MURRAY-DARLING BASIN ESSAY

Essay #3 in a series of nine by Australia's leading water experts

Surface water and groundwater connectivity in the Murray-Darling Basin: Integrated management of connected resources

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Above: The gates opening on Lock 11 on the Murray River near Mildura. ncox1585, iStock.

EXECUTIVE SUMMARY

Ross and Williams state that the increased use of groundwater, supporting baseflow to the unregulated rivers, depletion of streamflow due to water extraction and changes in weather conditions are due to identifiable risks (i.e., climate change, irrigation and floodplain harvesting, afforestation, coal seam gas and coal mining) associated with groundwater-surface water connectivity. Drier seasons always worsen these risk factors.

They also mention that improvements and expanded coverage in integrated groundwater and surface water models are essential to develop the integrated management of those resources. These will require enhanced long-term monitoring, assessment and effective management.

Additional investments will be required to improve the accuracy of measurements and the interpretation of monitoring results, and to extend and improve integrated modelling of connected water resources, taking account of the impacts of climate change and cross impacts of extractions."

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Surface water and groundwater connectivity in the Murray–Darling Basin: integrated management of connected resources

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Summary and vision

Integrated management of connected groundwater and surface water resources in channels, floodplains, and wetlands is essential in order to achieve optimum use of Murray–Darling Basin (MDB) water resources and storage for human and environmental purposes. Although Australian legislation and policy provides a basis for the management of connected water resources, there are serious weaknesses in the implementation of integrated groundwater and surface water management.

To better identify risks associated with managing groundwater-surface water connectivity due to an increase in groundwater use and climate change requires greatly improved coordination with Basin state governments, giving particular attention to leveraging existing knowledge as well as generating new knowledge to ensure that groundwater policy reform and management is underpinned by the best available science.

In short, to address these risks will require the Basin Plan to be significantly amended in terms of the current risk framework, and in particular, give attention to: a more precise definition of groundwater-surface water connectivity so to clarify the meaning of material impact of significant cross-resource connections; to include measurable indicators of connectivity; and to include targets to measure progress in relation to groundwater-surface water connectivity.

The Basin Plan should be amended to include an agreed assessment time frame to be applied to the estimation of water balances and resource condition indicators, including predictions of drawdown and evaluation of risk of long-term changes in groundwater salinity and water quality.

This extended framework for assessing groundwater-surface water connections and cross impacts of increased extractions on connected water resources and ecosystems would facilitate such considerations being fully incorporated in the water resource plans (WRP), which are cornerstones of the Basin Plan.

This would extend current arrangements by requiring the WRPs to consider: long-term cross impacts of groundwater and surface water extractions beyond the planning period; long-term risks when connectivity is expected to be reduced; and impacts of extractions on an expanded range of groundwater-dependent ecosystems (GDEs) including baseflows, aquatic ecosystems, terrestrial vegetation, and subterranean ecosystems. Implementation of WRPs will be improved by context-specific rules and tools to manage impacts of climate change and extractions, integrated management of water storage and water banking, and long-term measurement and monitoring.

This vision for integrated management of connected groundwater and surface water resources will require the following enabling conditions:

- the volume of connected groundwater and surface water, their uses and their connections, will be measured or estimated and monitored;

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- groundwater and surface water planning and allocation will fully account for the impacts of water use on connected resources and ecosystems, and manage these resources to achieve socially acceptable socio-economic and environmental outcomes; and
- the values of groundwater and surface water resources and ecosystems will be determined in consultation with stakeholders, and water users will pay a socially acceptable charge for water use.

1. Introduction

Australia is the world's driest inhabited continent with highly variable climate patterns, rainfall and water supply with recurrent droughts and floods (Productivity Commission 2021). Droughts (and floods) can have devastating environmental consequences such as algal blooms and fish death events (Vertessy et al. 2019).

There are 2.3 million people residing in the Murray–Darling Basin (MDB or Basin) where 40% of Australia's agricultural production is located. Demand for water in the MDB is increasing because of population and economic growth (Williams 2017), but water availability is falling due to climate change (Prosser et al. 2021). The use of groundwater resources is increasing, especially in dry years.

Effective management of connected groundwater-surface water resources throughout the Basin helps to preserve connections between rivers, aquifers, floodplains, wetlands and flows to the Murray Mouth thereby sustaining groundwater and surface water resources in good condition (MDBA 2020a). But the benefits and risks related to groundwater-surface water connectivity have not been effectively accounted or managed in the MDB.

The extent of groundwater-surface water connectivity and steps towards integrated groundwater and surface water management were documented 15 years ago (Evans 2007). Since 2007 there has been some progress towards recognition of groundwater-surface water connectivity in legislation and policy, and improvements in the classification and measurement of connectivity. But planning and management of most groundwater and surface water resources continues to be separated, with limited or no accounting for connectivity and few examples of integrated water management (Lamontagne et al. 2012; Ross 2014, 2018).

In this essay, we define groundwater-surface water connectivity and outline resource connectivity in the MDB. We summarise the impact of extractions on connected groundwater-surface water resources and dependent ecosystems, and driving forces that will affect future groundwater-surface water connectivity in the MDB including climate change, agriculture, irrigation, and coal seam gas (CSG) development. We review the management of connected groundwater and surface water resources and ecosystems and adaptation to change, and discuss improvements in the management of connected water resources, adaptive management strategies and tools. We finish the essay with proposals for improved management of connected groundwater and surface water resources and ecosystems.

2. The nature of groundwater-surface water connectivity in the MDB and implications of connectivity for water resource management

In this section, we set out elements of groundwater-surface water connectivity in the MDB, and outline impacts of increasing water use on connected groundwater-surface water resources and ecosystems. We also introduce a classification of levels of connectivity.

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2.1. Elements of groundwater-surface water connectivity

The importance of groundwater-surface water connectivity and integrated management of connected groundwater and surface water resources is recognised in the National Water Initiative (NWI) (Commonwealth of Australia 2004) and the Murray–Darling Basin Plan (MDBP) (Commonwealth of Australia 2012). The objectives of the NWI include 'recognition of the connectivity between surface and groundwater resources and connected systems managed as a single resource' (Commonwealth of Australia 2004, Section 23x). Managing connectivity is fundamental to the purpose of the MDBP 'to manage the Basin as a whole connected system' (MDBA 2019). Hydraulic connectivity is defined as 'the ease with which, or the rate at which, groundwater moves: (a) within an aquifer; or (b) between aquifers; or (c) between aquifers and the adjacent or overlying surface water system' (Commonwealth of Australia 2012, Part 1.07, Definitions).

Adjacent groundwater and surface water resources are usually connected, although the extent and timing of connection is variable (Evans 2007). Surface water and groundwater connectivity can be evaluated according to three criteria (Conant et al. 2019) as illustrated in Figure 1:

1. The dynamics of groundwater and surface water resources, and their potential to interact at the interface or in the transition zone between resources through groundwater and surface water flows and biogeochemical and biological processes.
2. Processes of groundwater and surface water interaction; their spatial patterns and temporal variability.
3. Potential impacts of groundwater-surface water interaction on water quantity, water quality and ecosystems.

Integrated management of connected groundwater and surface water resources is essential in order to achieve optimum use of MDB water resources and storage for human and environmental purposes. The expected outcomes for managing connectivity throughout the Basin include maintaining baseflow, increasing tributary flow, managing return flows from irrigation to groundwater and streams, increasing flows to the Murray Mouth, mitigating salinity and pollution, and maintaining or reinstating, where possible, connection between rivers, their floodplains, and wetlands (MDBA 2020a). To achieve these outcomes, the surface water and groundwater connections and interactions as depicted in Figure 1 provide the foundation for effective integrated water management in the MDB.

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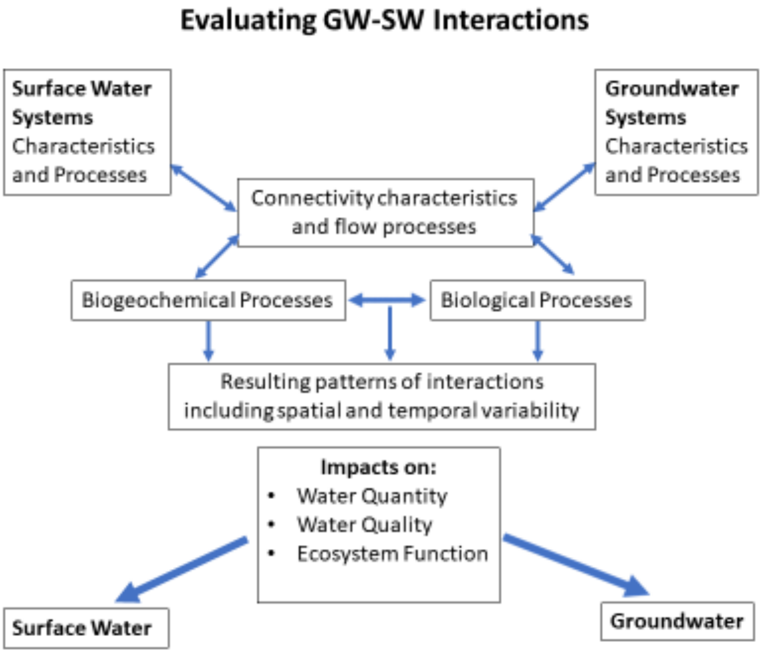

Figure 1. Groundwater-surface water connectivity, interactions, and impacts on water quantity, water quality and ecosystem function. (Redrawn from Conant et al. 2019).

2.1.1. Potential for, and processes of, interaction

Groundwater tends to flow to rivers when the aquifer watertable is higher than the level of the river (gaining rivers). If the watertable is below the level of the river, surface water will tend to flow to and recharge the aquifer (losing rivers). If the aquifer and river are separated by a semi-permeable layer of material (e.g. clay) this will slow the water flow between the two resources (Evans 2007; Jolly et al. 2013). These scenarios are illustrated in Figure 2 below.

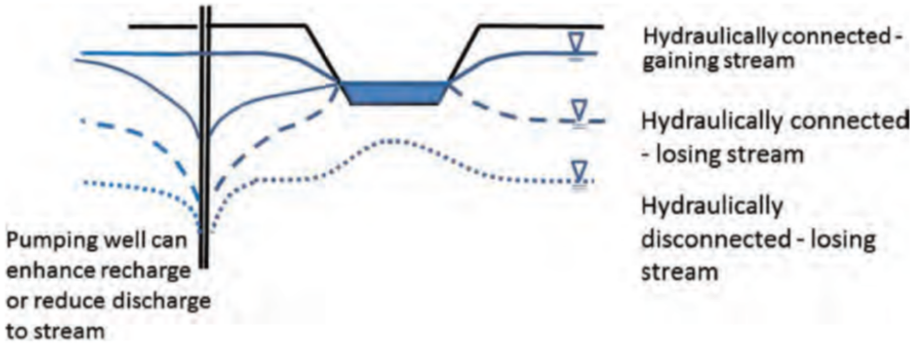

Figure 2. The nature of simple groundwater-surface water connectivity. (Redrawn from Evans et al. 2018).

Groundwater-surface water connections vary spatially along rivers and across aquifers. Rivers may change from gaining to losing, and aquifers may underlie several rivers with different degrees of connection. Groundwater-surface water connections adjacent to a river tend to be stronger and faster than those distant from a river (Jolly et al. 2013), although the nature of the material that the water has to travel through is more important than the distance to the river (Evans 2007).

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Gaining and losing rivers at the catchment scale in the MDB were mapped by Parsons et al. (2008) – see Figure 3.1.

Groundwater-surface water connections also vary over time. Surface water responds relatively rapidly to inflows and extractions, often within days or weeks (depending upon the length of the river system). Groundwater systems often respond relatively slowly, and long time-lags are common, extending to years, decades and even millennia (RMCG 2021), and often falling outside the accounting period for state water planning (SKM 2011).

Groundwater-surface water interactions in the MDB occur on a continuum between two endpoints. At one end, groundwater is directly connected to rivers with a 1:1 connection (Evans 2007); at the other end, there is effectively no groundwater discharge to rivers, and instead groundwater discharges to ecosystems (wetland or terrestrial). For example, in mid-river portions of the major rivers in New South Wales (NSW), there is a rapid interchange between alluvial groundwater and overlying surface water, whereas the large groundwater systems of the Riverine Plain are overlain by a semi-confining layer that dampens interaction between groundwater and overlying rivers.

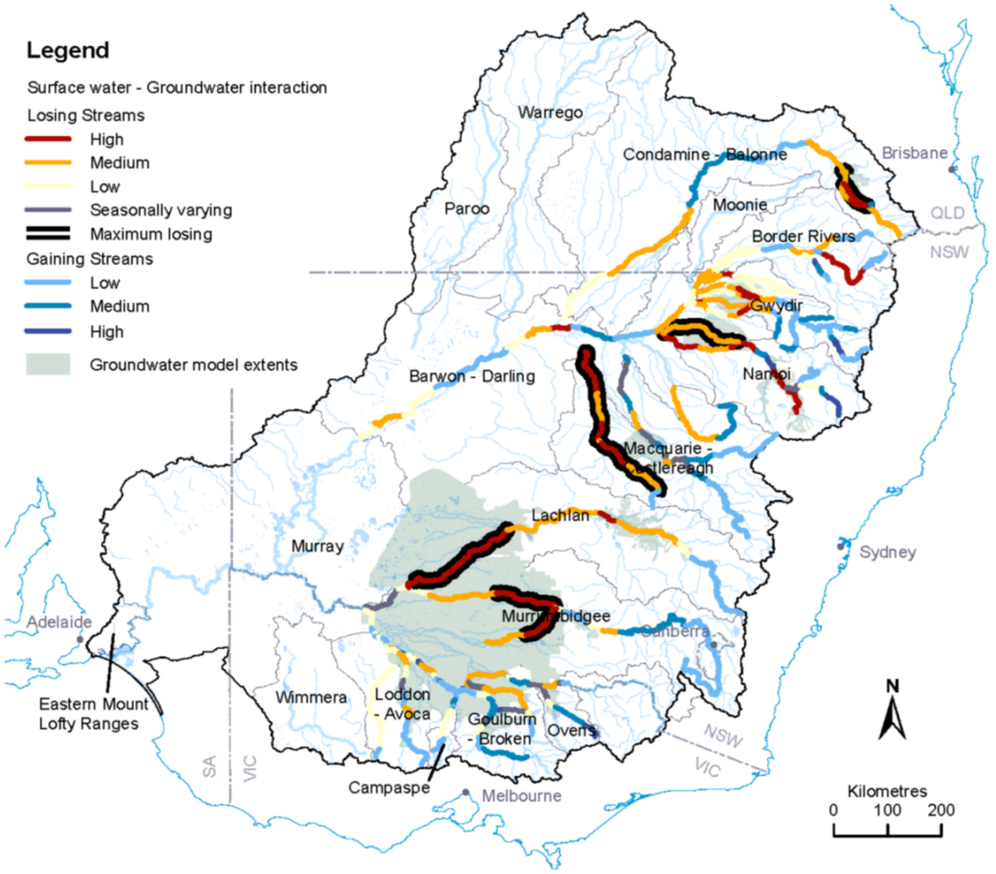

Figure 3.1. Surface water-groundwater connectivity for major rivers of the MDB. (Redrawn from Figure 5.1 of Parsons et al. 2008).

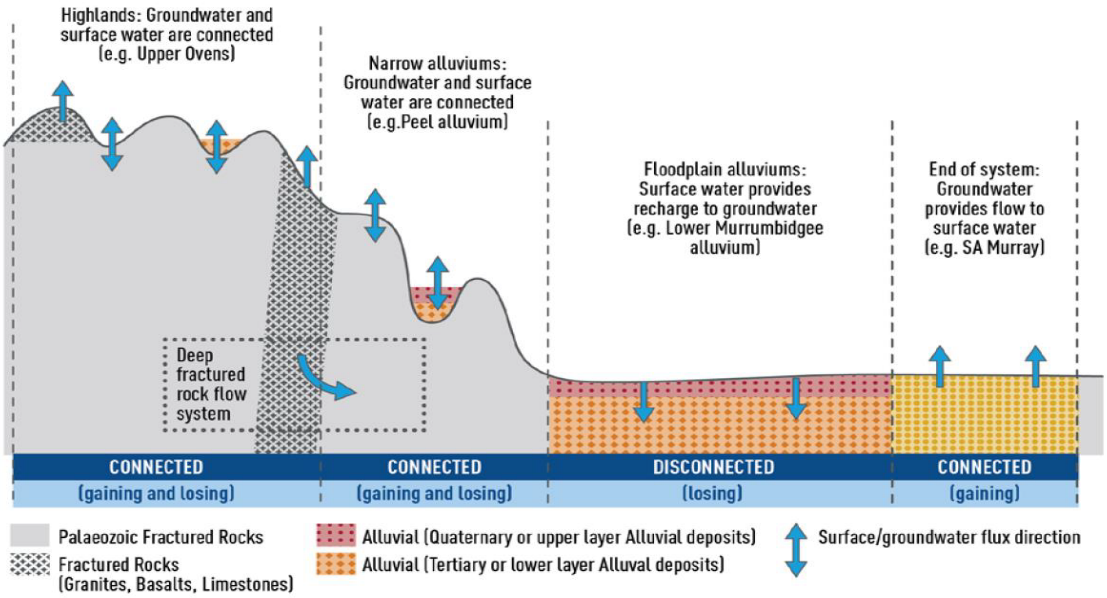

Figure 3.2. Connected systems classification (adopted from Braaten et al. 2001) showing the connectivity between surface and groundwater considering geology and topography (MDBA 2020b).

Figure 3.2 illustrates the river-aquifer connections in the main geomorphological zones in the MDB (Braaten et al. 2001), which can be summarised as follows:

- in upland areas, streams receive flows of freshwater from fractured rock aquifers;
- in mid-sections of larger rivers, high rainfall in narrow floodplains results in shallow watertables with strong river-aquifer connections;
- in the wide semi-arid plains, rivers generally discharge to groundwater systems and freshen the groundwater;
- towards the end of the Murray–Darling system, rivers tend to be neutral or gaining, and the discharge of saline groundwater increases salinity in the lower Murray.

2.2. Human impacts on connected groundwater-surface water resources and their interactions

Groundwater extraction results in a lower watertable that affects surface water flows either by captured groundwater discharge or by induced recharge from surface water. Unless there is a proportionate addition of water from another source, groundwater pumping lowers the flow of groundwater (baseflow) into a connected river or increases the rate at which surface water leaks into a connected aquifer. The relationship between groundwater pumping and river flows is complex, with variable time-lags depending on local geology, topography, vegetation and evapotranspiration (Evans 2007; Hartman 2021).

In alluvial settings where the aquifer and river are closely connected, groundwater pumping has a relatively rapid impact and causes a gradual reduction in streamflow. On flat plains, bores may be located long distances from rivers and the time lags in impacts of groundwater extraction on river flows may be very long. Groundwater pumping from shallow aquifers lowers the watertable and reduces the amount of water available for vegetation and evapotranspiration. Groundwater extraction distant from rivers often impacts on vegetation before streamflow (Evans 2007; Jolly et al. 2013).

The main risks to connected groundwater and surface water resources are from increased extractions, especially in dry years, and climate change (van Dijk et al. 2006). In addition, there are 'synergistic' risks resulting from combined cumulative effects of multiple risks such as lower inflows, declining surface water and aquifer storage, declining water quality, and water supply shortages (Pittock et al. 2023). There has been more attention given to risks to connected groundwater-surface water systems from groundwater extraction than to risks from surface water extraction (Ross et al. 2022).

2.2.1. Estimated impacts of groundwater extraction on connected surface water resources

In 2006, van Dijk et al. cited an estimate of future reductions of surface water resources owing to groundwater extraction ranging between 275 and 550 gigalitres (GL) in 20 years, with a median estimate of 330 GL. Walker et al. (2020a) estimated that the impact from 40 years of growth in groundwater extraction would be up to 580 GL/year, but more likely 100–400 GL/year. On average this represents up to 4% of river flows, using the MDB baseline diversion limit (13,623 GL/year) as an indicator of the available volume of water (Pittock et al. 2023). The impact of groundwater extractions on rivers is much greater than average during low flows (Walker et al. 2020b).

The estimated impacts of increased groundwater extraction are concentrated in a relatively small number of high-impact groundwater management areas (GMA), notably in the Lachlan Fold Belt and the Shepparton Irrigation Region of the Goulburn-Murray GMA (Walker et al. 2020b). Medium to high impacts are concentrated after 40 years, and unlikely within 20 years. However, groundwater extractions are cyclical, with increased extractions during dry periods. After the high levels of extractions during the drought of the 1980s and 1990s, groundwater extractions did not return to the lower levels which existed prior to the drought. This behaviour may be repeated. Therefore, adaptive management is needed to manage the risk that by the time the lagged effects of increased extractions are evident, it will be difficult to reverse them (Walker et al. 2020b).

Also, many groundwater management areas are large, and the spatial distribution of impacts is highly variable. Groundwater extractions can be concentrated in areas of fresh groundwater with high transmissivity, and can cause severe local impacts on environmental flows and ecosystems. These impacts need to be managed by local rules (Walker et al. 2020b).

2.2.2. Impacts of groundwater extractions on groundwater-dependent ecosystems (GDEs)

GDEs can be grouped into three broad classes: (1) terrestrial GDEs, including all vegetation communities that rely on the subsurface presence of groundwater; (2) aquatic GDEs, including riverine baseflows, wetlands and springs that rely on groundwater discharge to surface water; and (3) subterranean GDEs which include aquifer and karst systems (Dabovic et al. 2019).

Groundwater extractions may manifest as reduced streamflow, or other discharge mechanisms, primarily evapotranspiration (Ross et al. 2022). Management of the impacts of groundwater extractions on the quantity and quality of water in shallow aquifers is of vital importance to riverine forests and woodlands dependent on groundwater. Information about these impacts is generally poor, although there has been some progress in understanding the impacts of climate change and land-use change on water yields (Zhang et al. 2018). The impacts of pumping on GDEs are not well understood because of incomplete knowledge about the water needs of GDEs and relationships between watering and different types of GDEs (rivers, wetlands, terrestrial vegetation) (Saito et al. 2021).

2.2.3. Impacts of surface water extractions on groundwater resources

There is a shortage of data and assessments related to the impacts of surface water extractions on groundwater resources. It is easier to obtain estimates of the effects of groundwater pumping on river flow than the impacts of surface water extractions on groundwater. It can be argued that surface water extractions have limited influence on overall groundwater levels in the MDB because most groundwater recharge comes from episodic events (Crosbie et al. 2010), but surface water extractions can have significant local impacts on groundwater levels.

2.2.4. Connectivity between connected water resources and ecosystems in an irrigation zone

Irrigation accounts for about 70% of consumptive water use in the MDB and has a dominant impact on hydrological flows. The interactions between groundwater and surface water in rivers, streams, floodplains, and wetlands are depicted in a systems flow diagram in Figure 4 and illustrated by cross-sectional and oblique view diagrams in Figure 5. Water extraction for irrigation and the return flows from irrigation to groundwater and surface water interact strongly with the flow regimes of Figure 4, and the spatial flooding and drainage patterns in Figure 5, (which are key factors influencing flows to and from groundwater and floodplain wetlands).

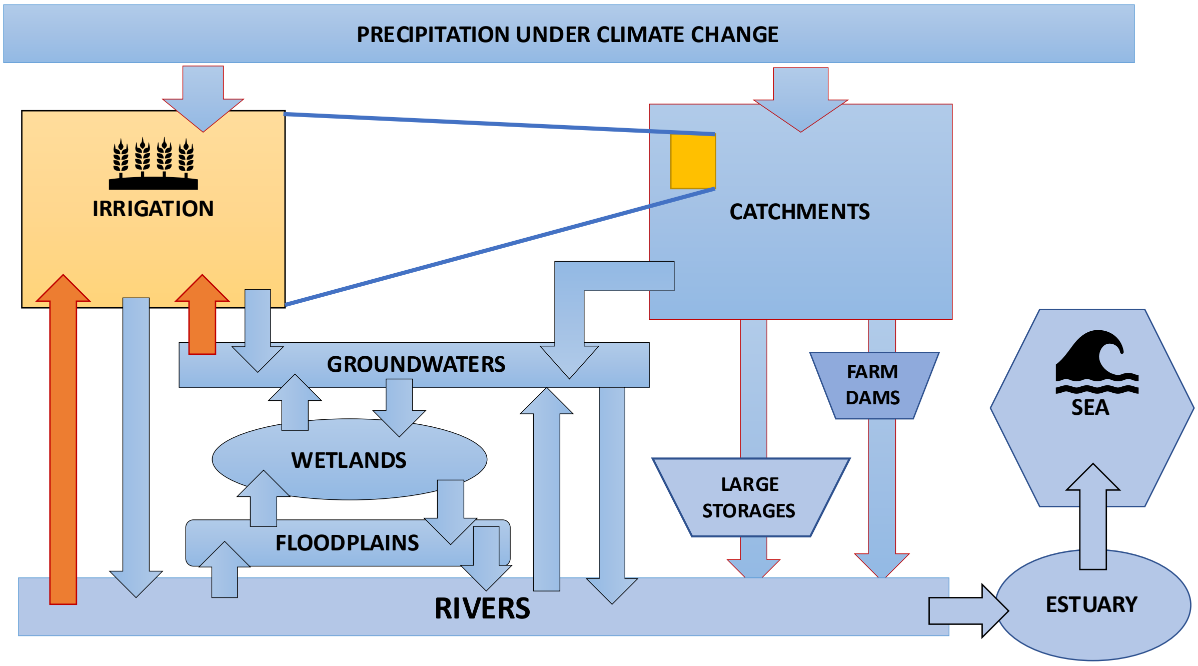

Figure 4. Catchments, farm dams, large storage dams, irrigation areas, rivers, floodplains, wetlands and groundwater connections, management cycles and flows. Consumptive flows to irrigation areas are shown in orange while all other water flows are shown in blue. (Redrawn from Figure 3.01 of Williams et al. 2004).

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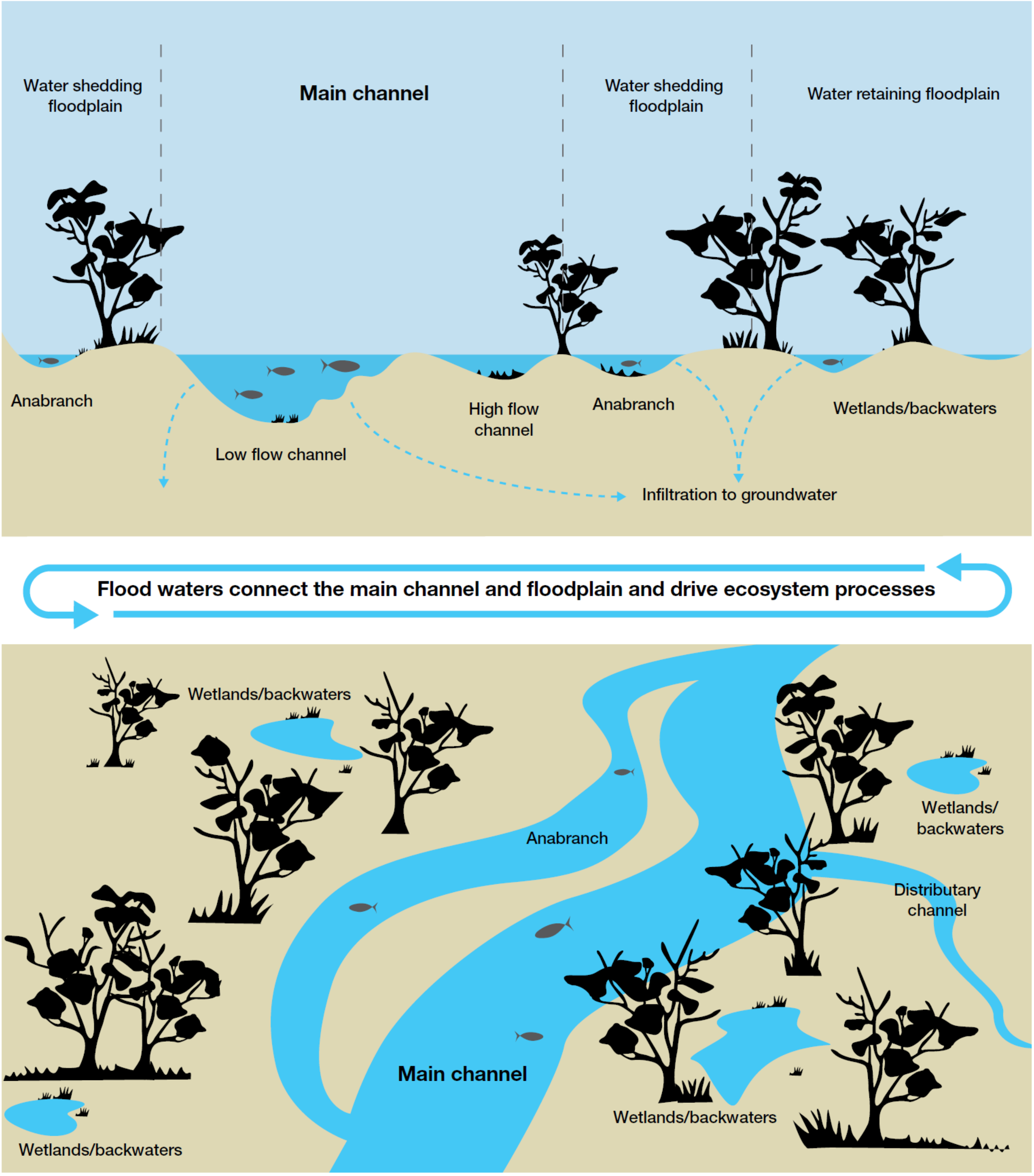

Figure 5. A cross-section and map of surface water connectivity in a riverine floodplain and their connection to groundwater. (From Figure 8.3 of NRC 2009).

2.3. Classification and measurement of connectivity

During the last 15 years, there has been significant development of methods to characterise and measure groundwater-surface water connectivity (Lamontagne et al. 2012). REM (2006) proposed that a definition of surface water and groundwater connectivity should describe the nature, rate, and time frame of the interaction. The definition should be quantifiable and applicable over a range of spatial scales.

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The National Framework for Integrated Management of Connected Groundwater and Surface Water Systems (SKM 2011) proposed a three-tier classification of connectivity based on the potential for connection, the time lag between extraction and impact, and other factors important for the management of the system including seasonality and extent of use. In the MDB, the most highly connected systems are the alluvial valleys.

The Murray-Darling Basin Authority (MDBA 2020b) adopted a modified version of this classification as an input for the establishment of sustainable groundwater diversion limits. Connected systems are assessed as high risk when groundwater discharge provides baseflow to the unregulated river reach and groundwater extraction is likely to result in streamflow depletion. Systems are assessed as medium risk where more than 50% of groundwater extraction would have contributed to river flow within 50 years, and as low risk when less than 50% of groundwater extraction would have contributed to streamflow within 50 years. The MDBA considered that extractions to manage salinity and water logging in shallow groundwater systems are low risk to the groundwater system and beneficial to connected surface water.

3. Driving forces and risks that affect water resources and water resource connectivity in the MDB

Major driving forces and risks affecting connected groundwater and surface water resources and impacts of extractions on water resources and dependent ecosystems include climate change, irrigation and floodplain harvesting, afforestation, coal seam gas and coal mining.

Climate change is leading to reductions in rainfall, reduced river flows, and reduced groundwater recharge. Medium to large flows and overbank flows will become less frequent (Prosser et al. 2021) and water quality problems will increase (Beavis et al. 2022).

The most at-risk groundwater systems are sedimentary and alluvial systems dominated by diffuse recharge (Fu et al. 2019).

Demand from agriculture and irrigation for water is projected to increase, especially under dry climate scenarios (Gupta et al. 2020). Increased irrigation efficiency and floodplain harvesting is leading to reduced groundwater recharge and river flows (Williams et al. 2022).

Although the impacts of increased afforestation on MDB water resources has been relatively small, further research and analysis is required on the effects of changes in crop mix and carbon plantings on groundwater-surface water connectivity (Lane et al. 2022).

There are significant uncertainties about the impacts of coal seam gas and coal mining on groundwater-surface water connections, and the cumulative impacts on ecosystems and communities (Williams et al. 2012).

The impacts of these driving forces and risks on MDB water resources are summarised in Table 1.

Table 1. Impact of climate change, changes in irrigation, and coal seam gas extraction on connected groundwater and surface water resources, ecosystems and water quality.

Driver	**Impact of driver on GW-SW connections**	**Impact on connected water resources and water quality**
Climate change	– Reduced GW flow to SW – Reduced SW flow to GW – Reduced GW recharge	– Reduced GW levels and storage – Reduced GW baseflow and contribution to river flow – Deterioration in water quality
Irrigation and floodplain harvesting	– Reduced return flows from irrigation to GW – Reduced SW flow and GW recharge	– Reduced GW levels and storage – Reduced GW contribution to river flow
Coal seam gas extraction	– Changes and reversals in GW flow paths – GW contamination	– Reduced GW contribution to river flow – Deterioration of GW quality

4. Legislation, policy, and adaptive management

The following section reviews current federal and state government approaches for defining and measuring groundwater-surface water connectivity, managing cross-connection impacts of groundwater and surface water extractions, and outlines adaptation to changes affecting connected water resources.

4.1. Legislation and policy related to the management of connected surface water and groundwater resources

The MDBP and state WRPs recognise connectivity between surface water and groundwater resources and require protection and/or restoration of connectivity. They do not, however, clearly define how risks related to connectivity are assessed, or what measures are to be incorporated to address the identified risks (Ross et al. 2022).

4.1.1. Treatment of groundwater-surface water connectivity in the MDBP

The MDBP requires protection and restoration of connectivity between water-dependent ecosystems, ensuring that processes dependent on hydrologic connectivity between the surface and subsurface are protected and restored (Commonwealth of Australia 2012, Section 8.06, (3)(b)(iii)). The MDBP also provides that state WRPs:

- have regard to the management and use of resources which have a significant connection to the water resources of the WRP area (MDBP, Section 10.05);
- set out monitoring and actions to respond to groundwater take (MDBP, Section 10.14);
- have regard to whether it is necessary to have rules that ensure that the operation of a groundwater resource plan '… does not compromise the meeting of environmental watering requirements (for example, base flows)' (MDBP, Section 10.19 (1)).

However, the MDBP does not include a clear definition of significant groundwater-surface water connectivity, or any indication of how significant groundwater and surface water connections will be measured. While the MDBA has had exhaustive consultation with the states to define 'significant hydrological connectivity', a consistent approach between states has not been achieved (Ross et al. 2022). In effect, this leaves the definition and measurement of connections with the Basin states to be managed through state WRPs.

Section 10.19 of the MDBP includes two criteria for significant connection between surface water and groundwater: (i) that water from one resource is physically able to move to the other, and (ii) that activities in one resource may have a material impact on the state of the other. However, there is no guidance on how material impact of *extractions* on connected water resources is to be determined, which creates the risk that some significant impacts will remain uncontrolled (Ross et al. 2022).

Schedule 7 of the MDBP defines targets to measure hydrological connectivity between the river, the floodplain and valleys, but neither the MDBP nor its schedules include targets to measure progress on maintaining connections between groundwater and surface water resources (Commonwealth of Australia 2012).

4.1.2. Management of groundwater-surface water connections in state water resource plans (WRPs)

(a) Definition of hydrologic connectivity, risks related to connectivity and their significance

The lack of a precise definition in the MDBP of groundwater-surface water connectivity and material impact of activities, including extractions, allows MDB jurisdictions to establish varying, inconsistent definitions of connectivity and material impacts. New South Wales established a narrow definition that required 70% of groundwater pumping to be drawn from streamflow within an irrigation season. Victoria has not set a specific threshold.

In addition, there have been differences between the treatment of surface water-groundwater connectivity in surface water and groundwater plans. In the first generation of state WRPs, most groundwater plans recognised that connectivity exists, and a few included measures to address it, but most surface water plans assumed that connectivity does not exist or was not a significant issue (Ross 2014, 2018).

(b) Rules to manage risks related to groundwater-surface water connections at different spatial scales

The MDBP (Section 10.19 (2)) specifies that WRPs for groundwater with a significant hydrological connection to surface water may include rules to prevent impacts on environmental watering requirements. These may include resource condition limits and rules that limit the times, places and rates at which groundwater can be taken.

At the Basin and catchment scales, the risks to connected water resources posed by overextraction are managed by volumetric sustainable diversion limits (SDLs) and allocations. The MDBA considers these risks to be low because more than two-thirds of the groundwater SDL resource units have average annual use levels 50% below the unit SDL (MDBA 2019), although groundwater use can rise substantially in dry years, such as 2019.

Most water management areas in the MDB are relatively large and local cross-connection impacts of extraction on connected water resources are highly variable. Local management rules administered by the states are used to manage high cross-connection impacts of extraction (Stewardson et al. 2021), such as high groundwater extractions near to a river and impacts of extractions on aquatic ecosystems with high ecological value. In practice, most jurisdictional management effort is prioritised towards 'hot spots' with high levels of groundwater 'take' and relatively rapid cross-connection impacts such as larger alluvial systems (e.g. Gwydir, Murrumbidgee, Murray catchments) and narrower alluvial systems (e.g. Upper Ovens and Peel river catchments), where there is empirical evidence of short-term impacts of groundwater take on streams.

(c) Management of variable timescales of groundwater-surface water connections

Management of hydrologic connectivity between groundwater and surface water resources is complicated by the different timescales of the response of surface water and groundwater systems. It is important to take account of the fact that impacts of groundwater extractions on water availability from connected surface water resources may be expressed within a season, within the lifetime of a WRP, or outside the time frame of WRPs depending on geology, topography and vegetation (Evans 2007). When groundwater extractions have a large impact on connected surface water resources with a long time-lag, SDLs and associated local management rules have to be managed adaptively and monitored using resource condition indicators (Stewardson et al. 2021).

Currently, the few WRPs that explicitly recognise groundwater-surface water connections throughout a connected system are attempting to manage short-term seasonal impacts. In the few WRPs where jurisdictions have recognised long-term impacts, such as the Upper Ovens River, they have retrofitted conjunctive water management approaches.

4.1.3. Measurement and modelling

Surface water and groundwater resources with a high level of exploitation, a high potential for connection, and a relatively short time-lag between extraction and impact, experience high impacts from extractions. Between 1999 and 2019, many bores in the highly productive alluvial resources in the MDB were declining, such as the Namoi, Lachlan and Murrumbidgee resources (Australian Government, Bureau of Meteorology 2020). These areas have been thoroughly assessed using models and well data, but there is much less information about the impacts of increasing groundwater extractions in other areas.

Basin Plan modelling has not been updated since 2012 and does not include changes to river operating rules. There is a need for expanded coverage by models and improvements in integrated groundwater and surface water models (Pittock et al. 2023).

4.1.4. Knowledge about groundwater-surface water connectivity and cross impacts of extractions on connected resources and dependent ecosystems

Management of groundwater-surface water connections requires knowledge about groundwater levels and the response of water balances to flows between connected water resources, extractions from these resources, and changes in climate and land use.

There have been some significant advances in knowledge. Connectivity has been estimated using a connectivity factor (Walker et al. 2020a), measurements of hydraulic head (Lamontagne et al. 2012), application of environmental tracers (Smith et al. 2018), and bioregional assessments of cumulative impacts of coal seam gas and coal mining projects.

However, the South Australian MDB Royal Commission (Walker 2019) noted that there remains considerable uncertainty and knowledge gaps in the management of groundwater and GDEs. Connections between groundwater and surface water ecosystems have not been explicitly assessed for each GMA. Management of high ecological value aquatic ecosystems (HEVAE) including GDEs is still being incorporated into state water allocation plans. In Victoria, work was undertaken to develop methods to map the distribution of GDEs on a regional basis (Dresel et al. 2010), and for NSW a state-wide approach is reported in Kuginis et al. (2016). The NSW framework for assessing GDEs illustrates a way forward (NSW Government 2023), and there is increasing appreciation of the importance of protecting GDEs and their function under some components of the *EPBC Act 1999* as reflected in Matters of National Environmental Significance (MNES), but to date this has not been exercised. While there is recognition of the importance of GDEs, there are

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significant knowledge gaps and uncertainty about the water requirements of GDEs (Saito et al. 2021), especially in dry conditions, and from the impact of coal seam gas and large coal mining developments.

While definition and mapping of priority environmental assets and ecosystem functions are improving, GDEs are potentially at risk from local impacts of extractions that are not regulated within the state water resource planning framework (Ross et al. 2022). Technical input to state WRPs is often insufficient to integrate surface water and groundwater processes to test the range of risks to resources and their connectivity – the Gwydir WRP provides an example – see Section 5.3.

4.2. Adaptation to change affecting connected groundwater and surface water resources

A flexible adaptive management approach is needed to respond to risks and uncertainties arising from impacts of climate change and increasing demand for water on connected water resources and ecosystems (see Section 3). These risks and uncertainties are increased by shortfalls in the baseline knowledge of hydraulic relationships, the immaturity of integrated groundwater-surface water management frameworks, and the likelihood that demand for groundwater resources will increase as surface water availability decreases (Walker et al. 2021).

The National Water Commission (NWC) recommended that future water plans explicitly consider the impacts of climate change on water resources and the environment (NWC 2009, 2014). The Productivity Commission (2018) found that further consideration is needed of emerging risks to Basin water resources from climate change, including impacts on river flows and environmental condition of key Basin assets. Risks from climate change interact with irrigation diversions and floodplain harvesting (Pittock et al. 2023), increasing the cumulative impact of individual risks.

Regional sedimentary and alluvial groundwater systems are especially vulnerable. In these cases, dry scenarios need to include extremes beyond the historical range (Walker et al. 2021).

There has been insufficient consideration of integrated management of groundwater and surface water, and neglect of metering and independent auditing of connected water resources. Unregulated take from floodplain harvesting poses substantial risks (Williams et al. 2022).

National legislation suffers from legal and policy ambiguity in considering cumulative effects of CSG and coal mining (Nelson 2019a, 2019b). The Condamine-Balonne WRP (Government of Queensland 2019) illustrates how the Commonwealth's approach does not deal adequately with the gaps in state law, such as unlimited take of groundwater for CSG activities which pose potentially significant risks to GDEs (Nelson 2021).

5. Discussion: steps towards improved integrated management of connected water resources

Managing and addressing connectivity is perhaps the most significant differentiator between predicting the hydrological response of surface water decisions and groundwater decisions (RMCG 2021). A surface water response largely manifests within days or weeks, but for groundwater, long time-lags are common and can extend to decades in many parts of the Basin. For this reason, connectivity has a relatively high profile in the groundwater-specific components of the Basin Plan. It is given effect through the requirements to consider 'interception activities' and 'significant hydrological connection' in the estimation of SDLs and in the requirements for WRP rules (RMCG 2021).

While Australian legislation and policy provides a basis for the management of connected groundwater and surface water resources, there are serious weaknesses in the provisions for maintaining and improving beneficial connectivity and for managing risks of reduced connectivity or disconnection between these resources. There are a number of steps that can be taken towards integrated management of connected groundwater and surface water resources and ecosystems including:

1. The definition and measurement of groundwater-surface water connectivity.
2. The management of cross-connection impacts of extractions.
3. Improved monitoring and modelling, rules and adaptive measures, including current data analytics and real-time digital technology.
4. Improved knowledge and technical inputs.

5.1. Framework for assessing groundwater-surface water connectivity and impacts of extractions on connected water resources and ecosystems

5.1.1. Framework for assessing groundwater-surface water connectivity and related risks and impacts

The Australian Government, in consultation with state governments, has made efforts to define a common standard for 'significant hydrological connectivity' but a consistent approach between the states has not been achieved (RMCG 2021). It is important to establish a common definition and framework for assessing significant connectivity and the material impact of connectivity in order to ensure that cross impacts of extractions on connected water resources and ecosystems are recognised and controlled.

The MDBP should be amended to include a more precise definition of groundwater-surface water connectivity and to clarify the meaning of material impact of significant cross-resource connections. Measurable indicators of connections between groundwater-surface water resources and ecosystems should be included in the schedules to the MDBP.

An extended framework for assessing groundwater-surface water connections and cross impacts of increased extractions on connected water resources and ecosystems in WRPs can be developed building on the existing national framework (SKM 2011). This framework would extend current arrangements by requiring the WRPs to consider: long-term cross impacts of groundwater and surface water extractions beyond the planning period; long-term risks owing to reduced connectivity; and impacts of extractions on an expanded range of GDEs, including terrestrial vegetation and subterranean ecosystems (Ross et al. 2022). Priorities for maintaining and/or restoring groundwater-surface water connectivity in state WRPs can be established with a reference to this framework.

The extended framework could include:

1. Physical surface water and groundwater environments and the potential for connection between resources.
2. Extent and direction of connection between groundwater and surface water resources.
3. Cross-connection impacts of groundwater and surface water extractions on connected water resources and water-dependent ecosystems, including impacts on river baseflow, terrestrial vegetation and subterranean ecosystems.
4. Impacts on salinity and groundwater and surface water quality.
5. Time lag between extraction and impact.

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6. Influence of climatic conditions and level of water resource development on connected groundwater and surface water resources and ecosystems.

5.1.2. Transition to improved integrated management of connected groundwater and surface water resources

It is likely to take some time to coordinate state policies and information to implement the above framework. In order to provide a transition path, the MDBP could be amended to include an agreed assessment time frame to be applied to the estimation of water balances, predictions of drawdown, and evaluation of risks of long-term changes in groundwater salinity and water quality in connected groundwater-surface water systems. This would provide a consistent approach informing ALL planning and regulatory decisions that have implications for connectivity, irrespective of scale, including significant impacts beyond the statutory time period for WRPs (RMCG 2021).

This would be an important step forward from the current status quo which, in the absence of policy-relevant directions, is commonly determined case-by-case or project-by-project resulting in a lack of consistency in the management of connected groundwater and surface water systems. Predicted impacts on SDL units arising from changes in groundwater-surface water connectivity should be considered in the review of the MDBP (RMCG 2021).

5.2. Rules and management approaches to manage connected groundwater-surface water resources and ecosystems

Improved management of risks to connected water resources in a drying and more fluctuating climate can be promoted by rules and tools tailored to specific contexts, and by adopting longer planning and management time frames. The efficacy of different rules and tools to manage the impacts of extractions depends on the hydrological and social context, objectives for managing connected resources, along with both time and space scales of management (Stewardson et al. 2021).

Volumetric limits and allocations in the MDBP and WRPs control long-term impacts of extraction and provide a secure supply for groundwater users, but do not consider spatial hot spots of groundwater drawdown and do not protect local GDEs. Buffer zones limit short-term impacts of abstraction on groundwater level and flow, but it is difficult to determine appropriate zonal boundaries, and buffer zones usually delay rather than prevent long-term impacts. Groundwater response triggers aim to directly control groundwater levels, but their success depends on accurate estimation of the trigger value and appropriate location of the observation wells, and requires costly monitoring (Noorduijn et al. 2019).

The planning period for most groundwater WRPs is too short to account for long-term impacts of changing climate and extractions on connected water resources. The slow movement of groundwater pressure responses means that pumping permitted from the beginning of the MDBP and in decadal WRPs could lock-in undesirable long-term impacts. The planning period for WRPs should be extended for connected systems where there are significant long-term risks and uncertainties (RMCG 2021).

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5.3. Measurement and monitoring

Measurement and monitoring of connected groundwater-surface water resources is crucial to enable the MDBP: 'to establish a sustainable and long-term adaptive management framework for the Basin water resources' (MDBP, Section 5.02 (1)(b)). Catchment water balances provide an important baseline for the measurement of surface water and groundwater resources, storage and flows. Other important indicators for ongoing measurement and monitoring include river flows, well water levels, salinity, turbidity, and the condition of high value water-based ecosystems.

Inadequate groundwater monitoring and modelling by state agencies pose risks to GDEs from groundwater-surface water interactions, which are not adequately addressed in the implementation of WRPs (Ross et al. 2022). There are ongoing challenges to ensure good consistent data from monitoring bores, which are necessary to correctly interpret water level data and identify machine measurement errors. Technologies of measurement and data analysis are advancing rapidly and need to be applied to the next generation of water management. This will require additional investment in monitoring to improve accuracy of measurement and interpretation (Pittock et al. 2023).

Measuring and monitoring of groundwater-surface water connections can be improved by increased use of new and improved hydrological and chemistry-based approaches. Gravitational measurements are supplementing field observations to improve data on aquifer levels at the regional scale, and small-scale mobile gravitational measuring devices offer additional measurements at the local scale (Chen et al. 2016).

5.4. Improving knowledge and technical inputs for planning and decision making

As water scarcity and risks owing to climate change increase, more thorough and detailed management is required for closely connected and highly exploited surface water and groundwater resources (Walker et al. 2021; Ross et al. 2022).

Currently, insufficient technical work has been done on understanding the cross-connection impacts of groundwater and surface water use and storage on the total consumptive pool, especially in dry climate scenarios. The lower Gwydir groundwater source within the Gwydir alluvium WRP in NSW (Department of Planning and the Environment (NSW) 2019), provides an example of a water allocation plan where it is acknowledged that the connection between surface water and groundwater is occurring – but the level of technical input is less than appropriate. In circumstances such as this, decision-support modelling that integrates surface water and groundwater processes is required and a broader range of use scenarios should be tested.

There are a number of tools that can be used to improve the adaptive management of water resources in response to climate change. These include scenario modelling and planning (to understand potential impacts of climate change under a range of water availability and demand assumptions), soil-vegetation-atmosphere transfer (SVAT) models to estimate reductions in groundwater recharge, and vulnerability mapping to prioritise the most affected resources and regions. Regional sedimentary and alluvial groundwater systems that are already near to the sustainable extraction limit are especially vulnerable. In these cases, dry scenarios need to include extremes beyond the historical range (Walker et al. 2021).

Four key steps are required to enable better adaptation to change and uncertainty, and to improve connected water management in an uncertain future (Williams et al. 2022):

- improved data collection, accessibility and analysis of water and salt balances, and water accounts (Molden 1997) that accurately measure water flows, including return flows, are critical to manage changing water availability in the MDB;
- independent audits of the condition of connected water resources to manage critical risks, such as salinisation and deterioration of riparian environments;
- robust risk analysis to identify cumulative risks from floodplain harvesting, farm storages and irrigation infrastructure subsidies;
- holding key decision-makers accountable for their actions in delivering key objectives of the *Water Act 2007*.

Stafford Smith et al. (2011) identified adaptive measures that reduce decision risk while acknowledging uncertainty, including improved conveyancing and water efficiency, and increased planting of water-efficient crops.

Aquifer storage provides a buffer for managing uncertainty and variability in water supply, and adds to adaptive capacity (Yu et al. 2021). Managed aquifer recharge (MAR) can play an important role in restoring over-allocated groundwater resources, protecting water-dependent ecosystems, and enhancing urban and rural water supplies and storage (Dillon et al. 2016). Water banking in aquifers using MAR is widely practiced overseas, and scientific investigation has documented the potential for water banking in the MDB (Ross 2012; Gonzalez et al. 2020).

6. Conclusions and vision

Integrated management of connected groundwater and surface water resources is essential in order to achieve optimum use of MDB water resources and storage for human and environmental purposes. Although Australian legislation and policy provides a basis for the management of connected water resources, there are serious weaknesses in the implementation of integrated groundwater and surface water management. Therefore, there is an urgent need for policy reform and significant amendments to the Basin Plan. The MDBA has identified that there are many risks to Basin water resources that may not be fully mitigated through state water resource plans (WRPs), which are the cornerstones of the MDBP.

Successful implementation of integrated management of connected groundwater and surface water resources in the MDB requires improved coordination between Basin state governments and a number of legislative, policy and administrative measures. Improved coordination with Basin state governments will be needed to manage risks to surface water-groundwater connectivity owing to increased groundwater use and climate change, giving particular attention to leveraging existing knowledge and generating new knowledge to ensure that groundwater policy reform and management is underpinned by the best available science (MDBA 2019).

A vision for integrated management of connected groundwater and surface water resources includes the following enabling conditions:

- the volume of connected groundwater and surface water, their uses and their connections, will be measured or estimated and monitored;
- groundwater and surface water planning and allocation will fully account for the impacts of water use on connected resources and ecosystems, and manage these resources to achieve socially acceptable socio-economic and environmental outcomes;

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- the values of groundwater and surface water resources and ecosystems will be determined in consultation with stakeholders, and water users will pay a socially acceptable charge for water use.

The following legislative, policy and administrative measures are required to manage risks and to implement integrated management of connected water resources. The Basin Plan would need to be significantly amended in terms of the current risk framework, and in particular, give attention:

- to include a more precise definition of groundwater-surface water connectivity to clarify the meaning of material impact of significant cross-resource connections;
- to include measurable indicators of connectivity; and
- to include targets to measure progress towards connectivity.

The MDBP will also need to be amended to include an agreed assessment time frame to be applied to the estimation of water balances and resource condition indicators, including predictions of drawdown and evaluation of risk of long-term changes in groundwater salinity and water quality (RMCG 2021).

In addition, the existing framework for assessing groundwater-surface water connections and cross impacts of increased extractions on connected resources (SKM 2011; MDBA 2020b) will need to be extended to require state WRPs to consider: long-term cross impacts of groundwater and surface water extractions beyond the planning period; long-term risks when connectivity is expected to be reduced; and impacts of extractions on an expanded range of GDEs including baseflows, aquatic ecosystems, terrestrial vegetation, and subterranean ecosystems.

Context-specific packages of rules and tools will need to be developed and included in WRPs to manage local impacts of groundwater extraction on groundwater entitlement holders and GDEs. Adaptive management of extraction limits and rules will need to be undertaken to address uncertainties about local cross-connection impacts, with ongoing monitoring and review. Longer planning periods will need to be established to manage connected groundwater and surface water systems, with significant long-term risks and uncertainties related to impacts of water extractions on connected water resources and ecosystems.

Improved long-term measurement and monitoring will need to be undertaken to monitor trends in connected groundwater and surface water resources and the effectiveness of management measures. Additional investments will be required to improve the accuracy of measurements, the interpretation of monitoring results, and to extend and improve integrated modelling of connected water resources, taking account of the impacts of climate change and cross impacts of extractions.

Improvements in data collection, independent audits of the state of connected water resources, and improved analysis of cumulative risks will enable adaptive management of risks and uncertainty related to connected water resources and ecosystems. Integrated management of water resources and storage and water banking will need to be developed further to improve water security and community resilience and to address the growing risks of severe droughts and floods.

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