priority areas is summarised herein. Streams are considered as boundaries for groundwater models: they either act as a source of water (i.e. losing water to the groundwater system), or they act as a drainage boundary (i.e. gaining water from the groundwater system). The difference in level between the stream stage and the groundwater level determines whether a stream is losing water to, or gaining water from, the groundwater aquifer. The time series flows at key gauging stations (which is converted to stage height, i.e. head) feeds into the groundwater model as a time varying river boundary condition, which the groundwater model uses to calculate the dynamic exchange flux between the river and groundwater aquifer. As time-variant (dynamic) exchange fluxes cannot be incorporated into all river models, a long-term average (herein termed dynamic equilibrium) flux is estimated. This is achieved by running the groundwater model with the river boundary condition for a warm-up period of 111 years followed by another 111 years in order to estimate the long-term average exchange flux at dynamic equilibrium (quasi-steady state) condition. The river model is then re-run with this modified exchange fluxes imported from the groundwater model.

River management models do not explicitly account for surface–groundwater interactions. However, these interactions are implicitly accounted for during the calibration period, implying that only groundwater developments that exist during the calibration period of the river model are implicitly taken into consideration. The groundwater developments that are accounted for in the river model are estimated (those that match the exchange fluxes already built in the river model). The groundwater model is run with those developments and an exchange flux is estimated accordingly (this is the fraction of the long-term flux that is implicitly accounted for in the river model calibration). The difference between this flux and the one previously estimated from the groundwater model (i.e. the long-term dynamic equilibrium) is added as an extra loss or gain to the river model. All other scenarios are compared to this baseline scenario. A more detailed description of the methodology is found in Appendix II.

3 Discussion

A number of lessons have been learnt during the Murray-Darling Basin Sustainable Yields Project with respect to the quantification of surface–groundwater exchange fluxes. In this discussion, a number of issues that arose from the approach, especially the 'dynamic equilibrium' approach, will be described with some recommendations for improvements.

There are several reasons behind the choice of the dynamic equilibrium approach. River models were run in the project for 111 years to cover a sufficiently long climate sequence to be considered representative. To estimate surface–groundwater fluxes, groundwater models needed to be run in conjunction with these river models, covering the same climate sequence in order to have inputs of river heads, flood recharge, etc. This effectively meant running models for 111 years. Without running a 'warm-up' period, there would be confounding effects from changes that occurred from the initial groundwater state as well as the climate sequence. By trying to achieve a dynamic equilibrium in the first 111 years, the second 111-year sequence should reflect climate alone. However, this approach is not without difficulties.

By definition, this approach assumes that a state of dynamic equilibrium is reached towards the end of the first groundwater model simulation. If this state is not reached, the integrity of the approach may be compromised. There are a few reasons why dynamic equilibrium is not attained. They include the use of unstable starting conditions, the existence of unsustainable groundwater extractions, and other stresses (such as irrigation and land clearing) whose effects were not fully realised during the groundwater model simulation period.

Groundwater models were usually calibrated over short periods of times (5 to 30 years) and models were generally designed to run over shorter periods of time. Running of the models under the dynamic equilibrium approach necessitates running them for 222 years. Issues that arose from this long run time include (i) the effect of boundary conditions that may artificially lead to high inflows, and (ii) long-term model predictions that are well beyond the calibration period (and hence the predictive capacity) of the model.

None of the groundwater models used were fully integrated surface–groundwater models and there were no instances of joint calibration of the groundwater and river models. In many cases, there were different calibrations for the surface water and groundwater models and changes in groundwater extractions and river management occurred during the calibration of the river model.

As the models were not designed to be run over the longer time periods, often evapotranspiration functions were not included and these became important. Available data became an issue as well as the practicality of transferring data between groundwater and surface water models.

This discussion is structured around these four groups of issues as summarised schematically in Figure 3-1. In Figure 3-1, the upper and lower blue rectangles represent the river and groundwater models, respectively; their lengths represent model run time. The dotted rectangle in the middle includes issues related to surface–groundwater interaction.

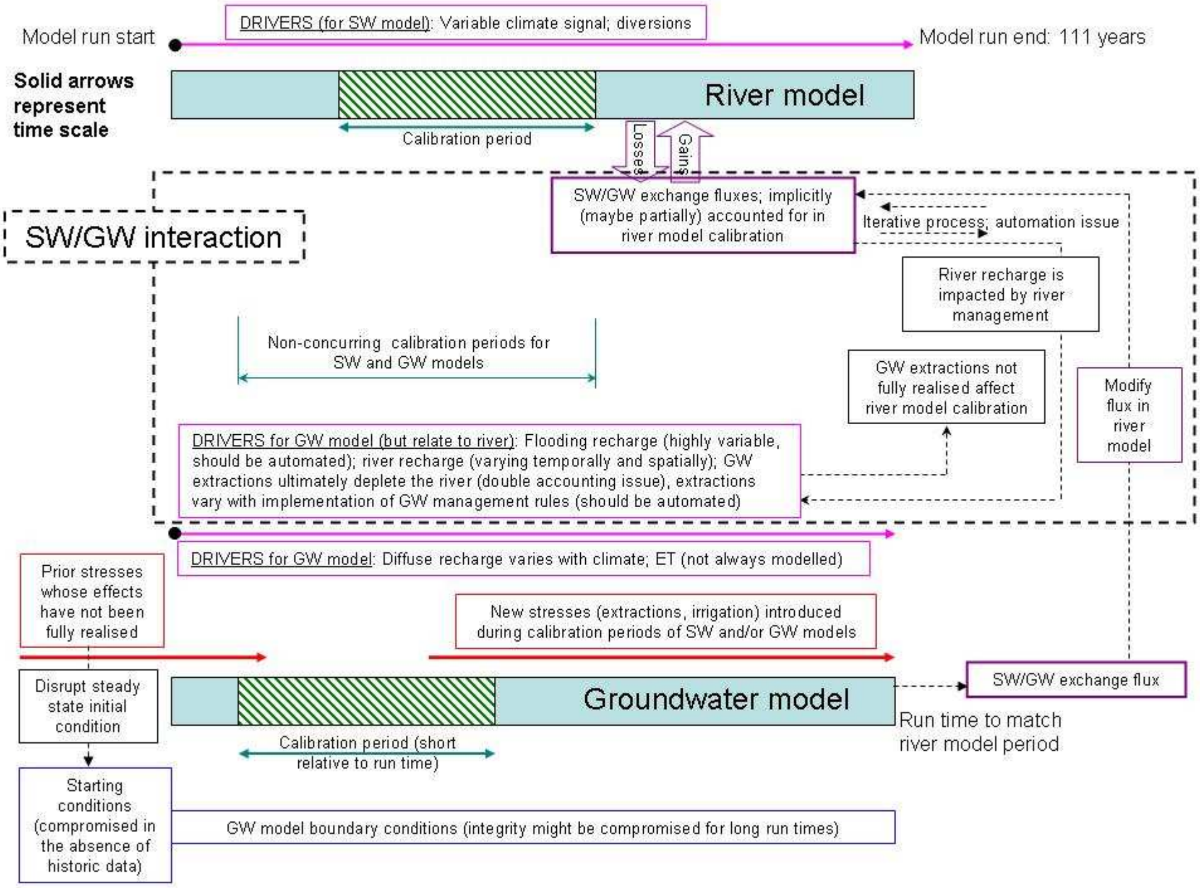

Figure 3-1. Schematic showing issues relevant to dynamic equilibrium approach

3.1 Why dynamic equilibrium is not always attained

As mentioned previously, not attaining a dynamic equilibrium may violate the underlying assumptions of the approach. This may be attributed to three different reasons:

- If the model is not calibrated with an initial steady state condition, and if the initial head distribution does relate to this steady state, then long-term change in model prediction may be related to this calibration rather than physical drivers.
- If the spatial distribution of groundwater extractions is not sustainable then groundwater storage continues to deplete. The aquifer is highly stressed. The stress state may be unsustainable when the applied pumping stresses exceed the total potential for recharge to the aquifer (both specified and head-dependent recharge fluxes).
- Stresses may be sustainable, but the steady state is not being achieved because the magnitude of the stresses is large and/or the aquifer diffusivity is low, both resulting in a slow response where the impacts require a long time to be realised (could be beyond the simulation time of the model).

The latter two dot points cannot be distinguished and hence are discussed together.

3.1.1 Starting conditions for numerical models

All models need to start from a user-defined initial condition. A hydrologically stable initial condition minimises any potential numerical problems that are likely to occur during the execution of the model. The most stable initial condition that can be used in modelling is steady state; under this condition, fluxes into and out of the model domain are equal and no water is taken from or added to aquifer storage. However, this condition is only realised long after a stress has been introduced to an aquifer system.

To predict the impact of recent groundwater developments, the most obvious initial condition should relate to without-development conditions (i.e. before irrigation from either groundwater or surface water, and in some cases before clearing of native vegetation). The steady state initial condition described above can only be achieved with a proper calibration process that requires a good set of without-development data. Often, there is not the appropriate data available and models are calibrated in a stressed state (e.g. the Upper Condamine model). In such cases, it is unclear whether the calibration of the model would have led to the initial conditions of the model and if not, when the model is used for prediction, it is likely to lead to long-term drifts in outputs that are unrelated to physical drivers. A steady state without-development model was used as the starting condition for the Lower Namoi model. However, this did not occur for most of the other models (e.g. Upper Namoi and Upper Condamine).

There are several complications in deriving a without-development steady state condition:

- It may be difficult to obtain data especially for groundwater extraction and head distributions for earlier times.
- There may be a large change in the surface–groundwater connection. In some areas, streams changed from being gaining to losing as a result of sustained pumping. Thus conditions may have changed considerably from those now and hence model calibration needs to be appropriate for conditions of both gaining and losing streams. For example, evapotranspiration may have been important in the without-development situation but not for the developed aquifer. Hence in the current model, an evapotranspiration function may not exist and hence is not able to replicate pre-developed heads.
- Surface water irrigation introduced in the 1970s in many regions of the MDB has resulted in increased recharge occurring for some period of time before groundwater extraction started. This leads to groundwater mounds forming and expanding. Hence, the chosen without-development period ideally should precede these surface water irrigation developments.

3.1.2 Highly stressed aquifers

The most commonly observed situation where steady state cannot be achieved is when groundwater extractions exceed inputs (i.e. pumping exceeds recharge) for some part of the aquifer. Groundwater storage continues to deplete until parts of the aquifer dry out or cones of depression expand until there is sufficient recharge captured to match the extraction rates. Other drivers that prevent dynamic equilibrium being attained include increased recharge as a result of surface water irrigation or clearance of native vegetation for dryland agriculture. For regional aquifers the response time for this increased recharge may be longer than 111 years.

Figure 3-2 shows the change in groundwater level over the duration of Scenario A for the Lower Namoi groundwater model. Drawdown is shown for Layer 1 of the model and water level declines of more than 10 m can be seen. Figure 3-2 also illustrates that several model cells have dried out (groundwater levels have fallen below the base of the cell) during the course of the model run. Hydrographs predicted at locations near the centre of groundwater pumping (Figure 3-3) illustrate groundwater levels that fall in response to ongoing extraction and then rise as the model cells dry out and pumping is automatically terminated from those cells. Figure 3-4 shows that the total recharge under Scenario A is, on average, lower than pumping and total pumping exceeds total recharge 68% of the years under Scenario A.

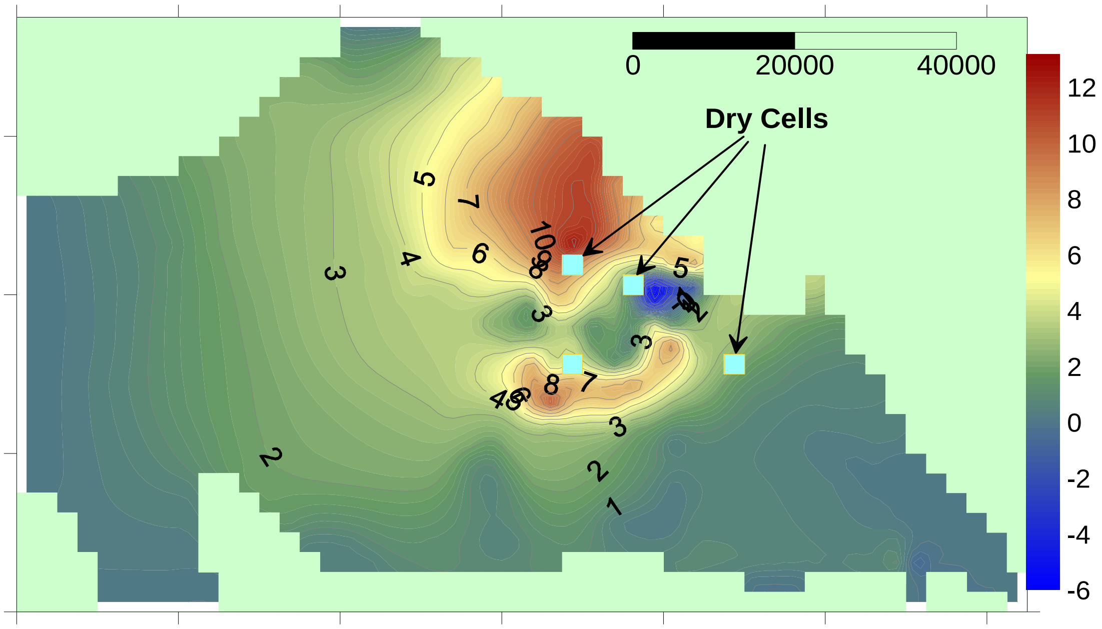

Figure 3-2. Drawdown (m) in layer 1 after 111 years for Lower Namoi model under Scenario A

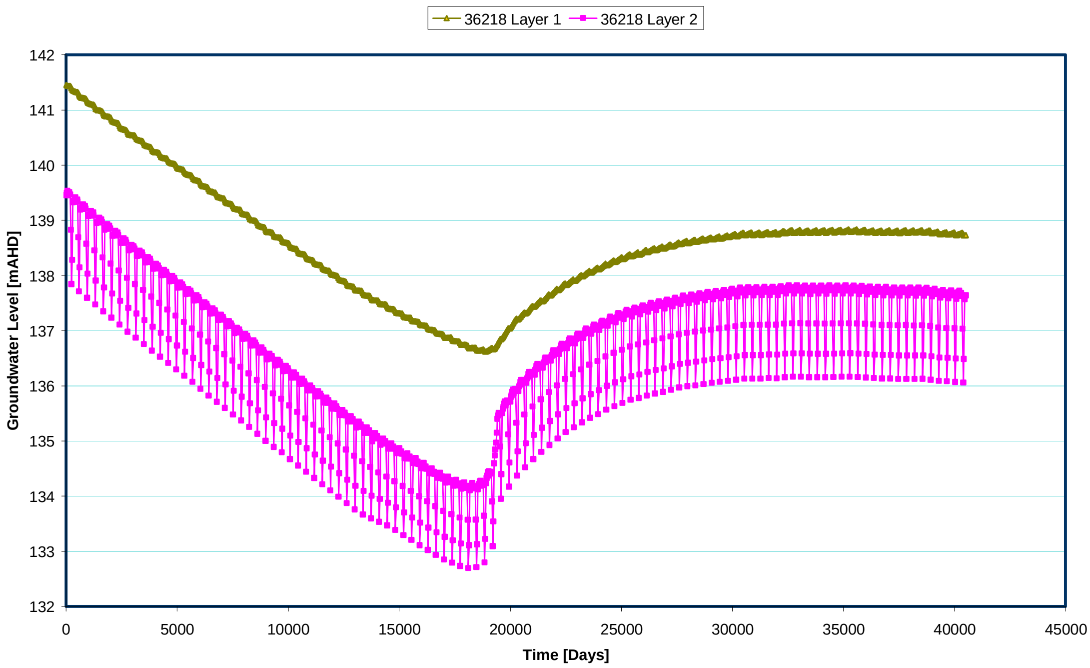

Figure 3-3. Calculated hydrographs at Bore #36218 for Lower Namoi model under Scenario A

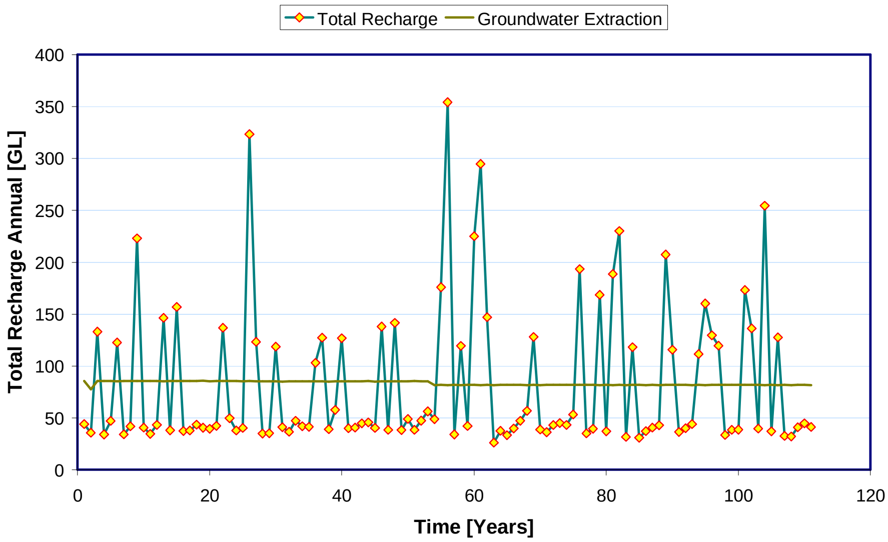

Figure 3-4. Total recharge and groundwater extraction for Lower Namoi model under Scenario A

The Lower Lachlan model simulates a large area; in fact the model area is several times larger than the area in which extraction bores have been drilled. This model, when run through the warm-up and scenario models, never reaches dynamic equilibrium because storage changes associated with falling groundwater levels persist throughout. This can be seen in predicted hydrographs (Figure 3-5) and in the changes in mass balance components that arise from the introduction of groundwater pumping to the model.

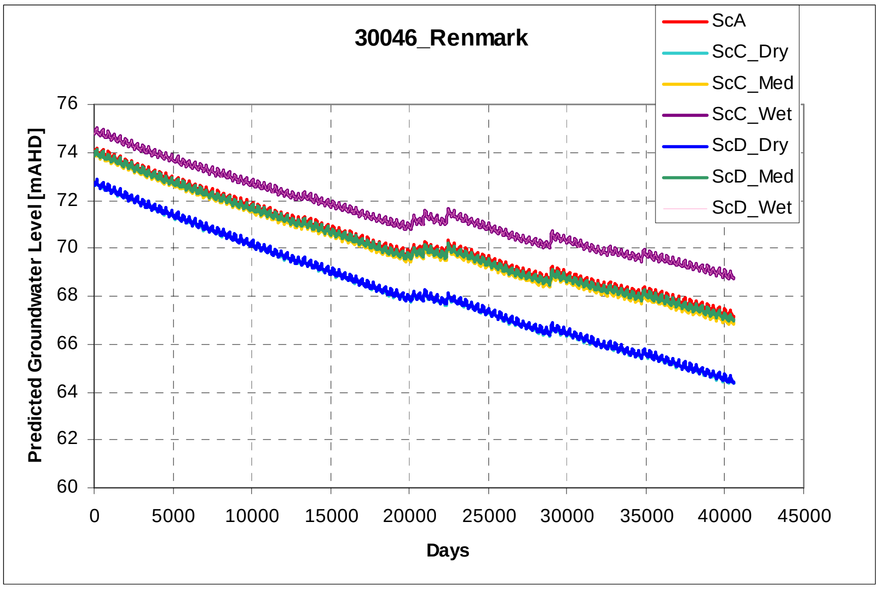

Figure 3-5. Calculated hydrographs at Bore #30046 (Renmark Group) for Lower Lachlan groundwater model under scenarios A, C and D

Figure 3-6 shows the changes in mass balance components under Scenario A that result from the introduction of groundwater extraction. It has been obtained by comparing the model fluxes under Scenario A (including the warm-up period) with those found under the no pumping version of Scenario A. It can be seen that for the entire duration (222 years) changes in groundwater storage associated with falling water levels provide the majority of water extracted from the aquifer. As the model runs proceed in time, lateral groundwater fluxes and river recharge rise.

Figure 3-7 shows that the changes in river flow (reduction in baseflow and increase in leakage from the river to groundwater) continue to rise for the duration of the scenario.

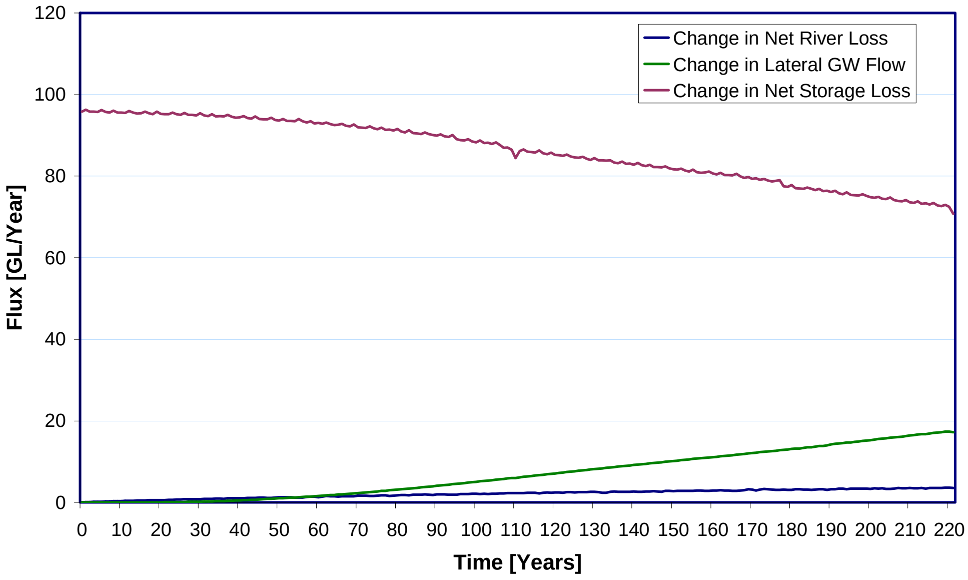

Figure 3-6. Mass balance changes caused by groundwater extraction in Lower Lachlan model

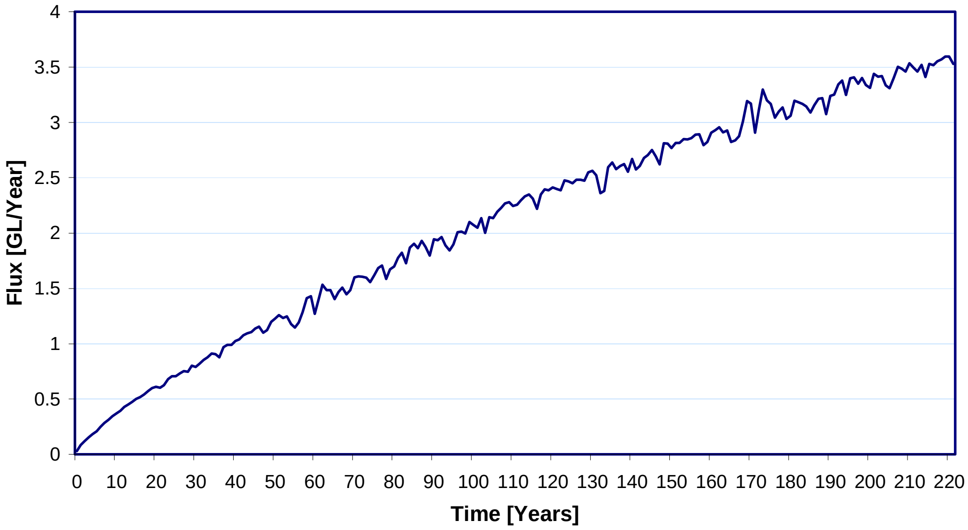

Figure 3-7. Groundwater flux to the Lachlan River from Lower Lachlan model area under Scenario A

Implementation of management rules

The dry cells shown in Figure 3-2 indicate that the level of groundwater extraction is not sustainable. Falls in groundwater levels are likely to trigger management intervention or changes in irrigator responses, either of which are likely to lead to reduced groundwater extraction. There needs to be a shift to groundwater management models which have rules not dissimilar to those of surface water planning models. These rules may include trigger groundwater levels, water trading, irrigator response to changing watertables, river flows and climate variability and water quality changes. Simulation of management intervention was carried out for the Campaspe groundwater model. This allowed actions to be taken (namely reductions in groundwater withdrawals within predefined zones) at user-specified intervals on the basis of a set of operational rules involving the aquifer system performance (for example, piezometric head relative to given benchmarks) evaluated at given trigger locations. The management intervention scheme resulted in reduced pumping rates by as much as 70%. However, in most cases they did not cause groundwater levels to rise above the trigger levels. It is also possible to prevent cells from drying by relating water extraction to pressure head, which can be achieved using the drain package of MODFLOW. This is an easy way to implement management rules that prevent the aquifer from drying out when modelling long-term dynamic equilibrium.

3.2 Issues related to boundary conditions caused by the dynamic equilibrium approach

Specifying the appropriate boundary conditions is one of the most critical tasks in groundwater modelling. In contrast with model parameters, boundary conditions cannot be calibrated (iteratively changed during sequential runs until model outputs are in good agreement with observed data). As boundary conditions are so critical, they should be derived from a comprehensive understanding of the hydrogeological setting of the modelled aquifer.

It is common practice in modelling to place boundaries at a very large distance away from stress locations, so that the type and location become less important. As long as the perturbations do not reach the boundary, the modelling exercise is sound. However, sometimes this condition is violated. Once this happens, the type of the boundary can make a great difference, e.g. a head boundary (constant or general) means an infinite supply of water into the model domain whereas a no-flow boundary would by definition stop any water from flowing into the model area. This phenomenon becomes critical when run time becomes large. Groundwater models are usually calibrated over shorter periods of time during which the model is not sensitive to boundary conditions. Once the boundary conditions become more important in the scenario run, it is highly likely that the calibration no longer holds.

Groundwater extraction can lead to large changes in the different components of the groundwater balance. It is sometimes useful to think how the quantity of water being extracted relates to changes in the different components, i.e. a 10 GL/year extraction might lead to a change of 5 GL/year to rivers, 4 GL/year in evapotranspiration and 1 GL/year in lateral fluxes. In this regard it is important to understand that changes in lateral groundwater flows at the model's boundaries are often modelling artefacts that do not necessarily identify the true changes in the water cycle that arise from groundwater extraction. If there is insufficient recharge within the model area, the zone of impact of groundwater extraction will expand until changes in the fundamental mass balance components match the applied groundwater pumping stresses. In other words, changes in lateral groundwater flows at the model boundary do not represent a true source term in the mass balance equation for the entire hydrological domain.

Figure 3-8 shows the change in mass balance components for the Upper Condamine groundwater model. This data has been obtained by comparing mass balance fluxes under Scenario A (including 111 years of warm-up) to the same fluxes under Scenario A with no groundwater pumping. The fluxes shown in Figure 3-8 represent changes in the model mass balance brought about by the groundwater extraction of Scenario A. In this case the Scenario A pumping stabilises at about 32 GL/year. Changes in lateral groundwater flow represent about 5 GL/year by the end of the Scenario A model. This change in mass balance is approximately 15 percent of the total pumping included in the scenario. If the lateral flow artefact is removed from the model then the potential change in river flow might rise from about 12 to 17 GL/year.

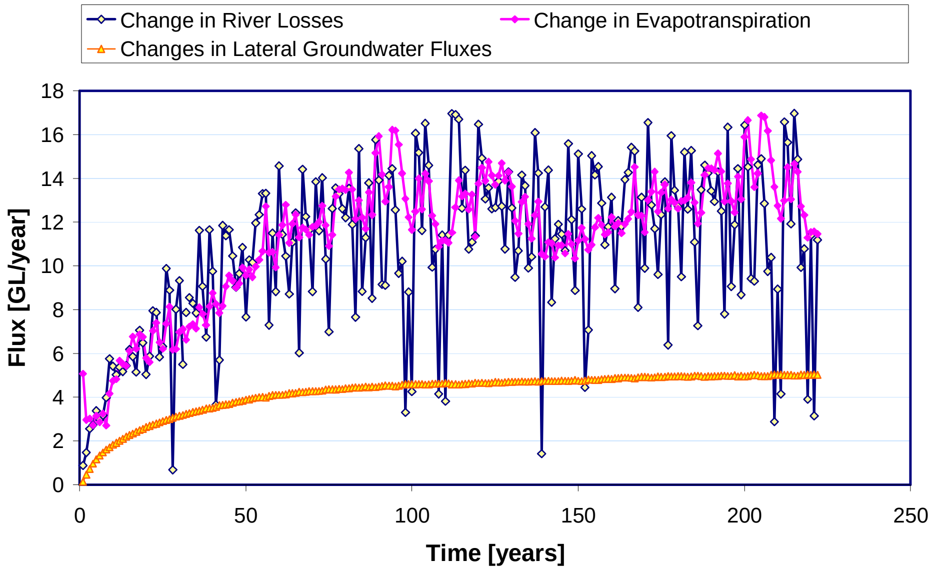

Figure 3-8. Effects of groundwater extraction on model mass balance for the Upper Condamine model

3.3 Issues related to the coupling of surface water and groundwater models

3.3.1 Calibration periods for groundwater and river models

The most common calibration approach for river modelling is to calibrate over a period of time for which there is good data on mass balances and surface water diversions. River models implicitly account for surface–groundwater interactions that occur during their calibration period, often through unattributed gains and losses. These terms also include fluxes due to other processes (e.g. wetland filling, floodplain evapotranspiration etc) as well as mass balance errors in the model. The river model will then be used to support decision-making over another period of time. The groundwater fluxes to the streams are likely to have changed from the calibration period and this change needs to be accounted for.

Most of the groundwater models were calibrated over a period of time for which there was good groundwater data available. Often there were increases in groundwater extraction during the calibration period. Within the models, river interaction may be accounted for using flow predictions during that period of time or known flood sequences. They would include recharge from surface water irrigation.

Since the surface and groundwater models are generally developed independently, the calibration periods may be quite different. The climate period may be atypical of that for the longer period, river regulation may have changed during the groundwater calibration period, groundwater fluxes may have changed during the surface water calibration, etc.

Figure 3-1 shows schematically the issues that relate to estimating the changes in surface–groundwater exchanges. These changes in fluxes are measured relative to the calibration period of the river model. To estimate fluxes, there should be a time period common to both the river and groundwater model calibration periods that is used as a reference. This may mean extending calibration periods to ensure a common period.

3.3.2 Stream recharge

Streams can be an important source of recharge to groundwater systems. Modelling this recharge raises a number of issues.

Ephemeral streams

The modelling of stream recharge from the river channel occurs through the setting of river cells in the groundwater model. This can be problematic, where streams are either naturally ephemeral or have become intermittent in flow due to excessive diversion and groundwater extraction. In modelling such phenomena, it is important to introduce a mechanism by which the boundary condition can be activated and de-activated to allow recharge of the aquifer only when they flow. The main branch of the Upper Condamine River was only activated during observed flow conditions (this was achieved by manipulating the MODFLOW river conductance term); the northern branch of the Upper Condamine River was deactivated completely reflecting the fact this branch rarely flows and watertables are now more than 20 m below the stream bed.

Flood recharge

The importance of flood recharge varies from one area to another in the MDB. For example, in the Lower Namoi, 56 percent of the groundwater inputs are river recharge. This predominantly is a result of flooding inundation. In contrast, the Upper Namoi has a 23 percent river recharge component out of which only 4.5 percent is flood recharge. The Lower Gwydir model does not have a flood recharge component.

In areas where flooding is an important mechanism of recharge, uncertainties in the frequency of flooding events and their magnitudes may lead to large errors. Therefore, inundation areas should be dynamically linked to river flows and should be verified based on historical evidence. Increasing the magnitude of recharge during the simulation may be achieved by increasing the river conductance during the event. The magnitude of the increase in recharge may be estimated using a mass balance approach where volumes are calculated following flood events based on observed heads. This approach was implemented in the Lower Namoi model. The Lower Lachlan recharge zones are shown in Figure 3-9. This map demonstrates the extent of flooding assumed in the model as the area that receives elevated recharge fluxes at times of river flooding. In areas that have low-permeability impeding layers, water would perch and hence delay or eliminate recharge.

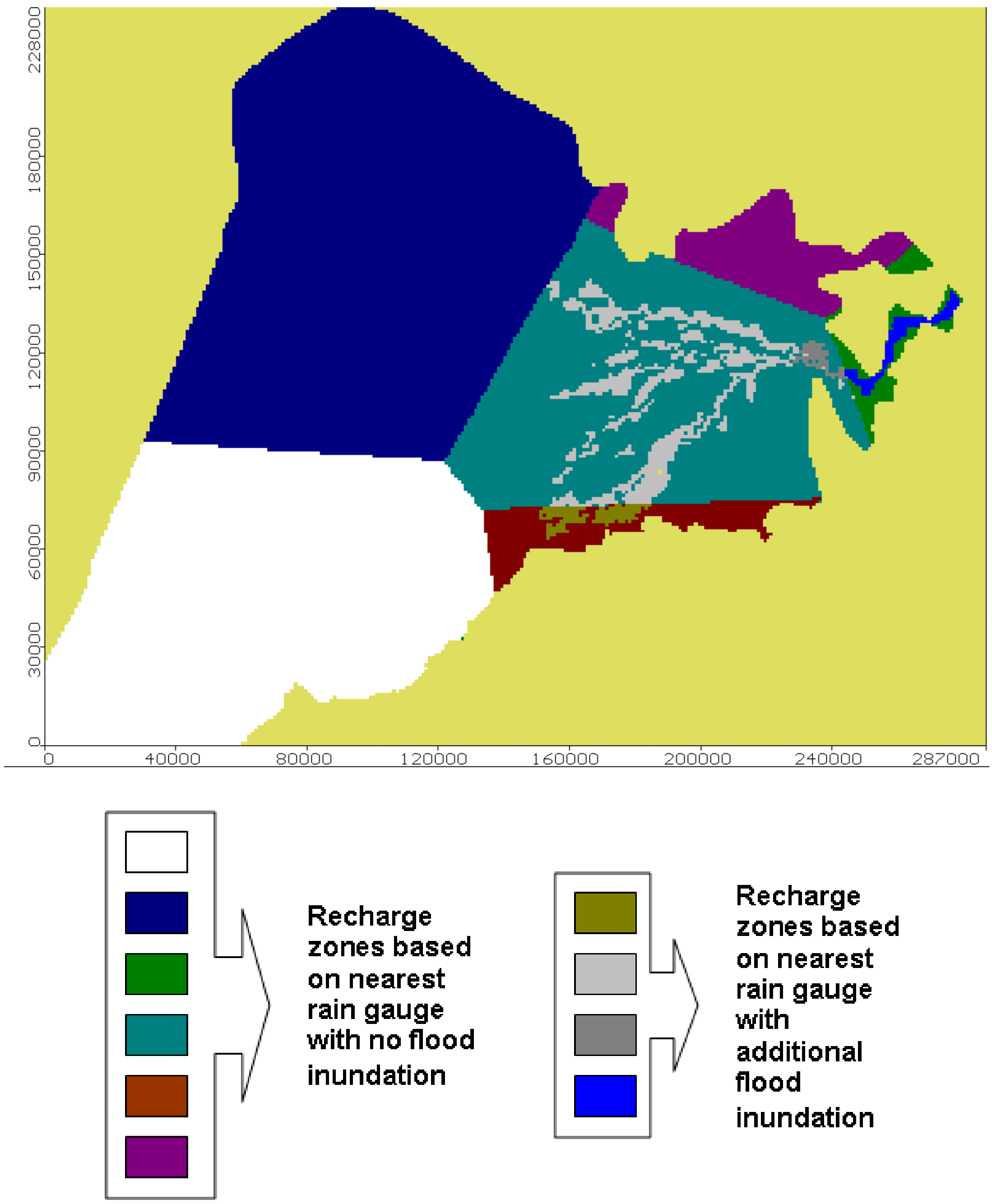

Figure 3-9. Recharge zones showing regions of periodic inundation in the Lower Lachlan

In the Lower Namoi model, river bed conductance was increased during flood events. Also, inundation zones in floodplains were defined based on observed stream hydrographs.

3.4 Other issues

3.4.1 Evapotranspiration

Evapotranspiration is a major component of the groundwater water budget in vegetated areas that have relatively shallow groundwater levels especially in areas with wide floodplains. Many of the groundwater models in the MDB did not include evapotranspiration such as the Lower Lachlan, the Lower and Upper Namoi and the Gwydir. The new Upper

Lachlan model did model evapotranspiration; Figure 3-10 shows mass balance and amount of evapotranspiration. Note that groundwater pumping, which lowers the watertable, may capture water that would otherwise discharge as groundwater evapotranspiration (see Rassam et al., 2007). This further complicates the task of establishing without-development models as they might have had an evapotranspiration component that does not exist today due to the impacts of groundwater development.

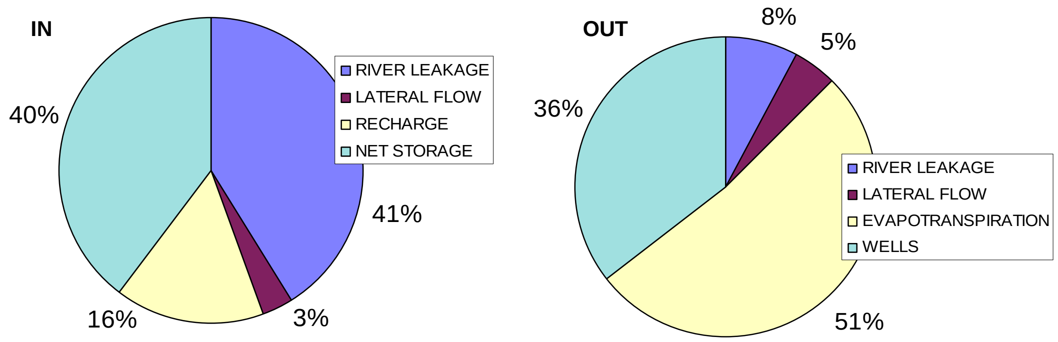

Figure 3-10. Mass balance for calibration model (total flow in = total flow out)

3.4.2 Reliability of data

Reliable groundwater extraction data is critical to model calibration and especially where surface–groundwater interactions are involved. This data includes the spatial distribution and magnitude of pumping. The use of metered data alone (i.e. ignoring unmetered bores or stock and domestic supply) can grossly under estimate total extraction. Many areas suffer from unreliable data, e.g. in the Upper Condamine, the Lower Oakey Creek alluvium has no extraction records. Under-reporting of extractions is common in areas where there is no control over meter reading.

In the Murray-Darling Basin Sustainable Yields Project, future groundwater developments (Scenario D) were modelled merely by scaling up the pumping rates without any spatial expansion of the pumping areas. Ideally this would be done through consideration of potential scenarios for groundwater extraction. The spatial distribution of groundwater extraction can lead to different drying patterns for the aquifer. A more distributed extraction would decrease the likelihood of aquifer drying. However, it is not always possible to predict how groundwater extraction will be distributed in future and hence the need for analysis of several different scenarios. The proximity of groundwater extraction to streams can affect the impact of streams.

Figure 3-11 shows a scenario analysis for the Mid-Murrumbidgee groundwater model.

Another common and serious problem is the lack of reliable AHD levels at gauges. The lack of reliable records may lead to serious errors as this would directly impact the pressure head imposed as a river boundary in the groundwater models.

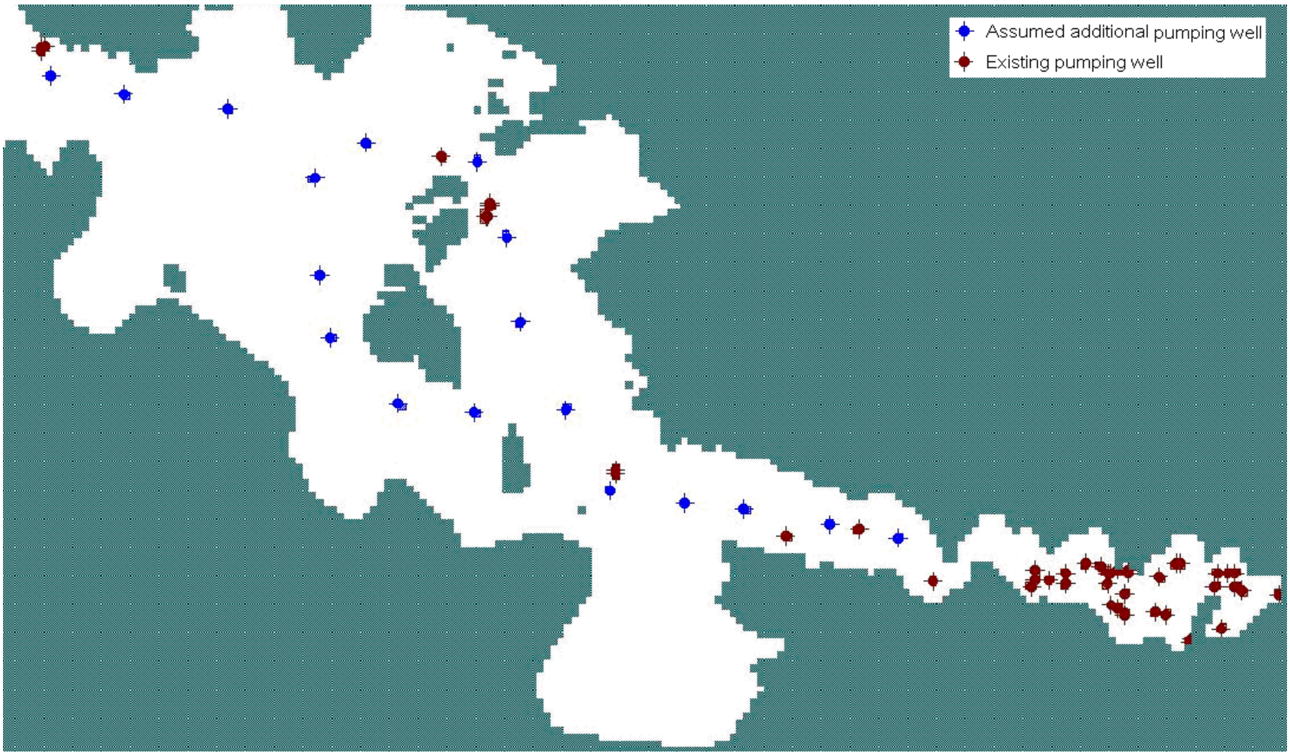

Figure 3-11. Spatial extent of pumping under Scenario D in the Mid-Murrumbidgee model

3.4.3 Automation of tasks

The sequencing of model runs and the transfer of data from surface water model to groundwater model and vice versa can be tedious and long, given the long time periods being simulated. The translation of river flows to stage heights, the interpolations of these heads and the modification of groundwater input files are often done outside of any of the current packages. Where several scenarios need to be run or stochastic modelling is involved, this can be simply impractical. In this report, co-calibration of groundwater and surface water models is recommended. This involves several iterations of both groundwater and surface water models and would be nearly impossible without some automation.

In the Murray-Darling Sustainable Yields Project, the Southern Riverine and Murrumbidgee groundwater models were linked to river models in an automated mode, as described in Appendix II. This is not the only way such models could be linked, but does represent a significant advance in the limited time available. It is likely that in Project D3 of the eWater Cooperative Research Centre this issue will be re-examined within the river modelling framework being developed by eWater.

A further impetus for automation is in the need for including management rules. While this capacity is included in some versions of groundwater models, these are rarely done in existing implementations. It is also likely that there is a need to link to other models to drive these management rules. This can be made relatively easy through software linkages.

Automating certain processes within groundwater models such as flooding recharge is required. This issue becomes particularly significant in areas where flooding is an important mechanism of recharge. In such areas, inundation should be dynamically modelled in the groundwater model based on observed flow time series obtained from the river model. This may be achieved by changing the river bed conductance during the simulation. This approach was implemented in the Lower Namoi model.

3.5 Proposed alternative modelling approaches for future studies

3.5.1 Stochastic modelling approach to avoid the need for prolonged run times

Many of the problems of the dynamic equilibrium approach can be dealt with through measures such as having steady state without-development models, larger model areas, longer run times etc. Nonetheless, there is a need to consider alternatives that avoid these problems.

The main purpose of such modelling is to provide inputs to the water allocation or water sharing process. These processes vary between jurisdictions but are meant to occur every 5 or 10 years. Hence the plans are formulated on the basis of supporting water allocation for the following 5 to 10 years. Therefore groundwater modelling needs to be concerned with the state of the groundwater system over that period and hence is strongly related to the current state of the groundwater system. Normal groundwater modelling uses a 'forecasting' approach which projects groundwater state from the current system.

The dynamic equilibrium approach leads to a break from the current groundwater state. The rationale for this is described above. The 111-year simulation provides a representative distribution of climate for the river models and the dynamic equilibrium approach allows these models to be run in conjunction with groundwater models.

There is an alternative that allows the groundwater models to be used in the normal 'forecasting' mode but also allows a full range of rainfall scenarios to be considered in conjunction with the river models. The following sequence is suggested (shown schematically in Figure 3-12):

Obtain river heads

The river model is run and calibrated in the normal way. The river flows are converted to stage heights and exported to the groundwater model to become a river boundary condition. River models have unaccounted gains/losses built into their calibration, although surface–groundwater exchange fluxes are only a component of these. This surface–groundwater flux can only be estimated correctly by a groundwater model.

Obtain true surface–groundwater exchange flux

A groundwater model is built to estimate the exchange fluxes that have implicitly been considered in the calibration of the river model. The groundwater model should ideally start from a steady state without-development condition.

Re-calibrate river model

Exchange fluxes that occurred during the calibration of the river model (estimated by the groundwater model) are imported back into the river model and are treated as 'known groundwater gains/losses'; the river model is then re-calibrated.

Scenario river modelling

River models are run for 111 years in order to capture climate variability for the various climate scenarios. Alternatively, the river model can be run in a stochastic manner for periods ranging from 20 to 30 years. Those periods should coincide with the calibration periods of existing groundwater models. That way we capture the climate variability but avoid the problem associated with the prolonged runs of the groundwater models.

Estimate true surface–groundwater exchange flux under various scenarios from groundwater model

Time series for river heads under the various climate scenarios are exported from the river model to the groundwater model. Depending on the run time of the groundwater model, all the stochastic head time series (hundreds of them) or representative head time series (which are selected statistically, for example the median, the 10th and/or the 90th percentile) are imported into groundwater models. The groundwater model is run and the exchange flux is estimated.

Re-calibrate river model

The fluxes under the various scenarios are exported back to the river model, which is then re-calibrated; subsequently, the storages of the river model are finally adjusted. The exchange fluxes under the various scenarios (reported as upper- and lower-bound exchange fluxes) are compared with the baseline (Scenario A) flux.

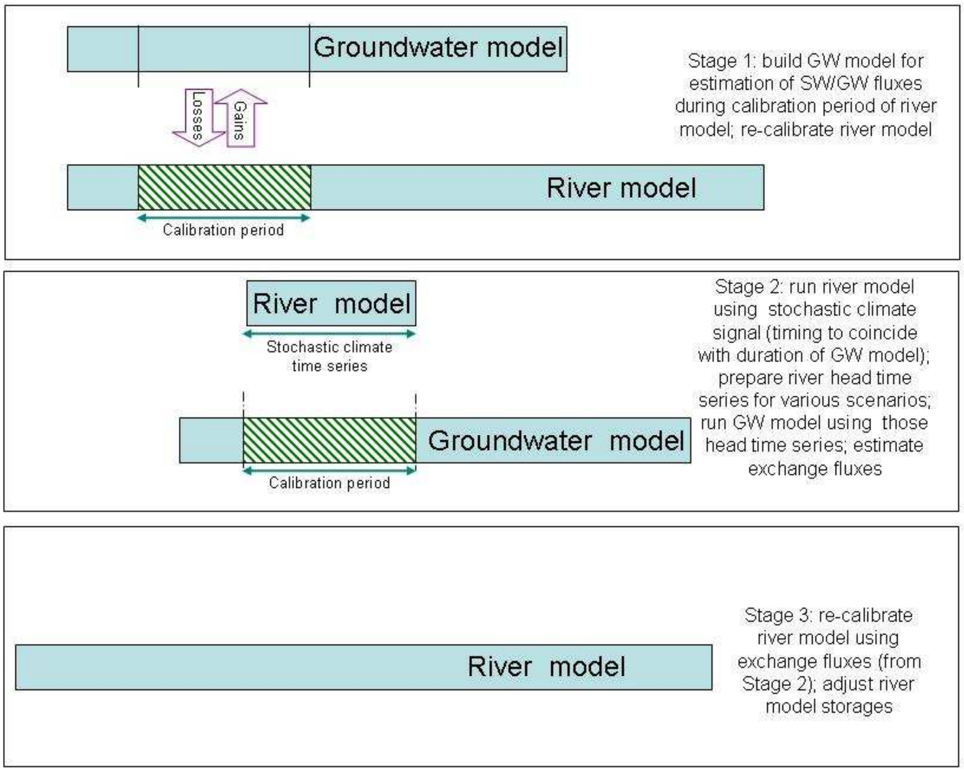

Figure 3-12. Schematic showing stochastic modelling approach

The proposed methodology overcomes the shortcomings associated with the dynamic equilibrium approach (discussed in this report) as follows:

- A groundwater model that is calibrated based on historical without-development conditions is used to estimate the true surface–groundwater exchange flux, which is used to re-calibrate the river model.
- The stochastic approach avoids running the groundwater model for prolonged periods of time thus overcoming the problem associated with the long run times.
- The coincidence of the timing of the stochastic runs with the calibration periods of the groundwater model ensures that the estimated exchange flux is correct, i.e. includes effects of river management on groundwater models and vice versa.

3.5.2 Proposed methodology for narrow alluvial areas without a groundwater model

Low priority areas were recognised as those that do not have substantial groundwater development. However, the cumulative impacts of individual developments are significant on the basin scale. Such areas do not have, and are unlikely to have, numerical groundwater models. A simpler approach has been used for this project (see Appendix III). The key issues related to this analysis included:

- The estimation relies on a connectivity that is effectively a best-bet estimate. These estimates will improve as more studies of surface–groundwater connectivity are completed.
- Data on spatial distribution of groundwater extraction is poor for non-metered extraction. The methodology relies on knowing in what catchment the extraction is occurring.

- Surface water inflows are modified assuming that groundwater extraction impacts are constant. For areas near the river, temporal patterns of impacts are far from constant and induce leakage from the river.

An approach is proposed here in response to the last issue. This is particularly important where extraction occurs from narrow alluvia adjacent to the river.

The river network is spatially classified based on the type of surface–groundwater interaction that is prevailing (see Table 2-1). This is informed by the connectivity mapping that has been done for the MDB as shown in Figure 2-2. Further interactions may occur during flood events within bank capacity and during overbank flood events. Groundwater pumping triggers further (man-made) interactions as extracted groundwater eventually depletes nearby streams. The relevant processes are conceptually shown in Figure 3-13. This approach is being implemented in Project D3 of the eWater Cooperative Research Centre. Analytical solutions (e.g. Glover and Balmer, 1954) that require minimal parameterisation are used to quantify the surface–groundwater exchange fluxes. A groundwater bucket that accounts for the exchange fluxes with the groundwater is coupled to the river model. Based on our best understanding of the surface–groundwater interaction processes that are likely to take place, we estimate those interactions as an in-out flux to and from the river model links.

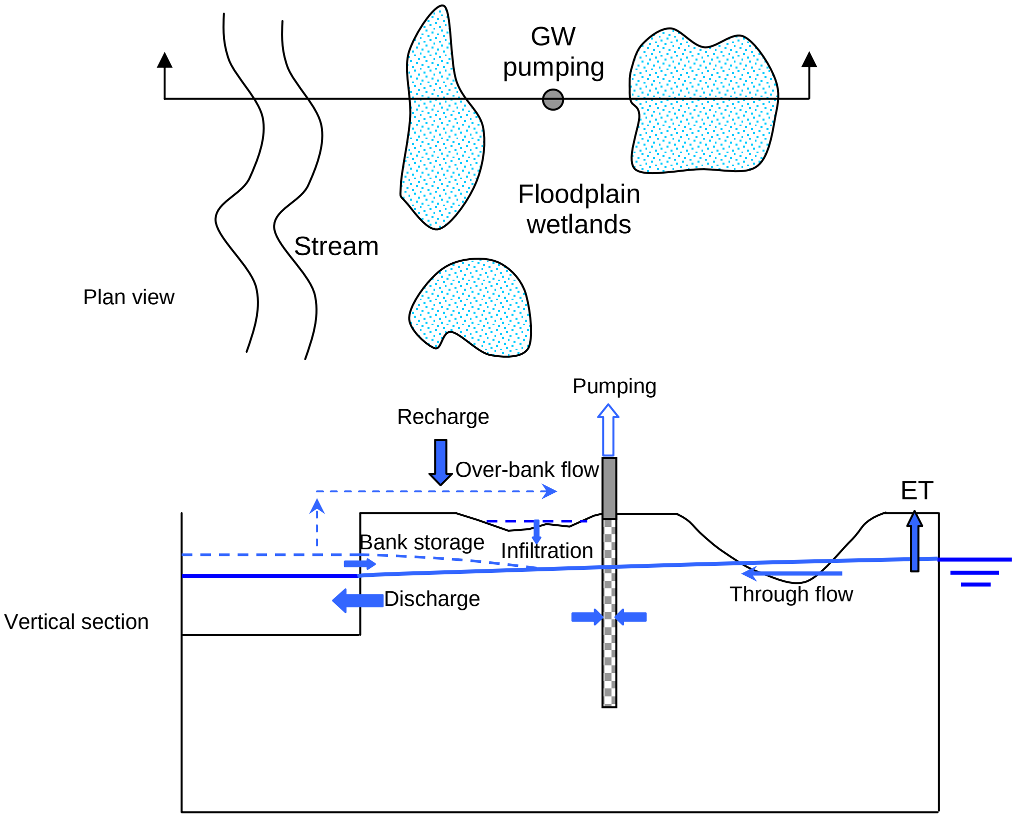

Figure 3-13. Conceptualisation of surface–groundwater interaction in floodplains

4 Recommendations

The following recommendations for future modelling exercises are based on lessons learnt from the Murray-Darling Basin Sustainable Yields Project.

1. For a successful implementation of the dynamic equilibrium approach, the following guidelines are recommended:

1.1. Ensure that dynamic equilibrium is reached. This is achieved as follows:

- Calibrate groundwater models for steady state conditions, preferably from a without-development state. This ensures that the simulation is sufficiently stable in order to be able to be run over periods of 100 years in line with surface water planning models.
- Ensure that groundwater extractions are sustainable. This may require a shift to groundwater management models. Such models have rules similar to those of surface water planning models to ensure sustainable groundwater extraction. These rules may include trigger groundwater levels, water trading, irrigator response to changing watertables, river flows and climate variability and water quality changes.
- Simulate for a long enough time to ensure that the impacts of the imposed stresses are fully realised.

1.2. Models should have sufficiently large areas to ensure that the imposed boundary conditions are distant enough so that they do not lead to artificial inflows that may occur due to prolonged run times.

1.3. There needs to be consistent calibration periods for surface water and groundwater models where the impacts of groundwater development are accounted for in river model calibration and river management rules are accounted for in groundwater model calibration.

1.4. There is a need for greater automation of changing input and output files in both groundwater and surface water models. This includes dealing with floods in a predictive sense, changing flows into stage heights and interpolation between gauging stations and including changes in fluxes into loss and inflows to river models. This issue is particularly relevant for stochastic runs.

1.5. There is a need to obtain extraction data within GMUs and within subcatchments, showing distance from river and aquifer being used. There is great emphasis on the reliability and consistency of groundwater extraction data regarding both magnitude and spatial distribution.

1.6. There is a need to better handle areas with wide floodplains and shallow groundwater levels where the effects of evapotranspiration and flood recharge are taken into consideration.

2. A consistent methodology to evaluate surface–groundwater interactions in areas with no groundwater models needs to be established. Such areas might not have groundwater models since groundwater development is not high. However, the cumulative impacts of developments may still be significant in those areas.

3. Alternative approaches to the dynamic equilibrium approach should be considered in order to avoid some of the associated problems. Running river models for 20 to 30 years stochastically then statistically selecting representative head time series and importing them into groundwater models may overcome the problems associated with running the groundwater models for prolonged durations (over 100 years). It is also recommended that once the exchange fluxes are imported back to river models, they should be re-calibrated, with storages modified accordingly.

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Appendix A: Methodology for modelling surface–groundwater interactions

The groundwater modelling and assessment quantitatively assesses the behaviour of groundwater systems across the Murray-Darling Basin (MDB) under each of the four scenarios. This is achieved by modelling and assessing groundwater management units (GMUs) using a range of methods appropriate to differing resource importance of different GMUs. In addition to the climate aspects of the scenarios, the following scenario aspects are used for the groundwater modelling. Scenario A: (i) river heights from river model; (ii) historical flood data used; and (iii) current groundwater use (taken as irrigation use in 2004/05 season if this is close to average). Scenario B and C: (i) river heights from river model; (ii) diffuse recharge based on Scenario A adjusted by a factor calculated from WAVES model outputs; (iii) flood data from estimates of flood recharge as a function of flow volume (or other method); and (iv) current groundwater use. Scenario D: (i) river heights from river; (ii) diffuse recharge estimated using a factor calculated from outputs of the WAVES model; (iii) flood data from estimates of flood recharge as a function of flow volume (or other method); and (iv) changes in groundwater use and application of groundwater management rules.

IQQM, REALM and MSM-BIGMOD models are calibrated to achieve mass balance within calibration reaches over time. In some cases models are calibrated over a short fixed period of time (e.g. 10 years) with loss relationships and ungauged inflows derived to achieve mass balance (explicit calibration). The period used in each calibration reach may vary depending on the availability of data over time. The model is then run for an extended period of time and consequently the relationships that are derived during calibration are represented over the extended period of time. In other cases the calibration involves deriving an unaccounted difference between upstream and downstream gauges over the entire modelling period (implicit calibration). In such cases the losses and gains represent the change in loss and gains across that period. In other cases a combination of approaches may be applied.

As the explicit calibration is derived over a short period of time the groundwater losses or gains that exist over that period of time are contained within the relationships derived to achieve mass balance. For the implicit calibration the groundwater losses and gains represent the change in groundwater loss or gains over the full period of the model.

The current surface water to groundwater flux is estimated from the groundwater models as the average flux that exists at the time of calibration for each calibration reach. For the implicit calibration this is likely to be close to the undeveloped or minimal groundwater extraction scenario for all reaches.

The method used in this project aims to represent the surface–groundwater fluxes that would exist for a fixed set of development conditions. To determine these fluxes the groundwater models are run to achieve what is termed a dynamic equilibrium, i.e. a flux that is only driven by climate inputs and not development. This is achieved by running the groundwater models for a warm-up period of 111 years and then a further 111 years to determine the dynamic equilibrium flux. Where groundwater impacts are considered significant (at least 50% of the 95th percentile flow of when it is flowing) and models do not exist, an estimate of the dynamic equilibrium groundwater flux is made.

To be able to make reasonable comparisons between the scenarios the groundwater models need to reach dynamic equilibrium. This creates a new baseline scenario that considers the difference between the groundwater fluxes that are currently included in the model and the ones at dynamic equilibrium. There are two ways of approaching this problem: (i) add the change in flux between what currently exists in the surface water models and dynamic equilibrium; or (ii) subtract the groundwater fluxes that are currently considered in the surface water model and then add the fluxes for dynamic equilibrium. Both methods achieve the same results but the first method is used as it is easier to implement in the surface water models. Note for this case the difference between all scenarios and the current groundwater flux needs to be included in the surface water model. Impacts in the low-priority catchments are applied in a similar manner to the inflows into the surface water models.

The following sequence of steps accounts for the exchange of water between rivers and aquifers (and ensures there is no double accounting of water):

1. River models IQQM, REALM and BIGMOD are run for the baseline scenario with historical climate inputs for the catchment being investigated. The period and nature of calibration for each reach of the river model and each model inflow impacted by groundwater pumping is documented and used in this assessment.

2. The flows at key gauged reaches are converted to heights along the reach by a combination of rating curves and interpolation along the reach. These heights provide a 111-year time series of water levels in the river that are used as input to the groundwater models.

3. The groundwater model is configured for current development conditions and run with historical climate for a 111-year warm-up period then a further 111 years to determine the lag time to reach dynamic equilibrium and the dynamic equilibrium interaction flux.

4. The development history of groundwater extraction is documented alongside the calibration period.

5. An estimate of the groundwater development that best represents the groundwater loss during the calibration period is made for the river model.

6. The groundwater model is configured for development conditions estimated at Step 5 and run with historical climate for a 111-year warm-up period then a further 111 years to determine the dynamic equilibrium flux. The losses/gains determined by this model represent the losses/gains that already exist in the river model.

7. The difference between the fluxes estimated at Step 4 (current development) and Step 7 (calibration period development) is then included in the river models as either additional loss or gain. Note that losses are included below the last loss node in the calibration reach and gains are included just below the upstream gauge. Also note that where groundwater models are not available and groundwater interactions are significant, this difference is estimated and incorporated into the model.

8. Where groundwater impacts are significant in subcatchments feeding into the river models, the difference between undeveloped groundwater losses/gains and those expected under current dynamic equilibrium is assessed. The inflows into the river models are adjusted for this difference.

9. The river model adjusted at steps 7 and 8 is re-run for the 111-year period. The results from this model are reported and represent the baseline with dynamic equilibrium groundwater included. All other scenarios are compared against this baseline.

10. The river inflows and climate are adjusted for the relevant scenarios B, C and D, where applicable, and the river models are run for each scenario.

11. River flows at key locations for each scenario are converted to heights in a similar manner to Step 2 and are provided as inputs into the groundwater models.

12. The groundwater models are then re-run for each of the scenarios B, C and D, where applicable, and groundwater fluxes for each of the scenarios are extracted.

13. The differences between each of these fluxes and the baseline groundwater model (Step 4) are calculated.

14. The differences are included in the river model by adding to the groundwater loss/gain relationships that were established at Step 8.

15. Where river model inflows are impacted by groundwater, adjustments relative to undeveloped conditions are made.

16. The adjusted river models are re-run for each scenario for the 111-year period and results are reported against the baseline results obtained at Step 9.

Appendix B: Automating linkages between models

In this project, software engineering was used to automate linkages between river system models. This requires: (i) accounting for the time step differences between various models; (ii) accounting for any water balance discontinuities between models; (iii) determining ways of configuring models for any important feedback loops; and (ii) using parallel processing and gridded computing to greatly reduce model run times.

The linking framework developed in TIME provided algorithms to:

- run the existing river and groundwater models in batch mode
- identify and extract flow results from model output files
- save model results to the central results database
- convert model flow results so that they are compatible as inputs to receiving models.

The model linking framework also provides:

- a graphical user interface that facilitates the linking of models. The saving and recovery of this information is via an XML file
- the ability to associate model system files with different versions of the model (for example many of the IQQM systems run under different versions of IQQM)
- an easy way of running models for the range of different scenarios, including the ability to run models stochastically
- management of metadata associated with the various models
- the ability to determine the sequencing of model runs and run them using parallel processing to reduce the total run time.

On a basin-wide scale, upstream models are run first and then their flows are used as inputs to the connecting downstream models. For each river basin model where there is a groundwater model overlapping the area of the river model:

- The river basin model scenario is run.
- The groundwater model takes in the river flows at control points along the river (converted to river heights and interpolated along the length of the river, usually as part of the groundwater model batch file).
- The groundwater model is run with these river levels as inputs.
- River–groundwater leakage fluxes are output from the groundwater modelling for each reach of interest to the river basin modellers.
- These fluxes are adjusted by the model calibration period fluxes and fed back into the river basin model as the groundwater loss (or gain) component.
- The river basin model scenario is re-run with these new fluxes.

The interaction between groundwater and surface water was explicitly modelled in this project to avoid double accounting that may occur if the security of surface water and groundwater were examined separately. There are a number of models that simulate surface water and groundwater flow and their interaction, either in an integrated manner (surface water and groundwater flow are simultaneously modelled) or by coupling models (fluxes and water heads are exchanged between surface water models and groundwater manually or in an automated manner). The methodology adopted in this project falls under the latter category.

The large scale of the project means that the whole system cannot be modelled as a single unit. The contrasting level of understanding of the component systems means that different modelling approaches have to be implemented based on data and availability of models. The project had to build on pre-existing models and knowledge for two critical reasons: firstly, due to the limited time available for delivery; and secondly, to recognise the independent views and experiences of the relevant authorities in state government departments responsible for managing the groundwater resources in question.

Appendix C: Groundwater pumping impacts on surface water: non-modelled groundwater management units

The Murray-Darling Basin Sustainable Yields Project aims to assess the impacts of climate change, land use change (plantation forestry and farm dams) and groundwater development on both surface water and groundwater sharing plans. Most surface water sharing plans are developed using water planning models such as IQQM, REALM and MSM-BIGMOD to assess these impacts. These models are calibrated to achieve mass balance over the calibration period and as part of this calibration they are implicitly including groundwater fluxes to and from streams that existed during the period of calibration. There are two separate aspects of the model calibration process:

1. Estimation of subcatchment inflows to the river system model which is a combination of observed data and extension of this observed data through the calibration of rainfall-runoff models such as Sacramento or SimHyd. These models in combination with observed data provide water input to the nodes of the river planning models. These are generally lumped conceptual models which include a groundwater bucket to better reflect the slow flow component. Such models do not explicitly include groundwater pumping from these subcatchments.

2. River model subcatchment calibration through unattributed losses and gains. The calibration of river models leads to mass balance differences between river gauges. These can be due to physical processes, such as groundwater fluxes, evaporation from the surfaces of rivers and connected wetlands, and pumping from the river, or due to errors in the gauging or calibration process. Often groundwater fluxes are considerably smaller than the unattributed losses and gains.

Since the river planning models implicitly include groundwater fluxes, the surface water sharing plans also implicitly account for surface–groundwater interactions. This so-called 'double accounting' issue arises when either groundwater management (often pumping) or surface water management leads to changes in these fluxes not accounted for in the original surface water and groundwater assessments. In the case of river planning models, this is often due to the impacts occurring after the calibration period. Groundwater processes lead to time lags between groundwater pumping and the full impacts on streams. These time lags are described in the methodology report.

Most of the current impacts on streams occur in groundwater management units in which there is a history of groundwater pumping. Consequently they often have groundwater models to support groundwater management. The estimation of surface water impacts from such areas where they interact along a regulated reach of the river is also described in the methodology report. However, there are some areas for which: (i) there is a history of pumping but no current groundwater model exists; or (ii) groundwater models exist but interact with headwater subcatchments. In some cases, these impacts may be small and of little consequence for the objectives of this project. We define a significant impact as being 2 GL/year which is equivalent to about 5 ML/day of surface water flow. Allowing for inefficiencies due to connectivity, this implies that for a significant effect, groundwater pumping needs to be of the order of 4 GL/year or more.

Areas for which there is a history of pumping but no current groundwater model exists

In the areas that have been considered sufficiently important, groundwater models have been developed as part of this project. Examples include Upper Lachlan and Upper Murrumbidgee. The methodology is the same as for pre-existing groundwater models. Areas for which no current groundwater model is available and groundwater pumping is significant include, for example, the Peel Alluvium GMU in the Namoi region or the alluvium in the Ovens region. The groundwater impact on the stream is estimated by

$$\int_{t_{ref}}^{t} c.\Delta q_j\left(t'\right).F\left(t-t'\right).dt' \qquad [1]$$

where:

$\Delta q_j(t')$ is the change in pumping rate in subcatchment j at time t' relative to that at the reference time

t_{ref} is the reference time, i.e. the period when the surface water model was calibrated

F(t) is a function relating to the time lag between a change of pumping and its impact on the stream at time *t* later

c is an estimated connectivity factor.

Under a groundwater equilibrium, the change in volume of water extracted must match an equivalent change in volume of water coming through the boundary of the region being considered. The connectivity factor is the fraction of the change in volume coming through the boundary that is derived from streams as opposed to lateral flows, evapotranspiration, diffuse recharge etc. This is estimated using the groundwater levels adjacent to the river relative to river level, the conductance between the groundwater pump and the river, and the hydrogeological setting. In both of the examples, the alluvium is in high connection with the stream and connectivity has been assumed to be high (>0.8) and time lags are short (<2 years).

To spatially distribute the impacts, the following methods were used:

1. Using ARCINFO GIS, a map showing the union of GMUs and region subcatchments was produced.
2. The area of each GMU/subcatchment combination was estimated: A_{ij} for GMU_i and subcatchment *j*.
3. The groundwater pumping impact for a GMU as estimated above is distributed across subcatchments pro-rata with the fraction of the area of the GMU for that subcatchment, i.e. $q_{ij} = q_i \cdot A_{ij} / \Sigma_j A_{ij}$
4. The total groundwater impact on a subcatchment j (q^j) is then obtained by summing up the contributions from each GMU in the subcatchment, i.e. $q^j = \Sigma_i q_{ij}$
5. The estimated impact is then either used in equation [3] for unregulated catchments or in equation [1] provided that q^j is greater than 2 GL/year.

Under Scenario D, future impacts of groundwater development are included in the dynamic equilibrium concept described in the methodology report. The level of development is generally assumed to be the entitlement or the long-term average extraction limit in either the groundwater sharing plan or for New South Wales the maximum likely groundwater extraction limit in the macroplan. For third tier and unincorporated areas in Victoria, future development is estimated assuming that usage will remain at current levels for urban and unlicensed stock and domestic bores and other usage will increase at a rate equal to the mean annual increase in water usage in Australia from 1983/84 to 1996/97 (Australian Water Resources Assessment, 2000). However is capped at the current entitlement volume for incorporated areas.

To estimate the future impacts of current groundwater usage and the impacts of future developments, the groundwater usage assumed above for Scenario D relative to the groundwater usage at the reference time is treated using the methods described above. Note that for macro-plan areas, the groundwater usage at the reference time was considered to be current use.

The estimated current or future groundwater impact is then included as a loss term for the relevant reach. This loss term is derived to achieve the groundwater impact defined in equation [1].

Areas for which groundwater models exist but not along regulated stretches

Such areas include the Cox's Creek component of the Upper Namoi model and the Zone 8 model of the Upper Namoi GMU. For these, the groundwater model is used to estimate the groundwater impact on streams but the impact is used to modify the inflows to the river planning models. The inflows are modified as follows:

$$Q' = max(0, Q - Q_0) \qquad [2]$$

Where *Q'* is the modified inflow, *Q* is the unmodified river inflow, and Q_0 is a modifying factor derived from knowledge of the amount of losses to groundwater.

The amount of groundwater loss each year (GL/year), GW_{loss}, is identified from the groundwater model. Subsequently, the total volume of surface water lost to groundwater over the modelling period, V_{loss}, is defined as follows:

$$V_{loss} = GW_{loss}(Y_e - Y_s + 1) \times 1000 \qquad [3]$$

where V_{loss}, is the volume lost to groundwater over the modelling period, GW_{loss} is the annual amount of groundwater loss, and Y_e and Y_s are the end and start years of the modelling period, respectively. The river inflows are then modified by Q_o to allow for the total loss term V_{loss}.

This is achieved by shifting the flow duration curve such that the change in area under the curve is equivalent to $V_{loss.}$ This is represented mathematically as follows:

$$V_{loss} = \left[Q_0(p') \times (1 - p) + \int_1^p Q_0(p')dp' \right] \times [t_e - t_s] \qquad [4]$$

where $Q(p)$ is a function derived from the daily flow duration curve of the unmodified inflows from 01/07/1895 to 30/06/2006, p is the probability that the flow is greater than or equal to $Q(p)$, and t_e and t_s are the end time and start time, respectively. Equation 4 is solved using a search routine starting with a low value for Q_0 and increasing until V_{loss} is exceeded. Linear interpolation based on the ratio of volumes is then used to determine a Q_o that will achieve V_{loss}.

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