An Australian Government Initiative

Funded through the Murray–Darling Water and Environment Research Program

Synthesis of indirect impacts of climate change in the Murray-Darling Basin

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MD-WERP Deliverable: T1.FS1

October 2021

Citation

Robertson DE, Dwyer G, Lester RE, Holt G, Bailey J, Job M, Coleman M. (2021) Synthesis of indirect impacts of climate change in the Murray-Darling Basin. MD WERP Deliverable T1.FS1, CSIRO, Australia.

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Acknowledgments

This work was undertaken as a part of the Murray–Darling Basin Water and Environment Research Program (MD-WERP) Climate Adaption Theme. The MD-WERP is an Australian Government initiative to strengthen scientific knowledge of the Murray–Darling Basin that is managed through a partnership between the Department of Agriculture, Water and the Environment, the Commonwealth Environmental Water Holder and the Murray–Darling Basin Authority. The Climate Adaptation Theme brings together researchers from CSIRO, Deakin University and eWater.

The authors pay respect to the Traditional Owners and their Nations of the Murray−Darling Basin. We acknowledge their deep cultural, social, environmental, spiritual and economic connection to their lands and waters.

Executive summary

The Murray-Darling Basin has a wide range of social, economic, ecological and cultural values that are under threat from climate change. The higher temperatures and lower rainfall that is projected within the Basin under climate change will have direct impacts on the availability of and demand for water, the viability of some agricultural systems and the frequency and intensity of bushfires, among many examples. However, secondary impacts will also arise that may amplify or modulate direct impacts, for example the changes in catchment runoff, and hence water availability, from changed bushfire regimes.

This report documents the knowledge of 9 indirect impacts of climate change on water supply, demand and management in the Basin used to prioritise detailed investigations during the co-design of the MD-WERP Climate Adaptation Theme (Table 1). Existing knowledge is found to be variable in its ability to characterise the magnitude and geography of likely indirect impacts on water supply and management. In addition, new and emerging sources of data are likely to provide opportunities to update existing understanding.

Indirect impacts for detailed investigation were prioritised using a range of criteria that considered data availability, extent of impacts across the Basin and strategic importance to Basin management. The priority indirect impacts that will be further investigated are:

- catchment interception by farm dams,
- increased bushfire frequency and intensity,
- non-stationary dominant hydrological processes, and
- hypoxic blackwater events.

Table 1 Summary of knowledge of indirect impacts of climate change on water supply demand and management

Impacts	Expected magnitude	Process understanding	Existing impact quantification	Influence of natural resource management
Farm dams	High	High	Medium	High
Bushfires	High	High	Low	Low
Non-stationary hydrological processes	High	Medium	Low	Low
Land use change	Medium	Medium	Low	High
CO_2 fertilisation	Low	Low	Low	Low
Cropping and farming system changes	Medium	Medium	Low	Medium
Blue-green algae blooms	Low	Medium	Low	Medium
Hypoxic blackwater events	High	High	Low	High
Pest plants and animals	Low	Medium	Medium	Medium

Category definitions	Expected magnitude	Process understanding	Existing impact quantification	Influence of natural resource management
Low	Local impacts or small impact on water availability	Limited knowledge, conflicting models or evidence	Little quantification of impact under climate change	No or limited ability to influence impacts
Medium	Valley impacts or medium impact on water availability (10s of GL)	Qualitative understanding, limited modelling or quantification	Limited climate change impacts quantified or new data available to update assessment	Some opportunity to influence impacts
High	Widespread impact or large impact on water availability (100s of GL)	Consistent quantitative evidence or modelling exist	Climate change impacts quantified using current data	Impacts can be controlled or directed

1 Background

The Murray-Darling Basin (MDB) covers more than 1 million km^2 and is one of the most productive agricultural regions in Australia. Economically, the MDB contributes more than $20 billion per year in agricultural production, including more than $8 billion from irrigation (50% of Australia's irrigated agricultural production) [*Hart et al.*, 2021]. Tourism is also estimated to contribute nearly $8 billion per year to the Basin economy [*Hart et al.*, 2021]. Much of the tourism in the Basin focusses on the large number of environmental assets, including approximately 400,000 water-dependent ecosystems and many internationally significant (Ramsar) wetlands. Many of these water-dependent environmental assets are supported by the Basin's ~3000 GL of environmental water entitlements [*Hart et al.*, 2021].

Climate change is likely to threaten many of the Basin's social, economic, environmental and cultural values. Across the basin, climate change will manifest as warmer temperatures and lower rainfall, with rainfall declines most likely in the southern areas. Many of the direct impacts of climate change on Basin water resources have been extensively documented [*Whetton and Chiew*, 2021]. Reductions in rainfall across much of the Basin will directly lead to reductions in streamflow and hence water availability for economic, environmental, cultural and social uses. At the same time, temperature increases will result in increased evaporative demand and therefore increases in plant water requirements, particularly in the irrigation sector. Temperature increases will also result in more extreme heat days which have a direct impact on the liveability of the Basin and viability of some agricultural systems.

A large number of secondary or indirect impacts of climate change can also modulate or amplify the direct impacts. For example, it is well established that bushfires can have a strong influence on catchment runoff, and climate change will increase the frequency and intensity of bushfires in many parts of the Basin. The effects of these changes in fire frequency and intensity on catchment runoff quantity and quality across the Basin, like many other indirect impacts of climate change, are not well quantified.

The objective of this report is to document the potential indirect impacts of climate change on water supply, demand and management in the Basin identified during the scoping phase of the Climate Adaptation Theme of the Murray-Darling Water and Environment Research Program (MD-WERP). It seeks to summarise the knowledge and evidence that was used to inform the prioritisation of indirect impacts for further detailed investigation. Where available, we seek to characterise current understanding of the expected magnitude and geography of the identified indirect impacts and highlight where recent advances in data and understanding can be used to further enhance knowledge. We conclude by describing the criteria for prioritisation and listing the topics for further detailed investigation.

2 Identified indirect impacts of climate change

Here we summarise understanding of the indirect impacts of climate change on water supply, demand and management that was used to inform the prioritisation of indirect impacts for further detailed investigation within MD-WERP. The summary excludes the known direct impacts, such as the conversion of rainfall to runoff and increases in potential evapotranspiration, that have been extensively investigated previously [*Whetton and Chiew*, 2021; *Whetton et al.*, 2015]. The indirect impacts identified are:

- Catchment interception by farm dams
- Increased bushfire intensity and frequency
- Non-stationary dominant hydrological processes
- Land use change
- CO_2 fertilisation
- Cropping and farming system changes
- Blue-green algal blooms
- Hypoxic blackwater events
- Pest plants and animals

For each of these indirect impacts, we describe the pathway by which water supply, demand and management can potentially be impacted, characterise current understanding of the magnitude and geography of the impacts, including an assessment of the confidence in understanding, and describe the opportunities for management to influence the outcomes.

2.1 Catchment interception by farm dams

2.1.1 Context

Farm dams supply the water needs for domestic, stock, and irrigation uses in rural areas. Much of the catchment runoff that is captured and stored in dams is ultimately used or evaporates and, therefore, the presence of farm dams leads to lower streamflow. In the headwaters of catchments farm dams in the upper catchments intercept landscape runoff, while dams and ring tanks on floodplains are predominantly filled by overbank riverine flow during periods of flooding.

The presence of farm dams is expected to amplify the effects of climate change on streamflow [*Chiew et al.*, 2008]. Under a drying climate, catchment runoff will reduce, and water demands are likely to remain constant or increase due to increasing evaporation rates. The combination of these effects will lead to dam levels being lower, on average and, as a result, the proportion of catchment runoff captured by farm dams will increase. In addition, there is the potential for increases in the number of farm dams to supply stock and domestic needs however, the number of large farm dams to support irrigation is unlikely to change due to regulatory limits.

2.1.2 Expected magnitude and geography of impacts

The Murray-Darling Basin Sustainability Yields (MDBSY) project [*Chiew et al.*, 2008] estimated the reduction in mean annual runoff arising from climate change and *additional* future farm dam development in headwater catchments. Additional farm dam development (2030 relative to 2008) was estimated to result in an additional average reduction in mean annual runoff of 0.7% across the Basin. Individual valley reductions in mean annual runoff were estimated to vary between 0.0% and 3.2%. Geographically, the largest reductions in annual runoff resulting from additional farm dam development are located in the Adelaide Hills, northern Basin headwater catchments, and southern Basin unregulated catchments with a confluence downstream of major irrigation storages.

2.1.3 Confidence in understanding impact

Number, size and distribution of farm dams

The MDBSY project used a number of different methods to estimate the number, size and distribution of farm dams based on the data sources and availability then [*Chiew et al.*, 2008]. Since the MDBSY project, state governments have developed high-resolution data sets on the size and distribution of farm dams. More recently, a nationally consistent farm dam data set has been compiled by *Malerba et al.* [2021], which includes estimates of the changes in the number and size of farm dams since 1990. Current data show that there are many more farm dams than the MDBSY project estimates.

The MDBSY assumed future growth in farm dams for stock and domestic purposes was related to population growth. Growth in other dams was assumed to be minimal in Victoria and Queensland and related to legislative limits on water harvesting in NSW and South Australia. Future farm dam development for irrigation and commercial purposes is now limited under state water legislation.

Modelling of farm dam impacts

Methods to model the impact of headwater farm dams are well established [*Fowler et al.*, 2015]. However, impact assessments tend to focus on the sensitivity of streamflow to farm dams, by taking an assumed natural streamflow and assessing the percentage reduction streamflow resulting from farm dam development. The sensitivity approach is taken because few assessments have explicitly considered the effect of farm dams in deriving the natural streamflow. Assessing how existing (and new) farm dams interact with climate change requires the effects of farm dams to be modelled separately from natural streamflow. Including farm dams into model conceptualisations and calibration is one of the key limitations in existing modelling [*Fowler et al.*, 2015].

Modelling the impacts of floodplain dams and ring tanks is complicated by data uncertainties related to diversion infrastructure. While such infrastructure requires government approval, the timing of infrastructure construction (following approval) is not necessarily precisely known. This can impose significant challenges in the calibration of river systems models and consequently limit the accuracy of impact assessment, historically and under climate change.

2.1.4 Role of management

The future impacts of farm dams on streamflow can be influenced by water policy. In most states, large farm dams used for irrigation and commercial purposes require licences under state water legislation. However, smaller dams for stock and domestic purposes do not necessarily require licenses. The impacts of farm dams on low flows can also be moderated by installing low-flow bypasses, which can be encouraged through licencing requirements and programs to support their installation.

2.2 Increased bushfire frequency and intensity

2.2.1 Context

Climate change will increase the frequency of weather conditions conducive to the occurrence and severity of bushfires in the Murray-Darling Basin [*Scientific Reference Panel for the Murray-Darling Basin Commission Living Murray Initiative*, 2003]. Bushfires are known to have impacts on water supply and management through two mechanisms. Immediately after bushfires, sediment, carbon and other constituents, including metals, are mobilised leading to poor water quality. This poor water quality can lead to impacts on aquatic ecosystems, including fish deaths [*Biswas et al.*, 2021], urban water supplies, requiring additional treatment measures, and agriculture particularly through mobilised sediment.

Over longer timeframes, vegetation removal and regeneration influences water balance and the yield from catchments [*Hill et al.*, 2008; *Mannik et al.*, 2013; *Marcar et al.*, 2006]. Immediately following a bushfire, reduced vegetation cover has been shown to increase runoff coefficients, leading to greater levels of streamflow relative to rainfall. The subsequent response of streamflow to vegetation regeneration is dependent on the forest species composition. For forests that consist of mountain ash (*Eucalyptus regnans*), alpine ash (*E. delegatensis*) and snow gums (*E. pauciflora*), trees are often killed by fires. During regeneration of these forests, runoff coefficients can reduce to 50% of pre-fire levels at 20-30 years after a fire, before slowly returning to pre-fire levels. For other forests that consist mainly of eucalyptus species that are not killed by fire, runoff coefficients can return to pre-fire levels within 3-10 years.

2.2.2 Expected magnitude and geography of impacts

The water quality impacts of bushfires under climate change do not appear to have been assessed. However, following historical bushfires, water quality impacts have been observed in all regions of the Basin [e.g. *Biswas et al.*, 2021].

The MDBSY project estimated that bushfires will have minimal impact on mean annual runoff in addition to the direct effects of climate change across the MDB in the long term [*Chiew et al.*, 2008]. Some valleys were shown to have an additional 1% reduction in mean annual runoff under the highest impact climate scenarios. These conclusions were supported by a desktop review by *Marcar et al.* [2006] who suggested that the impacts of individual bushfires tend to be localised and therefore over large regions, such as the MDB, the average impact is likely to be small. However, modelling of historical bushfires in the south-east MDB [*Mannik et al.*, 2013], suggests that the impacts of bushfires in the early 2000s could result in reductions in the mean annual flow of up to 10 % for 10-to-30-year periods in valleys that experience widespread fire impacts and have fire-sensitive vegetation.

2.2.3 Confidence in understanding impact

Significant uncertainties exist in the estimates of the impact of bushfires on runoff under a changing climate. Relationships between bushfire occurrence and subsequent reductions in runoff have been established for a wide range of vegetation types across the MDB. However, the effects of burn frequency are not well understood as frequent burns can potentially change the species composition and therefore the relationship between bushfire occurrence and runoff reductions that apply under more frequent bushfires.

To predict future impacts requires relationships between the weather conditions conducive to bushfires and the occurrence, areal extent and intensity of bushfires. These relationships are not well quantified in the MDB. The MDBSY project undertook some basic analysis relating the annual cumulative Forest Fire Danger Index (FFDI) to the mean proportion of Victorian forest burnt each year using unpublished data [*Chiew et al.*, 2008]. More sophisticated and locally specific models to predict fire ignition probability and cumulative area burnt from weather conditions have been developed and applied to explore the impacts of climate change outside the MDB [*Bradstock et al.*, 2009]. However, these have not been linked with hydrological impact assessments.

2.2.4 Role of management

There is little role of the Murray-Darling Basin Authority in the direct management of bushfires or their increase frequency and intensity under climate change. Management actions that can reduce the intensity and frequency of bushfire potentially include fuel reduction burning and the construction of fuel breaks, which are likely to have impacts that are analogous to, but more contained than, bushfires. However, there is continuing debate about whether these practices will continue to be effective under a changing climate where fire behaviour is driven by weather conditions and where opportunities for their use may decline [*Hislop et al.*, 2020; *Morgan et al.*, 2020]. Post-fire measures can mitigate some of the impacts of fire on water quality, such as erosion and sediment control measures, however there is also a need to plan for alternative water supplies when water supply infrastructure is impacted by poor water quality.

2.3 Non-stationary hydrological processes

2.3.1 Context

Models used for water resources assessment and planning commonly assume the relationship between rainfall and runoff is stationary – that is a model fitted to historical observations will be appropriate for future conditions. However, during the Millennium Drought in the southern MDB, most streams displayed non-stationary behaviour where the relationship between rainfall and runoff appeared to change, manifesting as lower amounts of runoff being observed for the same amount of rainfall (lower runoff coefficients) [*Potter and Chiew*, 2011; *Saft et al.*, 2015]. Following the conclusion of the drought, the pre-drought rainfall-runoff relationship has been observed to return for some streams but not for others [*Peterson et al.*, 2021]. A major cause of non-stationary hydrological behaviour is related to the soil moisture and groundwater levels declining over extended dry periods leading to disconnection between streams and the underlying groundwater systems, and larger soil moisture deficits requiring additional rainfall required to induce runoff [*Chiew et al.*, 2014]. Many current models used for water assessments are unable to replicate these non-stationarities [*Fowler et al.*, 2016].

Non-stationary hydrological processes may also influence river management and the efficiency of river system operations. Drying out of riverbeds and reduced groundwater levels resulting from extended dry periods are known to increase transmission losses in river systems.

Climate change is projected to result in lower average rainfall and more severe extremes – both wet and dry. Therefore, under climate change non-stationary hydrological behaviour is likely to amplify runoff reductions and also may reduce the efficiency of river system operations.

2.3.2 Expected magnitude and geography of impacts

The impacts of hydrological non-stationarity on water supply and management in the MDB in the future are not well characterised, particularly in the northern Basin. Historically observed non-stationarity has been quantified at some gauges across the Basin and most comprehensively in Victoria. During the Millennium Drought in Victoria, catchments that displayed non-stationary behaviour had runoff reductions 20-40% larger than those expected from rainfall reductions alone [*Department of Environment et al.*, 2020; *Saft et al.*, 2015]. Geographically, the larger reductions occurred in the drier and flatter catchments, rather than those in steep mountainous areas.

2.3.3 Confidence in understanding impact

While reductions in runoff coefficients have been observed during the Millennium drought, the causes appear to be complex and are not fully understood, particularly as the process of recovery after the drought has not been uniform. Many of the conceptual rainfall-runoff models that are used to generate future runoff projections do not necessarily simulate the observed changes in rainfall-runoff relationships [*Fowler et al.*, 2016]. Therefore, it is not well understood how rainfall-runoff relationships may vary in space or time. However, as modelling used for water resources assessments does not consider changes in rainfall-runoff processes, current runoff projections are likely to underestimate any reductions in future runoff.

2.3.4 Role of management

It is unlikely that management will be able to change or influence hydrological non-stationarity as it is the manifestation of landscape scale interactions between climate and hydrological processes. Developing an improved understanding of the processes leading to hydrological non-stationarity will enable managers to have more confidence in estimates of future water availability and operational water management challenges and thus plan for these challenges.

2.4 Land-use change

2.4.1 Context

Changes in the coverage of vegetation types within the MDB have occurred historically and are likely to continue to occur in the future. Such land-use changes can be both managed and unmanaged. Managed land-use change can include the establishment of forested areas, including for plantation forestry or carbon abatement, or the clearing of forested areas for agriculture, while unmanaged land-use change may include the ingress of woody vegetation in grasslands. These land-use changes are influenced by a combination of government policies, climate and economic conditions and change.

The hydrological effects of land-use change can be complex. Annual water yield (streamflow) from forested catchments is lower than that from grassed catchments given the same annual rainfall [*Zhang et al.*, 2001]. Therefore, transitions between grassed and forested land uses will result in changes in catchment water balances, however, the extent of change will be dependent on climate and soil characteristics and vegetation physiology [*Andréassian*, 2004]. Under a changing climate, changes in precipitation and evaporative demand are likely to amplify the effects of land use change.

Climate modelling studies also indicate that large-scale (e.g. basin-wide) land-use change can also influence regional climate. Forested regions have more efficient turbulent mixing and increased water vapour in the lower atmosphere, which favours the formation of rainfall and lower surface temperatures. These studies suggest that widespread revegetation could modulate the effects of climate change.

2.4.2 Expected magnitude and geography of impacts

In the MDBSY project, the effects of projected increases in plantation forestry in the Murray, Murrumbidgee and Eastern Mount Lofty Ranges catchments were found to reduce mean annual runoff in 2030 by less than 1%, primarily because the additional area of plantation forests was small relative to the catchment areas [*Chiew et al.*, 2008].

Climate model sensitivity studies across the MDB have suggested that returning the entire basin to its pre-settlement vegetation conditions could increase rainfall and decrease extreme temperatures. The magnitude of these effects is uncertain, however multiple modelling studies indicate that the effects are likely to be strongest in the southeastern MDB [*Hirsch et al.*, 2014; *Wen et al.*, 2017]. However, such landscape scale revegetation is unlikely.

2.4.3 Confidence in understanding impact

Relationships between water yield and land cover have been developed using data from catchments around the world and validated in Australia. Projections of future land-use change, however, are highly uncertain as they are sensitive to government policy and business choices. For example, projections of increasing plantation forestry made during the MDBSY project were based on government policies at the time supporting investment [*Chiew et al.*, 2008]. However, these policies changed and little change in plantation areas has been subsequently observed [*Downham and Gavran*, 2020].

The impact of land-use change on regional climate has been demonstrated through modelling sensitivity studies, however the magnitude of these impacts is uncertain. The impacts of land-use change on regional climate have been suggested to have a second-order effect compared to changes occurring to the global circulation [*Bates et al.*, 2008] but there is no conclusive evidence.

2.4.4 Role of management

Governments have a significant role in influencing land-use change both directly and indirectly. Land-use planning controls on the clearance of vegetation and the establishment of plantation forestry exist throughout the Basin, which can consider the hydrological direct impacts. Policies related to greenhouse gas abatement, taxation and native vegetation protection also impact land-use changes indirectly by influencing investment choices and the supply of goods, such as timber.

2.5 CO_2 fertilisation

2.5.1 Context

Carbon dioxide (CO_2) fertilisation is a plant-scale response to increased atmospheric CO_2 concentrations that are associated with climate change. Plant photosynthesis involves the conversion of CO_2 and water into sugars and starches in the presence of light. As plants open their stomata to allow carbon dioxide to diffuse into leaves, transpired leaf water evaporates into the atmosphere. Increased atmospheric concentrations of CO_2 increase the rate of photosynthesis and also the water efficiency of leaves, as smaller or less frequent stomatal openings are required to diffuse similar amounts of CO_2. Increased rates of photosynthesis result in increased plant growth rates, increased carbon storage in leaves, wood and roots, and can also reduce mineral concentrations of agricultural fruit and grain crops. However, these effects can be moderated by other factors influential in plant growth, such as soil and air temperatures and the availability of water and nutrients. At the catchment or regional scale, the net effect of CO_2 fertilisation may result in more or less plant water use depending on the counter-balancing processes related to additional leaf growth and lower stomatal conductance.

Changing dynamics of plant water use due to elevated CO_2 levels has the potential to change landscape scale hydrology. The combination of increased plant growth rates and modified water use efficiency can influence transpiration, soil evaporation, soil moisture dynamics and catchment-scale runoff.

2.5.2 Expected magnitude and geography of impacts

Global sensitivity and attribution studies have associated increasing historical CO_2 concentrations with increased runoff across the globe [*Gedney et al.*, 2006]. Modelling study by [*Raupach et al.*] for Australia indicated that the doubling of CO_2 with no change in climate inputs could increase runoff by 6%. However, a study focussed on Australia found the reverse, associating increasing historical CO_2 concentrations with runoff decreases of up to 28% in sub-humid and semi-arid regions, including large parts of the MDB [*Ukkola et al.*, 2016].

For water resource planning assessments, however, the effects of CO_2 fertilisation are generally neglected in modelling used to generate future projections of catchment runoff, and particularly that undertaken in the MDB.

2.5.3 Confidence in understanding impact

Laboratory investigations into the effects of increasing atmospheric CO_2 show that plant water use efficiency increases with atmospheric CO_2 concentration at the leaf scale. However, larger scale field investigations suggest CO_2 fertilisation effects are complex and dependent on how different plant varieties interact with their growing environment. Therefore, it is difficult to upscale the knowledge gained through these experiments to provide regional assessments of the impact of CO_2 fertilisation on runoff due to the complex interactions and feedbacks between the controlling biological, atmospheric and hydrological processes [*Chiew et al.*, 2008; *Yang et al.*, 2021]. As a result, the CO_2 fertilisation effects are likely to remain an epistemic uncertainty in runoff projections.

2.5.4 Role of management

There is likely to be irreducible uncertainty in the impacts of CO_2 fertilisation on future runoff in the Basin and therefore management decisions need to consider that these uncertainties exist.

2.6 Cropping and farming system changes

2.6.1 Context

Agriculture in the MDB is expected to be impacted by increased temperatures and lower rainfall under climate change [*Crimp et al.*, 2010; *Gunasekera et al.*, 2007]. The yield of many agricultural crops grown in the MDB is sensitive to both rainfall and air temperatures at various times of the day or year. Lower rainfall will reduce the yield of non-irrigated crops while increasing water demands for irrigated crops. Temperature increases can also impact agricultural crop yields in a number of other ways. Many horticultural crops require chilling to break dormancy and enable flowering and fruit production. Increasing temperatures will reduce the amount of chilling available and therefore reduce crop yields. The yield of some horticultural crops is also reduced by heat stress. Broadacre crops can also display temperature sensitivities. For example, wheat yields can be reduced by frost, while growth rates of some preferred pasture species can be reduced by high air temperatures.

These changes to the yield of agricultural and horticultural crops will potentially influence the viability of some farming systems within the MDB and hence influence the geography, magnitude and timing of water demands and overall water management in the Basin.

2.6.2 Expected magnitude and geography of impacts

While the impacts of climate change on crop viability are characterised, the subsequent consequences for water management in the Basin are not well understood. Longer-term temperature changes are likely to reduce the yield of some horticultural and broadacre crops, due to factors such as heat stress and reduced chilling, and potentially increase yields of others, due to factors such as reductions in frost days [*Ekström et al.*, 2015; *Timbal et al.*, 2015].

Geographically, areas where the temperature related effects are expected to negatively impact crop productivity are more likely to be in the mid and lower reaches of the Murray and Darling Rivers, while the cooler temperate areas in the upper catchments are more likely to have positive impacts on crop productivity due to lower incidence of frost. However, these general responses are conditional on the actual crops grown.

2.6.3 Confidence in understanding impact

The impacts of temperature on specific crops and varieties are relatively well characterised. However, as crop varieties display variable sensitivity to temperature, increasing temperatures will not necessarily result in changes in cropping systems. Rather agricultural businesses have a range of choices available if their existing crop varieties display yield declines related to temperature increases, including planting crop varieties or types that are less sensitive to temperature changes, relocating their business to a more conducive climate or managing local climate through crop protection measures. These choices will be informed by a wide range of factors beyond just climate change, including prevailing market conditions, and therefore will be difficult to predict.

2.6.4 Role of management

Agricultural businesses will adapt to climate change using a range of strategies, some of which will influence the timing, geography and magnitude of water demands within MDB. State governments, have opportunities to influence any changes in the location, and potentially timing, of water demands through trading and operational rules. Both state and federal governments can also influence adaptation through the provision of information on the projected climate changes to the agricultural sector to support informed decision-making.

2.7 Blue-green algal blooms

2.7.1 Context

Blue-green algae (cyanobacteria) are photosynthetic prokaryotes, with certain species also able to fix dinitrogen from the atmosphere. They tend to proliferate in still, warm, nutrient-rich water [*Reynolds*, 1998]. Climate change is likely to increase the occurrence of blue-green algal blooms, with longer periods of low flow and increased ephemerality of streams, increased nutrient concentrations due to extreme weather events (e.g., intense rainfall, dust storms, bushfires), increased atmospheric CO_2 concentrations, and higher water temperatures providing conditions conducive for algal blooms *[Baldwin, 2021; Cropp et al., 2013; Gobler, 2020]*. Turbidity and thermal stratification of water bodies with low flows also promote blue-green algal blooms. Low light penetration favours the buoyant algae and limits algal growth deeper in the water column. Stratified bottom layers can become anoxic and release phosphorus from the sediment. This provides the necessary nutrients for the N-fixing algae *[Walker and Prosser, 2021]*. Blue-green algal blooms pose significant risks to higher consumers, including native fish and other aquatic wildlife, domestic animals, and humans. These risks include depletion of water quality due to the production of toxic and potentially toxic compounds (such as prooxidants [e.g. microcystins], beta-methylamino-L-alanine, lipopolysaccharides *[Cox et al., 2005; Stewart et al., 2006]* and hypoxia (low oxygen concentrations) resulting from the collapse of the algal populations or mixing of stratified water *[Baldwin, 2019]*. In addition, algal blooms can further alter aquatic food webs *[Anzecc et al., 2000]*, as they can block sunlight and limit primary productivity deeper in the water column, and they are lacking in essential fatty acids required for the growth of higher consumers *[Baldwin, 2021]*.

2.7.2 Expected magnitude and geography of impacts

Globally, blue-green algal blooms are thought to be increasing in frequency, magnitude, and duration due to climatic and non-climatic drivers *[Gobler, 2020; Huisman et al., 2018]*. This trend is likely to occur throughout the MDB, particularly in storages, locks and weirs. In the northern basin, the Chaffey Reservoir catchment is prone to algal blooms, due to high phosphorous sediments *[Walker and Prosser, 2021]*. The lowland rivers of the northern basin are also at risk due to low flow, and high temperature and turbidity *[Oliver et al., 1999]*. In the southern basin, Lake Hume is subject to increases in bloom formation under drought conditions [*Murray–Darling Basin Authority*, 2019]. In the River Murray, substantial increases in total cyanobacteria counts occurred over the period 1994-2008 (in most sites studied), corresponding to the period southeast Australia entered a significant drought period (2000 to 2010). These increases ranged from 4% p.a. to 45% p.a., with larger increases found upstream compared to downstream sites *[Croome et al., 2011]*.

However, blue-green algal blooms in the flowing sections of the rivers of the MDB are generally rare *[Baldwin, 2021]*.

2.7.3 Confidence in understanding impact

The impacts of water nutrient levels, temperature, weather patterns and algal concentrations on blue-green algal blooms are relatively well characterised. However, these relationships are complex, time dependent (lag effects) and site specific *[Lal and Hargreaves, 2020]*. At selected sites in the MDB (such as Lake Hume), hyperspectral and satellite remote sensing and hydrodynamic modelling produce continuous 7-14 day forecasts of algal growth, however long-term projections are lacking. A key knowledge gap for accurate projections is the availability of detailed three-dimensional hydrodynamic models of the storages in the MDB *[Baldwin, 2021]*.

2.7.4 Role of management

Reducing the frequency and severity of blue-green algal blooms under climate change can be achieved by maintaining flows to avoid stratification and the production of anoxic benthic conditions, particularly in large weirs *[Baldwin, 2021]*. Reducing the supply of N or P from diffuse upstream catchment sources will not reduce the occurrence of major algal blooms in lowland rivers, as sediment and nutrient loads in these systems can support algal blooms during low flows independent of any transport from upstream catchments *[Walker and Prosser, 2021]*. Other active interventions include bubble-plume destratification of large storages, installation of structures at the inflow sites to prevent stratification occurring, or chemical amelioration to lock nutrients (particularly phosphorus) in the sediments *[Baldwin, 2021]*.

2.8 Hypoxic blackwater events

2.8.1 Context

Blackwater occurs when large amounts of organic material (e.g., leaves and bark) enters rivers or lakes, usually from the floodplain. This material releases tannins, dissolved organic carbon and other dissolved nutrients, which cause the blackish appearance. Microorganisms metabolise the dissolved organic carbon, while also consuming oxygen from the water column. This is a natural process that supports the productivity of the river. However, if oxygen consumption outpaces the rate of oxygen replenishment, this can result in hypoxic (low oxygen) conditions, which can suffocate and kill native aquatic life (e.g., fish, crayfish, yabbies, shrimp). The long-term impacts of these events on freshwater communities may be exacerbated as alien species (e.g., carp, roach, mosquito fish) are often tolerant to hypoxia. Increases in temperature accelerate microbial metabolism, reduce the amount of oxygen that can be dissolved in water, and increase the rate that dissolved organic matter accumulates in the water *[Engel et al., 2010]*. Accordingly, carbon stocks and water temperature are the most critical factors that determine the severity of hypoxic blackwater events *[Baldwin, 2021]*. These factors are strongly dependent on climate, with reductions in rainfall and increases in temperature, flooding, atmospheric CO_2, the ephemerality of streams, and the incidence and intensity of bushfires potentially increasing the frequency of hypoxic blackwater events *[Baldwin, 2021]*.

2.8.2 Expected magnitude and geography of impacts

Climate change may increase the frequency of blackwater events throughout the MDB, however the magnitude of long-term future change is unknown with little research reported. Across the Basin, the greatest risks of severe blackwater events are likely to be associated with high build-up of leaf litter in floodplain forests.

2.8.3 Confidence in understanding impact

Relationships between flow and litter loads have been developed using data from systems in the MDB. The blackwater plug-in of eWater Source allows a regional scale assessment of blackwater events in fairly complex river systems *[Joehnk et al., 2020]*. The plug-in model incorporates previous inundation dynamics (timing, duration, area, depth, water exchange), temperature (time-series), litter loading, and dilution flows (from rivers and floodplain creeks) to predict DO and DOC. However, the model does not incorporate litter dynamics (e.g., litter flushing and redistribution, litter age, vegetation types, seasonality). In addition, the modelled outputs rely on quality input (including the underlying hydrological model, extended monitoring data) for site-specific model calibration. Where these data are available, outputs compare well with observed DO concentrations. Projections of future blackwater events, however, are highly uncertain as they depend largely on flow management (pre-wetting flow pulse volumes and timing) and land-use (agricultural crop, red gum forest) within a floodplain *[Liu et al., 2020]*.

2.8.4 Role of management

Reducing the frequency and severity of hypoxic blackwater events under climate change can be achieved with regular flooding of floodplains to reduce carbon stock accumulation, maintaining adequate flow rates in warmer weather, and providing sufficient dilution and aerated flows to ameliorate low dissolved oxygen concentrations. As these water requirements may be unfeasible, alternate methods of reducing and ameliorating blackwater need to be studied, such as physical aeration for high-value sites or addition of peroxide-producing ameliorants (e.g. calcium peroxide) to produce oxygen *[Baldwin, 2021]*.

2.9 Pest plants and animals

2.9.1 Context

Currently there is considerable investment in managing impact of pest plants and animals on agricultural productivity, water management and ecology in Australia [*Hoffmann and Broadhurst*, 2016]. The projected rainfall reductions and increases in temperatures associated with climate change in the MDB are expected to lead to changes in the distribution and prevalence of pest plants and animals and therefore may result in new impacts and management challenges. Under a changing climate, it is anticipated that the growth rate of many tropical pest species could increase and the southern limit on the range will extend further south, while the range of species sensitive to water shortages or high temperatures is likely to be reduced [*Crimp et al.*, 2010].

The extension and contraction of the range of agricultural pest plant and animal species is generally unlikely to have substantial impacts on water supply and demand in the Basin other than through changes to the viability of agricultural crops and businesses and also through land-use changes that have been covered earlier.

Climate change impacts will potentially have implications for operational water management and ecology. Infestations of aquatic pest plants can reduce aquatic flora diversity, impact recreational water use and hinder the flow of water though regulating structures on natural and constructed waterways [*Dugdale et al.*, 2013b]. Traditionally, drawing down waterway levels to expose aquatic pest plants to frost or desiccation has been an important non-chemical control mechanism [*Dugdale et al.*, 2013a; *Dugdale et al.*, 2012]. Projected reductions in the number of frost days are likely to reduce opportunities for non-chemical control and water requirements to refill constructed waterways following any drawdown are likely to increase due to lower rainfall and increased evaporative demands.

2.9.2 Expected magnitude and geography of impacts

Models have been used to assess changes to the spatial range of many pest plants and animals in response to climate change. These models are species specific and characterise the potential areas where pest plants and animals could exist, but the actual presence of pests will be dependent on a range of other factors that influence growth and spread [*Lawrence and Stokes*, 2008]. There appear to be few, if any, investigations that provide a quantitative understanding of magnitude and distribution of the impacts of pest plants and animals on agriculture or water management under climate change.

2.9.3 Role of management

The control of pest plants and animals is undertaken by a wide range of actors across the MDB. Many of these actors are likely to require new methods to manage pest plants and animals as they need to deal with climate change introducing new species locally, reducing effectiveness of existing control methods and other factors such as restrictions on chemical controls. Few, if any, of these management strategies are related to the mandate of the MDBA.

3 Priorities for further investigation

The WERP Climate Adaptation Theme does not have sufficient time or resources to investigate all the indirect impacts identified. A prioritisation process was undertaken to identify those indirect impacts to be investigated in more detail. The prioritisation process considered the indirect impacts to be high priority for investigation within the Foundational Science project if:

- New information or data are available to update current understanding of impacts;
- Data are available to develop validated modelling methods to support an evaluation of impacts at the basin scale;
- Management levers are available to the MDBA to influence impacts on Basin outcomes, or impacts are primarily related to strategic water resource availability and management, and not day-to-day operation of the water delivery system;
- Impacts are not localised but are likely to be felt across multiple parts of the Basin or substantially influence Basin outcomes;
- Impacts or science was not being investigated as a part of other WERP projects.

Applying these criteria, 4 priority indirect impacts of climate change were identified for further investigation:

- Catchment interception by farm dams
- Bushfire impacts on water supply and quality
- Hydrological non-stationarity induced by climate change
- Blackwater events

Investigations into these indirect impacts will develop validated modelling methods that can assess the extent to which direct impacts of climate change are amplified or modulated.

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