Evaluation of the connectivity between surface water and groundwater in the Murray-Darling Basin

Report prepared for the Murray-Darling Basin Commission

Resource and Environmental Management

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Postal Address GPO Box 409, Canberra ACT 2601
Office location Level 5, 15 Moore Street, Canberra City
Australian Capital Territory

Telephone (02) 6279 0100 international + 61 2 6279 0100
Facsimile (02) 6248 8053 international + 61 2 6248 8053
E-Mail info@mdbc.gov.au
Internet http://www.mdbc.gov.au

For further information contact the Murray-Darling Basin Commission office on
(02) 6279 0100

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Murray-Darling Basin Commission
Values Statement

We will manage and conduct our business in a highly professional and ethical manner, and according to the values jointly agreed with the Community Advisory Committee. These values require particular behaviours that will cement our relationships with our stakeholders and the wider community, and will underlie all decisions, actions and relationships we enter into. We will promote the values so that all people and organisations which have dealings with the Commission know what to expect from us and what we expect from them.

Our values

We agree to work together, and ensure that our behaviour reflects the following values.

Courage

We will take a visionary approach, provide leadership and be prepared to make difficult decisions.

Inclusiveness

We will build relationships based on trust and sharing, considering the needs of future generations, and working together in a true partnership.
We will engage all partners, including Indigenous communities, and ensure that partners have the capacity to be fully engaged.

Commitment

We will act with passion and decisiveness, taking the long-term view and aiming for stability in decision making.
We will take a Basin perspective and a non-partisan approach to Basin management.

Respect and honesty

We will respect different views, respect each other and acknowledge the reality of each other's situation.
We will act with integrity, openness and honesty, be fair and credible, and share knowledge and information.
We will use resources equitably and respect the environment.

Flexibility

We will accept reform where it is needed, be willing to change, and continuously improve our actions through a learning approach.

Practicability

We will choose practicable, long term outcomes and select viable solutions to achieve these outcomes.

Mutual obligation

We will share responsibility and accountability, and act responsibly, with fairness and justice.
We will support each other through necessary change.

Executive Summary

ES1. Background

All jurisdictions have attempted to set sustainable groundwater yield as the upper limit to the amount of groundwater that can be extracted from each groundwater management unit (GMU). However, one of the key uncertainties or gaps within current estimates of sustainable yield relates to quantification of the exchange of water between streams and aquifers, and quantification of the potential impact that groundwater extraction may have on stream flow.

The lack of knowledge regarding surface water – groundwater interaction has led to the double accounting of water (that is, allocation of the same volume from surface water and groundwater) and unmanaged reduction in stream flow due to groundwater extraction. Both these issues have led to the unsustainable use of the water resource.

The Murray-Darling Basin Commission has identified the impact of groundwater extraction on surface water resources as a risk to the shared water resource and is working with the jurisdictions to develop an agreed approach to the management of this potential impact. However, lack of knowledge regarding connectivity and lack of data to support analysis of the impacts of groundwater extraction has made it difficult to assess the implications of connectivity at the basin-scale.

The aim of this project is to evaluate the level of knowledge, certainty and data gaps relating to the connectivity of surface water and groundwater within the Murray-Darling Basin. The key tasks within this project were:

- Review the current knowledge and methods used to determine hydraulic connectivity of groundwater systems and stream flow within the basin;
- Identify where this knowledge has been applied to groundwater management within the basin;
- Describe the current investigations and initiatives being undertaken within the basin to develop a better understanding of the connectivity between surface water and groundwater resources;
- Evaluate the extent to which inconsistencies in past and current assessment of connectivity limit the capacity to develop a coordinated assessment of groundwater extraction impacts at the basin-scale;
- Identify the critical gaps in the knowledge of connectivity where these knowledge gaps create the greater level of uncertainty in the current management arrangements; and
- Provide recommendations on steps required to develop a consistent approach to the assessment of connectivity with a view to supporting the implementation of agreed MDBC strategies and initiatives.

ES2. Key Findings and Conclusions

ES2.1 Definition of connectivity as it relates to potential impacts on streamflow

The fundamental knowledge gap in dealing with connected groundwater – surface water systems is the lack of a consistent definition of connectivity. Such a definition should be supported by the establishment of a set of guiding principles within which a definition can be framed. This report suggests a set of principles to support the definition of connectivity. It is recommended that the definition of connectivity should:

- describe the nature of the interaction between the surface water and groundwater resources for the developed state of the resource;
- convey the rate at which the interaction is occurring;
- have regard to the timeframe over which the interaction occurs;
- be quantifiable; and
- be able to be applied to a range of spatial scales (e.g. should cover river reaches or whole of aquifers).

The following draft definition of connectivity has been proposed as a basis for discussion between jurisdictions:

- Highly connected for systems where the conductance is high and there can be an expectation that groundwater extraction impacts will have an influence within a specified timeframe which is short. In these types of systems it might be expected that more than 70% of the volume of groundwater extracted is derived from stream flow within a specified timeframe of 10 to 50 years from the onset of groundwater extraction;
- Moderately connected for systems where both the conductance and hydraulic gradients are moderate. In these types of systems it might be expected that between 10 and 70% of the volume of groundwater extracted is derived from stream flow within the specified timeframe;
- Poorly connected for systems where the conductance is low. As well, there may be an expectation that groundwater extraction, whilst impacting on surface flows within a specified timeframe, will have a full impact at some time in the future that is outside the specified timeframe. In these types of systems it might be expected that less than 10% of the volume of groundwater extracted is derived from stream flow within the specified timeframe;
- Disconnected for systems where the base of the river or stream lies above the water table. This means that even though the groundwater

system may be reliant on infiltrating stream flow, groundwater extraction cannot induce losses from the stream; and

- Unconnected systems where the arrangement of aquifer, stream and intervening materials means there is no physical means by which measurable quantities of water can be exchanged between groundwater and surface water.

An alternative approach to the definition of connected systems would be to classify the degree of connectivity based on the time taken for the full impact of groundwater extraction to occur. For example, a highly connected system could be one where the full impact occurs within 5 years and a poorly connected system could be one where the full impact occurs after 50 years. The proposed definition of connectivity is based on the volumetric impact (for example, a highly connected system is one where greater than 70% of groundwater extracted is derived from stream flow) whereas the alternative approach is based on timeframes for impacts. If the definition of connectivity is to be used in the context of understanding threats to the shared water resource then a definition that uses a volumetric approach is considered to be more appropriate.

A final decision on the guiding principles and definition of connectivity needs to be made collectively amongst the jurisdictions and stakeholders.

ES2.2 Application of the draft definition of connectivity

The draft definition of connectivity has not been applied in this project.

The agreed definition of connectivity should be used to classify all GMUs and unincorporated areas within the basin at an appropriate scale. Application of the definition at an aquifer or river reach scale is suitable for basin scale assessments of risk while finer scale application of the definition across aquifers and river reaches is needed for the development of local scale (within GMU) management responses.

It is important that any future analysis of the understanding of current knowledge and methods used or needed to quantify connectivity must be developed so that it can address the guiding principles to the definition listed in ES2.1.

ES2.3 Identification of priority groundwater management units

The identification of priority GMUs provides a basis for targeting future investigations and management initiatives to those areas of the basin where groundwater extraction is likely to impact stream flow to the greatest extent. It is suggested that the prioritisation of GMUs be based on the following three step approach.

The first step of the prioritisation approach involves grouping the GMUs based on sustainable yield using the following categories:

- Priority 1 – sustainable yield is greater than 50 GL/yr;
- Priority 2 – sustainable yield is between 20 and 50 GL/yr; and
- Priority 3 – sustainable yield is less than 20 GL/yr.

The second step of the prioritisation approach involves grouping the GMUs based on the degree of connectivity using the following categories:

- High – connectivity is greater than 70%
- Moderate – connectivity is greater than 10% but less than or equal to 70%; and
- Low – connectivity is less than or equal to 10%.

The third step of the prioritisation approach is to estimate the impact of groundwater extraction on stream flow in 2052/53 was estimated by multiplying the sustainable yield for each GMU (the assumed upper limit to groundwater extraction) and the assumed degree of connectivity.

The priority GMUs have been assessed as those GMUs where the impact of groundwater extraction on stream flow is greater than 10 GL/yr in 2052/53. The priority GMUs are listed in Table ES1

Table ES1. Summary of priority groundwater management units

GMU Code	GMU Name	Estimated impact of groundwater extraction on stream flow at 2052/53 (GL/yr)[1]	Basis for assumption regarding degree of connectivity used in the prioritisation[2]	Current and planned initiatives (as at December 2005)
New South Wales				
N43	Young Granite	10.1	Regional scale best guess	

GMU Code	GMU Name	Estimated impact of groundwater extraction on stream flow at 2052/53 (GL/yr)[1]	Basis for assumption regarding degree of connectivity used in the prioritisation[2]	Current and planned initiatives (as at December 2005)
N23	Upper Murray Alluvium	15.2	Regional scale best guess	
N46	Mid and Upper Murrumbidgee Fractured Rock	16.8	Regional scale best guess	
N16	Lower Macquarie Alluvium	19.3	Regional scale best guess supported with numerical modelling	Conceptual and numerical groundwater flow modelling – although it is not clear whether the issue of connectivity will be addressed
N17	Upper Macquarie Alluvium	24.0	Regional scale best guess supported with numerical modelling	
N21	Mid Murrumbidgee Alluvium	71.2	Regional scale best guess	Conceptual and numerical groundwater flow modelling – although it is not clear whether the issue of connectivity will be addressed
N19	Upper Lachlan Alluvium	164	Regional scale best guess	Conceptual and numerical groundwater flow modelling – although it is not clear whether the issue of connectivity will be addressed
Victoria				
V37	Murmungee	10.0	Regional scale best guess	Assessment of impacts of groundwater extraction on stream flow
V42	Campaspe	18.6	Regional scale best	Conceptual and numerical groundwater

GMU Code	GMU Name	Estimated impact of groundwater extraction on stream flow at 2052/53 (GL/yr)[1]	Basis for assumption regarding degree of connectivity used in the prioritisation[2]	Current and planned initiatives (as at December 2005)
			guess	flow modelling
V45	Mid Loddon	22.3	Regional scale best guess	Conceptual and numerical groundwater flow modelling
V39	Katunga	24.3	Regional scale best guess	
V43	Shepparton	72.0	Regional scale best guess	
Queensland				
Q73	Border Rivers	18.0	Numerical modelling	Development and application of techniques to quantify connectivity

[1] Data taken from overview report (MDBC, 2004).

[2] Data taken from MDBC (2005).

The location of priority GMUs is shown in Figure ES1.

ES2.4 What is the current knowledge and methods used to determine connectivity of groundwater and surface water systems?

A range of methods have been used to characterise the nature of stream - aquifer connectivity. These methods can be partitioned between two fundamental types – measurements or models. Measurement techniques include approaches that use hydrologic data to assess connection (such as hydrograph analysis, or hydraulic gradient mapping) or tracer techniques that involve measuring physicochemical parameters (such as major ion chemistry, radiogenic species such as radon or basic parameters such as temperature). Modelling techniques rely on an analysis of the water balance, either by simple means or via complex numerical simulations. Very few of the measurement and modelling techniques have been applied in a management sense, except for some regional groundwater models.

All jurisdictions have estimated the degree of connectivity within the major GMUs but this information has been based on varying levels of analysis; regional scale groundwater flow modelling, water balances and best guesses. In most priority GMUs the degree of connectivity and estimate of the impact of groundwater extraction is based on 'regional best guesses' supported with

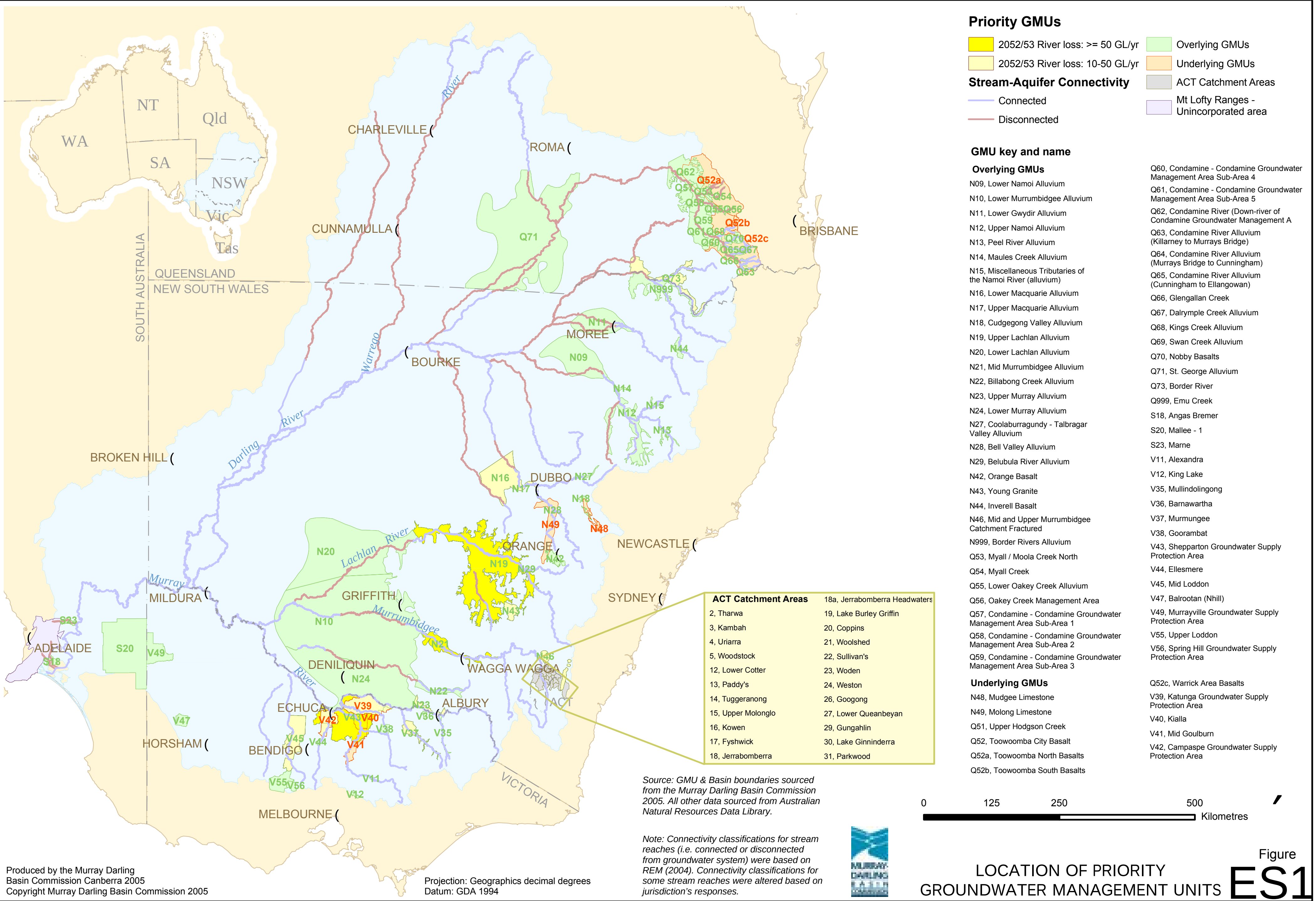


Figure ES1

LOCATION OF PRIORITY GROUNDWATER MANAGEMENT UNITS monitoring data and simple water balance calculations in some GMUs (Table ES1).

In several non-priority NSW GMUs, estimates have been made of the quantity of groundwater sources from stream flow under the developed conditions using numerical models and water balance calculations. These GMUs appear to be the only ones in the basin where there is an estimate of the volume of water exchanged between surface water and groundwater.

Hydrogeochemical methods and modelling has been undertaken in South Australia to semi-quantitatively describe connectivity. Investigations in Victoria are occurring to build the understanding of conceptual models for some GMUs which will explicitly account for the exchange of water between rivers and aquifers.

ES2.5 Where and how has this knowledge (if available) been applied?

Basin scale information regarding connectivity and the impact of groundwater extraction on stream flow compiled by the Murray-Darling Basin Commission has been used to develop and quantify an understanding of the risk to the shared water resource and to assist in the development of a basin groundwater policy (MDBC, 2004).

It is recognised by all jurisdictions that information on connectivity should be used in the water planning process. The main impediments to better information being used appear to be related to the lack of robust analysis and the priority attached to generating new information by the jurisdictions.

ES2.6 What are the current investigations and initiatives being undertaken that lead to a better understanding of connectivity?

There is a relatively small amount of work occurring within the basin that will provide explicit rates of water exchanged between rivers and aquifers. It appears that most work is undertaken in relation to local priorities rather than at a GMU or basin scale. Local priorities are partly driven by the need to manage GMUs where groundwater extraction is large and where there are impacts on the groundwater resource such as declining groundwater levels. These impacts may be occurring where there is little connection to streams.

This report contains an overview of the current investigations and initiatives (planned or underway) to better understand connectivity in priority GMUs. A summary of the investigations (as of December, 2005) for priority GMUs is provided in Table ES1.

There are some investigations planned for priority GMUs such as the development of conceptual and numerical models in the Murmungee, Campaspe and Mid Loddon GMUs in Victoria and the Border Rivers GMU in Queensland. There are plans to improve existing conceptual and numerical models in the Upper Lachlan, Mid Murrumbidgee and Lower Macquarie GMUs, but it is not clear whether this work will allow for an improved understanding of connectivity.

ES2.7 Critical gaps in knowledge of connectivity

The analysis undertaken in this project leads to the conclusion that the approaches to quantification of connectivity being adopted by the States, somewhat implicitly, are inadequate given the lack of knowledge of connectivity and lack of quantification of connectivity under developed conditions especially for priority GMUs. Only four of the thirteen priority GMUs (Murmungee, Campaspe, Mid Loddon in Victoria and Border Rivers) are subject to current and/or planned research and investigations that will deal with the issue of connectivity. There are three NSW GMUs that are the subject of further modelling (Lower Macquarie, Upper Lachlan and Mid Murrumbidgee) but it’s not clear whether these investigations will quantify connectivity. A summary of current investigations is provided in Section 5 of this report. The following key data gaps have been identified:

- Only a small amount of work is occurring within the basin that will provide explicit rates of water being exchanged between stream flow and groundwater. The majority of this work will be based around the natural water balance. There is a need to quantify the post-development water balance so that the impact of extracting groundwater can be estimated.

- Most GMUs do not conform to aquifer boundaries, and as such, there may be problems associated with the impact of groundwater extraction within GMUs occurring outside the GMU boundary and therefore going unaccounted in any analysis.

- Some jurisdictions have commented that there are inconsistencies between GMU boundaries and surface water gauging stations, with some GMUs covering a number of surface water catchments. This creates problems where there is a need to compare groundwater balances with estimates of baseflow from stream hydrographs.

- Modelling techniques are considered the appropriate approach to derive a GMU scale and basin scale estimate of the impact of groundwater extraction on stream flow. Most of the priority GMUs (listed in Table ES1) do not have robust conceptual or numerical groundwater models which are able to quantify the exchange of water between rivers and aquifers or quantify the timing and magnitude of impacts of groundwater extraction on stream flow. A review of modelling approaches by REM (2002) recommended that an integrated modelling approach is needed to allow stream and aquifer systems to be simulated in detail.

- The biggest impediments to undertaking a more complex approach to modelling the priority GMUs will be the lack of historical groundwater extraction data (magnitude and timing) and the lack of information on the permeability of the sediment that lies at the interface of the stream and aquifer.

- Estimates of impacts of future groundwater extraction on streamflow in priority GMUs are limited by lack of information on drivers to groundwater extraction and lack of information on likely future patterns of groundwater extraction at the GMU scale.

- The focus of future investigations and analysis should be on the priority GMUs listed in Table ES1. However, there may be a large number of connected GMUs that will not be analysed through modelling owing to their small size. Collectively groundwater extraction in these smaller GMUs may have a significant impact on stream flow.

- There does not appear to be any current or planned activity that would investigate the role of climate variability on the extraction rate and the impacts of groundwater extraction on stream flow. At this stage, there is an implicit conclusion that the impact is linearly related to the groundwater extraction rate. For example, it is assumed that extracting 10 GL in a dry year has the same impact as extracting 10GL in a wet year. This may not be the case which means that estimates of impacts on stream flow based on simple extrapolation from extraction rates that don't take into account lag times could be unreliable. Overall this is considered to be a minor issue.

ES2.8 What is the extent to which inconsistencies in past and current assessment of connectivity limit the capacity to develop an assessment of groundwater extraction impacts at the basin scale?

Obtaining a robust basin-wide estimate of the volumes of stream flow being impacted by groundwater extraction has been shown to be difficult in previous work (e.g. MDBC, 2004). This situation does not appear to have changed within the last year or so.

The implications of the current inadequate approach will result in an inability to determine and prioritise a response to the double accounting and impact of groundwater extraction on stream flow based on a risk assessment of the magnitude of the impact. The lack of adequate analysis will result in an inability to communicate the effect of the management response to stakeholders in a consistent manner.

Part of the inconsistency in past and current assessments of the risk of groundwater extraction to the risks to the shared water resource is driven by the lack of an agreed definition of connectivity.

ES3. Recommendations

It is recommended that the Murray-Darling Basin Commission and partner jurisdictions work together to develop a consistent approach to assess connectivity by implementing the following actions:

1. Endorse a set of guiding principles for the definition of connectivity to form the basis for a common definition of connectivity across the Murray-Darling Basin.

2. Develop a definition of connectivity that can be applied to assess individual geographic areas, consistent with the guiding principles.

3. Prepare a discussion paper to be used as the basis of consultation with the jurisdictions to develop an agreed definition of connectivity. It is recommended that the guiding principles and proposed definition detailed in this report be used to form the basis of the discussion paper.

4. Classify the connectivity of all GMUs and unincorporated areas within the basin using the agreed definition. The agreed definition of connectivity should be applied to a range of spatial scales (e.g. should cover river reaches or whole of aquifers).

5. Establish criteria for prioritisation of GMUs. This report has proposed a set of criteria for this purpose.

6. Adopt the GMUs listed in this report (Table ES1) as the initial priorities noting that the list may change as more data and analysis becomes available.

7. Agree to an approach and associated data required as inputs to the planning process to address the risks of groundwater extraction on the shared water resource. This may be dependent on the level of the management response required which may be based on a perceived level of risk. A summary of the data gaps and investigations to be considered for priority GMUs is provided in Appendix C of this report. The key types of data and analysis required to derive a basin wide estimate of the impact of groundwater extraction on stream flow are:

    - Quantification of the exchange of water between the stream and aquifer;

    - Current and future impacts of groundwater extraction quantified;

    - Adequate surface water and groundwater monitoring; and

    - Current groundwater extraction quantified and future patterns of groundwater extraction estimated.

8. Agree to timeframes for completion of the technical studies in each priority GMU and identify organisations responsible for the work. It is recommended that the Murray-Darling Basin Commission develop partnership approaches to ensure that any additional work is built on existing programs of works.

9. Establish robust technical studies of the developed water balance and the development of calibrated numerical models for the priority GMUs to quantify the exchange of water at the GMU scale and to quantify the impact of groundwater extraction on stream flow. In the first instance it is recommended that the focus be on the Upper Lachlan and Mid Murrumbidgee GMUs because groundwater extraction in these GMUs

provides the greatest potential for an impact on stream flow over the next 50-years within the basin.

10. The MDBC maintain a close working relationship with the CRC eWater so that priority GMUs can be a focus of eWater projects.

11. Use the technical output from the GMU scale assessments of connectivity and impacts of groundwater extraction on stream flow to assess the risk of groundwater extraction to the shared water resource, and provide options for the management of impacts in the priority GMUs. Quantification of the impact of the management response is recommended. The initial management response may need to be conservative and adapted over time as monitoring data and new analysis becomes available.

12. Implement an open reporting approach and independent accreditation of groundwater models as practiced for the Surface Water Cap on Diversions, and for groundwater models under the BSMS.

13. An Independent Audit Group be established to review the progress of the following tasks within, initially (agreed) priority, individual GMU:

    - the quantification of the impact of groundwater extraction on streamflow;

    - the development and implementation of management responses; and

    - implementation of a monitoring and evaluation program.

Table of Contents

List of Tables and Figures

TABLES

FIGURES

1 BACKGROUND AND SCOPE

1.1 Background and scope

1.1.1 Background

The groundwater resources of the Murray-Darling Basin (Basin) are managed at the groundwater management unit (GMU) scale by each of the jurisdictions. The volume of water extracted from each GMU varies from less than 5 gigalitres each year (GL/yr) to over 300 GL/yr. Groundwater extraction in the basin has increased substantially over the last several years (e.g. it increased by around 44% between 1999/00 and 2002/03, MDBC (2004)).

In all jurisdictions the extraction of groundwater within many of the GMUs is subject to a management plan which sets out the rules upon which the water resource can shared (e.g. between consumptive and environmental users). In some cases the groundwater resource is being extracted near surface water resources which have their own water sharing plans. The Murray-Darling Basin Commission undertook an investigation of the way in which groundwater was managed within the basin (REM, 2004) and found that all jurisdictions aim to set sustainable yield as the upper limit to extraction, but in many cases there is a mismatch between the significance of the groundwater resource and the way in which sustainable yield has been estimated. That is, the resources made available in the past were not sufficient to always calculate sustainable yield using best-practice approaches. It was also found that there is significant variation between jurisdictions in the way sustainable yield has been estimated.

In many GMUs the planning process (which included a discussion of access rights to the resource) went ahead without there being a robust estimate of the sustainable yield.

One of the key uncertainties or gaps within current estimates of sustainable yield relates to quantification of the exchange of water between streams and aquifers, and quantification of the potential impact that groundwater extraction may have on stream flow.

The lack of knowledge regarding surface water – groundwater interaction has led to the double accounting of water (that is, allocation of the same volume from surface water and groundwater) and unmanaged reduction in stream flow due to groundwater extraction. Both these issues have led to the unsustainable use of the water resource.

The issue of increasing groundwater extraction and the potential to adversely affect stream flow and impact on initiatives such as the Cap on surface water diversions (the Cap) and, indirectly, on The Living Murray (TLM) has been identified in a number of studies (e.g. SKM, 2003 and REM, 2005).

Information collected from the first stage of the Watermark groundwater project (REM, 2004) has highlighted that increased groundwater use can potentially impact on surface water flow in those catchments where groundwater is hydraulically connected to surface water systems. It was estimated that increased groundwater extraction within GMUs with a connection to a surface water system could reduce stream flow by up to 550 GL/yr (EarthTech, 2003). This represents a small proportion of the total water use in the basin, but more importantly, represents a volume equivalent to the water savings being targeted by The Living Murray.

The information from SKM (2003) and REM (2004 and 2005) has been used in a general assessment of the impact that groundwater extraction could have on stream flow. These previous assessments have considered the potential for historical impacts that might have undermined the Cap on Surface Water Diversions as well as future impacts within the context of initiatives such as the Living Murray. All of the analyses have suffered from uncertain data, and all have been based on gross assumptions that lead to a level of uncertainty that is probably unacceptable.

A number of studies have attempted to predict future levels of groundwater extraction within the Basin. The outcome from these studies is the same – further groundwater is able to be extracted from the Basin's groundwater systems as the limit defined by current sustainable yield is greater than the current rate of groundwater extraction in many GMUs. This creates a problem where the estimate of sustainable doesn't take into account the exchange of water between the river and aquifer.

It is also recognised that there may be a trade-off between reducing waterlogging and salinity and minimising impacts of groundwater extraction on stream flow in some areas such as the Shepparton region within Victoria and the Riverland in South Australia.

1.1.2 Scope

The overall aim of this project is to provide a comprehensive and technically rigorous overview of the current understanding, key uncertainties and knowledge gaps in relation to groundwater and surface water interactions across the Basin. The project focuses mainly on the GMUs which are likely to be a priority for management of the impact of groundwater extraction on stream flow.

The following tasks were undertaken during this project:

1. Review of the current knowledge and methods used to determine hydraulic connectivity of groundwater systems and stream flow within the basin;

2. Identification of where and how this knowledge has been applied to groundwater management within the basin;

3. Description of the current investigations and initiatives being undertaken by jurisdictional and scientific organisations within the basin to develop a better understanding of the connectivity between surface water and groundwater resources;

4. Evaluation of the extent to which inconsistencies in past and current assessment of connectivity limit the capacity to develop a coordinated assessment of groundwater use impacts at the basin-scale;

5. Identification of critical gaps in the knowledge of hydraulic connectivity and identify from a spatial perspective, i.e. GMU basis, where these knowledge gaps create the greater level of uncertainty in the current management arrangements; and

6. Provision of recommendations on steps required to develop a consistent approach to the assessment of connectivity between groundwater and surface water resources across the basin, with a view to supporting the implementation of agreed MDBC strategies and initiatives.

1.2 Approach

The information in this report has been collated from discussions with jurisdictional representatives, research providers and purchasers, and from literature and internet searches. The information contained in this report was collected in the period from October 2005 to January 2006.

The focus was to obtain information that would allow an analysis of the assessment of the connection between groundwater and surface water for specific GMUs, as well as an analysis of current and planned activities that directly related to estimating connectivity.

2 DEFINITION OF CONNECTIVITY AND NATURE OF INTERACTION BETWEEN SURFACE WATER AND GROUNDWATER

2.1 Definition of connectivity

2.1.1 Background

The scope of work for this project did not explicitly require that the term *connectivity* be defined. However, it is apparent that there are a number of different definitions for the term and these definitions provoke a range of interpretations amongst stakeholders. Whilst this work will not provide a new definition for the term, it is important to set out a range of principles that might constrain how the term is defined and a suggested definition as a starting point for discussions amongst the stakeholders. A final definition will only be reached once stakeholders have been canvassed and any operational subtlety required in the day to day workings of the jurisdictions has been fully understood.

It is becoming increasingly understood, especially in relation to the risks to the shared water resources of the Murray-Darling Basin, that groundwater extraction has an impact on surface water flows in some situations. These instances have been loosely defined as occurring within *connected* surface water and groundwater systems, and there are various definitions and general usage meanings of the term *connected*.

Fundamentally, the terminology used to describe the systems needs to reflect the purpose for which it is intended. For instance, in the case of describing the impacts of groundwater extraction on stream flow, the term connected should reflect the fact that groundwater extraction can influence stream flow, and that this influence will occur within a specified timeframe that is of interest to water resource management, whilst still providing an understanding of the timing of the full impact.

The discussion below provides a starting point for the development of a meaningful definition of connectivity, with the terminology based on Winter (1998) with some modification.

The physical characteristics of a catchment such as topography, geology and climate dictate how streams and aquifers interact. Streams that receive flow from groundwater are referred to as gaining streams (that is, they gain water), whereas streams that leak water to the aquifer are termed losing streams. Some streams can be gaining and losing in different parts of their catchment, and some can be gaining and losing at different times in the same reach depending upon the season and other physical conditions. The nature of stream-aquifer interactions can also be classified according to whether the river or stream, and aquifer, are connected or disconnected. This latter terminology has evolved over time and reflects a stream-centric definitional approach that describes the nature of the connection in terms of whether groundwater extraction will impact on stream flow.

A connected stream is one where there is a vertical zone of continuous saturation between the river and the aquifer. Where the pressure in the aquifer is higher than the river, water will flow to the river and the connectivity can be termed connected and gaining. Where the pressure is reversed, the flow will be from the river to the aquifer and the connectivity can be termed connected losing.

Where the stream and aquifer are separated by an unsaturated zone, the connectivity is termed disconnected. Due to the unsaturated zone, the pressure in the aquifer will always be lower than the river and flow will occur from the river to the aquifer. It is useful to note, however, that water will still flow from the river to the aquifer in a disconnected stream (that is, water will flow across the unsaturated zone between the base of the stream and the water table). Connected streams can be either gaining or losing, and disconnected streams are losing.

In some cases there may be an extremely low permeability barrier between the stream and the aquifer which effectively means there is no exchange of water between the river and aquifer in either direction. There cases can be classified as being unconnected.

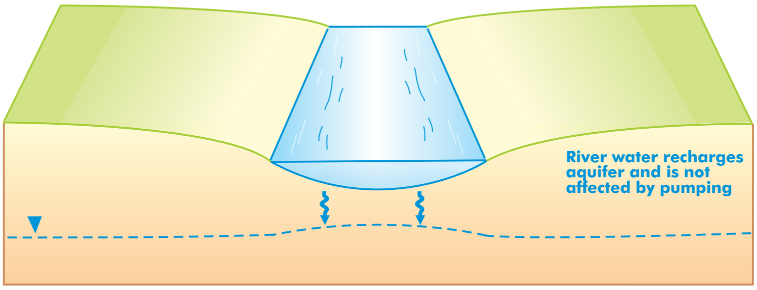
A schematic of different types of river – aquifer interaction is provided in Figure 1.

In some cases the groundwater flow may be parallel to the river with minimal head difference between groundwater and surface water. These instances are described as *underflow*. In yet other cases, the groundwater flow may be perpendicular to the river, with flow of groundwater into one side of the river, and flow out of the river to groundwater on the other. These instances are described as *throughflow*.

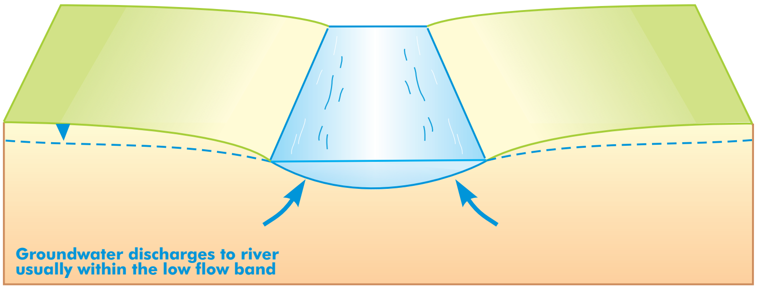
In terms of describing the potential for groundwater extraction to impact on surface water it is more beneficial to apply the classification at the aquifer level. For example, an aquifer may cover a large area, sometimes up to several hundred kilometres. As a river traverses the aquifer, it may have reaches that are connected losing, disconnected and connected gaining. In some cases, the connection might be classified as disconnected for the majority of the stream length. However, the critical understanding might be required where the river is connected gaining and losing, as it is in these regions that impacts of groundwater extraction will manifest, even though the groundwater extraction may occur directly underneath where the stream is classified as disconnected.

The term *connected* is also a subjective one that relies on a consideration of the conductance of the materials immediately adjacent to the river. In most cases connected groundwater and surface water will be via material that has a high conductance, for example, a river running through coarse alluvium. However, it is possible to conceive of materials that have low conductance which can support a saturated zone between the river and the aquifer. In some cases this low conductance material may be relatively thin, and hence not present an impediment to flux of water between the two sources. In other cases, the material may be thick, as in the case of a semi-confining layer such as the Shepparton Formation, overlying the Calivil Formation aquifer. In these cases the timing of

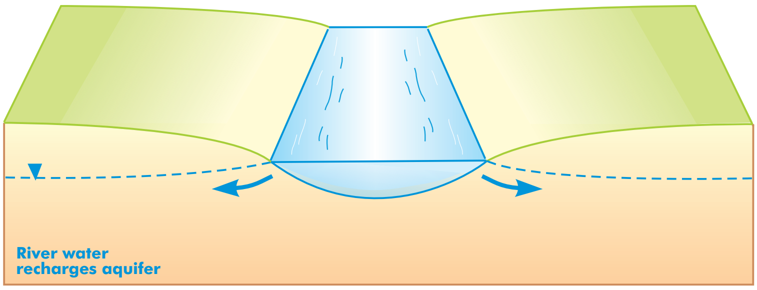
DISCONNECTED LOSING RIVER



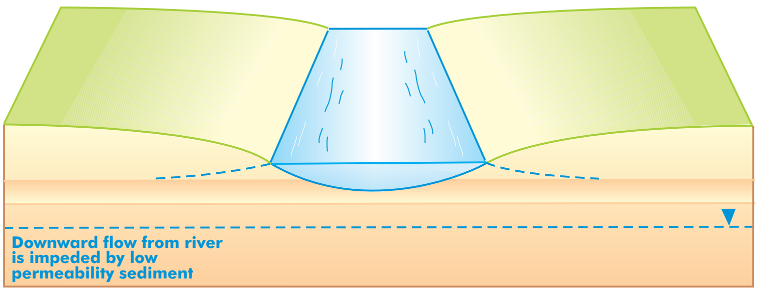
CONNECTED GAINING RIVER



CONNECTED LOSING RIVER



UNCONNECTED LOSING RIVER



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rem

Types of river-aquifer interaction

Figure
1

the impacts of groundwater extraction will be related to the conductance, amongst other variables. The lower the conductance, the slower the leakage and hence the longer the time to realise the full impact for a given groundwater extraction event. In cases where the conductance is so low it provides a limit on the transfer rate, the time taken to achieve full impact will be extremely long, as the lower rate will presumably cause an increased hydraulic gradient in the underlying groundwater system. In these cases the impacts will be somewhat constant over time. This temporal character implies that some idea of the time over which the connectivity is being considered needs to be included within any classification scheme.

The nature of the connectivity between surface water and groundwater will also change depending on the level of development of the aquifer system. Connected stream reaches under natural conditions may become disconnected under developed conditions. Therefore, it is important to know the circumstances under which a particular classification was made as well as the circumstances under which it is to be used in the future.

2.1.2 Principles Constraining the Definition

Any definition of connectivity should conform to certain principles or have specific attributes. These principles are:

- It should describe the nature of the interaction between the surface water and groundwater resources for the developed state of the resource;
- It should convey the rate at which the interaction is occurring;
- It should have regard to the timeframe over which the interaction occurs;
- It should be quantifiable; and
- It should be able to be applied to a large spatial scale (e.g. should cover river reaches or whole of aquifers).

2.1.3 Draft Definition for Discussion

It is proposed that a common approach to classifying stream connectivity is adopted that better implies the nature of the interaction. A draft definition is given below as a basis for discussion between jurisdictions:

- Highly connected for systems where the conductance is high and there can be an expectation that groundwater extraction impacts will have an influence within a specified timeframe which is short. In these types of systems it might be expected that more than 70% of the volume of groundwater extracted is derived from stream flow within a specified timeframe of 10 to 50 years from the onset of extraction;
- Moderately connected for systems where both the conductance and hydraulic gradients are moderate. In these types of systems it might be

expected that between 10 and 70% of the volume of groundwater extracted is derived from stream flow within the specified timeframe;

- Poorly connected for systems where the conductance is low. As well, there may be an expectation that groundwater extraction, whilst impacting on surface flows within a specified timeframe, will have full impact at some time in the future that is outside the specified timeframe. In these types of systems it might be expected that less than 10% of the volume of groundwater extracted is derived from stream flow within the specified timeframe;

- Disconnected for systems where the base of the river or stream lies above the water table. This means that even though the groundwater system may be reliant on infiltrating stream flow, groundwater extraction cannot induce losses from the stream; and

- Unconnected systems where the arrangement of aquifer, stream and intervening materials means there is no physical means by which measurable quantities of water can be exchanged between groundwater and surface water.

In effect, the definitions for connected systems are dealing with the timing of impacts, rather than the magnitude, as groundwater extraction in any system at a given level will eventually have the same impact.

An alternative approach to the definition would be to classify the degree of connectivity based on the time taken for the full impact of groundwater extraction to occur. For example, a highly connected system could be one where the full impact occurs within 5 years and a poorly connected system could be one where the full impact occurs after 50 years. A final decision needs to be made amongst the jurisdictions and stakeholders.

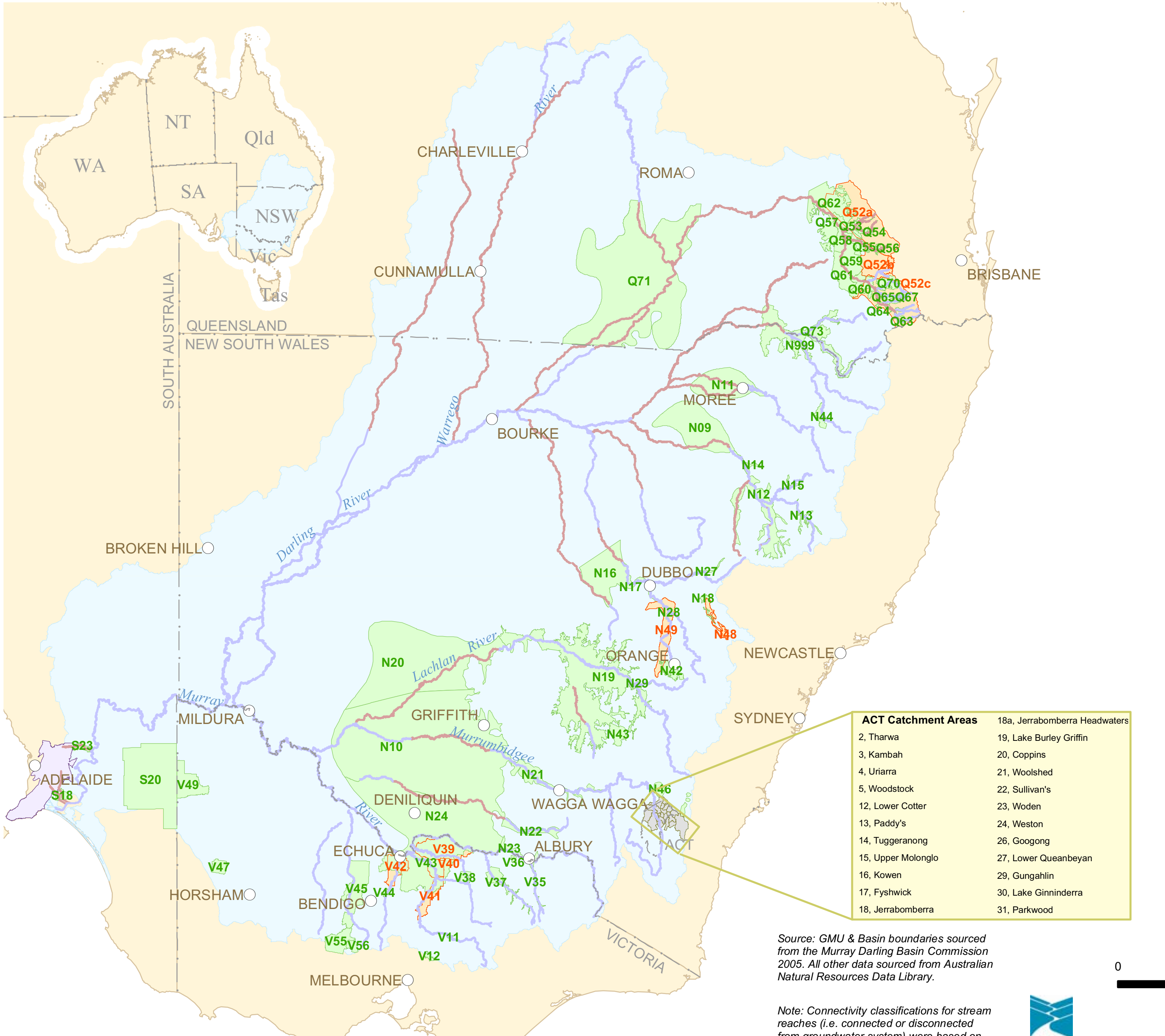
2.2 Overview of connectivity across the basin

A map of the GMUs across the Basin and the distribution of connected and disconnected streams are provided in **Figure 2**. The connectivity between groundwater and surface water shown in Figure 1 was developed previously based on information provided to the MDBC by the jurisdictions during the preparation of the overview report (MDBC, 2004). The connectivity was classified as:

- connected where the watertable is above the base of the river or creek; and

- disconnected where the base of the river or creek is separated from the watertable by an unsaturated zone.

The connectivity mapped in Figure 2 was developed to aid a basin scale analysis of the impacts of groundwater extraction on stream flow. Note that the basis for the mapping does not conform to the draft definition provided above, nor does it meet the principles for the definition.



Overlying GMUs
Underlying GMUs
Mt Lofty Ranges - Unincorporated area
ACT Catchment Areas
Murray Darling Basin

Stream-Aquifer Connectivity

Connected
Disconnected

GMU key and name

Overlying GMUs

N09, Lower Namoi Alluvium
N10, Lower Murrumbidgee Alluvium
N11, Lower Gwydir Alluvium
N12, Upper Namoi Alluvium
N13, Peel River Alluvium
N14, Maules Creek Alluvium
N15, Miscellaneous Tributaries of the Namoi River (alluvium)
N16, Lower Macquarie Alluvium
N17, Upper Macquarie Alluvium
N18, Cudgegong Valley Alluvium
N19, Upper Lachlan Alluvium
N20, Lower Lachlan Alluvium
N21, Mid Murrumbidgee Alluvium
N22, Billabong Creek Alluvium
N23, Upper Murray Alluvium
N24, Lower Murray Alluvium
N27, Coolaburragundy - Talbragar Valley Alluvium
N28, Bell Valley Alluvium
N29, Belubula River Alluvium
N42, Orange Basalt
N43, Young Granite
N44, Inverell Basalt
N46, Mid and Upper Murrumbidgee Catchment Fractured
N999, Border Rivers Alluvium
Q53, Myall / Moola Creek North
Q54, Myall Creek
Q55, Lower Oakey Creek Alluvium
Q56, Oakey Creek Management Area
Q57, Condamine - Condamine Groundwater Management Area Sub-Area 1
Q58, Condamine - Condamine Groundwater Management Area Sub-Area 2
Q59, Condamine - Condamine Groundwater Management Area Sub-Area 3
Q60, Condamine - Condamine Groundwater Management Area Sub-Area 4
Q61, Condamine - Condamine Groundwater Management Area Sub-Area 5
Q62, Condamine River (Down-river of Condamine Groundwater Management A
Q63, Condamine River Alluvium (Killarney to Murrays Bridge)
Q64, Condamine River Alluvium (Murrays Bridge to Cunningham)
Q65, Condamine River Alluvium (Cunningham to Ellangowan)
Q66, Glengallan Creek
Q67, Dalrymple Creek Alluvium
Q68, Kings Creek Alluvium
Q69, Swan Creek Alluvium
Q70, Nobby Basalts
Q71, St. George Alluvium
Q73, Border River
Q999, Emu Creek
S18, Angas Bremer
S20, Mallee - 1
S23, Marne
V11, Alexandra
V12, King Lake
V35, Mullindolingong
V36, Barnawartha
V37, Murmungee
V38, Goorambat
V43, Shepparton Groundwater Supply Protection Area
V44, Ellesmere
V45, Mid Loddon
V47, Balrootan (Nhill)
V49, Murrayville Groundwater Supply Protection Area
V55, Upper Loddon
V56, Spring Hill Groundwater Supply Protection Area

Underlying GMUs

N48, Mudgee Limestone
N49, Molong Limestone
Q51, Upper Hodgson Creek
Q52, Toowoomba City Basalt
Q52a, Toowoomba North Basalts
Q52b, Toowoomba South Basalts
Q52c, Warrick Area Basalts
V39, Katunga Groundwater Supply Protection Area
V40, Kialla
V41, Mid Goulburn
V42, Campaspe Groundwater Supply Protection Area

Source: GMU & Basin boundaries sourced from the Murray Darling Basin Commission 2005. All other data sourced from Australian Natural Resources Data Library.

Note: Connectivity classifications for stream reaches (i.e. connected or disconnected from groundwater system) were based on REM (2004). Connectivity classifications for some stream reaches were altered based on jurisdiction's responses.

Produced by the Murray Darling Basin Commission Canberra 2005

Projection: Geographics decimal degrees
Datum: GDA 1994

Figure 2

LOCATION OF GMUs AND CONNECTIVITY

The aquifers of the Murray-Darling Basin can be divided into a number of regions – the upland fractured rock, the upland alluvial valleys, the southern and northern riverine plains, and the Mallee.

Aquifers in the upland fractured rocks are generally connected to streams only in the discharge parts, that is, rivers that drain these landscapes are generally connected gaining. Impacts on surface water flows from groundwater extraction in these areas will be via reduced groundwater discharge.

Aquifers in the upland alluvial valleys are generally variably connected, with gaining and losing sections over their entire length. The conductance of intervening material between the river and the aquifers is usually high.

Aquifers in the southern riverine plain are usually characterised by regions in the upstream area where streams are connected (losing), middle reaches where the river is connected to the overlying semi-confining layer and may be an underflow system as well, and connected (gaining) in the downstream areas.

Aquifers in the northern riverine plain are usually characterised by regions in the upstream and middle areas where streams are disconnected and in the downstream reaches where they are connected (gaining).

Aquifers in the Mallee region are usually disconnected over most of their length, except in the immediate discharge end where they are connected to gaining streams.

2.3 Impacts of groundwater extraction on surface water flows

Initially, when a well is pumped, the groundwater supplied to the well is provided from storage immediately around the well casing. As groundwater extraction continues, the area of aquifer contributing groundwater to the well becomes larger and groundwater moves into the area of depleted storage from within the aquifer. As the time of groundwater extraction becomes long, groundwater moves to the depleted area of storage from further and further away in the aquifer, until some balance is achieved by inducing groundwater away from sources external to the aquifer. These could be recharge sources such as surface water bodies; groundwater that is captured from discharging baseflow; or other saturated materials in the subsurface where the groundwater is given up as induced leakage.

This implies that it is extremely important to understand the discharge mechanisms just as well as the recharge mechanisms.

The degree to which storage remains the primary source of water to groundwater extraction wells over longer times relies on the volume being pumped, a range of critical aquifer parameters, the size of the aquifer and the volumes being recharged.

Depending on the aquifer properties and its size, the depletion of aquifer storage will show as a reduction in discharge at some stage in the future. However, the flow length and storage character of the aquifer are frequently such that the time for the reduced throughflow to impact on discharge is longer than the time frame of aquifer development.

The impacts of groundwater extraction on surface systems can either result in water being induced into the aquifer from surface water sources (“induced recharge”), or captured from leaving the aquifer as discharge (“captured discharge”).

2.4 Induced recharge

When the influence of a groundwater extraction bore, or area of groundwater extraction, is close enough to a river or stream, the hydraulic gradients between the area of groundwater extraction and the stream can be reversed such that water flows from the stream to the aquifer where it may have been flowing from the aquifer to the stream prior to groundwater extraction. In these cases, a new volume of water moves to the aquifer and this is called induced recharge. In situations where the hydraulic gradient is already from the river to the aquifer, groundwater extraction will cause the hydraulic gradient to increase causing more water to flow into the aquifer. This additional water recharging the aquifer due to the groundwater extraction is also called induced recharge.

In general, the time frame for the onset of the impacts of induced recharge can be short, but the time to full impact will depend on a range of factors including: the volumes pumped compared with the volume of water in the river system; the degree to which the hydraulic gradients are changed; and the broader aquifer properties.

In some circumstances where groundwater extraction is intense, the water level can be drawn down to the point where unsaturated conditions are established immediately below the river. In these cases, the aquifer-stream relationship goes from one of connected to one of disconnected. When the aquifer becomes disconnected, the rate at which water moves from the stream is then governed by the hydraulic properties of the unsaturated zone. In some cases the flow rate in disconnected systems may still be greater than the flow rate to the aquifer in the natural (connected) state.

Induced recharge cannot occur in a stream-aquifer system that is disconnected under natural conditions, as the unsaturated zone between the river and the watertable acts as an effective limit to water movement. No matter how far the watertable is drawn down, there is no increase in the rate at which water moves to the groundwater.

2.5 Captured discharge

In aquifers where groundwater extraction occurs remotely from the stream and the changes in hydraulic gradients do not result in induced recharge, the major impact is the interception of groundwater flow that would have discharged to the river at some point down hydraulic gradient. In general, captured discharge intercepts either groundwater recharged through rainfall recharge or from stream flow (including flood flows) further up the catchment.

The capture of discharge can be evident either as diminished stream flow in the river itself, or as a reduction of water flowing to discharge environments separate from the river zone. This latter case will manifest as reduced water supply to groundwater dependent ecosystems remote from the river, or as reduced evapotranspiration by other ecosystems.

Although the focus of this report is on connectivity as it relates to the potential impact of groundwater extraction on stream flow, it is recognised that the impact of groundwater extraction on other groundwater discharge features may be more important in some catchments.

In general, the timeframe for the onset of the impacts from captured groundwater discharge will be longer than for induced recharge. However, this depends on the distance of groundwater extraction from the stream and the relative change in the hydraulic gradient between the groundwater extraction and the stream. In some cases, such as when groundwater extraction is adjacent to a stream and the change in the hydraulic gradient is substantial, the impacts may manifest almost immediately.

As with induced recharge, the time to full impact will depend on a range of factors including the volumes pumped compared with the volume of water in the river system, the degree to which the hydraulic gradients are changed, and the broader aquifer properties.

2.6 Induced leakage from other aquifers

Where an aquifer is semi-confined (that is, where the aquifer is capped by a leaky confining layer), extraction of groundwater from the aquifer can induce leakage of water from the overlying semi-confining layer. This leakage represents a non-replenishable addition of water to the water budget, unless the rate of leakage is matched by an addition of water at the top of the semi-confining layer (such as from irrigation or from a river or unconfined aquifer).

In cases where there is limited water above the semi-confining layer to replenish the leakage to the aquifer, the semi-confining layer will dewater and become unconfined. In these cases, land subsidence may occur.

The response of the aquifer to induced leakage from the semi-confining layer is usually indistinguishable from that of induced recharge. This represents a problem when describing the connection between surface water and groundwater.

2.7 Timing of impacts

It is well known that when groundwater systems are pumped they will impact on linked surface water systems in a manner that depends on the connection. The timing of such impacts is less well known and there are two issues to consider. The first is the timing of the first impact in the river; that is, how long before the impact starts. The second issue is the timing of the full impact in the river; that is, how long before 100% of the impact is manifest.

Jenkins (1968) published the first simple guide to calculating stream depletion from groundwater extraction. Jenkins reported, amongst other issues, that the effects of groundwater extraction on a stream, which is the sole source of recharge for the aquifer, continue after groundwater extraction ceases and that as time approaches infinity the volume of stream depletion approaches the volume pumped.

REM (2005) has undertaken some preliminary numerical modelling to describe the timing of the response of surface water systems to groundwater extraction. The aquifer systems modelled by this work were analogous to the upland alluvial valley and southern riverine plains aquifers described in Section 2.2.

The results of the REM work are in accord with the conclusions made by Jenkins and suggest that:

- The onset of the initial impact on stream flow from groundwater extraction is rapid, but the impact appears to be long lived (decades);

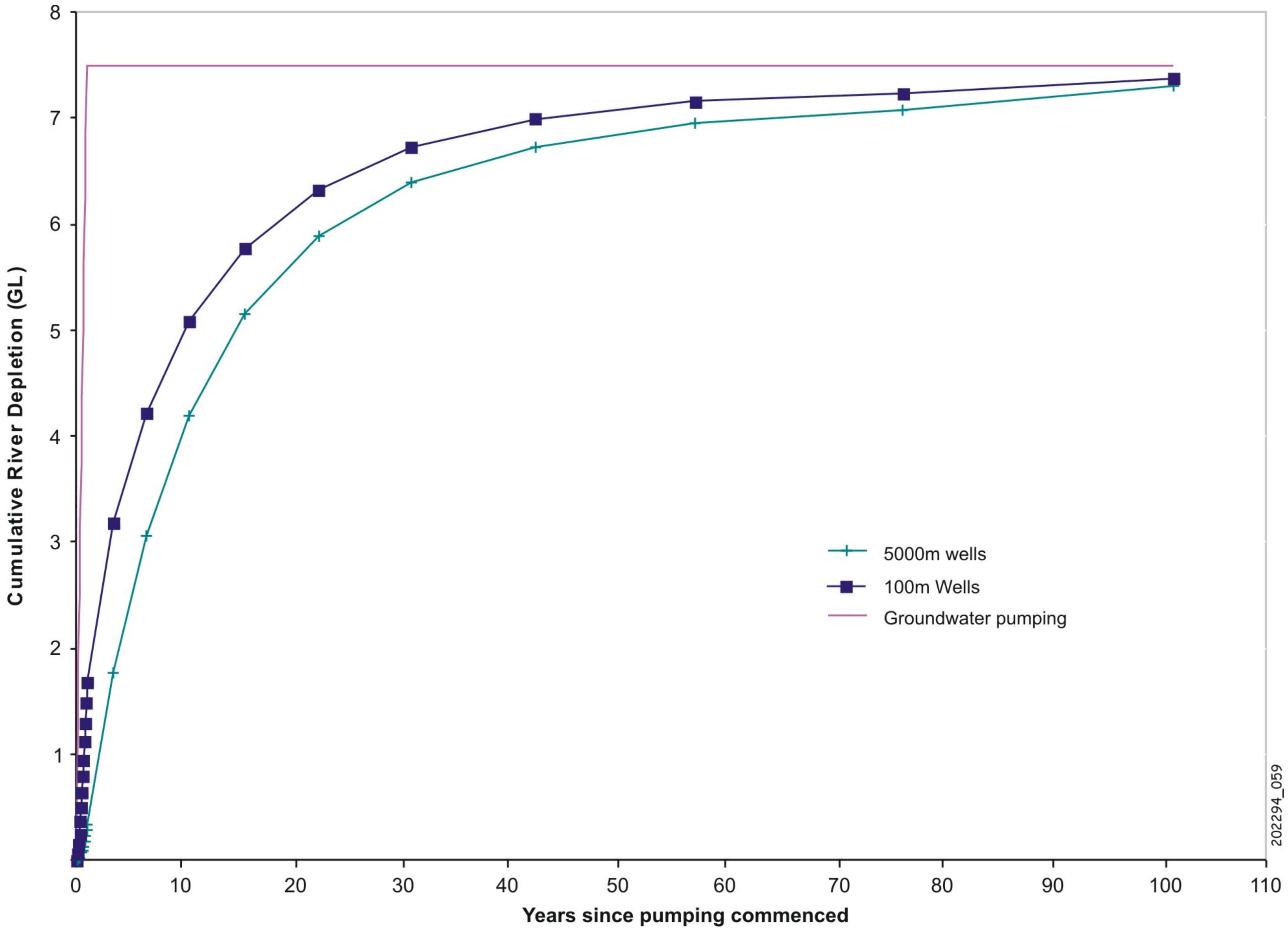
- The lag between the onset of impacts on stream flow due to a groundwater extraction cycle and the establishment of the full impact means that, at any one time, there is a legacy of impacts due to past development. This legacy of previous groundwater extraction provides inertia to the impacts on the river – large changes in short term groundwater extraction do not have a correspondingly large change on river impacts;

- The magnitude of the lag time suggests that aquifer management plans need to be sensitive to the extraction response time, and that this may be typically 20 or more years rather than five to ten years;

- Distance of groundwater extraction from the river, for the same pumped rate, does not substantially alter the magnitude of the *full* impact on stream flow. Whilst there are some lags in the timing of the onset of the impacts, a groundwater extraction regime will eventually have the same magnitude of impact on the river. These initial lags may be small in comparison with the overall lag time to the onset of full impacts. This effect is demonstrated in **Figure 3** which shows output from a groundwater modelling scenario;

- The major determinant on the size of the impact from groundwater extraction on stream flow is the volume of groundwater extracted; and

- The estimate of impact of groundwater extraction is highly dependent on the assumed rate of recharge within irrigated areas.



MURRAY-DARLING BASIN COMMISSION

CUMULATIVE RIVER DEPLETION
FROM ONE YEAR OF PUMPING

Figure
3

3 CURRENT KNOWLEDGE AND METHODS, AND SUMMARY OF HOW THIS INFORMATION HAS BEEN USED

3.1 Overview of available data

Gauging Networks

In most of the major GMUs across Basin, regional groundwater monitoring networks comprise dedicated observation bores that are 25 to 40 years old. Most of these bores are in areas where groundwater yields are high and salinity is low and do not necessarily target other areas within the catchment where there is surface water-groundwater interaction (eg end-of-valley discharge areas). Some bores have been lost over the years with limited replacement of bores across the regional networks. More recently some project networks have been established in areas where there are specific hydrogeological issues to address and these provide additional data to assess local and regional management issues.

Many stream gauging stations were established immediately prior to the major dam construction programs in the 1950s, 1960s and 1970s to assess natural stream flow. With the completion of the major dams, these networks have been made smaller and are now limited to those essential for operational requirements along the regulated streams and major unregulated streams.

Monitoring networks (both surface water and groundwater) were mostly established for resource assessment purposes and over the last 25 years have been used to assess water level/flow variations and water quality changes. With surface water and groundwater traditionally being considered separate resources, it was unusual to have combined programs (except in some project studies like the dryland salinity networks established in the early 1990s). Rarely did stream gauge locations or monitoring bore locations coincide in the major valleys. Hence there are virtually no locations where the long-term characterisation of stream aquifer interaction can be accurately determined. However there is sufficient data on a regional scale in some GMUs to characterise streams as losing or gaining and to prepare water balance estimates and develop numerical groundwater models that satisfactorily simulate surface water-groundwater interaction.

What is missing most are local networks that provide data to allow for a quantitative analysis of the exchange of water during different stream flow stages, and allow for quantification of losses in connected losing systems, and gains in connected gaining systems. A better understanding of these processes would assist in the verification and improvement of numerical models, and also allow for local management rules to be applied if induced recharge or captured discharge was considered to be excessive. In NSW, for instance, it is the mid-catchment alluvial areas where additional data is mostly required on stream-groundwater interaction. This is where the greatest growth in groundwater usage may occur. New data is required to better understand:

- Bed conductance;
- Aquifer leakage between shallow and deep aquifers near streams;
- Losses to aquifers under flood conditions when river stage/water table height are high; and
- Bank storage returns/gains to rivers following high river stages.

Very few stream gauging sites have their levels tied into the Australian Height Datum (AHD) grid, which means little use can be made of the data when comparing it with groundwater level data. As well, river bed levels are poorly described in terms of their absolute elevation.

Groundwater monitoring networks are costly to install, to maintain and to replace. The life of monitoring bores cannot be expected to last more than 50 years and hence many monitoring networks will require refurbishment or replacement over the next 15-20 years. In NSW alone, the cost of replacement of monitoring bore networks with the same bore density is likely to be in excess of $100 million. If networks could be reduced, bores refurbished or new bores sited in better locations (eg near rivers), it may be possible to reduce replacement costs. Innovative approaches are required to assess monitoring network requirements for the next 30 to 50 years.

The first stage in any rationalisation of networks is to assess the management issues, prioritise the issues and impacts, and tailor monitoring programs to suit. The current urgency is to install new stream gauges and nested monitoring bores in critical connected-losing or connected-gaining areas, to monitor water exchange processes and to identify reduced baseflow conditions. Several locations are required across a GMU to monitor different connectivity situations. An initial program is underway across NSW but additional sites are required.

Groundwater Use

Long term (20 to 30 year) metering records of groundwater use are available for relatively few (less than 10) GMUs within the basin. With increased focus on the management of groundwater resources since the 1990s, higher quality usage data has been collected across more of the developed and developing GMUs. The highest quality data across most GMUs has been collected since the mid 1990s.

In NSW, expansion of groundwater use monitoring has not occurred in recent years as agency resources diminish. Consequently use in some of the lower priority GMUs is not quantified and the frequency of monitoring in other higher priority areas is reducing rather than increasing. In other jurisdictions such South Australia, Victoria and Queensland there are plans to improve the coverage of meters.

Additional funding and resourcing is required to broaden metering activities to obtain groundwater usage data in all areas.

Management Tools

The key tool to quantifying stream flow losses or gains is numerical models that are calibrated and verified against the additional interaction data that is collected from new observation bores and gauging stations to better understand these interaction processes. It is important that the models are developed at a scale which is consistent with the scale of management and planning. If models can be improved by better estimates of bed conductance (plus any time variability in this parameter) and better estimates of leakage between aquifers near rivers, then this would have substantial water management and environmental benefits.

In NSW there are 10 developed GMUs with regional models that have been built for Water Sharing Plans (WSP) and groundwater allocation purposes. There are no models in South Australia or the ACT, and only one in each of Victoria and Queensland (though both are undergoing or will require major revision). All these models need to be constantly updated as new data sets (especially usage) are obtained. At a minimum, updates should be applied every 4 to 5 years so that the model is capable of optimal predictions, and water balances, particularly river loss and gain estimates. Ideally models should be updated annually with the latest usage data.

The major impediment to this work is funding and resourcing. For example, update and model maintenance is required in NSW for the 10 existing models once the current WSP plan initiative is completed. Additional models are required for at least 4 new GMUs.

3.2 Approach to the definition of connectivity and knowledge of connectivity

Murray-Darling Basin Commission

The Murray Darling Commission has not had a central role in defining connectivity for the GMUs of the Basin to the present time. The Commission’s involvement has been mostly via interest in the impacts of extraction of groundwater on stream flow within the context of the risks to the shared water resource.

The MDBC has analysed the connected nature of the Basin’s streams and aquifers in an attempt to provide quantitative advice on the likely impacts of groundwater extraction on surface water flows. As well, work by SKM (2001) has also attempted to estimate the connections between surface water and groundwater in the upland fractured rock environments. This information provides an insight into likely impacts.

A survey of baseflow fractions was undertaken by SKM (2001) for the uplands unregulated catchments of the Murray-Darling Basin. This work analysed 178 stream gauge sites within the upland fractured rock aquifer region (see Section 2.2). The study found that baseflow fractions at these sites varied between 4 and 75 % on a volumetric basis. This data is useful when considering the groundwater systems in the uplands region, but of little relevance to the Basin-wide issue of connectivity due to the low level of groundwater development in the uplands, and the difference in connectivity processes in the regions where large volumes of groundwater are pumped. These baseflow percentages do not provide knowledge of the amount of groundwater that discharges from the aquifer to the streams or of the amount of groundwater extracted that might impact on the stream. In fact, in the upland fractured rock environment it is highly likely that 100% of groundwater discharge ends up as stream flow.

In a study of projections of groundwater extraction rates and implications for future demand and competition for surface water, SKM (2003) adopted “for planning purposes” that 60% of groundwater pumped is assumed to be derived from surface water flows. The value adopted is speculative and based on a Basin-wide consideration of factors that influence connectivity.

As part of an assessment of risk to the shared water resources MDBC (2004) compiled information provided by the jurisdictions (assisted by REM) relating to the potential impact of groundwater extraction on stream flow within each GMU within the Basin (subsequently referred to as the ‘overview report’). Additional information was provided in a subsequent report (MDBC, 2005).

The compiled information was supported with other MDBC products such as reports from the Watermark project (REM, 2005) and the Groundwater Status Report (URS, 2004).

Work by MDBC (2004) relied on the classification of river reaches across the basin on the basis of whether the river was connected or dis-connected using information provided by the jurisdictions.

It was also noted by MDBC (2004) that there is very limited quantitative understanding of the connectivity between aquifers and streams across the Basin. An estimate of the current and future impact of groundwater extraction was provided (for each GMU) based on current and future (10-year and 50-year) rates of groundwater use and assumed estimates of the degree of connectivity (expressed as the percentage of the volume of groundwater pumped that is derived from stream flow above natural conditions). The analysis did not take into account the lag between a change in the groundwater extraction rate and an impact on the stream.

There was variable confidence in the estimated impacts. In some cases the estimates of the degree of connectivity were based in calibrated numerical models (e.g. for riverine GMUs in NSW) and in other cases there was no supporting quantitative analysis and the 60% value (taken from SKM (2003)) was used. It was concluded that ‘the development and implementation of effective management arrangements are also dependent on improved information gathering linked to continued assessment of sustainable yield issues, including data collected at the appropriate time and spatial scales’.

Apart from the modelled GMUs in NSW the level of certainty in estimates of connectivity across the basin between surface water and groundwater is generally considered to be low.

Work undertaken in the Watermark project by REM (2005) investigated the time lags associated with the impacts of groundwater extraction on stream flow. Some of the primary conclusions from that work were:

- The onset of impacts from groundwater extraction is rapid and long lived;
- The impacts on stream flow at any one time are mostly due to past groundwater extraction rather than current groundwater extraction; and
- The eventual (full) magnitude of the stream flow impact is independent of the distance of the groundwater extraction bore from the river.

New South Wales

There is no formal definition of connectivity that is being applied to surface water and groundwater water resources across NSW and the respective Water Sharing Plans (WSP) under the Water Management Act (2000). However, all stream reaches in the Murray-Darling Basin in NSW are being classified as high, medium or low connectivity. This is an assessment based on existing data sets and knowledge.

There is recognition that the interaction is quite variable and that management approaches must cater for this variability. In particular, surface water - groundwater interaction is dynamic across the mid-section alluvial valley segments of river basins in the Murray Darling Basin in south west, central west, and north west NSW. Conditions can change from connected to disconnected and from connected gaining to connected losing (and vice-versa)[1], especially under low flow river conditions and where there is increased extraction of groundwater.

In the upland sections of river basins where fractured rock aquifers predominate, there is a recognition that streams are most often connected gaining and that stream baseflows are primarily derived from groundwater discharge and ultimately antecedent rainfall recharge.

Given the variability of stream – aquifer interaction that is likely to occur under natural and groundwater extraction conditions, the connectivity between different water sources (and zones within each of these water sources) are managed locally and on a water year basis under the WSP rules. This approach is consistent with changing developing pressures and changing climatic cycles. Connectivity recognises that both captured discharge and induced recharge are important consequences of groundwater extraction in connected surface water-groundwater systems.

High connectivity stream – aquifer situations will be defined in NSW as cases where greater than 70% of groundwater pumped comes from riverine sources (either floods or stream leakage) over a 50 year period; medium connectivity will be cases where 10 to 70% of groundwater pumped comes from riverine sources;

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[1] It is worthwhile noting that in NSW the current definitions for connectivity are slightly different to those proposed in Section 2.1 eg (1) connected streams are those with strong surface water-groundwater interaction that may dry up under climatic and some extractive conditions, and (2) gaining streams are those where flow generally increases due to groundwater inflow and tributary inflows

while low connectivity will be cases where less than 10% of groundwater pumped comes from riverine sources.

There are 5 gazetted groundwater WSPs in the Murray Darling Basin in NSW for alluvial groundwater systems, although all have deferred commencement. In addition there is one draft WSP in this area for the deep Great Artesian Basin (GAB) aquifers and one draft WSP for the Lower Murray (deep) alluvium. There is 5 other coastal groundwater WSPs or integrated surface water-groundwater WSPs.

The remaining aquifer systems across the state (both coastal and Murray-Darling Basin) will be covered by Macro Water Sharing Plans (MWSPs) and local water sharing rules in 2006. Enhanced approaches are being developed in these MWSPs (particularly in respect to connectivity) that will apply to the remaining water sources that have not previously been intensively managed. The primary management issue that is being tackled is the loss of stream flow to groundwater extraction through increased induced recharge losses. There is recognition of captured discharge in some source areas but it is difficult to quantify and manage. It is expected that these new approaches will also be applied in the existing WSP areas where local area rules are required to protect groundwater dependent ecosystems (GDEs) and stream baseflows.

Victoria

There are currently six approved Groundwater Management Plans within the Victorian part of the Basin that are the statutory equivalent to the Water Sharing Plans in NSW. Impacts of groundwater extraction on stream flow have not been quantified within the plans for Campaspe and Katunga GMUs. However, these plans are explicit in the management of groundwater levels to those measured in 1999/2000 and minimising falls in groundwater levels at the boundaries that would induce further leakage from rivers. Water level triggers will be applied to other GMUs under investigation.

There is no formal definition of connectivity in Victoria. Connectivity within Victoria has been classified at the broad scale and reported in work by REM (2005) and SKM (2003).

The Department of Sustainability and Environment (DSE) have indicated that no work has been undertaken in the last 12 months that would justify changing the information in the overview report (MDBC, 2004). The Victorian response in the overview report was based on very limited information regarding the degree of connectivity and the volumetric impact groundwater extraction would have on stream flow. The information provided by Victoria to the overview report was considered to have a low level of confidence attached to it.

Discussions with Goulburn Murray Water (G-MW) indicate that rivers and aquifers that are separated by a semi-confining layer would be considered to be connected. In these situations an understanding of the lag time is important in the development of a management approach. It is recognised by Victoria that more work is needed to adequately classify the nature and degree of connectivity.

It is likely that Victoria would accept both induced recharge and captured discharge as impacts from groundwater extraction.

The Victorian approach is to consider the importance of links between surface water and groundwater on a case by case basis, focusing on the higher priority management units. G-MW has indicated a need for guidelines on how to manage connected systems, for example definition of planning timeframes.

Queensland

There is no formal definition of connectivity for use in groundwater allocation planning in Queensland.

Connectivity has always been a consideration in the determination of a groundwater licence but never in the consideration of a surface water licence. In terms of groundwater, connectivity has been considered at an early stage when an estimate of the total resource available for allocation has been made. Generally, most GMUs in the Queensland part of the MDB have been subject to some form of water balance modelling, where surface water and groundwater connectivity processes have been explicitly considered. This simple connectivity estimate has then been an implied part of the sustainable yield estimate that was used to inform the allocation of the groundwater resource. Management of the resource after this point has generally been via a three step process – where the nature of each step means that there has been no reason to re-assess the connectivity of the system. This leads to the current situation where the connectivity estimates for most Queensland GMUs are somewhat dated.

The following describes the approach used in Queensland to manage groundwater resources. It provides some context to the inclusion of recharge sources from surface water in the groundwater budget at an early stage of the process, and that the management approach doesn't require continual improvement in the quantification of the connectivity.

The first step in the Queensland process is to restrict entitlement to the capacity of the infrastructure, once an overall estimate of the sustainable yield has been derived. This has the effect of keeping groundwater use close to the entitlement. The aquifer performance is monitored as development of the groundwater resource occurs. New applications for increases in entitlement are processed in such a way that any entitlement granted will be matched to any new infrastructure proposed.

Where entitlements approach the sustainable yield of the groundwater system, a second step of imposing a restriction regime is involved. This is generally triggered by an assessment of unacceptable changes in groundwater levels. In these cases, access to groundwater is controlled by controls on groundwater extraction periods and other lower level access rules.

Where entitlements are over and above sustainable yield levels, the third stage of announced allocations on an annual basis is implemented. This management approach is only done in concert with groundwater use metering.

This approach does not rely on the recalculation of the impacts of groundwater use on stream flow, and does not require any monitoring of stream flows as an aid to determining impact. These initial estimates of connectivity are now 10 years or more old.

There is a strategy that will require all high priority GMUs to be subject to a Water Management Plan. The GMUs in the basin will be subject to this planning requirement within the next 3 to 5 years. This planning approach will require that any GMU subject to a plan will need a more complex analysis of the connectivity between surface water and groundwater sources.

South Australia

South Australia does not have a specific definition for connectivity. The interaction between surface water and groundwater is determined as part of the conceptualisation of the groundwater systems on a catchment-by-catchment basis. The Natural Resource Management Act 2004 is the driver for the need to understand the interaction between surface water and groundwater because there is a need to assess the impact of ‘taking’ water from one resource (e.g. a productive aquifer) on another resource (e.g. an ephemeral creek).

The Natural Resource Management Act 2004 also requires the consideration of groundwater dependent ecosystems (GDEs) in an assessment of the capacity of a resource to meet demand. Interaction between a surface water feature and a shallow (non-productive) aquifer, which is separated from a deeper productive aquifer by a leaky confining layer, would be considered connected, however the impacts of groundwater extraction would be judged in the broader context of setting a sustainable yield.

South Australia is unlikely to define connectivity in terms of impacts of groundwater extraction only, but to characterise connectivity (quantitatively where possible) in terms of annual volumes exchanged between surface water and groundwater (irrespective of whether that is captured discharge and/or induced recharge) and timing of that interaction.

Australian Capital Territory

The ACT via its Water Resources Management Plan has made an implied assumption that all groundwater systems are fully connected with their surface water resources and that this connection occurs equally at the sub-catchment level. As such there is no distinction between developed or undeveloped conditions.

The way in which ACT has used this information is slightly different from other jurisdictions, in that the ACT has assumed a degree of connection prior to allocating water for use and has incorporated the degree of connection into the volumes determined as sustainable.

The approach to characterisation of connectivity in the ACT is determined to a large extent by the way in which sustainable yield is defined. The sustainable yield is defined as 10% of the available recharge, and is determined as a long term volume. The intent of this approach to sustainable yield is to allow 10% of the baseflow from surface water systems for groundwater uses. Thus, this assumes that 10% of the baseflow of the surface water systems is equal to 10% of the recharge to the aquifer.

The approach explicitly deals with captured groundwater discharge as the main source of groundwater use. In areas where groundwater use would likely cause an impact on the surface water flow by inducing recharge directly from the stream, it is proposed to institute zones where groundwater abstractors would be treated as surface water users.

3.3 Determining the degree of connectivity

3.3.1 Locations and methods

The following section outlines the locations where work has been undertaken on connectivity, as well as outlining the methods employed. A number of generic methods have been defined as a means of classifying the different approaches to determining the degree of connectivity. These methods might include direct measurement (either chemical of hydrologic), modelling or by assumption.

New South Wales

In NSW, individual management areas are now known as groundwater sources rather than groundwater management units (GMUs). There are now 45 groundwater sources in the NSW part of the Basin (a variety of fractured rock, alluvial, and sedimentary rock aquifer systems) and 95 across NSW in total. There are a few systems where the degree of connection is so strong between surface water and groundwater that a single water source plan is proposed. These are mainly basaltic fractured systems and shallow unconfined alluvial aquifer systems. There are no single source plans proposed for the Murray-Darling Basin at this time.

The 45 water source areas and the respective data sources/methods for determining water balances and or long term average extraction limits are provided in Table 1.

Table 1 Summary of methods used to quantify connectivity in NSW

Code	Groundwater Source	Data Source
N09	Lower Namoi Alluvium	Model
N10	Lower Murrumbidgee Alluvium	Model
N11	Lower Gwydir Alluvium	Model
N12	Upper Namoi Alluvium	Model
N13	Peel River Alluvium	Rainfall and River
N14	Maules Creek Alluvium	Now Part of 4
N15	Miscellaneous tributaries of the Namoi River (Alluvium)	Now Part of 4
N16	Lower Macquarie Alluvium	Model
N17	Upper Macquarie Alluvium	Rainfall and River
N18	Cudgegong Valley Alluvium	Rainfall and River
N18	Cudgegong Valley Alluvium	Rainfall and River
N19	Upper Lachlan Alluvium	Model
N20	Lower Lachlan Alluvium	Model
N21	Mid Murrumbidgee Alluvium	Model
N22	Billabong Creek Alluvium	Rainfall
N23	Upper Murray Alluvium	Rainfall
N24	Lower Murray Alluvium	Model
N27	Coolaburragundy-Talbragar Valley Alluvium	Rainfall and River
N28	Bell Valley Alluvium	Rainfall and River
N29	Belubula River Alluvium	Rainfall and River
N999	Border Rivers Alluvium	Model
	Misc Alluvium Barwon Region	Rainfall
	Lower Darling Alluvium	Rainfall
	Upper Darling Alluvium	Rainfall

Code	**Groundwater Source**	**Data Source**
	Bungendore Alluvium	Rainfall
	Martindale alluvium	Model
	Great Artesian Basin alluvials	Rainfall
	Great Artesian Basin	Model
	Gunnedah Basin	Rainfall
	Oxley Basin	Rainfall
	Western Murray Porous Rock	Rainfall
	Ivanhoe Sandstone	Now Part of 811
N42	Orange Basalt	Rainfall
N43	Young Granite	Rainfall
N44	Inverell Basalt	Rainfall
	New England Fold Belt	Rainfall
N46	Mid and Upper Murrumbidgee Fractured Rocks	Rainfall
N48	Mudgee Limestone	Now Part of Lachlan Fold Belt
N49	Molong Limestone	Now Part of Lachlan Fold Belt
	Lachlan Fold Belt	Rainfall
	Galarganbone Basalt	Rainfall
	Liverpool Ranges Basalt	Rainfall
	Kanamantoo Fold Belt	Rainfall
	Adelaide Fold Belt	Rainfall
	Peel Valley Fractured Rock	Rainfall

Each of the 45 water sources is subject to either a WSP or proposed MWSPs where water balances have been derived by either empirical or numerical modelling approaches. This modelled information has then been translated into recharge and discharge volumes, and estimates of long term average annual recharge. After community consultation and an assessment of environmental requirements, this has then been described in the respective plans as either sustainable yield or long term average extraction limits.

Connectivity is classified for each of the source areas (although rarely to the zone level). The stream loss volumes are averages over space and time and the natural loss component is recognised. Where additional losses are now apparent, the impacts are managed locally based on the observed variability and water level trends. Groundwater source performance is monitored periodically and described in Status Reports that are released locally for important water sources.

The best compilation of information for the NSW part of the Basin describing whether streams are connected or disconnected to adjacent aquifers is provided in Braaten and Gates (2002) together with the loss estimations provided to MDBC for the overview report (MDBC, 2004). This data provides an overview of the connectivity of systems at the river basin scale, although additional work is planned and underway to better understand linkages at smaller stream segment scales. No reports or compilations are available at this time. This additional work involves a review of connectivity as the new MWSP and local management rules are being compiled, and new monitoring network programs to quantify stream-groundwater interaction.

The degree of connectivity on an individual water source basis has been determined using a broad scale water balance approach (where insufficient data is available for modelling) and then detailed numerical models for those systems where systems are highly developed and stream-aquifer interaction is a key component of the water balance.

Rainfall recharge estimation techniques coupled with root zone drainage methods have been used in the upland areas to determine rainfall recharge volumes. In the lesser-priority alluvial areas, rainfall estimation techniques and stream leakage have been used to assess recharge volumes and long term average extraction limits.

Direct measurement approaches are currently being developed and implemented.

Absence of hydrographic data has been a severe limitation in the past as stream gauging stations have been sited at locations which are not consistent with observation bore networks. This is now changing with a new monitoring program initiative with up to 12 stream gauge – groundwater monitoring bore sites being established in representative connected areas to better assess stream - aquifer interaction. There will be two representative sites in each of the three regions in the Murray-Darling Basin and a similar number in the three coastal regions. Work will commence in early-mid 2006. In addition, there is a new groundwater monitoring network initiative to establish observation bores in water source areas where there has been negligible monitoring of groundwater systems.

Hydrochemical methods and GDE mapping has also assisted in identifying and quantifying systems with strong surface water - groundwater connectivity, however most of these approaches have been at the project or local scale.

Victoria

The focus of investigations that have specifically tried to understand the connectivity between groundwater and surface water has been in the Ovens GMU, southern Campaspe Plains and the Katunga area, and in the unregulated upland GMUs (e.g. SKM, 2001).

DSE will extend the GDE assessment across the state, and undertake more fundamental investigations of groundwater status in selected GMUs. G-MW is preparing conceptual models for the Campaspe, Mid Loddon, Upper Loddon and Mid Goulburn GMUs.

DSE reported that there had not been any investigations other than a project by URS (project V1, section 5.1) which identified groundwater dependent ecosystems (GDEs). That project was limited to groundwater management units and did not extend to the higher priority water supply protection areas. DSE is planning to extend the analysis to the remainder of the state, but the exact scope is not clear at this stage.

DSE have indicated that they are basing their assessments of sustainable yield and surface water – groundwater interaction on conceptual hydrogeological models and monitoring data. DSE are moving from quantified water balances and modelling approaches towards decision making based on observed trends in groundwater condition. Under this approach the magnitude of exchange between aquifers and surface water systems would be inferred from trends in groundwater levels near the surface water system.

G-MW is currently monitoring groundwater levels in an area of the southern Campaspe Plains where a groundwater supply exists. The results of this investigation have not been documented, but it is expected that the monitoring results will be used to contribute to the understanding of the impact of extraction of groundwater in this area on stream flow. G-MW is also moving to develop conceptual and numerical models for Campaspe, Mid Loddon, and Mid Goulburn GMUs. These models will explicitly deal with the exchange of water between rivers and aquifers.

Work is being undertaken in the Ovens Valley to assess the level of connectivity and to develop a better understanding of response times. The Ovens project is targeting the development of a sound technical basis for incorporation of groundwater management decisions associated with management of groundwater extraction to achieve environmental objectives within a stream. The study will provide a summary of the technical understanding of issues associated with groundwater - stream interaction and provide a general framework and practical applications for managing interaction (pers comm. Greg Holland, G-MW).

Queensland

Volumetric estimates have been quantified for all GMUs in Queensland based on simple water balance models. In addition, a medium complexity model of the Border Rivers GMU was undertaken, but as yet, has not been formerly adopted.

The approach in the past had been to consider aquifer response as both the surface water and groundwater systems were being developed. If water levels in the aquifer were not declining and responding well to recharge events an application for a groundwater entitlement would be considered. If the system showed signs of long term stress the application would be refused and closure of the system to new entitlement would be considered.

The degree of connectivity was determined by simple water balance methods during the estimation of sustainable yield for each GMU.

Queensland intends to review the status of connected systems. The overview report (MDBC, 2005) list of connectivity estimates should not be regarded as current or agreed. In particular, Queensland would like the concept of *degree of connectedness* (for an agreed timeframe) built into the estimation. The overview report listed connected system regardless of whether they were well-connected or poorly connected.

South Australia

Detailed investigations of the connectivity between surface water and groundwater have occurred in the Marne catchment and within other parts of the Eastern Mount Lofty Ranges.

The degree of connectivity is determined on a sub-catchment basis using the following range of methods:

- comparison of groundwater levels and surface water levels along a stream reach;
- estimation of a catchment water balance with an estimation of baseflow from a stream hydrograph; and
- geochemical testing and analysis (salinity, major ion chemistry, stable isotope compositions and radioactive isotopes such as radon; e.g. Harrington, 2004a and 2004b).

Investigations to-date have focussed on the Marne GMU and the Eastern Mt Lofty Ranges (currently not defined as a GMU nationally, but recognised as a groundwater management unit within South Australia).

There have also been many studies of the interaction of floodplain aquifers and the River Murray within the South Australian Riverland as part of reporting to the Basin Salinity Management Strategy (BSMS) and the development of salt interception schemes. These investigations have focussed on groundwater monitoring and evaluation of the in-river salinity record through run of river surveys, geophysical (e.g. NanoTEM) surveys and estimates of unaccounted salt between flow and salinity monitoring stations.

Australian Capital Territory

The 14 GMUs where connectivity has been included in to water planning approaches with updated sustainable yield and therefore, quantification of connectivity in the ACT, are:

- Fyshwick;
- Tuggeranong;
- Jerrabomberra Creek;
- Woolshed;
- Woden;
- Weston;
- Lake Burley Griffin;
- Sullivan's Creek;
- Gungahlin;
- Tharwa;
- Lake Ginninderra;
- Parkwood; and
- Coppins.

In the first instance the ACT Government has assumed the degree of connectivity for all its constituent GMUs to be 100%. The approach used average annual data to develop recharge estimates from a gross water balance, with these recharge volumes assumed to be equivalent to volumes of groundwater discharge to the streams. More detailed modelling studies have been undertaken in priority GMUs. These studies have used a combination of methods to estimate actual connectivity, however, all methods rely on a modelling approach. The methods include simple numerical models, detailed water balance estimation using the method of Zhang and others, and base flow filtering using available stream gauging data.

The more detailed work has been undertaken in 2 stages and a total of 14 GMUs has been analysed using these methods. Individual sustainable yields have been calculated from estimates of the volume of groundwater discharge that is assumed to represent 10% of baseflow in the streams.

The conceptual model of connection relies on the following assumptions:

1. All recharge to the aquifer manifests as discharge from the aquifer under steady state conditions;

2. The discharge is from the aquifer which is being pumped or subject to management;

3. This groundwater discharge has occurred to streams in individual sub-catchments before the stream exits the sub-catchment;

4. All groundwater discharge appears as a component of stream flow. That is, there are no other discharge pathways;

5. Base flow adequately represents the contribution of groundwater discharge to stream flow; and

6. The base flow filtering technique can partition the true amount of base flow from the measured hydrograph.

3.4 Applying estimates of connectivity

This section deals with how the various jurisdictions have applied the estimates of connectivity.

Murray-Darling Basin Commission

The MDBC has used information provided by jurisdictions to develop an understanding of the current and future levels of groundwater use and to more clearly understand the risk of groundwater use impacting on surface water resources (reported within MDBC, 2004).

The analysis by MDBC was part of a work program agreed by the Murray-Darling Basin Ministerial Council to refine the understanding of increasing groundwater use as one of the six identified risks to the shared water resource.

The knowledge of connectivity and the impact of groundwater extraction on surface water provided by, or agreed by, the states is now the basis for the scoping of a policy on groundwater management within the Murray-Darling Basin. The policy is focused on the issue of management of groundwater use to minimise future impacts on surface water.

The data in the overview report has provided a basis for a discussion around the magnitude of the impact (but not timing) at the GMU and basin scales. This has been useful in designing a risk-based approach for the management of groundwater use by identifying the highest priority GMUs based on the degree of connectivity and the volume of groundwater abstracted currently and into the future. The analysis in the overview report uses the best information available at that time, there remain many uncertainties.

New South Wales

There has been some application of the connectivity framework and estimates for NSW where WSPs have been developed. In those areas where there is strong surface water – groundwater interaction, there has been a focus on the water balance components and an attempt to quantify the riverine losses under current developed conditions (some of these losses are also natural losses). This then provides a baseline beyond which further losses induced by groundwater extraction can be identified and potentially managed by either access licence restrictions, works approvals (i.e. moving groundwater extraction sites away from rivers) or local management rules (seasonal approach).

Even though NSW is moving towards access licences that are solely surface water or groundwater based, this interaction of sources is recognised and will be mostly managed at the local scale. For instance, for alluvial aquifers where there is strong connectivity with adjacent streams and there is an existing access licence and works approval in place, the following criteria are likely to apply:

- Less than 40 m from the high bank of the stream - a surface water works approval and surface water rules will apply;
- 40 to 200 m from the high bank of the stream - a groundwater works approval and surface water rules will apply; and
- Greater than 200 m from the high bank of the stream - a groundwater works approval and groundwater rules will apply.

With the periodic review of models and their outputs, additional local management rules are likely to be applied if the stresses cannot be relieved.

These initiatives are aimed at minimising induced recharge from adjacent connected streams although it is recognised that the rules will also assist in ensuring that captured discharge is minimised and baseflow discharges to important streams can be maintained.

Victoria

To-date there has been very little direct application of outcomes from investigations of surface water – groundwater interaction, mainly because there has been limited work completed.

Victoria is moving towards a groundwater management framework which involves setting a “licensing limit” which is the full entitlement, then having a seasonal allocation which is based on inter-annual trends in water levels relative to a benchmark year. This approach is now used at Katunga and Campaspe. While the impact of groundwater extraction on stream flow would be a driver to setting the right seasonal allocation, it is not factored explicitly (e.g. volumetrically) where this managed aquifer response approach is used. This approach also takes a no-regrets approach by not dealing with historical impacts from groundwater extraction.

G-MW is investigating the implications of lag times on the management response, and has begun a project looking at this issue in the Ovens catchment. G-MW concerns relate to the definition of an appropriate planning timeframe. The output from the Ovens project will be used to design a management approach, most likely based around the creation of management zones near streams.

Queensland

Estimates of connectivity have been derived on a volumetric basis for each GMU during the initial stages of estimating the sustainable yield. As such, there are no statewide, or inter-GMU rules for connectivity estimation.

South Australia

The information on connectivity has been used to:

- underpin the conceptualisation of the groundwater system in each GMU;
- quantify the water balance;
- identify strategies to protect groundwater dependent ecosystems; and
- develop water allocation planning policy for both groundwater and surface water.

Australian Capital Territory

The ACT has applied discrete estimates as determined by the conceptual models and assumptions derived for its GMUs.

3.5 Key findings

The overall understanding of connectivity and how it is being used in the Basin can be partitioned into three categories – how the broad definitions have been applied, whether the connections in the natural water balance have been quantified and whether the impacts of groundwater extraction on stream flow have been quantified.

3.5.1 Application of definitions

All jurisdictions have characterised the connectivity of the major streams and aquifers in the Basin. However, this has mostly been based on limited knowledge of the stream groundwater interaction, and in particular, on little data related to the developed water balance.

Most jurisdictions have an understanding that connectivity is an important issue in water resource planning and have characterised the connectivity either explicitly or implicitly. However, no jurisdiction has an explicit set of definitions of connectivity that are applied throughout their regions. Instead, all jurisdictions recognise that various reaches of rivers have particular connectivity attributes and deal with them accordingly.

There are some gaps in this approach.

There is no uniform definition of connectivity that incorporates the issues of time and space as outlined in Section 2. Further, the manner in which reaches of rivers have been classified in terms of their connectivity bears little to the characteristics of the underlying aquifers, that is, a river crossing a single aquifer has been classified into different connection styles for different reaches. The agreed definition of connectivity should be used at such a scale that a complete picture of the aquifer and its connectivity is obtained.

Finally, some jurisdictions are applying the definition to the current developed nature of the connection, whereas the majority of classifications are regarding the natural state. That is, in some places groundwater extraction has caused the style of connection to become disconnected where it once was connected, but the reach is now classified as disconnected. This is significant in that disconnected GMUs are not seen as a priority, whereas connected GMUs are. As well, the GMU in question may already be having a large impact on stream flow.

3.5.2 Quantification of connectivity under natural conditions

The level of knowledge used to quantify connectivity between streams and aquifers within the basin is not well developed. In most cases where a volume (or degree) of connection has been derived, it has been done so for the natural condition of the river and groundwater. It is more important that the connectivity be quantified for the post-development condition so that the impact of groundwater extraction can be determined.

In all of these instances, the volumes have been derived from simple water balance methods, or by estimation, and relate almost solely to the volumes derived from induced recharge. There are no cases where the volumes have been measured.

There are 11 GMUs (all in New South Wales) where the connectivity has been quantified at a sufficiently high technical standard. Detailed tracer investigations have been completed within the Eastern Mount Lofty Ranges in South Australia.

A range of methods exist to characterise the nature of a stream groundwater connection. These methods can be partitioned between two fundamental types – measurements or models. Measurement techniques include approaches that use hydrologic data to assess connection (such as hydrograph analysis, or hydraulic gradient mapping) or tracer techniques that involve measuring physicochemical parameters (such as major ion chemistry, radiogenic species such as radon or basic parameters such as temperature). Modelling techniques rely on an analysis of the water balance, either by simple means or via complex numerical simulations. Very few of these techniques have been applied in a management sense, except for regional groundwater models.

3.5.3 Quantification of connectivity under developed conditions

In a few cases in NSW, estimates have been made of the quantity of groundwater sourced from stream flow under developed conditions. All these instances occur on the southern riverine plain and have been derived via medium complexity numerical simulation. The reports of this work are not available to the consultant team at this stage, so it is yet to be evaluated.

The overview report by MDBC (2004) on the impacts of groundwater extraction on stream flow assumed a factor for each GMU that represented the proportion of stream flow that might be pumped as groundwater. This factor was then multiplied by the volume of groundwater pumped to derive the volumetric impact on stream flow. There was little basis for many of the proportions assumed in the report (with the exception of modelled GMUs in NSW), though all jurisdictions agreed at the time with the use of the values. Importantly, there has been no reported analysis to show that the proportions are representative of both induced recharge and captured discharge processes operating when a groundwater system is pumped.

The volumes of water identified as *connected* under developed conditions, in those NSW cases where connectivity has been quantified appropriately, is relatively small. These volumes are predicated on the analysis of a complex water balance due to the importation of large volumes of surface water for irrigation and processes operating in the thick semi-confining layers of the southern Riverine Plain. The conceptual models are complex and have not been able to be reviewed as part of this work.

At this stage, there has been little analysis of the role of captured discharge in the reduction of stream flow. This may lead to an underestimation of the impacts of groundwater extraction on stream flow, especially in terms of the timing of such impacts. In some cases, it may be that captured discharge via groundwater extraction will lead to substantial salinity benefits to the river.

All estimates of connectivity, either as a volume or as a proportion of groundwater pumped, are reported as average annual numbers. There has been no analysis to show how the connectivity changes with time, especially between wet and dry seasons.

There are few examples of where the timing of impact of groundwater extraction on stream flow has been quantified. This has been identified as an important issue by a numbers of workers (e.g. REM (2005) and Braatan and Gates (2002)).

3.5.4 Use of connectivity information

The States and Territory are endeavouring to use connectivity information in their respective water planning processes. This demonstrates that managers are accepting that the issue is real and that it needs to be actively accounted in the water planning process.

This demonstrates further that the jurisdictions are using, or trying to use, information to varying levels, but the information may not be appropriate. The main impediments to better information being used appear to be related to the lack of robust information and the priority attached to generating new information by the jurisdictions.

The summary analysis undertaken in this project leads to the conclusion that the approaches to quantification of connectivity being adopted by the States, somewhat implicitly, are inadequate given the lack of knowledge of connectivity especially for priority GMUs.

While the jurisdictions have recognised the issues referred to, the impact or ramifications of the inconsistent approach will result in:

- an inability to determine and prioritise a response to the problem based on a risk assessment of the magnitude of the impact; and
- an inability to communicate the size of the problem or the effect of the management response to stakeholders in a consistent manner that covers the planning areas of interest.

4 DATA AND INFORMATION GAPS

4.1 Framework for analysis of data gaps

Data gaps have been assessed in relation to the need to undertake an assessment of the impact of groundwater use on stream flow at the basin scale. The authors recognise that the potential impact of surface water diversions on the availability of groundwater to dependent ecosystems is an important issue which is not explicitly handled within this project.

A basin scale assessment requires an estimate of the quantity and timing of the impacts of past, current and future groundwater extraction on stream flow for each GMU. The only way to understand impacts is to consider the developed water balance. This means that aquifer-scale numerical groundwater flow modelling is the only tool to predict impacts.

Therefore, the analysis of data gaps focuses on how well the developed water balance is known, and how well it can be modelled. It is recognised that not all GMUs are going to be modelled, and that the priority list of GMUs may be different from the list of priority GMUs that will be modelled by the jurisdictions (for other purposes). This may lead to the conclusion that some high priority GMUs from a connectivity basis will never be modelled, and therefore the full impact of groundwater use on stream flow will never quantified.

An assessment of data gaps has been made based on whether the following information is available:

- Classification of the type of interaction between surface water and groundwater at the GMU and sub-GMU scale based on conceptualisation of the groundwater system;
- Groundwater and surface water data, and hydrogeochemical data;
- Historical groundwater use information;
- Current groundwater use information and an estimate of future patterns of groundwater use based on known use drivers.
- Quantification of the exchange of water at the GMU and sub-GMU scale through a water balance or point measurements; and
- Quantification of the current and future impact of groundwater extraction using a simple water balance or numerical modelling approach.

The evaluation of data gaps has been undertaken using a simplified risk based approach to ensure that the data gaps can be ranked. It is assumed that the highest ranked data gaps are those relating to GMUs where the impact of groundwater use is likely to be greatest.

A three-step approach to the prioritisation of the GMUs has been suggested to recognise that GMUs can be prioritised based on the combination of the volume of groundwater that could be extracted (a limit set by sustainable yield) and the degree of connectivity between surface water and groundwater (expressed as the increased loss of stream flow over natural conditions expressed as a percentage of groundwater extracted at a specified point in time).

The first step of the prioritisation involves grouping the GMUs based on sustainable yield using the following categories created by the authors of this report:

- Priority 1 – sustainable yield is greater than 50 GL/yr;
- Priority 2 – sustainable yield is between 20 and 50 GL/yr; and
- Priority 3 – sustainable yield is less than 20 GL/yr.

The second step of the prioritisation involves grouping the GMUs based on the degree of connectivity using the following categories. These categories have been the basis of previous discussions between the MDBC and the jurisdictions:

- High – connectivity is greater than 70%
- Medium – connectivity is greater than 10% but less than or equal to 70%; and
- Low – connectivity is less than or equal to 10%.

The third step of the prioritisation approach is to estimate the impact of groundwater extraction on stream flow in 2052/53 was estimated by multiplying the sustainable yield for each GMU (the assumed upper limit to groundwater extraction) and the assumed degree of connectivity.

The priority GMUs have been assessed as those GMUs where the impact of groundwater extraction on stream flow is greater than 10 GL/yr in 2052/53.The two tiered approach has been used to allow for identification of GMUs that may be important from a basin-scale perspective (e.g. Priority 1 GMUs with high degree of connectivity) and those GMUs important at the GMU or local scale (GMUs with high degree of connectivity) – as demonstrated in the matrix below.

	SY >50 GL	**20 < SY < 50 GL**	**SY < 20 GL**
Connectivity > 70%			
10% < Connectivity <= 70%			
Connectivity < = 10%			

Increasing priority from a basin scale perspective (dependent on volume and connectivity)

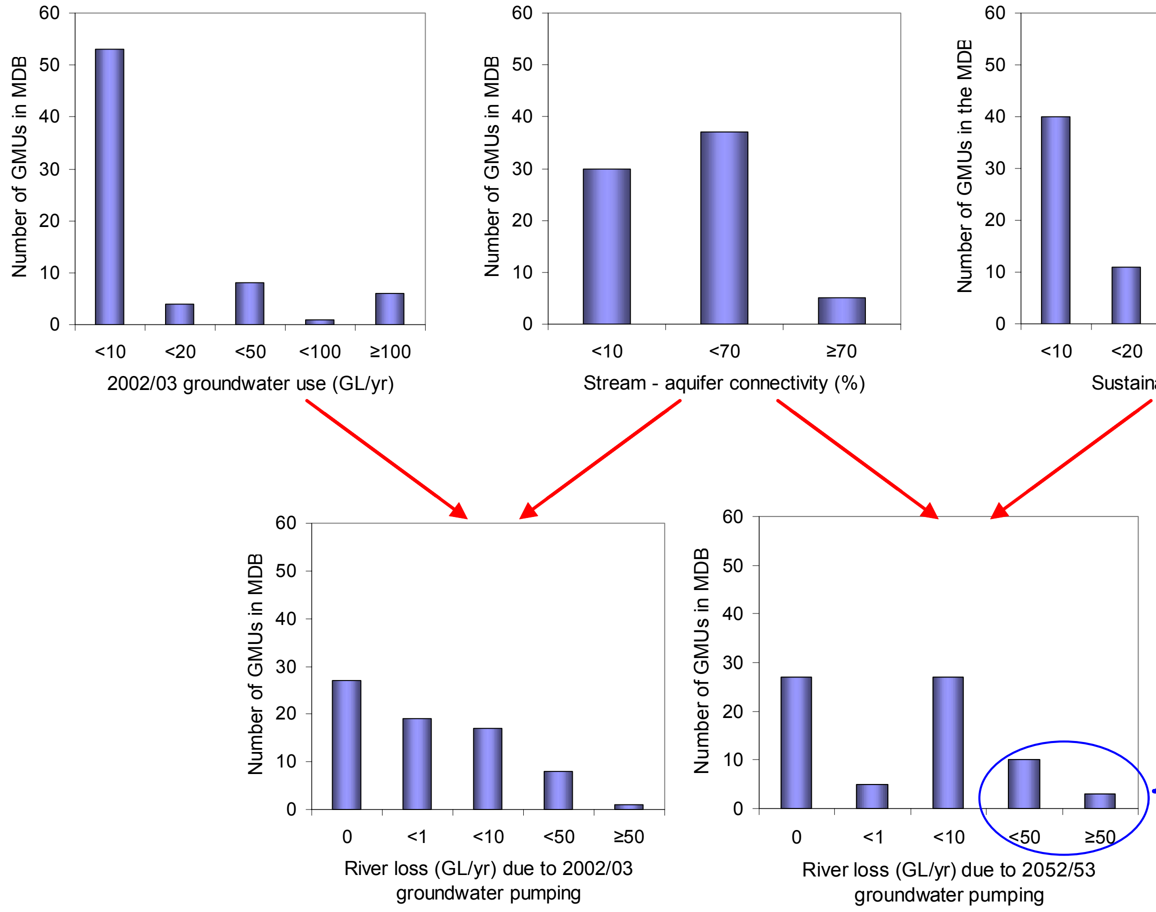
Increasing priority from a local perspective (independent of volume and dependent on connectivity)

Histograms of use, connectivity and potential impact of groundwater extraction on stream flow (02/03 and 2052/53) are provided in **Figure 4** using data from the overview report. The data in the overview report (MDBC, 2004) is not specific about the timeframe of the impact of groundwater extraction and applies the same percentage (of groundwater pumped derived from stream flow) to current, 10-year and 50-year estimates of groundwater use. This is considered to be a limiting factor to that work and future basin-scale estimates of groundwater use need to be more specific about the timeframe of the impact.

The GMUs where the impact of groundwater extraction on stream flow is potentially greater than 10 GL/yr over the 50 years (as determined from the data described in MDBC, 2004) are listed in **Table 2**. These GMUs could be considered (from a basin scale perspective) to be the priority GMUs. The location of these GMUs is provided in **Figure 5**.

Table 2. Summary of priority GMUs

GMU Code	GMU Name	Estimated impact of groundwater extraction on stream flow at 2052/53 (GL/yr)[1]
New South Wales		
N43	Young Granite	10.1
N23	Upper Murray Alluvium	15.2
N46	Mid and Upper Murrumbidgee Fractured Rock	16.8
N16	Lower Macquarie Alluvium	19.3
N17	Upper Macquarie Alluvium	24.0
N21	Mid Murrumbidgee Alluvium	71.2
N19	Upper Lachlan Alluvium	164
Victoria		
V37	Murmungee	10.0
V42	Campaspe	18.6
V45	Mid Loddon	22.3
V39	Katunga	24.3
V43	Shepparton	72.0
Queensland		



V37, Murmungee (10.0 GL/yr)
N43, Young Granite (10.1 GL/yr)
N23, Upper Murray Alluvium (15.2 GL/yr)
N46, Mid and Upper Murrumbidgee Fractured Rock (16.8 GL/yr)
Q73, Border Rivers Qld (18.0 GL/yr)
V42, Campaspe (18.6 GL/yr)
N16, Lower Macquarie Alluvium (19.3 GL/yr)
V45, Mid Loddon (22.3 GL/yr)
N17, Upper Macquarie Alluvium (24 GL/yr)
V39, Katunga (24.3 GL/yr)
N21, Mid Murrumbidgee Alluvium (71.2 GL/yr)
V43, Shepparton (72.0 GL/yr)
N19, Upper Lachlan Alluvium (164 GL/yr)

HISTOGRAMS OF USE, SUSTAINABLE YIELD, CONNECTIVITY AND POTENTIAL IMPACTS ON STREAMFLOW FOR MDB GROUNDWATER MANAGEMENT UNITS

Figure 4

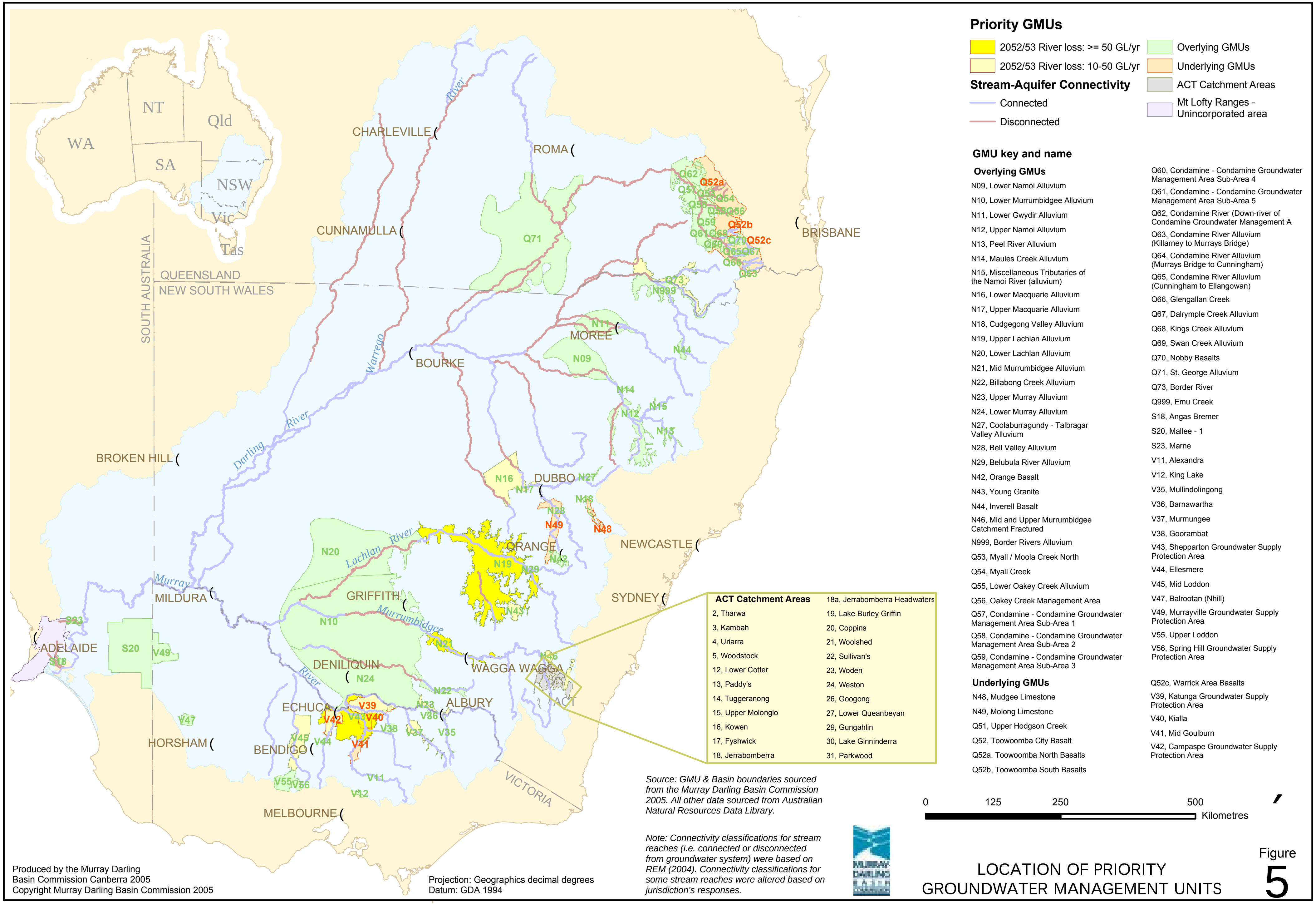


Figure 5

LOCATION OF PRIORITY GROUNDWATER MANAGEMENT UNITS

GMU Code	GMU Name	Estimated impact of groundwater extraction on stream flow at 2052/53 (GL/yr)[1]
Q73	Border Rivers	18.0

[1] Data taken from overview report (MDBC, 2004).

4.2 Sources of information on data gaps

Information on data gaps has been obtained from head office and regional hydrogeological staff from the state government agencies and water authorities. Information on data gaps has also been sourced from previous studies and an independent analysis of the management data that has been collected. There are no known specific documents prepared that specifically highlight data gaps and required project initiatives.

Relevant data/information sources relating to connectivity can be broadly described as:

- Monitoring bore networks and associated data sets;
- Stream gauging networks and associated data sets;
- Historical groundwater use data sets;
- Management tools being;
    - Numerical models;
    - Water balance assessments; and
    - Specialised studies (chemistry, environmental isotopes, tracers etc).

Information on data gaps for each GMU has been tabulated and presented in Appendix A.

4.3 Data gaps and their significance

The following discussion outlines the significance of the data gaps. The discussion deals with general data gaps across all GMUs in a particular State or Territory, and then provides comment on the significance of data gaps for the high priority GMUs in that jurisdiction.

However, there may be other significant data or knowledge gaps. These gaps relate to the knowledge used to prioritise GMUs in the first place. If key information on the type of the surface water – groundwater connection, the volume of groundwater usage or the sustainable yield estimate for the GMU is missing or erroneous, then the GMU may change priority ranking with more robust data.

Key datasets that support the prioritisation, such as metered groundwater usage, will continue to be a significant parameter to be collected.

New South Wales

Of the four data gaps identified in Appendix A, monitoring networks and numerical groundwater models are considered to be the most significant data gaps if the objective is to better quantify the impact of groundwater extraction at the basin scale.

Of the seven priority GMUs in NSW (see Table 2), there are monitoring networks in all except for Murrumbidgee fractured rock and Young granite. There are numerical groundwater models for all NSW GMUs except for Upper Murray alluvium, Upper Macquarie alluvium, and the Murrumbidgee fractured rock and Young granite areas.

An overview of monitoring networks and their appropriateness to assess connectivity issues for the priority GMUs in NSW is presented in Table 3.

Table 3 Monitoring network coverage in priority GMUs in NSW

Groundwater Source	Type of Interaction	Monitoring Network Coverage	Connectivity Issues Covered
Upper Murray alluvium	Connected – gaining and losing	Groundwater – Limited in area between Albury and Corowa – no coverage in tributary creek areas Surface water – adequate	No areas where there are adjacent surface water gauging stations and bores No numerical model at this time
Mid Murrumbidgee Alluvium	Connected – gaining and losing	Groundwater – Wagga to Narrandera only – limited in tributary creeks (Kyeamba Creek) Surface water – adequate	Some areas where this is good stream gauge and groundwater monitoring networks Sufficient for current numerical model
Upper Lachlan Alluvium	Connected – gaining and losing	Groundwater – Koorawatha to Condobolin – limited coverage in tributary creeks (Bland Creek) Surface water - adequate	Monitoring networks not located in key areas Insufficient for numerical model

Groundwater Source	Type of Interaction	Monitoring Network Coverage	Connectivity Issues Covered
Lower Macquarie Alluvium	Disconnected then connected - gaining	Groundwater – Limited coverage in tributary creeks (Bogan River) and inadequate in downstream area Surface water – unknown	Limited areas where there are adjacent surface water gauging stations and bores Insufficient for numerical model
Upper Macquarie Alluvium	Connected – gaining and losing	Groundwater – Wellington to Narromine – no coverage in tributary creeks Surface water – adequate	No areas where there are adjacent surface water gauging stations and bores No numerical model at this time
Mid and Upper Murrumbidgee fractured rock	Connected – gaining (many ephemeral streams with small baseflows)	Groundwater – nil networks except for some dryland salinity areas Surface water – unknown	No areas where there are adjacent surface water gauging stations and bores No numerical model at this time
Young Granite	Connected – gaining (mostly ephemeral streams with small baseflows)	Groundwater – nil networks Surface water – unknown	No areas where there are adjacent surface water gauging stations and bores No numerical model at this time

Without this specific data, groundwater parameters cannot be improved, models cannot be built or better calibrated, and better estimates of river losses and gains cannot be determined. It is the integration of this data on a GMU scale that will provide a better quantification of the impact of groundwater extraction at the basin scale.

Impact assessment models have been available for the more highly developed and stressed aquifers for a 5 to 10 year groundwater extraction period; however there is substantial effort required to maintain and update these models. Of the seven priority NSW GMUs in Table 2, initial impact assessment models have been constructed for three alluvial systems. The conceptual models behind, and the complexity of these models, is not known as the models and reports are not publicly available. However the models have been constructed in accordance with the MDBC modelling guidelines and it is understood that each has been internally peer reviewed.

Across NSW there are several more GMUs that could have numerical models built but the funding and resources are not available to provide these extra management tools. Without models for the priority GMUs the impact of groundwater extraction on stream flow cannot be quantified and the effect of management intervention cannot be tested. Given that the NSW portion of the Basin contains some of the largest and most highly connected GMUs, the lack of models and the slowness to update and improve existing models is significant in the context of stream flow impacts.

The lack of this data is most significant for those GMUs described as connected (gaining and losing) as these have the greatest potential to impact stream flow in the basin if groundwater extraction increases i.e. Upper Murray, Mid Murrumbidgee, Upper Lachlan and Upper Macquarie. Models are available for two of these GMUs (Mid Murrumbidgee and Upper Lachlan) but not for the others. The reliability of the models is uncertain in relation in their capacity to accurately quantify surface water-groundwater interaction. This lack of models and the general inadequacy of the monitoring networks to define surface water-groundwater interaction will not allow any new groundwater extraction impacts to be quantified and managed.

For the two fractured rock areas, new bore yields are expected to be low and provided bores are sited away from important streams then baseflow should be afforded some protection, except from captured discharge impacts. The lack of monitoring bores, gauging stations and groundwater use data are significant in these areas. This management data should be collected as a matter of priority.

Victoria

A range of data gaps exist in Victoria. There has only been broad scale classification of the interaction between surface water and groundwater with some qualitative rating of the degree of interaction. There are no studies that have quantified the exchange of water between surface water and groundwater at the GMU scale (DSE has concerns regarding the reliability of these types of studies). Katunga is the only GMU that has been numerically modelled, but that model does not have the functionality to quantify the impact of groundwater extraction on stream flow. A model of part of the Ovens catchment (sub GMU scale) has been developed by G-MW which is being used to assess the interaction between surface water and groundwater in the Upper Ovens.

There is extensive metering in most of the high priority areas but there remain many GMUs without metering so there is a low level of confidence attached to current use records and no studies have been completed which systematically investigate trends in future groundwater use at the GMU scale.

Victoria contains five priority GMUs (refer **Figure 5**) and there appears to be no current capacity to quantify the impact of groundwater extraction on stream flow in these GMUs. The development of robust conceptual models and numerical models for these GMUs is considered a priority along with the collection of supporting datasets. G-MW has begun a program to develop conceptual models for the Campaspe, Mid Loddon and Mid Goulburn GMUs with a view to the development of numerical models for these aquifers. A conceptual model is also under development for the Upper Loddon but a numerical model is not considered practical due to the complexity of the hydrogeology. The conceptual and numerical models developed by G-MW will include a capacity to account for the exchange of water between streams and aquifers under both the natural and developed conditions.

The current absence of these modelling tools for the priority GMUs is considered a significant data gap if the aim is to undertake a basin scale assessment of the impact of groundwater extraction.

Queensland

The major data gaps for all GMUs in Queensland relate to the lack of complex analysis of the developed water balance, including models. Therefore there is no ability to determine future impacts of groundwater extraction on stream flow. There is also little work looking at the way in which the connectivity may still be changing in response to ongoing groundwater extraction, and surface water monitoring systems will not support future models of connectivity.

These short falls suggest that the data gaps are substantial, depending on how individual GMUs are prioritised within the broader context of the basin.

However, most GMUs are very small and will not be subject to complex analysis under any future management scenarios. Impacts of groundwater extraction in these systems will always be estimates.

The significance of these data gaps is low as the impacts of groundwater extraction on stream flow from the non-priority GMUs in Queensland is either low or has already occurred.

The Border Rivers GMU has been subject to a complex modelling exercise. The model has not been fully accepted by the resource managers. This is due to some uncertainty surrounding the hydrogeological conceptualisation and formulation of the water balance. Basic groundwater monitoring and surface water gauging are also not ideally distributed.

These data gaps are significant as there is the potential for up to 18 GL of impact to occur in the light of new information and knowledge. This would not be crucial at the Basin scale, but is not insubstantial.

South Australia

The GMUs with connected reaches (Marne and Eastern Mount Lofty Ranges) are the focus of investigations by DWLBC. A groundwater flow model has been prepared for the Marne. The lack of estimates of impacts of groundwater extraction in the Marne is not considered to be a significant gap given that the connected reach in this GMU lies at the lower part of the catchment where demand for groundwater is low due to poor quality groundwater.

There has been some sub-GMU scale investigations of the connectivity and potential impact of groundwater extraction within the Eastern Mount Lofty Ranges, but to-date there are no estimates for the whole of this GMU. However, the volumes are likely to be small and not significant in the context of a basin scale estimate of the impact of groundwater extraction.

Australian Capital Territory

By assumption, all groundwater systems in the ACT are assumed to be 100% connected to stream flow. The use of groundwater has already been factored into water resource plans. There is no groundwater use data, which will limit the ability to accurately model the impact of groundwater extraction on stream flow. The lack of groundwater observation data will limit the capacity to manage the resource at the local level.

All GMUs in ACT are low priority due to the small volumes, so they don’t introduce great sensitivity into the overall basin estimate of groundwater extraction impacts.

4.4 Key findings

A prioritisation system has been put forward for discussion which is based on the limit to the volume of groundwater that can be extracted from a GMU (set by sustainable yield) and the assumed degree of connectivity. The combination of these factors will drive the prioritisation from a basin scale perspective, but the degree of connectivity will be more important to local scale management.

There have been investigations in several GMUs including the modelled riverine GMUs in NSW, investigations in the Eastern Mt Lofty Ranges of SA and within the Ovens Valley and some high priority GMUs in Victoria which provide a sound basis for the management of issues associated with connectivity between surface water and groundwater resources.

There are a range of significant data gaps that have been identified during discussions with jurisdictions. Data gaps have been assessed in the context of developing a basin scale understanding of the impact of groundwater extraction on stream flow.

Apart from the general issues of poor data quality across all major GMUs, the following are particular data gaps that will need to be addressed:

- There is a dearth of historical groundwater use data to underpin models of groundwater and surface water connectivity;
- Stream gauging networks do not align with GMU boundaries;
- Groundwater monitoring networks are generally targeted at deeper sections of the hydrogeological system, and detailed information on shallow groundwater conditions near streams and rivers is not collected; and
- There is currently a lack of numerical modelling in many high priority GMUs (with the exception of some NSW GMUs) that is needed to quantify impacts of groundwater extraction on stream flow.

All the above data gaps are considered to be equally important in the quantification of the exchange of water between streams and aquifers, and to the quantification of the impact of groundwater extraction on stream flow. It is more likely that the prioritisation of investment in future data collection and analytical activities be based more upon the importance of the GMU than prioritisation by data type. In particular, through the development and application of a definition of connectivity, and in the light of the knowledge gaps described in this Section, groups of river reaches (or aquifers as the case may be) will be (re)classified. These will then need to be prioritised within the context of the water resource management issues of the day, with these priorities guiding where investment needs to be made to gather more data and for additional modelling.

One of the objectives of the project is to describe the extent to which inconsistencies in the assessment of connectivity limit the capacity to develop a coordinated assessment of groundwater use impacts at the basin-scale.

This objective has been interpreted as describing what inconsistencies exist that precludes the development of a basin-wide volume of stream flow impacted by groundwater extraction.

Apart from the issue described in Section 3 in terms of the lack of a common definition of connectivity and the lack of key data in some areas, the main issues relate to the inconsistent effort being applied by each of the jurisdictions and the variable effort within jurisdictions between priority GMUs.

There is little effort to update the volumetric quantification of connectivity in Queensland due to the low priority placed on the issue. Victoria (G-MW) is undertaking some work on the issue by developing conceptual and numerical models for selected priority GMUs. South Australia has undertaken detailed investigations in the Eastern Mount Lofty Ranges, but this GMU is of little consequence in the overall size of the problem Basin-wide. New South Wales is most advanced, but it has no current priority of work aimed at quantifying connectivity in its high priority GMUs.

Obtaining a robust Basin-wide estimate of the volumes of stream flow being impacted by groundwater extraction has been shown to be difficult in previous recent work and this situation does not appear to have changed within the last year or so.

5 CURRENT AND PLANNED RESEARCH AND INVESTIGATION

The following is a summary of current and planned research and investigations as available to the project team. Previous work that has directly influenced decisions about connectivity has been summarised in Section 3.

A number of sources were surveyed for information on projects. These sources included research funders, research providers and research users. The list is not exhaustive and has been limited in some areas by confidentiality over funding decisions. In some cases projects are currently being considered for funding that are relevant to this milestone report, but are unable to be described here.

Specific project details are provided in Appendix B and a map showing the location of the investigations is provided as **Figure 6**.

There is a limited range of work currently underway, or planned, within the Basin. The work seems to be related more to the establishment of techniques and tools, than the actual measurement of the fluxes of water exchanging between stream flow and groundwater. The most notable projects are summarised below (numbers in brackets relate to project descriptions given in Appendix B).

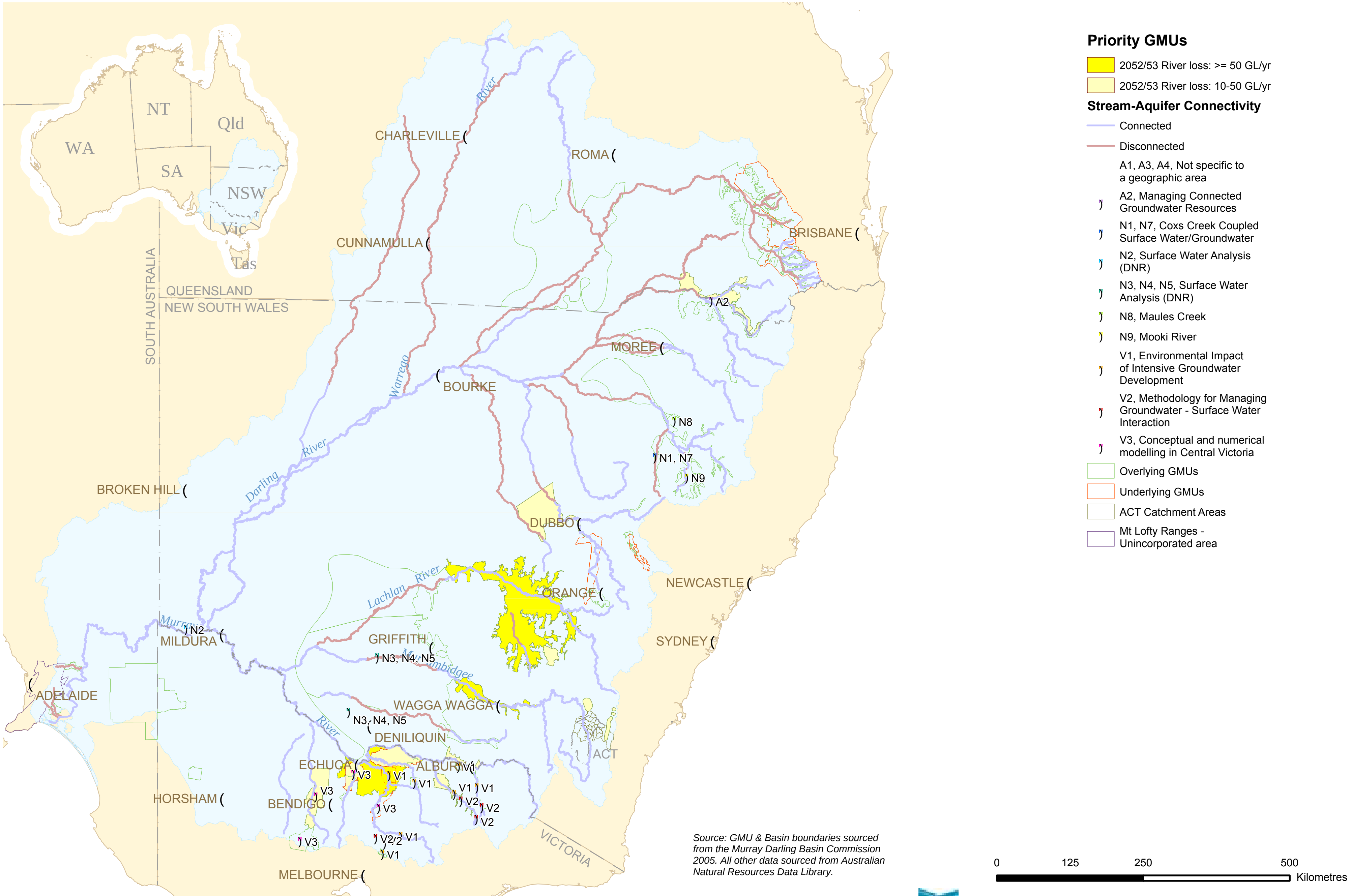
The CRC for Cotton Catchment Communities is funding a large program of work (N1, Appendix B) that has just commenced, predominantly in the Namoi Catchment of Northern NSW. This work has a primary focus on using modelling techniques to quantify the fluxes of water, with some companion work aimed at using tracer techniques.

This work appears set to build on a PhD project being undertaken at the Integrated Catchment Analysis and Modelling Centre, ANU. This work uses a simple four parameter rainfall runoff model that includes a groundwater storage component (IHACRES_GW) and has been developed in order to model ephemeral stream systems incurring groundwater losses.

The CRC for eWater (A6) is in the advanced stages of planning a large multi-year project to research the interconnections of lowland rivers in the Murray-Darling Basin. This project has a number of objectives and covers both modelling and tracer techniques. This project is likely to lead to analysis of a particular set of GMUs.

The Bureau of Rural Sciences is pursuing a large project in northern NSW and southern Queensland, partly in the Basin (A2). This project is also aimed at developing a range of techniques and applying them to field sites in the Border Rivers and Richmond River catchments. This project has jurisdictional partners and is co-funded via NHT and ARC sources.

SKM are undertaking two projects with a national focus (A3 and A4). These projects are aimed at developing technical and management frameworks for connected groundwater and surface water systems. The projects are at a broad level.



Source: GMU & Basin boundaries sourced from the Murray Darling Basin Commission 2005. All other data sourced from Australian Natural Resources Data Library.

Note: Connectivity classifications for stream reaches (i.e. connected or disconnected from groundwater system) were based on REM (2004). Connectivity classifications for some stream reaches were altered based on jurisdiction's responses.

Projection: Geographics decimal degrees
Datum: GDA 1994

LOCATION OF CURRENT AND PLANNED RESEARCH AND INVESTIGATIONS

Figure 6

SKM and G-MW are also undertaking a project in the Ovens Valley (V2) which is aimed at developing an understanding of the impact of groundwater extraction on stream flow and what policy adjustments might be required to better manage the impacts.

G-MW has begun the conceptual modelling phase of a project (V3) with the view to develop numerical models for Campaspe, Mid Loddon and Mid-Goulburn GMUs. The conceptual and numerical models developed by G-MW will include a capacity to account for the exchange of water between streams and aquifers under both the natural and developed conditions.

There is a range of work being undertaken specifically to investigate the environmental water requirements of groundwater dependent ecosystems. This work, whilst not directly aimed at quantifying fluxes between stream flow and groundwater will provide estimates of the likely connections in specific areas. Work involved includes the nationally focussed project by CSIRO, REM and SKM (A5), and the Victorian focussed project by DSE (V1).

SKM is also undertaking work on the analysis of baseflow in streams as an estimate of groundwater contribution to stream flow (A1).

DNR NSW is undertaking a range of smaller scale work across the various regional offices (N2 to N5)[2]. This work appears to be related to identifying the nature of the connection for particular river reaches, and the development of techniques to measure that connection.

The projects described above can also be summarised on the basis of location and the type of system that is being investigated.

Nationally, the main work is by SKM with the development of policy principles for the management of connected systems. The work is meeting resistance from most jurisdictions. The main issue appears to be that the principles are perceived to be too broad and there is a gap in enunciating a site specific approach to management.

It is also obvious from discussions with funding bodies, that the national approach is not well coordinated. There are several avenues for funding of activities aimed at understanding connected systems, and there does not appear to be much coordination of priorities or acceptance of a strategic direction.

The majority of work on connected systems appears to be occurring in New South Wales, via a number of funding routes. The work is split between the large projects in the connected systems of the southern riverine plain, the upland alluvial valleys (including the Border Rivers region), and the disconnected systems of the northern riverine plain.

[2] There are additional projects across NSW that have not been reported to the REM project team at this time. Many of the initiatives are in coastal areas where there is strong surface water-groundwater connectivity. DNR staff resourcing and project priority issues have delayed reporting of these additional R&D project summaries.

Some work is occurring in Victoria, with the most relevant in the Ovens catchment and the development of conceptual and numerical models in selected priority GMUs.

Work has been completed in South Australia and virtually none in Queensland.

There are only four of the thirteen priority GMUs (listed in Table 2) in which current and/or planned research and investigations are being undertaken. Three of these are located in Victorian GMUs; Murmungee (project V1, V2), Campaspe (V1, V3) and Mid Loddon (V3) and one is located in the Queensland Border Rivers GMU (A2). There are three NSW GMUs that are the subject of further modelling (Lower Macquarie, Upper Lachlan and Mid Murrumbidgee) but it’s not clear whether these investigations will quantify connectivity.

5.1 Evaluation of capacity to deliver relevant outputs and outcomes

An objective of this work is to provide an evaluation of current and planned work to deliver outputs and outcomes relevant to estimating the size of the impact of groundwater extraction on stream flow in the Murray-Darling Basin.

In order to achieve this objective it is necessary to frame some criteria that will semi-objectively assist in the evaluation.

Two criteria have been developed. Firstly, will the work provide a quantified estimate of the impact of groundwater extraction on stream flows for the developed state, taking into account all sources of impact? Secondly, is the estimate suitably scaled to apply to an aquifer system or GMU?

Table 4 sets out an evaluation of current and planned projects against the two criteria. The projects have been rated according to whether they meet the evaluation criteria in a simple yes/no sense. Where the project is in the planning stages, the criteria have been applied according to the likelihood of meeting the criteria based on achieving the stated outputs and outcomes.

Table 4 Summary of evaluation of current and planned research and investigation (there are more detailed descriptions of these projects in Appendix B).

Project Number	Project Name	Criteria 1 (Quantifiable estimates of impact on streams)	Criteria 2 (GMU or aquifer scale)	Comment
A1	Using Baseflow for Monitoring Stream Condition and Groundwater and Surface Water Resource Condition Change, Australia (SKM)	No	No	Technique development that will be of use. Work will be required on how these techniques can be applied in all situations and scaled to provide aquifer system estimates.
A2	Managing Connected Waters (BRS)	No	No	Relates to one GMU within the Basin. The project is demonstrating techniques rather than quantifying fluxes. Unclear how applicable this will be to developed water balances, and some scaling issues for tracer techniques.
A3	Stream Aquifer Interactions in Australia – Technical and Management Challenges (SKM)	No	No	Management focus aimed at developing high level principles.
A4	A draft National Framework for Managing the Impacts of Groundwater and Surface Water Interaction in Australia (SKM)	No	No	High level policy principles.
A5	Groundwater Dependent Ecosystem Toolbox, Australia (REM, CSIRO and SKM)	No	No	Aimed at developing techniques to assess EWR. Not aimed at assessing connected fluxes.
A6	eWater Project D3 (CSIRO + partners)	Yes	Yes	This project appears to be directly applicable to the Commission objectives for key GMUs.
N1	Coxs Creek Coupled Surface Water/Groundwater Model (PhD, ANU)	Yes	Yes	Modelling exercise directly related to the main objectives.
N2	DNR Surface Water Analysis (1)	No	No	Project is situated in the Sunraysia region, away from

Project Number	Project Name	Criteria 1 (Quantifiable estimates of impact on streams)	Criteria 2 (GMU or aquifer scale)	Comment
				any priority GMUs.
N3	DNR Surface Water Analysis (2)	No	No	A run-of-river technique development project.
N4	DNR Surface Water Analysis (3)	No	No	Objectives imply that this project is site-specific in nature and aimed at salt accession processes. May provide point scale understanding of some relevance.
N5	Surface and Groundwater Interactions, NSW (DNR)	No	No	Surface water groundwater interactions from a salinity management point of view. Restricted scale precludes widespread utility.
N6	Sydney Catchment Authority Fractured Sandstone Aquifer - Surface Water Interactions, Hawkesbury Nepean Catchment NSW	Yes	No	Quantifying surface water-groundwater interactions and likely impact of large borefield extractions. Will assist in understanding baseflows in upland catchments
N7	Surface water groundwater modelling framework for Cox's Creek, NSW	Yes	Yes	Quantifying surface water groundwater interactions as a guide to understand the impacts of groundwater extraction on surface water availability
N8	Maules Creek (CRC Cotton)	Unknown	Unknown	
N9	Mooki River (CRC Cotton)	Unknown	Unknown	
V1	Environmental Impact of Intensive Groundwater Development GMUs throughout Victoria (DSE)	No	No	Semi-quantitative assessment of GDE threats. Does not produce any estimates of quantities of groundwaters sourced from streams.
V2	Methodology for Managing Groundwater – Surface water interactions in Northern Victoria (G-MW)	Yes	Yes	Management focus, but appears relevant with some quantification of groundwater extraction impacts at the scale

Project Number	Project Name	Criteria 1 (Quantifiable estimates of impact on streams)	Criteria 2 (GMU or aquifer scale)	Comment
				of the aquifer system.
V3	Goulburn Murray Water, Conceptual and Numerical Modelling in Central Victoria (G-MW)	Yes	Yes	Conceptual and numerical models will account for exchange of water between streams and aquifers

5.2 Key findings

5.2.1 Overview

Only a small amount of work is occurring within the Basin that will provide explicit flux of water being exchanged between stream flow and groundwater. The majority of this work will be based around the natural water balance. This work also appears to be occurring in relation to specific project needs at a local scale rather than on a GMU or Basin-wide scale.

Figure 6 highlights that the current research and investigation activities (as listed in this section) do target some priority GMUs (defined in Table 2) especially in Victoria. There are three NSW GMUs that are the subject of further modelling (Lower Macquarie, Upper Lachlan and Mid Murrumbidgee) but it's not clear whether these investigations will quantify the degree of connectivity. Priority GMUs without targeted research and investigation are Young granite, Upper Murray alluvium, Mid and Upper Murrumbidgee fractured rock, Upper Macquarie alluvium, Shepparton and Katunga.

Further work is being considered by funding agencies such as the Department of Environment and Heritage, and the National Water Commission.

There is little work being undertaken that will quantify the volume of water being captured from stream flow (either via induced recharge or captured discharge) as a consequence of groundwater extraction. This may be due to the non-reporting of work specifically addressing this issue. Modelling techniques appear to be the only useful approach to answering this question, with tracer techniques providing an independent semi-quantitative measure of interconnection.

There is no indication if current and planned activities which deal with issues related to the impacts from captured discharge process.

Further key findings can be split between findings related to the techniques for quantifying connectivity itself, and to the manner in which these techniques are being applied.

A range of techniques have been identified and are being applied at specific sites around the Basin.

5.2.2 Modelling techniques

Modelling is being carried out in a range of groundwater environments and is providing quantities of groundwater that is connected to the streams via the simulations, for key GMUs.

Simple water balance models have been applied in some GMUs. These models tend to be for the natural (undeveloped) state and provide little information about the impacts of groundwater extraction on stream flow.

Some more complex models are being developed, and planned, for the aquifer systems on the riverine plain. It is important that the conceptualisation of model boundary conditions matches the reality of the aquifer systems, as model water balances will provide crucial data for management decisions about the impacts of groundwater on stream flow.

5.2.3 Measurement techniques

The effort on measurement techniques is increasing due to a number of projects currently underway. Appropriate techniques have been developed, with some qualification of outputs apparent.

Hydrographic techniques, where baseflow is measured from stream gauging data, are being applied, but lack widespread applicability. This is especially the case for the large groundwater systems of the southern Riverine Plain, where the technique suffers due to the losing and regulated nature of the streams. Hydrographic techniques may not be suited to these environments. Hydrograph techniques also provide a lumped estimate for the area above the gauging station. These estimates may represent net baseflow, and depending on the size of the catchment, may not be useful. However, baseflow indices do not provide an indication of the proportion of groundwater that is discharging to a surface water system; they only provide a volume of stream flow that may be sourced from groundwater.

Measurement techniques that use tracers have also been developed and show promise. However, the techniques are only semi-quantitative at this stage, suffering from scaling issues both spatially and temporally. In some instances, the tracer techniques suffer in that they may establish interchange with the near river environment (that is, at scales of less than 10 m), which may not be representative of processes operating over larger length scales.

Whilst there are a number of projects being undertaken, and some planned, there is still relatively little effort being expended in quantifying the connections between the high priority GMUs and related river systems with a view to influencing Water Sharing Plans.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Definition of connectivity as it relates to potential impacts on streamflow

The fundamental knowledge gap in dealing with connected groundwater – surface water systems is the lack of a consistent definition of connectivity. Such a definition should be supported by the establishment of a set of guiding principles within which a definition can be framed. This report suggests a set of principles to support the definition of connectivity. It is recommended that the definition of connectivity should:

- describe the nature of the interaction between the surface water and groundwater resources for the developed state of the resource;
- convey the rate at which the interaction is occurring;
- have regard to the timeframe over which the interaction occurs;
- be quantifiable; and
- be able to be applied to a range of spatial scales (e.g. should cover river reaches or whole of aquifers).

The following draft definition of connectivity has been proposed as a basis for discussion between jurisdictions:

- Highly connected for systems where the conductance is high and there can be an expectation that groundwater extraction impacts will have an influence within a specified timeframe which is short. In these types of systems it might be expected that more than 70% of the volume of groundwater extracted is derived from stream flow within a specified timeframe of 10 to 50 years from the onset of groundwater extraction;
- Moderately connected for systems where both the conductance and hydraulic gradients are moderate. In these types of systems it might be expected that between 10 and 70% of the volume of groundwater extracted is derived from stream flow within the specified timeframe;
- Poorly connected for systems where the conductance is low. As well, there may be an expectation that groundwater extraction, whilst impacting on surface flows within a specified timeframe, will have a full impact at some time in the future that is outside the specified timeframe. In these types of systems it might be expected that less than 10% of the volume of groundwater extracted is derived from stream flow within the specified timeframe;

- Disconnected for systems where the base of the river or stream lies above the water table. This means that even though the groundwater system may be reliant on infiltrating stream flow, groundwater extraction cannot induce losses from the stream; and

- Unconnected systems where the arrangement of aquifer, stream and intervening materials means there is no physical means by which measurable quantities of water can be exchanged between groundwater and surface water.

An alternative approach to the definition of connected systems would be to classify the degree of connectivity based on the time taken for the full impact of groundwater extraction to occur. For example, a highly connected system could be one where the full impact occurs within 5 years and a poorly connected system could be one where the full impact occurs after 50 years. The proposed definition of connectivity is based on the volumetric impact (for example, a highly connected system is one where greater than 70% of groundwater extracted is derived from stream flow) whereas the alternative approach is based on timeframes for impacts. If the definition of connectivity is to be used in the context of understanding threats to the shared water resource then a definition that uses a volumetric approach is considered to be more appropriate.

A final decision on the guiding principles and definition of connectivity needs to be made collectively amongst the jurisdictions and stakeholders.

Application of the draft definition of connectivity

The draft definition of connectivity has not been applied in this project.

The agreed definition of connectivity should be used to classify all GMUs and unincorporated areas within the basin at an appropriate scale. Application of the definition at an aquifer or river reach scale is suitable for basin scale assessments of risk while finer scale application of the definition across aquifers and river reaches is needed for the development of local scale (within GMU) management responses.

It is important that any future analysis of the understanding of current knowledge and methods used or needed to quantify connectivity must be developed so that it can address the guiding principles to the definition.

ES2.3 Identification of priority groundwater management units

The identification of priority GMUs provides a basis for targeting future investigations and management initiatives to those areas of the basin where groundwater extraction is likely to impact stream flow to the greatest extent. It is suggested that the prioritisation of GMUs be based on the following three step approach.

The first step of the prioritisation approach involves grouping the GMUs based on sustainable yield using the following categories:

- Priority 1 – sustainable yield is greater than 50 GL/yr;

- Priority 2 – sustainable yield is between 20 and 50 GL/yr; and
- Priority 3 – sustainable yield is less than 20 GL/yr.

The second step of the prioritisation approach involves grouping the GMUs based on the degree of connectivity using the following categories:

- High – connectivity is greater than 70%
- Moderate – connectivity is greater than 10% but less than or equal to 70%; and
- Low – connectivity is less than or equal to 10%.

The third step of the prioritisation approach is to estimate the impact of groundwater extraction on stream flow in 2052/53 was estimated by multiplying the sustainable yield for each GMU (the assumed upper limit to groundwater extraction) and the assumed degree of connectivity.

The priority GMUs have been assessed as those GMUs where the impact of groundwater extraction on stream flow is greater than 10 GL/yr in 2052/53.

ES2.4 What is the current knowledge and methods used to determine connectivity of groundwater and surface water systems?

A range of methods have been used to characterise the nature of stream - aquifer connectivity. These methods can be partitioned between two fundamental types – measurements or models. Measurement techniques include approaches that use hydrologic data to assess connection (such as hydrograph analysis, or hydraulic gradient mapping) or tracer techniques that involve measuring physicochemical parameters (such as major ion chemistry, radiogenic species such as radon or basic parameters such as temperature). Modelling techniques rely on an analysis of the water balance, either by simple means or via complex numerical simulations. Very few of the measurement and modelling techniques have been applied in a management sense, except for some regional groundwater models.

All jurisdictions have estimated the degree of connectivity within the major GMUs but this information has been based on varying levels of analysis; regional scale groundwater flow modelling, water balances and best guesses. In most priority GMUs the degree of connectivity and estimate of the impact of groundwater extraction is based on ‘regional best guesses’ supported with monitoring data and simple water balance calculations in some GMUs (Table ES1).

In several non-priority NSW GMUs, estimates have been made of the quantity of groundwater sources from stream flow under the developed conditions using numerical models and water balance calculations. These GMUs appear to be the only ones in the basin where there is an estimate of the volume of water exchanged between surface water and groundwater.

Hydrogeochemical methods and modelling has been undertaken in South Australia to semi-quantitatively describe connectivity. Investigations in Victoria are occurring to build the understanding of conceptual models for some GMUs which will explicitly account for the exchange of water between rivers and aquifers.

ES2.5 Where and how has this knowledge (if available) been applied?

Basin scale information regarding connectivity and the impact of groundwater extraction on stream flow compiled by the Murray-Darling Basin Commission has been used to develop and quantify an understanding of the risk to the shared water resource and to assist in the development of a basin groundwater policy (MDBC, 2004).

It is recognised by all jurisdictions that information on connectivity should be used in the water planning process. The main impediments to better information being used appear to be related to the lack of robust analysis and the priority attached to generating new information by the jurisdictions.

ES2.6 What are the current investigations and initiatives being undertaken that lead to a better understanding of connectivity?

There is a relatively small amount of work occurring within the basin that will provide explicit rates of water exchanged between rivers and aquifers. It appears that most work is undertaken in relation to local priorities rather than at a GMU or basin scale. Local priorities are partly driven by the need to manage GMUs where groundwater extraction is large and where there are impacts on the groundwater resource such as declining groundwater levels. These impacts may be occurring where there is little connection to streams.

This report contains an overview of the current investigations and initiatives (planned or underway) to better understand connectivity in priority GMUs. A summary of the investigations (as of December, 2005) for priority GMUs is provided in Table ES1.

There are some investigations planned for priority GMUs such as the development of conceptual and numerical models in the Murmungee, Campaspe and Mid Loddon GMUs in Victoria and the Border Rivers GMU in Queensland. There are plans to improve existing conceptual and numerical models in the Upper Lachlan, Mid Murrumbidgee and Lower Macquarie GMUs, but it is not clear whether this work will allow for an improved understanding of connectivity.

ES2.7 Critical gaps in knowledge of connectivity

The analysis undertaken in this project leads to the conclusion that the approaches to quantification of connectivity being adopted by the States, somewhat implicitly, are inadequate given the lack of knowledge of connectivity and lack of quantification of connectivity under developed conditions especially for priority GMUs. Only four of the thirteen priority GMUs (Murmungee, Campaspe, Mid Loddon in Victoria and Border Rivers) are subject to current and/or planned research and investigations that will deal with the issue of connectivity. There are three NSW GMUs that are the subject of further modelling (Lower Macquarie, Upper Lachlan and Mid Murrumbidgee) but it’s not clear whether these investigations will quantify connectivity. A summary of current investigations is provided in Section 5 of this report. The following key data gaps have been identified:

- Only a small amount of work is occurring within the basin that will provide explicit rates of water being exchanged between stream flow and groundwater. The majority of this work will be based around the natural water balance. There is a need to quantify the post-development water balance so that the impact of groundwater extraction can be estimated.

- Most GMUs do not conform to aquifer boundaries, and as such, there may be problems associated with the impact of groundwater extraction within GMUs occurring outside the GMU boundary and therefore going unaccounted in any analysis.

- Some jurisdictions have commented that there are inconsistencies between GMU boundaries and surface water gauging stations, with some GMUs covering a number of surface water catchments. This creates problems where there is a need to compare groundwater balances with estimates of baseflow from stream hydrographs.

- Modelling techniques are considered the appropriate approach to derive a GMU scale and basin scale estimate of the impact of groundwater extraction on stream flow. Most of the priority GMUs (listed in Table ES1) do not have robust conceptual or numerical groundwater models which are able to quantify the exchange of water between rivers and aquifers or quantify the timing and magnitude of impacts of groundwater extraction on stream flow. A review of modelling approaches by REM (2002) recommended that an integrated modelling approach is needed to allow stream and aquifer systems to be simulated in detail.

- The biggest impediments to undertaking a more complex approach to modelling the priority GMUs will be the lack of historical groundwater extraction data (magnitude and timing) and the lack of information on the permeability of the sediment that lies at the interface of the stream and aquifer.

- Estimates of impacts of future groundwater extraction on streamflow in priority GMUs are limited by lack of information on drivers to groundwater extraction and lack of information on likely future patterns of groundwater extraction at the GMU scale.

- The focus of future investigations and analysis should be on the priority GMUs listed in Table ES1. However, there may be a large number of connected GMUs that will not be analysed through modelling owing to their small size. Collectively groundwater extraction in these smaller GMUs may have a significant impact on stream flow.

- There does not appear to be any current or planned activity that would investigate the role of climate variability on the groundwater extraction rate and the impacts of groundwater extraction on stream flow. At this stage, there is an implicit conclusion that the impact is linearly related to the groundwater extraction rate. For example, it is assumed that extracting 10 GL in a dry year has the same impact as extracting 10GL in a wet year. This may not be the case which means that estimates of impacts on stream flow based on simple extrapolation from groundwater extraction rates that don't take into account lag times could be unreliable. Overall this is considered to be a minor issue.

ES2.8 What is the extent to which inconsistencies in past and current assessment of connectivity limit the capacity to develop an assessment of groundwater extraction impacts at the basin scale?

Obtaining a robust basin-wide estimate of the volumes of stream flow being impacted by groundwater extraction has been shown to be difficult in previous work (e.g. MDBC, 2004). This situation does not appear to have changed within the last year or so.

The implications of the current inadequate approach will result in an inability to determine and prioritise a response to the double accounting and impact of groundwater extraction on stream flow based on a risk assessment of the magnitude of the impact. The lack of adequate analysis will result in an inability to communicate the effect of the management response to stakeholders in a consistent manner.

Part of the inconsistency in past and current assessments of the risk of groundwater extraction to the risks to the shared water resource is driven by the lack of an agreed definition of connectivity.

6.2 Recommendations

It is recommended that the Murray-Darling Basin Commission and partner jurisdictions work together to develop a consistent approach to assess connectivity by implementing the following actions:

1. Endorse a set of guiding principles for the definition of connectivity to form the basis for a common definition of connectivity across the Murray-Darling Basin.

2. Develop a definition of connectivity that can be applied to assess individual geographic areas, consistent with the guiding principles.

3. Prepare a discussion paper to be used as the basis of consultation with the jurisdictions to develop an agreed definition of connectivity. It is recommended that the guiding principles and proposed definition detailed in this report be used to form the basis of the discussion paper.

4. Classify the connectivity of all GMUs and unincorporated areas within the basin using the agreed definition. The agreed definition of connectivity should be applied to a range of spatial scales (e.g. should cover river reaches or whole of aquifers).

5. Establish criteria for prioritisation of GMUs. This report has proposed a set of criteria for this purpose.

6. Adopt the GMUs listed in this report (Table ES1) as the initial priorities noting that the list may change as more data and analysis becomes available.

7. Agree to an approach and associated data required as inputs to the planning process to address the risks of groundwater extraction on the shared water resource. This may be dependent on the level of the management response required which may be based on a perceived level of risk. A summary of the

data gaps and investigations to be considered for priority GMUs is provided in Appendix C of this report. The key types of data and analysis required to derive a basin wide estimate of the impact of groundwater extraction on stream flow are:

- Quantification of the exchange of water between the stream and aquifer;
- Current and future impacts of groundwater extraction quantified;
- Adequate surface water and groundwater monitoring; and
- Current groundwater extraction quantified and future patterns of groundwater extraction estimated.

8. Agree to timeframes for completion of the technical studies in each priority GMU and identify organisations responsible for the work. It is recommended that the Murray-Darling Basin Commission develop partnership approaches to ensure that any additional work is built on existing programs of works.

9. Establish robust technical studies of the developed water balance and the development of calibrated numerical models for the priority GMUs to quantify the exchange of water at the GMU scale and to quantify the impact of groundwater extraction on stream flow. In the first instance it is recommended that the focus be on the Upper Lachlan and Mid Murrumbidgee GMUs because groundwater extraction in these GMUs provides the greatest potential for an impact on stream flow over the next 50-years within the basin.

10. The MDBC maintain a close working relationship with the CRC eWater so that priority GMUs can be a focus of eWater projects.

11. Use the technical output from the GMU scale assessments of connectivity and impacts of groundwater extraction on stream flow to assess the risk of groundwater extraction to the shared water resource, and provide options for the management of impacts in the priority GMUs. Quantification of the impact of the management response is recommended. The initial management response may need to be conservative and adapted over time as monitoring data and new analysis becomes available.

12. Implement an open reporting approach and independent accreditation of groundwater models as practiced for the Surface Water Cap on Diversions, and for groundwater models under the BSMS.

13. An Independent Audit Group be established to review the progress of the following tasks within, initially (agreed) priority, individual GMU:

    - the quantification of the impact of groundwater extraction on streamflow;
    - the development and implementation of management responses; and
    - implementation of a monitoring and evaluation program.

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Appendix A

Information on Data Gaps

The data gap categories are:

- Classification of the type of interaction at the GMU and sub-GMU scale based on conceptualisation of the groundwater system;
- Quantification the exchange of water at the GMU and sub-GMU scale through a water balance or point measurements;
- Quantification of the current and future impact of groundwater pumping using a simple water balance or numerical modelling approach;
- Groundwater monitoring networks, gauging stations and chemical data;
- Historical groundwater use information; and
- Current groundwater use information and an estimate of future patterns of groundwater use based on known use drivers.

The headers in the tables use abbreviated descriptors of these categories

South Australian GMUs

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Type of interaction classified	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Historical groundwater use quantified	Current groundwater use & patterns of future use quantified
S20	Mallee-1	Priority 1	Low	Yes	Yes	Yes	Yes	Partly	Current use quantified. Qualitative assessment of future trends
S18	Angas Bremer	Priority 3	Low	Yes	Yes	Yes	Yes	Yes	Current use quantified
S23	Marne (sedimentary)	Priority 3	Low	Yes	Some preliminary modelling but not reported	Some preliminary modelling – no pumping in connected reaches	Mostly	Yes	Current use estimated and no estimate of future use
	Eastern Mt Lofty Ranges (Marne fractured rock)	Unknown	Medium	Yes, at the broad scale	No	No	No	No	Current use estimated and no estimate of future use
	Sustainable Yield (GL/yr)		Connectivity (%)						
	Priority 1	> 50	High	> 70					
	Priority 2	> 20, < 50	Medium	> 10, ≤ 70					
	Priority 3	< 20	Low	≤ 10					

Victorian GMUs

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Type of interaction classified	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Historical groundwater use quantified	Current groundwater use & patterns of future use quantified
V43	Shepparton	Priority 1	Medium	Yes - broadly	No	No	Not targeting sw – gw interaction	Yes (3 to 4 years)	Yes (current) No (future)
V39	Katunga	Priority 2	Medium	Yes - broadly	No	No	Some bores targeting sw – gw exchange	Yes (3 to 4 years)	Yes (current) No (future)
V42	Campaspe	Priority 2	Medium	Yes - broadly	No – conceptual model under development	No	Some bores targeting sw – gw exchange – Sthn Campaspe	Yes (3 to 4 years)	Yes (current) No (future)
V45	Mid Loddon	Priority 2	Medium	Yes - broadly	No – conceptual model under development	No	Not targeting sw – gw interaction	No	Yes (current) No (future)
V11	Alexandra	Priority 3	Medium	Yes - broadly	No	No	Not targeting sw – gw interaction	No	No (current and future)
V35	Mullindolingong	Priority 3	Medium	Yes - broadly	No	Some modelling at the sub GMU scale	Not targeting sw – gw interaction	No	No (current and future)
V36	Barnawartha	Priority 3	Medium	Yes - broadly	No	No	Not targeting sw – gw interaction	No	No (current and future)
V37	Murmungee	Priority 3	Medium	Yes - broadly	No	No	Not targeting sw – gw interaction	No	No (current and future)
V38	Goorambat	Priority 3	Medium	Yes - broadly	No	No	Not targeting sw – gw interaction	No	No (current and future)
V40	Kialla	Priority 3	Medium	Yes - broadly	No	No	Not targeting sw – gw interaction	No	No (current and future)

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Type of interaction classified	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Historical groundwater use quantified	Current groundwater use & patterns of future use quantified
V41	Nagambie (Mid Goulbourn)	Priority 3	Medium	Yes - broadly	No – conceptual model under development	No	Not targeting sw – gw interaction	No	Yes (current) No (future)
V44	Ellesmere	Priority 3	Medium	Yes - broadly	No	No	Not targeting sw – gw interaction	No	No (current and future)
V55	Ascot (Upper Loddon)	Priority 3	Medium	Yes - broadly	No – conceptual model under development	No	Not targeting sw – gw interaction	No	No (current and future)
V56	Spring Hill	Priority 3	Medium	Yes - broadly	No	No	Not targeting sw – gw interaction	No	Yes (current) No (future)
V12	King Lake	Priority 3	Low	Yes - broadly	No	No	Not targeting sw – gw interaction	No	No (current and future)
V47	Balrootan (Nhill)	Priority 3	Low	Yes - broadly	No	No	Not targeting sw – gw interaction	No	No (current and future)
V49	Murrayville Groundwater Supply Protection Area	Priority 3	Low	Yes - broadly	No	No	Not targeting sw – gw interaction	No	No (current and future)
	Sustainable Yield (GL/yr)		Connectivity (%)						
	Priority 1	> 50	High	> 70					
	Priority 2	> 20, < 50	Medium	> 10, ≤ 70					
	Priority 3	< 20	Low	≤ 10					

Australian Capital Territory GMUs

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Type of interaction classified	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Historical groundwater use quantified	Current groundwater use & patterns of future use quantified
ACT	Fyshwick	Priority 3	High	Yes	Yes	Yes with a water balance	No	No	No
ACT	Tuggeranong	Priority 3	High	Yes	Yes	Yes	No	No	No
ACT	Jerrabomberra Creek	Priority 3	High	Yes	Yes	Yes	No	No	No
ACT	Woolshed	Priority 3	High	Yes	Yes	Yes	No	No	No
ACT	Woden	Priority 3	High	Yes	Yes	Yes	No	No	No
ACT	Weston	Priority 3	High	Yes	Yes	Yes	No	No	No
ACT	Lake Burley Griffin	Priority 3	High	Yes	Yes	Yes	No	No	No
ACT	Sullivan's Creek	Priority 3	High	Yes	Yes	Yes	No	No	No
ACT	Gungahlin	Priority 3	High	Yes	Yes	Yes	No	No	No
ACT	Tharwa	Priority 3	High	Yes	Yes	Yes	No	No	No
ACT	Lake Ginninderra	Priority 3	High	Yes	Yes	Yes	No	No	No
ACT	Parkwood	Priority 3	High	Yes	Yes	Yes	No	No	No
ACT	Coppins	Priority 3	High	Yes	Yes	Yes	No	No	No
	Sustainable Yield (GL/yr)		Connectivity (%)						
	Priority 1	> 50	High	> 70					
	Priority 2	> 20, < 50	Medium	> 10, ≤ 70					
	Priority 3	< 20	Low	≤ 10					

New South Wales GMUs

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Type of interaction classified	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Historical groundwater use quantified	Current groundwater use & patterns of future use quantified
N19	Upper Lachlan Alluvium	Priority 1	High	Yes	No	No	Yes – marginal in some river reaches and tributaries	Yes – variable quality data before mid 1990s	Yes – current No - future
N21	Mid Murrumbidgee Alluvium	Priority 1	High	Yes	No	No	Yes – marginal in some river reaches and tributaries	Yes – variable quality data before mid 1990s	Yes – current No - future
N16	Lower Macquarie Alluvium	Priority 1	Medium	Yes	No – limited modelling	No – limited modelling	Yes – marginal in lower valley connected area	Yes – variable quality data before mid 1980s	Yes – current No - future
N09	Lower Namoi Alluvium	Priority 1	Low	Yes	Yes – model	Yes - model	Yes	Yes	Yes – current No - future
N10	Lower Murrumbidgee Alluvium	Priority 1	Low	Yes	Yes – model	Yes - model	Yes	Yes	Yes – current No - future
N12	Upper Namoi Alluvium and Maules Creek Alluvium (N14)	Priority 1	Low (but some tributaries are medium)	Yes	Yes - model	Yes - model	Yes – marginal in some river reaches and tributaries	Yes	Yes – current No - future
N20	Lower Lachlan Alluvium	Priority 1	Low	Yes	Yes – model	Yes - model	Yes	Yes	Yes – current No - future
N24	Lower Murray Alluvium	Priority 1	Low	Yes	Yes – model	Yes - model	Yes – marginal in some river reaches	Yes	Yes – current No - future
N17	Upper Macquarie Alluvium	Priority 2	High	Yes	Yes – some modelling and water balance	Yes	Yes – marginal in some river reaches and tributaries	Yes – variable quality data before mid 1990s	Yes – current No - future

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Type of interaction classified	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Historical groundwater use quantified	Current groundwater use & patterns of future use quantified
N11	Lower Gwydir Alluvium	Priority 2	Medium	Yes	Yes – model	Yes - model	Yes	Yes	Yes – current No - future
N23	Upper Murray Alluvium	Priority 2	Medium	Yes	No	No	Yes – marginal in some river reaches and tributaries	Yes – variable quality data before mid 1990s	Yes – current No - future
N999	Border Rivers Alluvium	Priority 2	Medium	Yes	Yes – model	Yes - model	Yes – marginal in some river reaches and tributaries	Yes – variable quality data before mid 1990s	Yes – current No - future
N13	Peel River Alluvium	Priority 3	High	Yes	Yes – water balance	Yes	Yes – poor for tributaries	Yes – variable quality data before mid 1990s	Yes – current No - future
N18	Cudgegong Valley Alluvium	Priority 3	High	Yes	Yes – water balance	No	Yes – poor for tributaries	Yes – variable quality data before mid 1990s	Yes – current No - future
N15	Miscellaneous tributaries of the Namoi River (Alluvium)	Priority 3	Medium	Now part of Upper Namoi (N12) – some tributaries not modelled			No – very few gauging stations and no monitoring bores	No	No – current No - future
N22	Billabong Creek Alluvium (portion not within the Murray Basin)	Priority 3	Medium	Yes	Yes – water balance and model	Yes	Marginal – limited bores and few gauging stations	Yes – variable quality data before mid 1990s	Yes – current No - future
N27	Coolaburragundy-Talbragar Valley Alluvium	Priority 3	Medium	Yes	No	No	No – very few gauging stations and no monitoring bores	Yes – variable quality data before mid 1990s	Yes – current No - future
N28	Bell Valley Alluvium	Priority 3	Medium	Yes	No	No	No – very few gauging stations	Yes – variable quality data	Yes – current No - future

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Type of interaction classified	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Historical groundwater use quantified	Current groundwater use & patterns of future use quantified
							and no monitoring bores	before mid 1990s	
N29	Belubula River Alluvium	Priority 3	Medium	Yes	No	No	Marginal – limited bores and few gauging stations	Yes – variable quality data before mid 1990s	Yes – current No - future
N42	Orange Basalt	Priority 3	Medium	Yes	No	No	No	Yes – variable quality data before mid 1990s	Yes – current No - future
N43	Young Granite	Priority 3	Medium	Yes	No	No	No	Yes – variable quality data before mid 1990s	Yes – current No - future
N44	Inverell Basalt	Priority 3	Medium	Yes	No	No	No	No	No – current No - future
N46	Mid and Upper Murrumbidgee Fractured Rock	Priority 3	Medium	Yes	No	No	No	No	No – current No - future
N48	Mudgee Limestone *	Priority 3	Medium	Now part of Lachlan Fold Belt					
N49	Molong Limestone *	Priority 3	Medium	Now part of Lachlan Fold Belt					
N14	Maules Creek Alluvium	Priority 3	Medium	Now part of Upper Namoi (N12)					
	Lachlan, New England and Adelaide Fold Belt Fractured Rocks *	Priority 3	Low-medium	Yes	No	No	No	No	No – current No - future
	Darling River, GAB and miscellaneous alluvium *	Priority 3	Low-medium	Yes	No	No	No	No	No – current No - future

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Type of interaction classified	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Historical groundwater use quantified	Current groundwater use & patterns of future use quantified
Note	* NSW has just mapped some additional 17 groundwater sources (excluding the GAB aquifers) in the Murray Darling Basin to be managed under the Macro Water Sharing Plan process. Most of these are small alluvial and fractured rock areas (Priority 3) that have been described generically in this table because even though some are large in area, they are relatively small groundwater sources and have variable connectivity (generally low-medium, although some fractured rock systems could be high) with local streams.								

Sustainable Yield (GL)		Connectivity (%)	
Priority 1	> 50	High	> 70
Priority 2	> 20, < 50	Medium	> 10, ≤ 70
Priority 3	< 20	Low	≤ 10

Queensland GMUs

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Type of interaction	Exchange of water	Current & future impact of groundwater pumping	Groundwater monitoring & gauging stations	Historical groundwater use	Current groundwater use & patterns of future use
Q73	Border Rivers Qld	Priority 2	Medium	Yes	No	No	Groundwater monitoring commensurate with the level of development; gauging station location driven by surface water resource assessment, not by groundwater connectivity knowledge requirements	No	Current use is available, but no analysis of future use levels
Q52b	Toowoomba South Basalt	Priority 2	Low	Yes	No	No	As above	No	As above
Q52	Toowoomba City Basalt	Priority 3	Medium	Yes	No	No	As above	No	As above
Q63	Condamine River Alluvium (Kilarney to Murrays Bridge)	Priority 3	Medium	Yes	No	No	As above	No	As above
Q66	Glengallan Creek	Priority 3	Medium	Yes	No	No	As above	No	As above
Q67	Dalyrymple Creek Alluvium	Priority 3	Medium	Yes	No	No	As above	No	As above
Q68	King's Creek Alluvium	Priority 3	Medium	Yes	No	No	As above	No	As above
Q69	Swan Creek Alluvium	Priority 3	Medium	Yes	No	No	As above	No	As above

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Type of interaction	Exchange of water	Current & future impact of groundwater pumping	Groundwater monitoring & gauging stations	Historical groundwater use	Current groundwater use & patterns of future use
Q999	Emu Creek Alluvium	Priority 3	Medium	Yes	No	No	As above	No	As above
Q51	Upper Hodgson Creek	Priority 3	Low	Yes	No	No	As above	No	As above
Q52a	Toowoomba North Basalt	Priority 3	Low	Yes	No	No	As above	No	As above
Q52c	Warwick Area Basalt	Priority 3	Low	Yes	No	No	As above	No	As above
Q53	Myall/Moola Creek North	Priority 3	Low	Yes	No	No	As above	No	As above
Q54	Myall Creek	Priority 3	Low	Yes	No	No	As above	No	As above
Q55	Lower Oakey Creek Alluvium	Priority 3	Low	Yes	No	No	As above	No	As above
Q56	Oakey Creek Management Area	Priority 3	Low	Yes	No	No	As above	No	As above
Q57	Condamine - Condamine Groundwater Management Area Sub Area 1	Priority 3	Low	Yes	No	No	As above		As above
Q58	Condamine-Condamine Groundwater Management Area Sub-Area-2	Priority 3	Low	Yes	No	No	As above		As above
Q59	Condamine-Condamine Groundwater Management Area Sub-Area-3	Priority 3	Low	Yes	No	No	As above		As above

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Type of interaction	Exchange of water	Current & future impact of groundwater pumping	Groundwater monitoring & gauging stations	Historical groundwater use	Current groundwater use & patterns of future use
Q60	Condamine-Condamine Groundwater Management Area Sub-Area-4	Priority 3	Low	Yes	No	No	As above		As above
Q61	Condamine-Condamine Groundwater Management Area Sub-Area-5	Priority 3	Low	Yes	No	No	As above		As above
Q62	Condamine River (Down-river of Condamine Groundwater Management Area)	Priority 3	Low	Yes	No	No	As above	No	As above
Q64	Condamine River Alluvium (Murrays Bridge to Cunningham)	Priority 3	Low	Yes	No	No	As above	No	As above
Q65	Condamine River Alluvium (Cunningham to Ellangowan)	Priority 3	Low	Yes	No	No	As above	No	As above
Q70	Nobby Basalts	Priority 3	Low	Yes	No	No	As above	No	As above
Q71	St. George Alluvium	Priority 3	Low	Yes	No	No	As above	No	As above
	Sustainable Yield (GL/yr)		Connectivity (%)						
	Priority 1	> 50	High	> 70					
	Priority 2	> 20, < 50	Medium	> 10, ≤ 70					
	Priority 3	< 20	Low	≤ 10					

Appendix B

Current and Planned Research and Investigation

Project Identification	Project Name	Location	Project Description including Scope and Methods	Project Contact	Project Timeframe	Project Output and Outcomes
V1	Environmental Impact of Intensive Groundwater Development	Groundwater Management Areas (GMAs), Victoria	The purpose of the project was to determine where assets consisting of flow in streams, wetlands and vegetation communities are at greatest threat from groundwater extraction in GMAs. Specific objectives of the project consisted of: • Evaluating the degree of connection between groundwater and surface water. • Ranking the value of assets, such as river reaches and wetlands. • Ranking the assets in terms of risk of adverse impact from the threat of declining water levels. • Identifying needs for further investigation/monitoring. • The main elements to the project approach were: • Identification of a list of natural resource assets in the region. • Identification and assessment of asset values. • An assessment of the severity and extent of the threat posed by declining water levels across each region. • Determination of the risk of a threat to a particular value of an asset. The GMAs investigated were: **Alexandra**, Balrootan, **Barnawartha**, Colongulac, Corinella, Cut Paw Paw, Frankston, Gellibrand, Giffard, Glenelg, Glenormiston, **Goorambat**, Heywood, Jan Juc, **Kialla**, **Kinglake**, Lancefield, Leongatha, Merrimu, Moe, Moorabbin, **Mullindolingong**, **Murmungee**, Nepean, Newlingrook, Orbost, Paaratte, Portland, Rosedale, Southern Campaspe, Tarwin, Wa De Lock The GMAs in bold are those considered in the MDBC Overview report	Greg Curtin, DSE	Completed Mar. 2005	The main output from the project was a qualitative assessment of the risk of GDEs (mainly related to surface water) from declining groundwater levels. There has been a review of this work by the Victorian Technical Assessment Panel (TAP) which has raised a number of issues, but agreed that it represents a reasonable guide to the issues. The TAP also concluded that this study would not replace the need for detailed quantitative investigations. A qualitative ranking of surface water–groundwater connectivity (based on a broad understanding of the hydrogeology in each GMA) was provided in the report using a scale of 1 to 5. The report indicates other factors were considered in the assessment such as rate of water level decline and “buffer time” were considered, but it is not clear how these factors were used in the risk assessment. A connectivity score of 1 is used for systems that are poorly connected and a value of 5 is used for systems considered to be highly connected. The connectivity scores for the GMAs within the Murray-Darling Basin (and assessed in the Overview report) were: • Alexandra (5) • Barnawartha (4) • Goorambat (2) • Kialla (5) • Kinglake (5) • Mullindolingong (2) • Murmungee (5) The Overview report identified all these GMAs as being connected other than King Lake which was assumed to be disconnected from surface water in the MDB. The Overview report assumed that 60% of the volume of groundwater

Project Identification	Project Name	Location	Project Description including Scope and Methods	Project Contact	Project Timeframe	Project Output and Outcomes
						pumped in each of these GMUs would be derived from streamflow (either induced recharge or captured discharge).
V2	A Methodology for Managing Groundwater Stream interaction	Victoria	Groundwater and surface water resources are strongly interactive within many upper catchment environments within Victoria. The Victorian Government's White Paper (DSE, 2004) highlights the need for greater understanding of groundwater and surface water interaction and need to move towards conjunctive management of the resource. The White Paper also states that "in priority unregulated rivers and aquifers, the Environmental Water Reserve will be enhanced by requiring existing licences to be managed to provide an environmental water regime that will sustain ecological objectives within 10 years." Four of these priority regulated rivers, the Upper Ovens River, the Kiewa River, Yea River and King Parrot Creek are in areas where groundwater surface water interaction is known to be high. Each of these catchments have been targeted for the development of a Streamflow Management Plan, which at some level, will require consideration of groundwater impacts. There has been little work done within Victoria to date in developing technically sound methodologies that can be incorporated into a Streamflow Management Plan to deal with groundwater stream interaction. Unless a very large number of monitoring bores and gauging stations are established (which will be at a very high cost), there will always be gaps in our ability to measure the impacts of pumping on streamflow. Even where such an approach is affordable, the complexity and variability of many systems such as fractured rock aquifers will still inhibit understanding and quantification of interaction. This study is targeted at progressing the development of a sound technical basis for incorporation of groundwater management decisions associated with management of groundwater extraction to achieve environmental objectives within a stream.	Greg Holland G-MW		The study will provide a summary of the technical understanding of issues associated with groundwater stream interaction and provide a general framework and practical applications for managing interaction. Results from a desktop study of applying the management framework to the Upper Ovens River will also be presented.
V3	Goulburn Murray Water (GMW)	Campaspe, Mid Loddon, Ascot	GMW has begun a program to develop conceptual models for the Campaspe, Mid Loddon, Upper Loddon and Mid-Goulburn GMUs with a view to the development of numerical models for the GMUs.			The conceptual and numerical models developed by GMW will include a capacity to account for the exchange of water between streams and aquifers under both the natural and developed conditions.

Project Identification	Project Name	Location	Project Description including Scope and Methods	Project Contact	Project Timeframe	Project Output and Outcomes
N1	Coxs Creek Coupled Surface Water/ Groundwater Model	Namoi	• Develop a coupled surface water/groundwater model of a representative catchment with an unregulated stream at a daily time scale. • Separate groundwater hydrographic responses into causative components (river interaction, rainfall infiltration, irrigation deep drainage, groundwater extraction). • Integrate point and field scale estimates of groundwater recharge to landscape scale. • Fine-tune the volumetric contributions of each recharge source to aquifer sustainable yield. • Quantify the impact on groundwater levels and river flows due to uncertainty in deep drainage. Zone 2 will be extracted from the broader ANU and DNR models, with preservation of boundary conditions supplied by the larger models. Normally, groundwater models operate at a much longer time scale (monthly) than river models (daily) due to natural differences in response times, and due to lack of monitoring data (water levels, extraction rates) at a finer time scale. To adequately capture the short-term interactions at the river boundary, it will be necessary to reduce the time scale of the groundwater model. There is no reason why this cannot be done, in principle, but there has to be a pragmatic reduction in the length of the calibration period. As the current Upper Namoi groundwater model uses 192 monthly time periods, a daily model over one irrigation season will incur much the same effort. A daily model requires daily groundwater levels in addition to daily river flows. There are 22 DNR bores in the water table aquifer of Zone 2, and there are two river gauging stations. Up to 10 of the bores should have data loggers installed. Advanced signal analysis techniques will be applied to the high resolution data in order to isolate inputs from deep drainage, rainfall and rivers. This approach will be applied in parallel to Projects 2, 3 and 5 where other data loggers are planned. Calibration of a model of surface water and its links with groundwater is difficult in the Namoi catchment because there is limited stream gauge data available that contains sufficient information on baseflow switching behaviour (i.e. provides information on the thresholds of groundwater level at which baseflows are ‘switched off’). One possibility is to use	Noel Merrick	Nov. 2005 to Jun. 2008	• Separate impacts of management, soil water relationships and episodic climatic events on groundwater levels. • Opportunities identified for irrigation management under uncertain climate. • Quantified landscape scale impact of irrigation on groundwater resources. • A protocol for separating the river, rainfall, and irrigation components of a hydrographic signal. • Increased understanding of the important scales and connectivity between surface water and groundwater. • Improved estimate of aquifer sustainable yield. • Improved decision rules for river water extraction and groundwater extraction close to rivers.

Project Identification	Project Name	Location	Project Description including Scope and Methods	Project Contact	Project Timeframe	Project Output and Outcomes
			simulated information from more detailed groundwater based models to supplement river gauge data. Simulation with a well-calibrated groundwater model allows the information from groundwater bores contained and summarised in the groundwater-based model to be provided to the surface water based model for calibration. This information can be used to bound the behaviour of the model. Conversely the surface water based model can also be used to identify discrepancies between the gauged streamflow data and simulations from the groundwater-based model to inform the calibration of the groundwater model. Essentially, attempting simultaneous and joint calibration of stream hydrographs and groundwater hydrographs. There is limited work in integrating point and field scale estimates of recharge and deep drainage at the landscape level. In addition, there is discussion about the difference between potential recharge (i.e. deep drainage) and actual recharge (i.e. groundwater level changes). This discussion is partly due to the lack of coupling between local scale deep drainage estimates to landscape scale groundwater modelling. Integration of point scale soil water models in a GIS (i.e. spatial framework) and assessing the effect of episodic climatic events on groundwater recharge would improve estimation of deep drainage risks and thus improve landscape planning for irrigation development. Stochastic modelling will capture the impacts of episodic climatic events and deep drainage variability on groundwater levels and baseflow fluxes.			
N2	Surface Water Analysis (DNR)	Murray and Murrumbidgee Catchments, NSW	• Collaborative work with MDBC, Victoria and SA to define groundwater to surface water accessions through comprehensive modelling of the NSW and Victoria Sunraysia area salt budgets. • Manage consultancy support to Sunraysia Project Management board members. • Convene and Chair Technical panel investigating the suitability of various EC instrumentation. • Generate generic monitoring strategies to audit the effectiveness of any future remedial policies/ structures that will be used to protect streams from groundwater ingress. • Design program to map EC to salt load conversion factors.	F Harvey, DNR		
N3	Surface Water	Murray and	• Prospect of developing equipment and techniques for Run-	F Harvey,		

Project Identification	Project Name	Location	Project Description including Scope and Methods	Project Contact	Project Timeframe	Project Output and Outcomes
	Analysis (DNR)	Murrumbidgee Catchments, NSW	of-River capability. • Run-of-River/Creeks and strategic grab sampling. • Use the developed equipment to perform runs on a number of the major streams in the region.	DNR		
N4	Surface Water Analysis (DNR)	Murray and Murrumbidgee Catchments, NSW	• Broadly identify stream sections at which groundwater is interfacing with streams/rivers. • Attempt to pin-point locations at which 'point source' interactions are occurring. • Based on existing records, attempt to quantify the EC impact at identified trouble spots.	F Harvey, DNR		
N5	Surface Water Analysis (DNR)	Murray and Murrumbidgee Catchments, NSW	• Identify locations within the region where groundwater is having an impact on stream water quality. • Attempt to quantify salinity impacts in a selection of high impact reaches. • Develop generic approaches to monitoring the effectiveness of impact management strategies. • Compile a preliminary framework for determining volumetric exchange between the two sources.	F Harvey, DNR		
N7	IHACRES_GW	Cox's Creek, NSW	A simple, four parameter rainfall runoff model that includes a groundwater storage component has been developed in order to model ephemeral stream systems incurring groundwater losses. The development of IHACRES_GW represents a significant improvement in rainfall-runoff modelling of intermittent streamflow because an account of the groundwater storages are maintained throughout non-flow periods, which allows for the timing in the resumption of streamflow to be correctly simulated. Because of the continuous groundwater storage accounting, IHACRES_GW can be used to simulate the impact of groundwater extraction on river flows. The IHACRES_GW model is a conceptual model, and hence does not explicitly represent the spatial distribution of water fluxes and storages. This top-down, data driven approach to modelling quantifies water balances for the catchment area upstream of the streamflow observation point using streamflow and extraction data alone. The model was tested in the Namoi Catchment. Simulations at gauging station 419032 on the Cox's Creek at Boggabri suggest that groundwater extraction has resulted in a reduction in baseflow contributions to flow ranging from zero, for non flow periods, to a maximum value on the order of 1230 ML/Day. The modelled median reduction in baseflows over non-dry periods was	Karen Ivkovic	Completed 2006	This research demonstrates how a simple, conceptual model can be used to model the impact of groundwater extraction and other losses on river flows. This research also highlights the importance of managing aquifers according to water level responses in order to ensure that future streamflow targets developed to meet river flow and/or environmental requirements can be achieved.

Project Identification	Project Name	Location	Project Description including Scope and Methods	Project Contact	Project Timeframe	Project Output and Outcomes
			15ML/Day and the average reduction was 73ML/Day. The larger reductions in baseflow arising from groundwater extraction were associated with periods when the groundwater storage levels drop substantially below the level of the catchment outlet during a drought period coupled with greater than average volumes of groundwater extraction.			
N8	Maules Creek (CRC Cotton)	Namoi	Not available	Not available	Not available	Not available
N9	Upper Mooki River (CRC Cotton)	Upper Namoi	Not available	Not available	Not available	Not available
A1	Using Baseflow for Monitoring Stream Condition and Groundwater and Surface Water Resource Condition Change	Australia	To develop a series of tools for calculation of baseflow contributions to surface water resources and to monitor and report on trends in baseflow. These tools will be rolled out to NRM bodies and regulators to assist them in the monitoring and evaluation of surface water impacts from groundwater extractions within catchments. The tools will be trialled in catchments in Vic, NSW and Qld.	Rory Nathan, SKM	Sep. 2005 to Dec. 2006	Report describing baseflow analysis tools and case studies.
A2	Managing Connected Water Resources	National focus plus work in trial catchments (Border Rivers and Lower Richmond)	The project aims to provide a better understanding of the potential connectivity of surface water and groundwater and the management and policy implications of this connectivity. This involves providing policy makers, water managers and catchment groups with: • Information about the interaction of groundwater and surface water systems, enabling more robust estimates of sustainable yields, improved security of allocations, and improvements in assessing the impacts of water resource development. • Improved access to the methods available to assess the degree and nature of the connectivity between surface water and groundwater systems. • Information on the range of options available to manage connected surface water-groundwater systems. Project activities include: • Collation and review of tools available to assess and manage connected water resources. • Techniques for investigating surface water-groundwater interactions trialled in two contrasting catchments (Border Rivers and Lower Richmond). • Development of the ‘Connected Water’ website to provide access to information on the assessment and management of connected water resources.	Baskaran Sundaram, BRS (baskaran.sundaram@brs.gov.au) Ross Brodie, BRS (ross.s.brodie@brs.gov.au)	2004-2006	To date, the project has: • Convened a national workshop that defined the key impediments to integrating the management of groundwater and surface water. Three key principles for implementing a conjunctive management approach were recommended. • Developed the initial draft of the Connected Water website which is currently under review. The site contains modules on water management issues, hydrological processes, methods of assessing groundwater-surface water interactions, conjunctive policy options and investment options for on-ground works. A comprehensive reference database has been developed and several case studies have also been incorporated. • Several techniques for assessing connectivity trialled in the Border Rivers and Lower Richmond catchments. These include methods that are

Project Identification	Project Name	Location	Project Description including Scope and Methods	Project Contact	Project Timeframe	Project Output and Outcomes
			• A national workshop with water managers, policy groups, researchers and other stakeholders focusing on the opportunities and impediments to integrating the management of surface water and groundwater resources. • Developing a framework for assessing connectivity including definitions and categories for stream-aquifer connectivity, a summary of methods and mapping protocols. • Investigations of the economic issues of conjunctive water management including examination of available methods for evaluating management options. • Developing and trialling simple hydrological/economic tools that encompass groundwater and surface water processes and can be used to help develop management options.			routinely used (such as hydrographic analysis or comparison of groundwater and stream levels) as well as methods that have rarely been applied under Australian conditions (such as temperature monitoring). This assessment has been documented in conference papers (NZHS-IAH-NZSSS Auckland Conference, December 2005) as well as project reports.
A3	Stream Aquifer Interaction in Australia – Technical and Management Challenges		The management (at a practical level) of stream aquifer interaction rarely occurs and both surface water and groundwater users are the losers as a result of the double allocation of the one water resource in many catchments. The issues associated with this aspect of surface water-groundwater interaction are intrinsically complex, with significant technical and management issues. Three matters are being studied: • The time lag between commencing groundwater pumping and significant stream response. The significance of the time lag influences the management approach to be adopted. • Secondly, the nature of baseflow in streams is very complex and comprises multiple components of the water balance. • Finally, the link between the volume of groundwater pumped and the reduction in stream flow. At the practical management level, the development of a range of options for different jurisdictional and hydrogeological environments is being undertaken. Management action is required at the total catchment scale, where any groundwater use (regardless of distance from a stream) may reduce stream flow in the long term, and at the local scale where bores close to streams have short term impacts over critical low flow periods.	Rick Evans, SKM	Jan. 2005 to Feb. 2006	Report and vision for the future direction for technical and management aspects of surface water-groundwater interaction in Australia.
A4	A Draft National Framework for Managing the Impacts of Groundwater and	Australia	This project aims to prevent the unacceptable interference between surface water and groundwater resources in Australia by developing appropriate policy, management framework and management practices. This project aims to develop the national policy and framework	Rick Evans, SKM	Jun. 2004 to Dec. 2005	A national policy agreed by all the States and Territories.

Project Identification	Project Name	Location	Project Description including Scope and Methods	Project Contact	Project Timeframe	Project Output and Outcomes
	Surface Water Interaction in Australia		on water resource management as applied to the interaction of groundwater and surface water resources in Australia. The project involves how the issues associated with groundwater and surface water interactions are currently managed and how this can be improved upon by providing policy guidelines and a framework for use by Australian water resource management organisations.			
A5	Groundwater Dependent Ecosystem Toolbox	Australia	A joint project with CSIRO, REM and SKM aims to develop a technical "toolbox" of methods to determine the Environmental Water Requirements of Groundwater Dependent Ecosystems. The "toolbox" is then being applied at three sites, the Cockburn River in NSW, wetlands of the lower SE in SA and the terrestrial vegetation site at Ti Tree in NT. Recommendations for further work to better define the "tools" will be made.	Paul Howe of REM for report Rick Evans of SKM for toolbox Peter Cook of CSIRO for field sites	2005 to June 2006	Report documenting the scope.
A6	CRC eWater, Project D3, Preliminary stage	Murray-Darling Basin Lowland Rivers	This project aims to estimate exchange fluxes between groundwater and surface-water for lowland rivers and how these may change with groundwater and surface water management. Techniques for both estimation and prediction are well-developed for smaller areas (<3 km river reach), but much less developed for extrapolation beyond these scales. The project aims to provide a collation and assessment of measurement techniques (hydraulic, geophysical, etc) and trial development of best candidates at field sites. It also aims to model the relationship between groundwater management (1st 3 years) or surface water management (2nd 3 years) with exchange fluxes. Further development of a model for water and salt generation from upland areas (2CSalt) forms a supplementary activity with its own arrangements through MDBC.	Glen Walker, CSIRO	6 years	3 years • Modeling capability to relate groundwater management to long-term stream depletion. • Tested field methods for extrapolating exchange of water, salt and nutrients between lowland rivers and adjacent groundwater systems for different types of groundwater systems. 4-6 years • Modeling capability to relate river management to exchange fluxes of water, salt and nutrients between ground- and surface-water. • Understanding of near-river processes for key field sites related to exchange fluxes of groundwater and surface-water and groundwater-dependent ecosystems.

Appendix C

Summary of Suggested Investigations for Priority GMUs

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Current groundwater use & patterns of future use quantified
V43	Shepparton	Priority 1	Medium	Develop robust conceptual model and numerical model that allows for the quantification of exchange	Use numerical model to quantify the impact of groundwater pumping on streamflow	Review distribution of current surface water and groundwater monitoring network and construct monitoring infrastructure at sites targeting the potential influence of groundwater pumping on streamflow	Undertake investigation of the potential drivers and trends in groundwater use
V39	Katunga	Priority 2	Medium	As above	As above	Some bores targeting sw – gw exchange	As above
V42	Campaspe	Priority 2	Medium	As above (currently underway)	As above (currently underway)	Some bores targeting sw – gw exchange – Sthn Campaspe	As above

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Current groundwater use & patterns of future use quantified
V45	Mid Loddon	Priority 2	Medium	As above (currently underway)	As above (currently underway)	Review distribution of current surface water and groundwater monitoring network and construct monitoring infrastructure at sites targeting the potential influence of groundwater pumping on streamflow	As above
V37	Murmungee	Priority 3	Medium	Develop robust conceptual model and numerical model that allows for the quantification of exchange	Use numerical model to quantify the impact of groundwater pumping on streamflow	As above	As above

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Current groundwater use & patterns of future use quantified
N19	Upper Lachlan Alluvium	Priority 1	High	Review conceptual model and ensure that numerical model allows for the quantification of exchange	Use numerical model to quantify the impact of groundwater pumping on streamflow	Review surface water and groundwater monitoring network and construct new monitoring infrastructure at sites targeting losing and gaining segments with the potential for groundwater pumping to impact streamflow	As above
N21	Mid Murrumbidgee Alluvium	Priority 1	High	Review conceptual model and ensure that numerical model allows for the quantification of exchange	Use numerical model to quantify the impact of groundwater pumping on streamflow	As above	As above

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Current groundwater use & patterns of future use quantified
N16	Lower Macquarie Alluvium	Priority 1	Medium	Review conceptual model and ensure that numerical model allows for the quantification of exchange	Use numerical model to quantify the impact of groundwater pumping on streamflow	As above	As above
N23	Upper Murray Alluvium	Priority 2	Medium	Develop robust conceptual model and numerical model that allows for the quantification of exchange	Use numerical model to quantify the impact of groundwater pumping on streamflow	As above	As above

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Current groundwater use & patterns of future use quantified
N17	Upper Macquarie Alluvium	Priority 2	High	Review conceptual model and ensure that numerical model allows for the quantification of exchange	Use numerical model to quantify the impact of groundwater pumping on streamflow	Review surface water and groundwater monitoring network and construct new monitoring infrastructure at sites targeting losing and gaining segments with the potential for groundwater pumping to impact streamflow	As above
N43	Young Granite	Priority 3	Medium	Useful to determine an indicative water balance	No – requires more monitoring and usage data	Install appropriate networks	As above
N46	Mid and Upper Murrumbidgee Fractured Rock	Priority 3	Medium	Useful to determine an indicative water balance	No – requires more monitoring and usage data	Install appropriate networks	As above

GMU Code	Groundwater Management Unit	Sustainable Yield	Connectivity	Exchange of water quantified	Current & future impact of groundwater pumping quantified	Adequate groundwater monitoring & gauging stations	Current groundwater use & patterns of future use quantified
Q73	Border Rivers Qld	Priority 2	Medium	Review conceptual model and develop robust water balance	No – requires updated model that includes better estimates of conductances and more spatial and temporal monitoring data	Needs better temporal and spatial monitoring of groundwater levels across all aquifers, more detailed surface water gauging, particularly in the discharge end of the system to help calibrate the water balance	As above
	Sustainable Yield (GL/yr)						
	Priority 1	> 50	High	> 70			
	Priority 2	> 20, < 50	Medium	> 10, ≤ 70			
	Priority 3	< 20	Low	≤ 10			