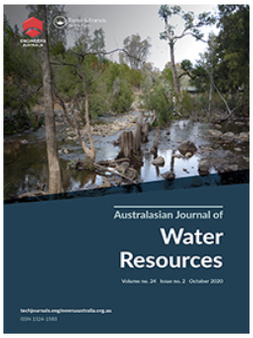

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Australasian Journal of Water Resources

ISSN: (Print) (Online) Journal homepage: https://engineersaustralia.tandfonline.com/loi/twar20

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To cite this article: Glen R. Walker , Quan J. Wang , Avril Horne , Rick Evans & Stuart Richardson (2020) Potential cumulative impacts on river flow volume from increased groundwater extraction under the Murray-Darling Basin Plan, Australasian Journal of Water Resources, 24:2, 105-120, DOI: 10.1080/13241583.2020.1804042

To link to this article: https://doi.org/10.1080/13241583.2020.1804042

Published online: 27 Aug 2020.

AUSTRALASIAN JOURNAL OF WATER RESOURCES
2020, VOL. 24, NO. 2, 105–120
https://doi.org/10.1080/13241583.2020.1804042

Potential cumulative impacts on river flow volume from increased groundwater extraction under the Murray-Darling Basin Plan

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ABSTRACT
A risk assessment of the reduction of streamflow in the Murray-Darling Basin (MDB) from potential increased groundwater extraction has been conducted. This incorporates the uncertainty of future extraction and connectivity between groundwater and surface water. The predicted impact from forty years of growth in extraction is less than 580 Gl/y, and likely to be in range of 100–400 Gl/y. Over 80% of this impact will result from extraction under limits existing before the Basin Plan, with most impact from extraction outside these limits occurring later. Groundwater units with high risk lie within a range of river valleys and hydrogeological domains, and particularly the Goulburn valley and zones of fresher groundwater discharge. Management rules in the new groundwater management plans are designed to reduce use in high impact zones. Monitoring is required to assess effectiveness of these as use increases and conjunctive water management becomes more common.

ARTICLE HISTORY
Received 26 March 2020
Accepted 25 July 2020

KEYWORDS
Murray-Darling basin; groundwater; cumulative impacts; groundwater-surface water connectivity; risk to streamflow

1. Introduction

Groundwater extraction can affect surface water flow by either reducing the baseflow to streams or inducing more leakage from streams (Winter et al. 1998). The effects are more evident at low flows, especially after extended periods of low rainfall. Reduced flows can affect inflows to reservoirs (Hughes, Petrone, and Silberstein 2012), and ecosystems dependent on low flows and water quality (Boulton and Hancock 2006). Water may need to be released from upstream reservoirs to maintain low flow and water quality, to avoid conditions that lead to algal outbreaks (Edgar and Davis 2007). Where the river system is highly allocated, the additional impact of groundwater extraction can undermine any restrictions placed on surface water extraction (MDBC 2003).

The Murray-Darling Basin (MDB) is a large surface water catchment in south-eastern Australia, where not only a limit has been placed on surface water diversions, but approximately 8 billion dollars are being spent to recover surface water entitlements, mainly from irrigators, for protection of environmental values. The MDB Basin Plan (BP) sets limits, called Sustainable Diversion Limits or SDLs, for both surface water and groundwater SDL resource units (Australian Government, 2012). The extraction of water from these units are administered by Basin states through water resource plans.

The BP is the first time that groundwater extractions across the whole of the MDB has been limited, including groundwater systems at a range of depths. SDLs are set for each groundwater SDL resource unit across the MDB. Previously, groundwater systems covering most of the MDB, did not have extraction limits as there was little development pressure on these groundwater systems. This was due to poor water quality; the aquifer being of low transmissivity; or remoteness from demand. The low water use contrasts with that of many of the major alluvial groundwater systems, where stress is high due to the good water quality and high transmissivity (CSIRO 2008).

The SDLs are designed to provide a limit to groundwater extraction, which together with rules in groundwater management plans, should ensure groundwater could be extracted up to the limit from these systems without significant adverse environmental impacts. When all groundwater SDLs across the MDB are aggregated, the total extraction (3494 Gl/y) is 2159 Gl/y greater than the mean groundwater extraction of 1335 Gl/y for the period of 2003–2017. The high aggregate SDL implies that should demand for groundwater change into the future, much larger volumes of groundwater could be extracted with acceptable impacts on streamflow, groundwater-dependent ecosystems, groundwater salinity and aquifers. This difference can be divided into two categories:

(1) 1045 Gl/y of unused water from commitments that existed prior to the Basin Plan (referred to as the Baseline Diversion Limit or BDL); and
(2) 1114 Gl/y unrelated to pre-existing commitments. This volume is called unassigned water and the SDL resource units, for which this is not

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zero, are called unassigned groundwater SDL resource units.

This large volume of unassigned water allowed under the MDB Plan, and the remaining unused water under the BDL, have led to concerns that potential increased groundwater extraction will have unaccounted impacts on surface water (Wentworth Group of Concerned Scientists 2017; SA 2019). Terms, abbreviations and notation are defined in Table 1.

Previous studies conducted cumulative impact analyses (CIA) from increased groundwater extraction on streamflow following an interim cap on surface water diversions (MDBC 2003; Earthtek 2003, 2004; CSIRO 2008). These studies show that historical increase in extraction before 2003 led to reduction of streamflow of 186–447 Gl/y, while the reductions in streamflow from potential increases after 2003 were predicted to be 245–711 Gl/y (1–3% of streamflow). Information about these studies can be found in Table 3 in the Supplementary Material.

These studies used the concept of connectivity factor (*CF*), a dimensionless and normalised variable (Walker et al. 2020) in an increasingly sophisticated fashion over the course of the studies. A value for CF of zero means that changes in groundwater extraction has no impact on streamflow within 50 years, while a value of one means that the streamflow would be reduced by whole of the increase in extraction. The value assigned to *CF* in the various studies went from being 0.6 for all units (MDBC 2003) to different values for different groundwater SDL resource units (CSIRO 2008), with the mean *CF* being reduced in the process.

The underlying assumptions about future extractions varied across these previous studies reflecting increasing groundwater regulation over the period the studies were undertaken. For example, the rights to water in major alluvial systems in NSW were reduced under the Achieving Sustainable Groundwater Entitlements (ASGE) programme from 2007. Also, the early studies ignored so-called unincorporated areas, for which there was minimal groundwater management.

The studies showed that most of the potential cumulative impact occur in the southern connected river system of the MDB, where flows are the greatest. CSIRO (2008) also showed that the impacts are likely to be regional in nature, rather than Basin-wide and much less than those from climate change. SKM (2009) and NSW (2010) used data from CSIRO (2008) to assess the risks of meeting the demand for water supply and ecosystem health and found that the risk for the former to be low, while those for the latter were variable. The cumulative impact in NSW catchments was predicted to be less than 1% of flow. The studies consolidated the view that impacts are likely to be isolated and regional, rather than significant across the whole MDB and that cumulative impacts are much less than from climate change alone.

To minimise cumulative impacts on streamflow under the BP, the SDL was constrained for those groundwater SDL resource units where the risk to surface water was considered to be high (MDBA 2012c). For sedimentary units, the SDL was not set higher than prior groundwater extraction limits, while for fractured rock systems, the SDL was limited to 8% recharge. Risk was considered high if there was baseflow to an unregulated river reach, under current conditions or where *CF* was greater than 0.5.

This approach to setting the SDL should have led to a lower cumulative impact than the previous studies. MDBA (2012a) conducted a CIA for the newly set SDLs, using values for *CF* based upon Richardson et al. (2008). The estimated cumulative impact (*CI*) did not meet acceptability criteria of 100 Gl/y and led to SDLs on fractured rock systems being reduced to meet the criteria. Under the current SDLs and groundwater use, the corresponding impact on streamflow would be 123 Gl/y from increases in extraction up to the BDL and another 71 Gl/y from unassigned water. The stated MDBA (2012a) policy is that the former should already be built into existing surface water management plans, and therefore the focus should be on unassigned water.

These actions in setting SDLs did not entirely allay concerns. The MDBA (2012a) analysis led to an average connectivity of only 0.09. While the approach to setting SDLs should lead to a lower *CF* than previous analyses, this value for mean *CF* is difficult to justify. Walker et al. (2020) show that the *CF* for low connectivity units can be in the range of 0.00–0.50. Also, it is not clear that existing surface water management plans have built in impacts from potential increased groundwater extraction. Finally, *CF* was set to zero, where there were environmental benefits from increased extraction, e.g. reduced salt load to streams. There is also an uncertainty in the location of future increases in extraction. While the location may be better understood for the extraction from pre-existing commitments, there may be little understanding about unassigned water.

Conversely, the MDBA (2012a) analysis does not incorporate time delays, which may mitigate the risks from increased groundwater extraction. There is no evident increase in groundwater extraction from 2003 to 2017 (Figure 1) and hence no immediate risk of reduced streamflow increased extraction during this period. Because much of the groundwater is saline or not easily accessible, growth in extraction between the aggregate BDL and the aggregate SDL is likely to occur slowly. The time delay for growth in extraction is in

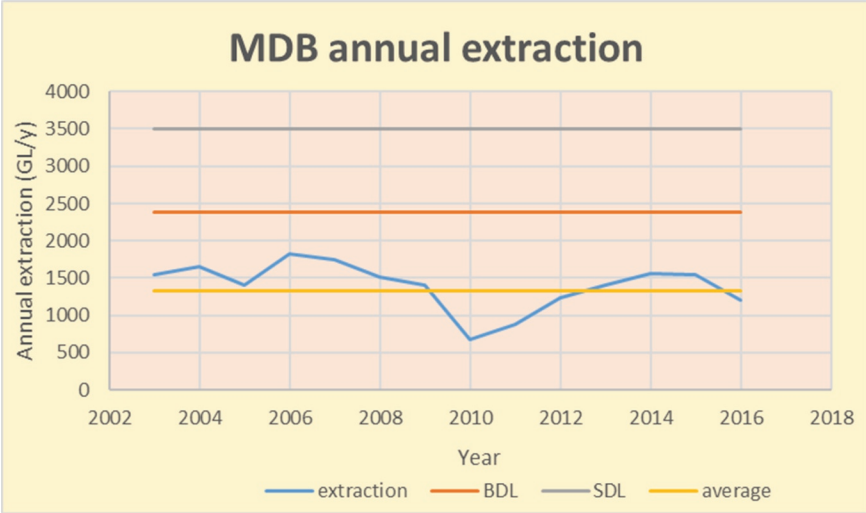

Figure 1. The historical annual groundwater extraction across the MDB (data from MDBA).

addition to the time delays for groundwater pressure change to move from the site of extraction to the impacted stream. While the latter time delay is built into the definition of *CF*, the former is not. Large time delays are considered to reduce risk as for each decade required for a given extraction to occur, it is likely to be easier to manage any impact.

This paper reports and builds on an independent review of the cumulative impacts (Wang, Walker, and Horne 2018). The objective of this study is to analyse the BP from the perspective of managing the risks of cumulative impacts; and to address many of the issues raised in the above discussion. In particular, a risk assessment for the cumulative impact of increased groundwater extraction on streamflow will be implemented, that:

Based on the BP and current groundwater use;

(1) incorporates uncertainty in the value of *CF* and the spatial distribution and timing of increased groundwater extraction;
(2) does not discount the impact because of any environmental benefit of extraction;
(3) separates the impacts from use of pre-existing commitments (within BDL) and unassigned water;
(4) provides information on the distribution of impacts across tributaries;
(5) identifies high risk groundwater resource units, which merit more detailed studies; and
(6) provides a sense of relativity to other risks to surface flow, such as climate change and water use efficiency improvements, that have been identified previously for the MDB and to discuss any implications for future integrated surface and groundwater management in the MDB.

2. Methods

2.1. Cumulative impact assessment

The cumulative impact, *CI*, on streamflow from potential future extraction, ΔE, is estimated (Walker et al. 2020) by:

$$CI = \sum_n \Delta E^n x\ CF^n \tag{1}$$

and

$$\Delta E = \sum_n \Delta E^n \tag{2}$$

where CF^n is the connectivity factor between SDL resource unit n and adjacent MDB stream network, ΔE^n is the future change in groundwater extraction from SDL resource unit n and Σ_n is the summation over all units. This approach is similar to that used in previous studies (MDBC 2003, 2006; CSIRO 2008; MDBA 2012a). This formula assumes that impacts from any unit is independent of extraction from other units. The simplicity of these formulae allows updating of information as it becomes available. It also allows easy identification of high impact units and easy interpretation of results. Given the uncertainty in both the timing and location of the future extraction and the uncertainty in the hydrogeology, it is difficult to justify a more complex approach.

2.2. Risk management

The uncertainties in ΔE^n and CF^n increase the chance that the objectives of the BP will not be met because of unaccounted stream losses. The objective of the risk management task is to take steps to ensure any losses are within acceptable limits despite deficiencies in

information. The risk assessment provides an indication as to whether there is a tangible risk and if so, should also provide information to manage the risk.

Flow modelling is required to define the consequence of any reduction of streamflow, but this requires a priori the spatial and temporal distribution of impacts. In the absence of that, we shall use as preliminary thresholds for *CI*, 100 Gl/y between low and medium impact, while 400 Gl/y is adopted as the threshold between medium and high. The MDBA (2012a) policy that 100 Gl/y is unacceptable provides a benchmark, noting that this was only for unassigned water. We shall consider both impacts from pre-existing commitments and unassigned water. The time delay is an important consideration for risk, as impacts that occur within the current BP cycle will be more difficult to manage than that 50 years into the future. Time delays are due to both the time for extraction increase and that for groundwater pressure to move from the site of action to the site of impact.

The likelihood of a given *CI* is dependent upon the likelihood of values for ΔE^n and CF^n. A moderate impact depends on moderate increases in extraction occurring in areas with moderate connectivity. In this study, a sensitivity analysis within a likely range will be done for CF^n. The details of this are discussed below. Also, sensitivity analyses will be done for growth rates of extraction. This gives a sense of time delays for a given extraction rate to be reached.

2.3. Future growth of groundwater extraction

Future extraction is dependent on a range of factors, including demand, technology, hydrogeological characteristics, government policy, mining and gas reserves and land-owners' ability and wishes. As it is impossible to accurately forecast the future, there is uncertainty in the timing of future extraction. While there will be some information with respect to pre-existing commitments, there is little information beyond this on future extraction. The data for extraction from 2003–2017 shows no evident increase in extraction, but studies show that growth in extraction from 1983–2003 occurred at a rate of 3.0–4.5% (MDBC 2003, 2006). High salinity and low transmissivity remain an impediment for groundwater use in many areas, but technology and economics may increase the likely use of such water. Climate change is likely to lead to longer droughts in the MDB (BoM & CSIRO, 2016) and lower autumn to spring rainfall (Reisinger, 2014), meaning there may be long periods of low availability of surface water. Desalination of brackish groundwater is already occurring in the MDB but at low volumes, but demand may be expected to increase into the future.

To give some sense of the time delays for growth to occur, a range of growth rates will be assumed. More specifically, we consider scenarios, in which the annual growth rate increases in a compound fashion at a range of rates, including 0, 0.5, 1, 2, 4 and 6%/y until the SDL for the unit is reached. Under this assumption,

$$\Delta E^n = minimum \{((1 + e * 0.01)^m - 1)E_0{}^n,\ SDL^n - E_0{}^n\}; \quad (3)$$

where $E_0{}^n$ is the current annual extraction rate for unit n, *e* is the rate of increase in extraction per year as a percentage of the extraction rate, *m* is time in years from now and SDL^n is the extraction limit for unit n. We shall further assume that *e* is the same across the whole MDB. The chosen range of growth rates is guided by (1) a belief that the average long-term rate will be positive and (2) historical rates of growth.

Equation (3) can be transformed to give the number of years for E^n to reach SDL^n, namely

$$m = log\ (SDL/E_0{}^n)/log\ (1 + e * .01) \quad (4)$$

This assumes that there are no other rules within groundwater management plan, that may prevent this limit being reached. The time to reach BDL^n can be obtained by substituting SDL^n with BDL^n in Equation (4). For the interpretation of results, we shall assume that when extraction is less than the BDL, the extraction is mostly occurring from pre-existing commitments. These are considered to be more likely to be used as investors have current groundwater right, and it is difficult to predict interest from those investors, who do not. As SDL resource units have different initial states, they will be at different stages at any given time, with a fraction having extraction less than the BDL and the rest between the BDL and the SDL.

Equation (3) is implemented for a range of timeframes (10, 20, 40 and 80 years) for all SDL resource units and summed to estimate the MDB-wide extraction, using Equation (1).

Under this model, ΔE and ΔE^n grow monotonically with *m*. Hence ΔE^n can be expressed as a function of total MDB extraction, $f_n(E)$. Because of this, the cumulative impact can be written as a function of the total extraction, rather than growth rate and time independently:

$$CI = \sum_n f_n(E)\ CF^n \quad (5)$$

The cumulative impact, CI_{BDL} of extraction from unused pre-existing commitments, ΔE_{BDL} can be calculated in a similar fashion to *CI*, by substituting relevant values for the BDL into Equations (1)–(5). Under the assumption of uniform growth in extraction across the MDB, CI_{BDL} and ΔE_{BDL} are also functions of *E*.

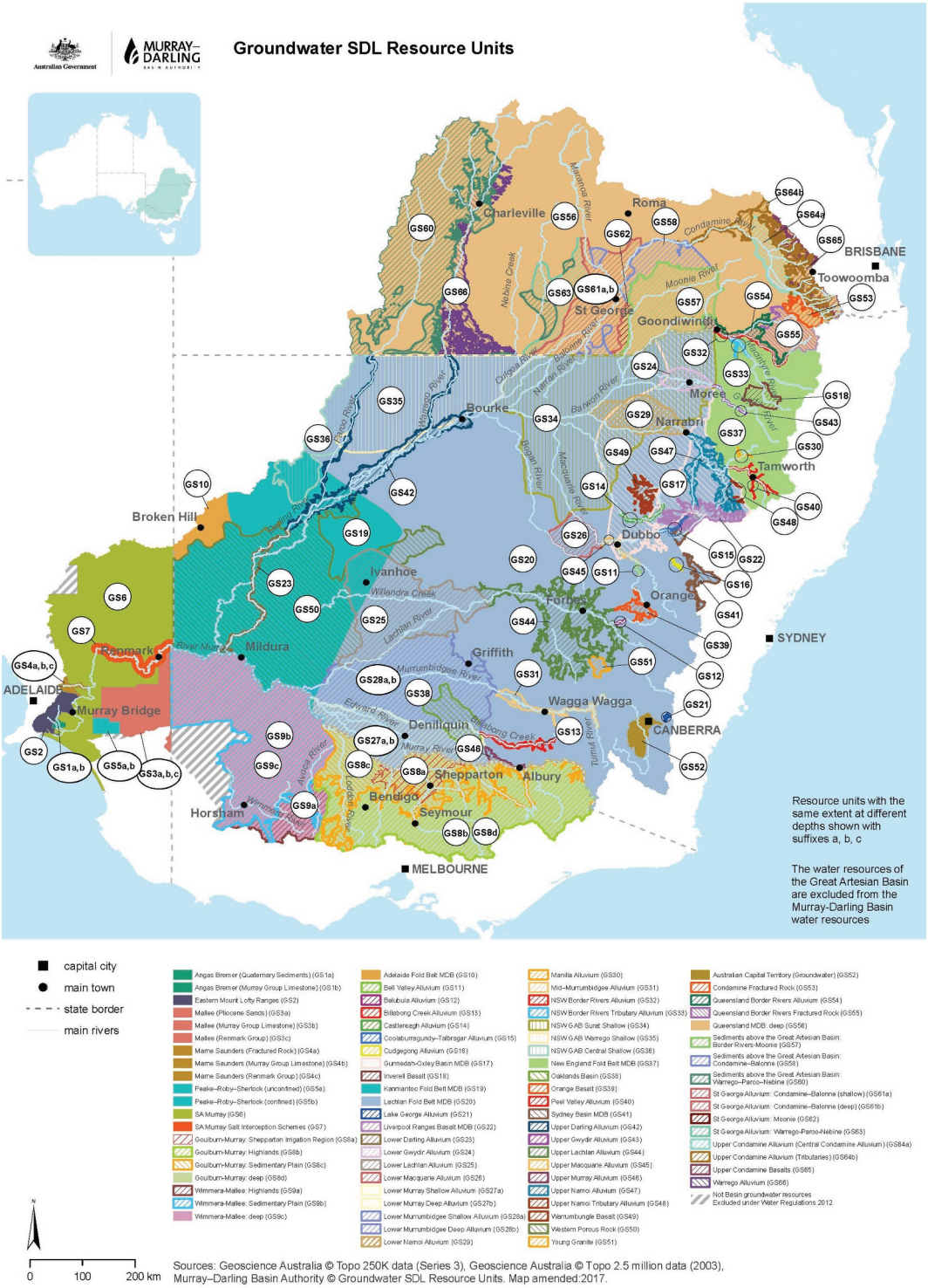

Figure 2. Map of the groundwater SDL resource units in the MDB. (Map provided by the MDBA).

Data was obtained from the MDBA on annual groundwater extraction between 2003 and 2017, and the BDL and SDL for each groundwater resource unit. The map of groundwater SDL resource units is shown in Figure 2. Data is given in Table 4 in the Supplementary Material. Other information on SDL resource units can be found in MDBA (2012b). The growth scenarios differed from Wang, Walker, and Horne (2018) in that (1) a 6%/y scenario was added; (2) a compound growth rate was used, rather than a simple linear rate; (3) 10, 20 and 80 year scenarios were added and (4) reporting for some variables are against total extraction, rather than time and growth rates.

2.4. Connectivity factor

Walker et al. (2020) discuss how *CF* may be estimated. There are largely two approaches. For areas, where groundwater models exist, existing modelling outputs may be used to estimate *CF* objectively. The second

approach is to categorise *CF*, based on knowledge of hydrogeology, spatial distributions of extraction and understanding of how *CF* may depend on these factors. Appropriate groundwater modelling outputs mostly exist for major alluvial groundwater systems, for which the SDL generally has been capped to the BDL. Therefore, impacts can only occur through unused, but existing commitments. For most of the others, not only do models not exist, hydrogeological information can be sparse. *CF* will depend on the spatial distribution of the increases in groundwater extraction (Evans, 2007). This will be poorly known outside of existing commitments.

The choice of *CF* was based on MDBA (2012a), which, in turn, was based on previous work, especially MDBC (2003) MDBC (2004), MDBC (2006) and Richardson et al. (2008). The assignment of connectivity factors was sometimes based on model outputs; but more generally opinion from experienced hydrogeologists considering geology, hydraulics and current state of groundwater levels; and at times regional best guesses. Early estimates of connectivity were high (e.g. 0.6–1.0) and with further and more refined assessments lower (e.g. 0. to 0.60).

These estimates have been reviewed for this study and modified based upon (1) any existing modelling and field studies and (2) not using environmental benefits of pumping to influence choice of *CF*. An uncertainty band has been set around these values to provide a low, preferred and high value for *CF*, as well as that used by MDBA (2012a). The MDBA (2012a) value was generally towards the lower end of the sensitivity range.

Two notable examples of environmental benefits from groundwater extraction are: 1) extraction from saline groundwater systems, and (2) extraction from shallow groundwater systems in irrigation areas. For the former, the collective governments responsible for the MDB have invested large sums of money into groundwater pumping schemes to prevent saline inflows and any further pumping may augment these schemes. For the latter, pumping may protect agricultural land from land salinisation and waterlogging as well as reducing saline inflows. Instead of assuming *CF* to be zero (CSIRO 2008; MDBA 2012a), the *CF* for these units has been modified to support best estimation of cumulative impacts.

This range of *CF* will be affected by rules within groundwater management plans. If there are effective rules that limit impact on streamflow, the effective *CF* will be lower. The groundwater management plans are still being finalised, so the effectiveness of any such rules is unknown. The data on *CF* is shown in Table 4 (Supplementary Material)

3. Results

3.1. Growth in extraction

Figure 3 shows the results of using Equation (4) for units of varying different initial extraction rates. It shows that if the initial extraction rate is less than 5% of the SDL, the annual extraction under the growth scenarios in a SDL resource unit may only reach the SDL, after hundreds of years. Alternatively, the SDL may be reached within 40 years if initial extraction is greater than 20% of the SDL and growth rate is greater than 4%. The same graphs apply to the BDL, if we substitute BDL for the SDL, effectively limiting extraction to current water right volumes. For many of the units with no prior regulation, the ratio of initial

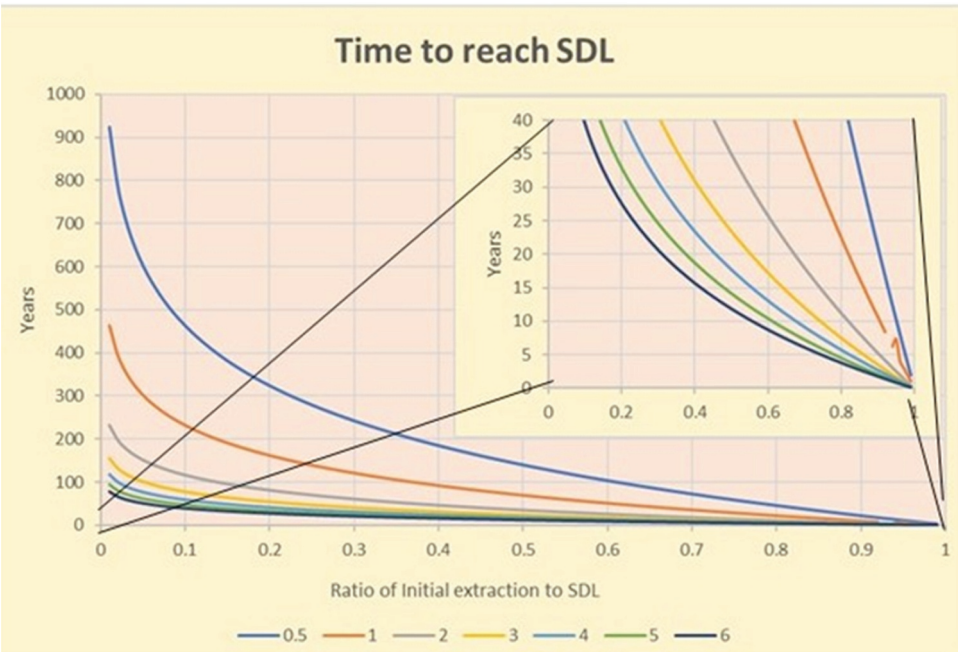

Figure 3. The time required for extraction to reach the SDL for different growth rates (%/y).

extraction rate to the SDL is towards the low end and hence the time to reach the SDL can be very long. The ratio of current extraction to the SDL is low for many of the units with limited regulation prior to the BP and hence time for the extraction rate to reach SDL may be 80 years or more for these units.

The aggregate MDB extraction for the different growth scenarios is shown in Figure 4. These results show that for growth rates above 4%/y that extraction reaches above 85% of the aggregate SDL within 80 years. Where growth rate is less than 2%/y, the extraction rate is modelled to be about the aggregate BDL for the MDB within 80 years.

For the 2%/y and 4%/y growth scenarios, the aggregate extraction, that occurs from units with extraction less than the BDL, plus those from extraction up to the BDL in the remaining units, relative to the total extraction is shown in Figure 5. The difference, i.e. the aggregate extraction that occurs above the BDL is small at 40 years. Thus, for timeframes of interest to management, the main risk is

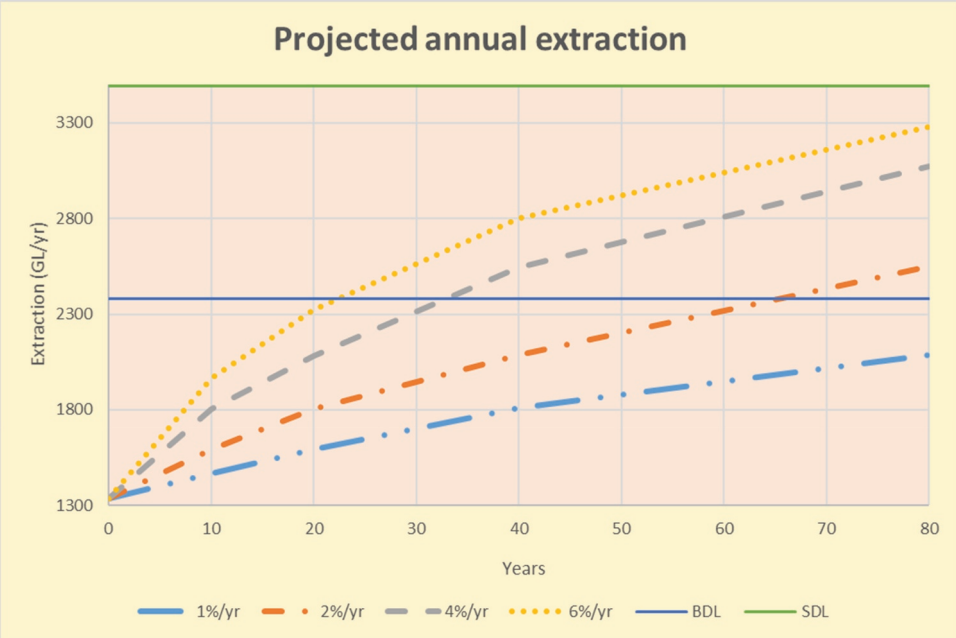

Figure 4. The projection of future extraction across the MDB for a range of growth rates. Extraction rates come from Equation (2) combined with the model in Equation (3).

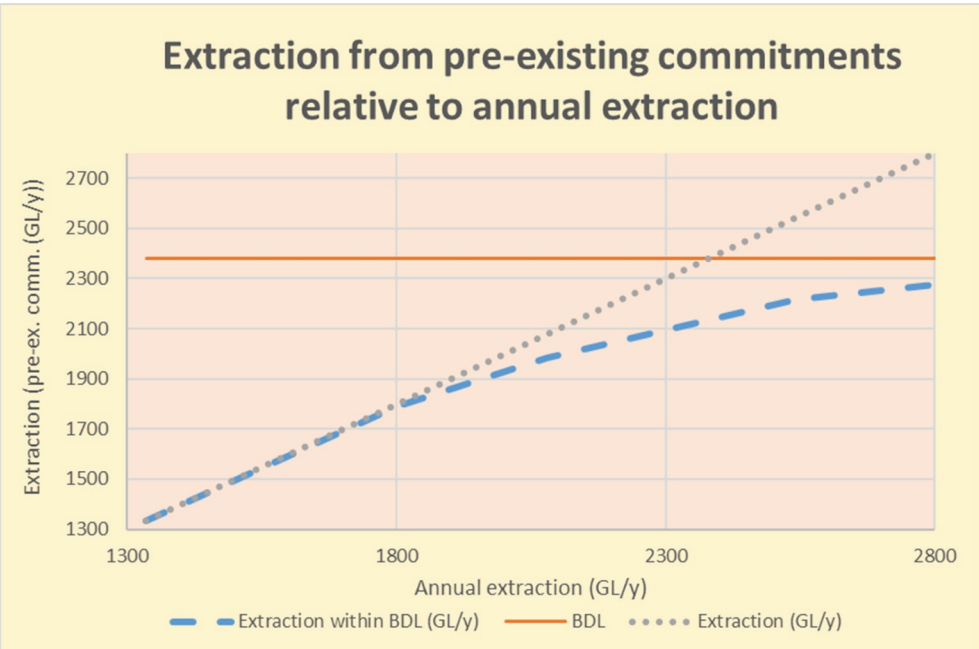

Figure 5. Groundwater extraction across the MDB from groundwater SDL resource units, where extraction is less than the BDL, together with the extraction up to the BDL in remaining units, relative to total extraction and as a function of total extraction.

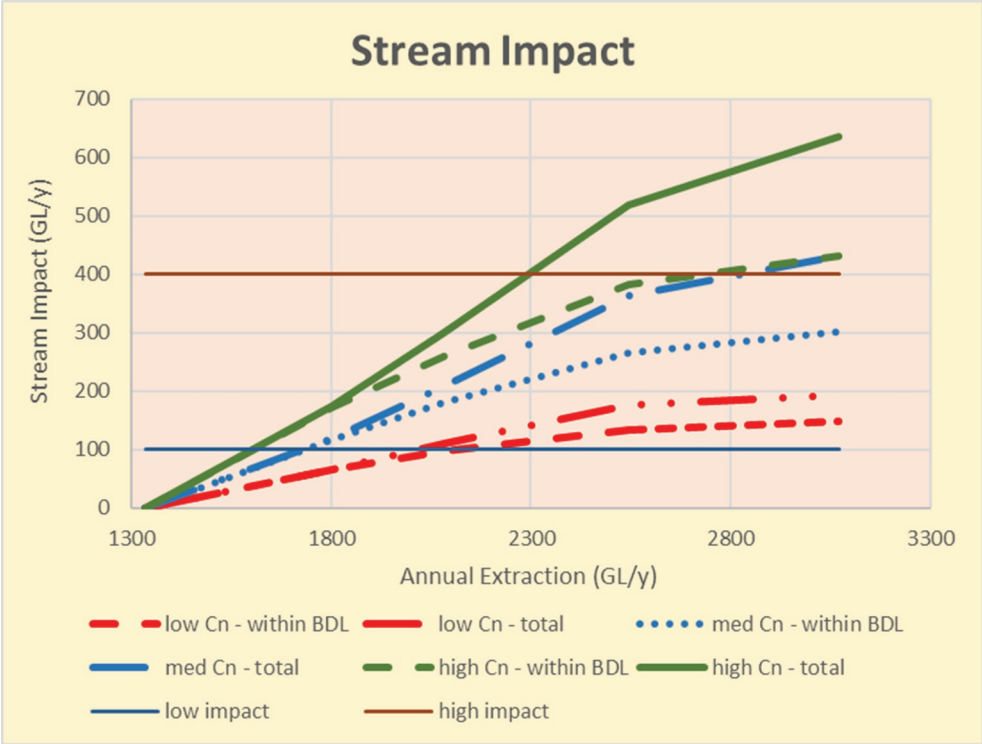

Figure 6. Cumulative Impact on streamflow across the MDB from increased groundwater extraction (total and from pre-existing commitments) for low, medium and high sets of connectivity factors.

Table 1. Glossary of terms, abbreviations and symbols.

Term	Abbreviation	Definition
Basin Plan	BP	The Murray-Darling Basin Plan for water management
Sustainable Diversion Limit	SDL	The limit on the volume of water that can be taken for human uses (including domestic, urban and agricultural use) from either a surface water or groundwater SDL resource unit. The SDL for the MDB, as a whole, is the aggregate of SDL volumes from SDL resource units.
Baseline Diversion Limit	BDL	The baseline against which SDL is assessed. It is the limit on groundwater use under water management arrangements existing at time of BP development. More precisely, the BDL is defined as (MDBA 2012c): (1) the plan limit, where a water management plan or proposed plan exists,;unless the plan limit is greater than the level of entitlement, in which case the BDL is the entitlement; (2) the entitlement along with the effect of any rules managing extraction, where there is no plan; and (3) the extraction limit under the agreement, where there is a cross-border agreement for groundwater management.
Unassigned Water	UW	The increase in extraction limit under the Basin Plan, i.e. the difference between the BDL and SDL, where this is not zero or negative.
SDL resource unit		The spatial units for either surface or groundwater for which there is a SDL and for which a water management plan is being prepared.
Connectivity Factor	CF, CF^n	The ratio of the volumetric impact on streamflow to the change in groundwater extraction that causes the impact.
Cumulative Impact Analysis	CIA	The process of estimating the aggregate impact from a large number of actions across the MDB, that each lead to an increase in groundwater extraction
Cumulative Impact	CI	The aggregate impact from a large number of actions across the MDB, that each lead to an increase in groundwater extraction
Aggregate extraction across MDB	E	
Change in annual extraction rate	ΔE, ΔE^n	
Initial extraction rate for SDL resource unit n	$E_0{}^n$	
Annual growth rate for extraction rate	e	

associated with commitments that existed prior to the Basin Plan. For extraction less than 1800 Gl/y, the extraction in very few units exceeds the BDL.

3.2. Cumulative impact

The predicted cumulative impact at different times is shown in Figure 6 as a function of total extraction,

showing sensitivity to *CF*. The cumulative impact from pre-existing commitments is also shown.

The results show that:

(1) impacts are likely to be medium (100–400 Gl/y) for most of the sensitivity range. The impact can be high for medium to high *CF* and high *E* and low for low to medium *CF* and low *E*; and

2. most of the impacts are due to pre-existing commitments for $E < 2300$ Gl/y or low to medium *CF*.

The mean *CF* can be estimated from the slope of the impact lines. While *CF* for each unit is assigned, the mean *CF* depends on the relative extraction from each unit over the time period. This shows that the mean *CF* is 0.18–0.45 for $E < 2500$ Gl/y and 0.03–0.18 for $E > 2500$ Gl/y. The change in the mean occurs due to growth occurring more quickly for areas, with existing high extraction, which also have higher connectivity. These then reach the SDL more quickly, and there are no further increases in extraction rate.

3.3. Risk

Figures 4 and 6 can be combined to provide an assessment of impact as a function of both time and extraction growth rate. The result is shown in Table 2 for medium to high combinations of *CF*. The results show a transition from low to high impact over eighty years. Table 2 shows that high impacts are likely to occur from 20 years for a 6%/y growth rate and longer than 60 years for growth rate less than 2%/y). These results suggest that assuming growth rates of 1–2%/y, the current Basin Plan will lead to low to medium impacts in forty years. A risk can be determined if we assign likelihoods to the parameter ranges and their inherent assumptions. Without explicitly doing this, we can screen options that will lead to unacceptable impacts.

Table 2. The cumulative impact (expressed as low (<100 Gl/yr)), medium (100–400 Gl/yr) and high (>400 Gl/yr) as a function of time (years) and growth rate (%/year). Under the precautionary principle, medium to high range of connectivity values have been used.

		Time (years)			
Impact		10	20	40	80
Growth rate (%/year)	1	Low	Low	Medium	Medium
	2	Low	Medium	Medium	High
	4	Medium	Medium	High	High
	6	Medium	Medium-High	High	High

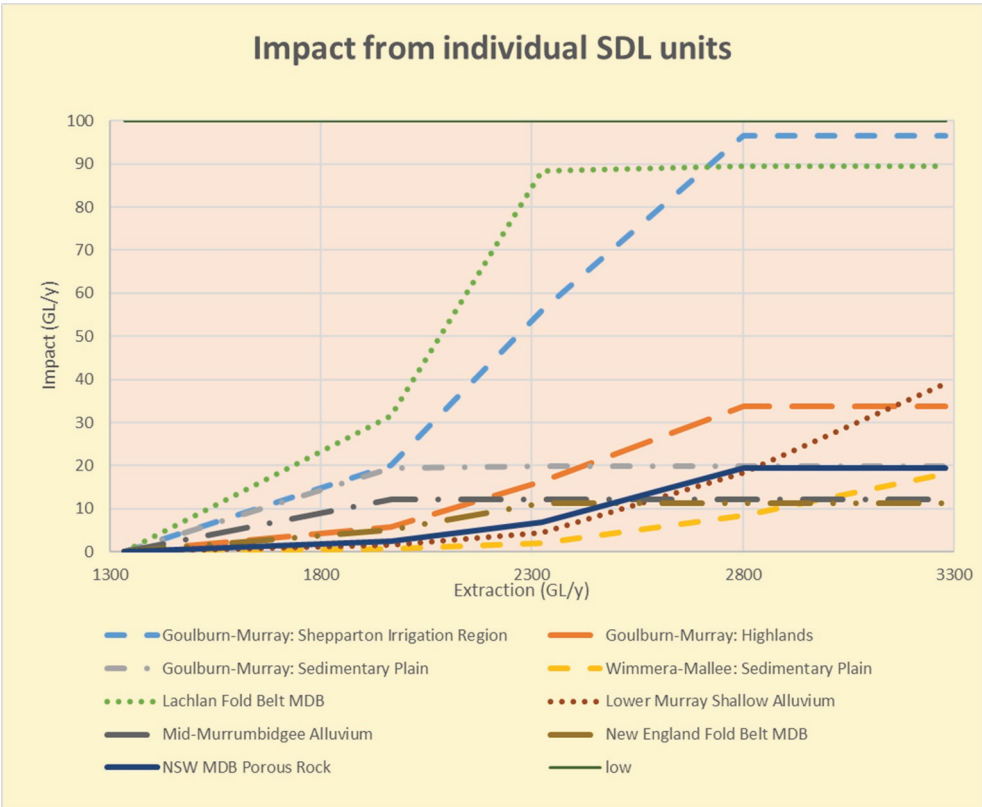

Figure 7. The impact on streamflow from selected groundwater SDL resource units as a function of total extraction for units, where impact is greater than 10 Gl/y by 80 years. These values of connectivity are in the medium range.

Figure 7 shows the groundwater SDL resource units with the highest impacts. Two units stand out, namely the Lachlan Fold Belt (up to 108 Gl/y, but likely to be 15–55Gl/y from 40 years of growth) and the Goulburn-Murray Shepparton Irrigation Region Formation (up to 135 Gl/y, but likely to 24–95 Gl/y from 40 years of growth) in the Goulburn-Broken Sedimentary Basin. Groundwater units from the Goulburn-Broken system are well-represented with both shallow and deep units of the Goulburn-Broken sedimentary systems and the highland fractured rock systems with a total impact of up to 215 Gl/y, but more likely 60–145 Gl/y from 40 years of growth.

4. Discussion

This paper has developed a risk assessment for the cumulative impact of potential future groundwater extraction under the Basin Plan on streamflow. The analysis incorporates, rather than ignores, the large uncertainties associated with the knowledge of hydrogeology related to stream-groundwater interactions and on the location and timing of future increases in extraction. These uncertainties manifest themselves into predictive uncertainty from the model and affect the confidence of the conclusions from studies on groundwater-surface water interactions. Risk management frameworks support the making of decisions under uncertainty and avoids the paralytic effect of decisions only being made when there is better information. This assessment provides information that allows the risks to be mitigated in a risk management framework. As such, it is important that the risk assessment:

(1) provides estimates of cumulative impacts with acceptable accuracy and bias;
(2) identifies those groundwater resource units that contribute the greatest risk, so that these are prioritised for further studies and management actions;
(3) separates the impacts from pre-existing commitments from those due to unasigned water;
(4) supports adaptive management; and
(5) supports prioritisation of risks, where there are multiple risks.

The main modelling outputs and the dependence on parameter uncertainty are described below.

(1) *Cumulative Impact estimates*: The results show that the mean *CF* for $E < 2300$ Gl/y ranges from 0.18–0.45; while for $E > 2300$ Gl/y, *CF* ranges from 0.03 to 0.18. This is consistent with the avoidance of setting higher SDLs. The range of values are consistent with the range obtained from modelling results (Walker et al. 2020). The change in *CF* for large *E* also reflects the large area of unassigned groundwater SDL units. The results are also consistent with previous studies, despite there being several important differences in assumptions. Differences include SDL being capped for high connectivity units, growth in units with minimal prior regulation being considered; connectivity being known better and the irrigation footprint having changed. The mean *CF* of 0.09 for MDBA (2012a) is on the low side of numbers here (0.18–0.45 for $E < 2500$ Gl/y and .03–0.16 otherwise). The CSIRO (2008) values of 0.24–0.35 is similar to the *CF* for $E < 2500$ Gl/y. The predicted mean *CF* appears to represent a reasonable range for sensitivity analysis.

The use of a single *CF* is an approximation to the response of streamflow to changes in groundwater. The impact of streams at any time is more accurately represented by a convolution of the distribution of the rate of change in groundwater extraction with the response function. The response function could be reapproximated by a constant value for very fast responding and very slow responding groundwater systems. It would be difficult to parameterise a response function across the large number of groundwater units. The results in this paper have been mostly expressed as a function of extraction, rather than on time specifically. Where time has been used, it has been used to indicate slow growth rates. The assumption of a constant *CF*, together with sensitivity analyses, should still provide a credible range of impact estimates.

These estimates of cumulative risk indicate that unless specific measures are taken, there is a significant risk from increased groundwater extraction. The impact from 40 years of growth in groundwater extraction (up to 580 Gl/y, but more likely 100–400 Gl/y). This represents up to 3% of streamflow, using the value of water availability for the MDB of 23,417 Gl/y (CSIRO 2008). The study has altered the methodology from that of Wang, Walker, and Horne (2018), as described in the Methods section. This has led to a slightly increased groundwater extraction for the same time period and a potentially higher limit. However, the likely range of impacts is similar.

(1) *High risk units*: The identification of high-risk units relies on there being both moderate connectivity and potential for moderate increases in groundwater extraction. Most of the increases are likely to result from existing commitments prior to the BP, and we would expect these to be well-known and likely to occur. All zones identified as being high risk above have at least moderate connectivity. The units are prioritised for further scrutiny, including

more detailed assessment of uncertainty. Only a small number of groundwater resource units have been identified with significant risks: The most obvious two of these are the Shepparton Irrigation Region and the Lachlan Fold Belt.

The high extraction limit for the Shepparton Irrigation Region groundwater resource unit is intended to protect land from salinisation and waterlogging (Goulburn-Murray Water 2015). A high extraction rate is required following very wet years in order to drop groundwater levels. While the pumping rate in those years is expected to be significant relative to the SDL, the long-term average extraction rate required to avoid waterlogging is only about 10–20% of the SDL. The maximum level of extraction which leads to stable water tables, is about 60% of the SDL. This would appear to make it inconsistent with the intent of SDLs in the BP. If the SDL is pumped continuously, water table levels would drop, leading not only to capture of discharge but also the inducement of fresh stream water (CSIRO & SKM 2010). *CF* has been estimated for this unit using a groundwater model (Walker et al. 2020). The issue appears to be that the nature of entitlements has been developed for a particular purpose and the entitlements are not intended to be fully used for most of the time. There may be rules within the groundwater management plan that prevents continuous extraction; otherwise the outcome of these entitlements being used will be reduced surface water.

The Lachlan Fold Belt is a very large groundwater resource unit of fractured rock separating the Murray and Darling sedimentary basins (Figure 2). Parts of it can be found in three river valleys. In the east, the unit consists of high rainfall dissected landscapes, where close extraction is in close proximity to streams, while in the west are semi-arid, more subdued landscapes, with ephemeral streams, implying that the *CF* will vary from being high in the east to being low in the west. The sheer size of the unit means that the impact will be relatively large compared to other units without specific measures in place.

The remaining high impact units are highly variable in nature, varying from highly connected alluvial systems, deep paleochannels, saline sedimentary basins in the west and highland fractured rock systems in the east. Mostly, the systems are not saline, suggesting that most of the groundwater extraction in the next 40 years will be reducing fresh, rather than saline, inflows to the rivers. Each of these units deserve further scrutiny in order to protect streamflow.

The main river valley affected is the Goulburn. This valley contains the Shepparton-Irrigation Region groundwater resource unit, the Goulburn-Broken Sedimentary Basin and Goulburn Highlands units. The Goulburn valley has one of the highest volumes of flow in the MDB, contributing regulated flow to the southern connected system. The total potential impact of future groundwater extraction is up to 215 Gl/y (or 6% of total flow), but more likely 60–145 Gl/y. This is large relative to the water recovery target for the Goulburn and Broken systems (356.1 Gl/y). The other affected units occur in a range of different valleys. There reporting against percentage of flow is poor, since groundwater will mainly affect low flows and baseflow-dependent ecosystems and major impacts can occur even for small percentages of flow. Nonetheless, it does provide some indication of impact and the ability to detect impacts.

(1) *Separation between pre-existing commitments and unassigned water*: The relative partitioning between pre-existing and unassigned water largely depends on the assumption that pre-existing commitments will be used ahead of unassigned water, together with there being a large volume of unused pre-existing commitments. While pre-existing commitments will not always be used before unassigned water, it seems a reasonable approximation as investors have already chosen them. The results imply that the highest risk within the next 20–40 years will be from commitments existing prior to the BP. These are more likely to be used and better understood than the unassigned water. This shows that risk management should initially focus on these pre-existing entitlements. While the risk from unassigned water is initially low, this is because there is little current demand for this water. If used, it may push impacts into the high range. This suggests a precautionary approach should be used for unassigned water, despite the low to medium risk over management timeframes. A precautionary approach could mean that these should be assigned, if shown to have minor impact on stream flow; rather than just lowering the SDL.
(2) *Slow response*: The prediction of the time scales for growth to occur has the greatest uncertainty as this is related to assumptions about growth rate. However, the choice of the range of sensitivity based on long term history should ensure that the sensitivity range of potential time scales is appropriate. This includes periods favourable for extraction and a period of virtually no growth during 2003–2017.There has been also an assumption that growth is even around the MDB. This is almost certainly incorrect. However, the analysis does allow different units to be analysed across a reasonable range of growth rates. There are two factors contributing to time delays: 1) time for extraction to

grow and 2) delays for groundwater pressure to move from extraction points to streams. Most results are presented as a function of the total MDB extraction rather than a function of time into the future and as such, avoids the sensitivity to growth rates. These functional relationships would be insensitive to the growth rate assumed.

The results show that any reductions in streamflow is likely to occur slowly. These results suggest that medium to high impacts are unlikely within 20 years, and growth rates that would lead to medium to high impacts after 40 years would be evident well before this. The time scale of these impacts is large compared to the surface water planning cycles of 10 years. These slow time scales suggest that adaptive planning should be feasible, even accounting for the slow groundwater response to any mitigation actions.

Adaptive management relies on monitoring. Monitoring of impacts is difficult as low flows are difficult to measure and monitor, let alone trends in low flows. Monitoring of surrogates, such as piezometric observations in the riparian zone is also problematic. Spatial and temporal heterogeneity means that cost of such piezometric monitoring to be effective could be resource intensive. Also, in areas of high connectivity, the piezometric response near streams may not be sensitive to exchange fluxes. Monitoring of the actions, rather than impacts, would involve monitoring of extraction rates. Extraction rates are currently estimated and reported for each groundwater SDL resource unit as part of the MDBA Register of Take (MDBA 2019b). The appropriateness of this for supporting adaptive management of surface water impacts are discussed below.

(1) *Annual variability in extraction*: A key issue for monitoring of extraction rates for adaptive management is the annual variability of extraction. Groundwater extraction rate is dependent on rainfall and other variables. Within the BP, a 'permitted take' can be defined that provides an annual limit for extraction in a SDL resource unit, based on climate and other variables, but over the long time ensures that extraction is less than the SDL even though it may be greater than the SDL in any one year (MDBA 2018, 2019b). This paper describes the cumulative impact of changing the long-term extraction, and hence the mean of the distribution of extraction (in response to climate variability. The extraction for the 2018–9 has increased from the 2016–7 year to 1887 GL/y in response to recent drought. In principle, this represents about half of the BDL 'bucket' and would have an impact of up to 220 GL/y impact on streamflow. The estimated extraction of 1823 Gl/y towards the end of the Millennial Drought in 2006–7 shows that a cyclic component of 500–700 Gl/y may be occurring. Extraction reduces during wetter periods (e.g. 675 Gl/y in 2010–1, resulting in a positive impact on streamflow. The need to separate year-to-year variability of extraction from long-term changes in extraction has implications for monitoring and adaptive management. Permitted Take is a relatively new concept in groundwater, even though similar concepts have long been used for surface water and there is a poor understanding of the variables affecting groundwater extraction from year to year. Reporting of groundwater extraction has only occurred for a relatively short period to provide a benchmark, with a lack of uniformity in reporting over the early period. During the 80's and 90's, groundwater extraction rates did not return from high values. Potentially, this behaviour could be repeated. Taken together, this means that by the time a trend is evident in MDB extraction, it may be too late to respond; especially allowing for the slow response of groundwater systems to changed actions. The sensitivity could be improved with the use of a statistical trend analysis, which incorporates empirical relationships for the annual extraction. The cumulative impacts managed accordingly within water management plans.

(2) *Local management rules*: The results here show that the 'acceptable' range of impacts (<100 Gl/y) will only be attained if the 'effective' mean *CF* is kept less than 0.05. To achieve this, adaptive management must include more targeted mitigation measures than just reducing groundwater and surface water SDLs. Otherwise, the SDLs will be unnecessarily low, which would have a negative economic effect. As most groundwater resource units are large, the SDL alone is insufficient to manage groundwater in that unit to avoid adverse impacts, as the spatial distribution of extraction is important. Often, groundwater extraction can be concentrated in areas of fresh groundwater and higher transmissivity causing environmental risks to be much higher than if the there was a more even spatial distribution. If the focus of groundwater extraction is near a stream, this will have a much greater impact than that further away. Adverse impacts of the spatial distribution of extraction can be mitigated by 'local' management rules in groundwater management plans, administered by state jurisdictions. The BP requires states to have regard to surface water–groundwater connectivity and to

incorporate rules in their water resource plans to manage streamflow impacts from increased extraction (MDBA 2019a).

The management approaches being used by states for connectivity include applying distance conditions from surface water bodies for new and replacement bores; creating zones within which groundwater use is limited; managing use to trigger levels and/or reduced levels of allowable use within a season; applying joint announced allocations (often on average annual limit) on surface water and groundwater use; and restricting the issuing of entitlements or restricting full use of entitlements by using announced allocations (MDBA 2019a).

The groundwater management plans were not complete at the time of this study and the local management rules were not reviewed in any detail. The suggested rules for managing connectivity will be variably effective in managing streamflow impacts. For example, triggers are less effective in systems, which are highly connected and distance offsets are often too small to prevent long-term impacts. Seasonal rules are usually designed to protect base-flow-dependent ecosystems. The rules need to be considered in the context of the whole management plan and for the specific unit being considered. It is important that the effectiveness of local management rules to mitigate the risk from potential future groundwater extraction across the MDB be reviewed and used to adjust estimates of cumulative impacts. It would be expected that these rules would be changed adaptively as better information becomes available. The identification of high-risk SDL resource units will aid the prioritisation of more detailed work to be conducted to review local management rules and other actions to mitigate impacts of increased extraction, including those from commitments prior to the BP.

Policies to deter new developments in high impact zones have previously succeeded in minimising salinity impacts. For example, the use of trading rules in the Victorian Mallee region in the western MDB led to more than 90% of the recent development occurring away from high impact zones (Mallee CMA 2017). It is reasonable to compare the efficacy of connectivity management with salinity management as the processes are similar. The success of the salinity zoning policy shows the value of appropriate monitoring and compliance reporting. The assignment of any new entitlements to very low impact zones may be a suitable precautionary approach for the current unassigned water.

Adaptive management of local management rules requires monitoring appropriate for this purpose. The monitoring of extraction across the whole SDL is too crude to assess local management rules. The example of salinity management in the Victorian Mallee would suggest considering using the level of extraction in 'high impact' zones as a metric for the efficacy of local management rules, rather than across the whole SDL, as is currently being used in the Register of Take (MDBA 2019b). The cost of identifying high impact zones, reporting extraction within these and reviewing the efficacy of rules would need to be justified in demonstrating that the BP is being effective in capping groundwater impacts on streams.

Adaptive management should also consider the longer-term vision of conjunctive management of groundwater and surface water along different river reaches to meet future challenges such as climate change, increased groundwater usage pressures in near-river zones and accounting properly for the consumptive pool, and existing challenges, such as waterlogging and salinity. Conjunctive management will require better understanding of connectivity and modelling, in order to meet these challenges, while accounting fully for cumulative impacts of surface and groundwater diversions.

(1) *Comparison to other risks*: One of the reasons for conducting a risk analysis is to provide relativity to other risks. The risk is sensitive to both magnitude and the time delay of impacts. CSIRO (2008) showed that the risk from groundwater extraction is less than that from climate change. The median change in water availability across the MDB was 11% by 2030, with the surface water run-off reducing by 9% by 2030 and 15% by 2050. The risk analyses of SKM (2009) and NSW (2010) also showed that the climate change risks were greater than those of increased extraction. The results here showed that impacts could be up to 3.0 % of streamflow, if local management rules are not effective. Wang, Walker, and Horne (2018) showed that the magnitude of change from infrastructure and water use measures was less than for increased groundwater extraction, but these changes had either been implemented or in the process of being implemented rather than hypothesised. All these risks gradually increase in time and exacerbate other risks, especially during extended dry periods.

5. Conclusions

The impact on streamflow volumes of increased groundwater extraction in the Murray-Darling Basin (MDB) has long been recognised as a potential issue. The development of groundwater SDLs under the Basin Plan (BP) took steps to reduce impacts, but there are residual risks. This study clarified some of these risks. It found that:

(1) The potential increased extraction of 2159 Gl/y is approximately evenly divided between the commitments already existing prior to the plan and unassigned water. Most of the extraction over the next 40 years is likely to derive from the pre-existing commitments, assuming that these will be used first and growth rates in extraction are less than 6%/y. While existing surface water management plans should have incorporated these impacts, it is not clear that this has occurred. The new groundwater management plans are meant to mitigate surface water impacts.
(2) This study has estimated that the cumulative impact of this potential increased groundwater extraction is less than 580 Gl/y from increased extraction over the next 40 years and up to 670 Gl/y from that over 80 years. Not surprisingly, most of that within 40 years are from the pre-existing commitments. MDBA (2012a) has suggested that impacts over 100 Gl/y are not acceptable. While occurring later, use of unassigned water are likely to push impacts into the high range, supporting the need for a precautionary approach to unassigned water.
(3) The analysis identified high risk units, the two highest being the Shepparton Irrigation Region (up to 135 Gl/y from 80 years of growth) and the Lachlan Fold Belt (up to108 Gl/y – over 80 years). The impacts occur over a range of tributaries, but the Goulburn River seemed to be particularly affected with potential impacts of up to 215 Gl/y from 80 years of growth. this represents up to 6% of total flow and is significant, when compared to environmental recovery targets for the Goulburn and Broken (356.1 Gl/y). Most of the impacts from the next 40 years of growth are for fresh to brackish groundwater systems. This means that any reduction of groundwater inflows to streams will generally be of good quality water.
(4) The large time scales associated with the growth of extraction and time delays between the increase in extraction and full impact on streamflow means that adaptive management is possible. Mitigation can involve changes to groundwater or surface water SDLs, but also local management rules would be strengthened. Adaptive management requires transparent monitoring of the extraction rates.
(5) The only way to attain 'acceptable' levels of cumulative impacts (<100 Gl/y) is for local management rules to be applied. Local management rules are being incorporated in groundwater management plans, as administered by states and rules within these plans will be developed, as required. These could be usefully compared to the successful use of impact zoning in the MDB salinity strategy. However, monitoring to support adaptive management will need to be of extraction in 'high' impact zones, rather than across the whole of the groundwater resource unit.
(6) The application of local management rules allows the discussion on cumulative impacts of groundwater extraction to move away from the large increase in the volume of unassigned water (i.e. high SDLs) to the effectiveness of the local management rules and the shift to conjunctive management of surface and groundwater for various river reaches. A precautionary approach to unassigned water may be to allow new entitlements to be only used in very low impact zones, rather than further reduce SDLs.

Acknowledgments

The work presented in this paper was partially supported by funding from the Murray-Darling Basin Authority (MDBA). The MDBA also provided Figure 2 and data for the analysis. The authors would like to thank Sebastien Lamontagne and Tariq Rana for constructive criticism of the draft manuscript.

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