Riverine Recovery Project

Historic Tree Condition Data Evaluation

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Department for Environment and Water

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Foreword

The Department for Environment and Water (DEW) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEW's strong partnerships with educational and research institutions, industries, government agencies, Natural Resources Management Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

John Schutz
CHIEF EXECUTIVE
DEPARTMENT FOR ENVIRONMENT AND WATER

Acknowledgements

This project was funded by the Riverine Recovery Project, a $98 million joint Australian and South Australian Government initiative to improve the health of the River Murray and its wetlands and floodplains from the South Australian border to Wellington.

This project has been supported by a Project Advisory Group, comprising the following DEW staff:

Mr Andrew Rettig	Project Manager, Adaptive Management, RRP and SARFIIP, Major Projects
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The Project Advisory Group is thanked for their support and guidance.

Dr Todd Wallace, Research Fellow, University of Adelaide is thanked for providing expertise in interpreting floodplain tree response, shaping the evaluation question, reviewing the first draft of the report, and acknowledged as the primary contributor of material provided in Appendix A.

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Jonathan Phillips and David Thompson, Senior Information and GIS Analysts, DEW, performed quality assurance and upload of multiple large tree condition data-sets to Biological Databases of South Australia for this project and they are thanked for their efforts.

The classification of sites by watering regime undertaken for this project utilised surface water modelling inputs which have been previously developed by Dr Dan McCullough (Senior Hydrologist, DEW) and Mahdi Montazeri (Hydrologist, DEW). Their support, and that of Dr Matt Gibbs (Principal Hydrologist, DEW) in providing and supporting interpretation of these products is gratefully acknowledged.

Ms Rebecca Turner, e-water Principal Project Officer DEW, Ms Callie Nickolai, Project Manager, Infrastructure Operations DEW, and Ms Carina Staer Howard, Project Manager, Infrastructure Operations DEW, have also contributed key information and data to this project, including insights to wetland and floodplain management activities and performing extracts from the Management Action Database.

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Summary

This project has been funded through The Riverine Recovery Project (RRP), a $98 million joint Australian and South Australian Government initiative to improve the health of the River Murray and its wetlands and floodplains from the South Australian border to Wellington. Operationally, RRP undertakes works and measures to enable hydrological management to reinstate a variable hydrograph for pool-connected wetlands, deliver environmental water to temporary wetlands, and improve flow and fish passage through priority anabranches and creeks. In addition, RRP has funded investigations, such as this project, to improve knowledge that can be applied to enhance the outcomes of wetland management.

The historic tree condition data evaluation project was initiated to utilise previously collected tree condition data to make recommendations about future data collection, and to inform hydrological management for floodplain tree outcomes. The Department for Environment and Water (DEW) has monitored the condition of trees at River Murray wetlands and floodplains for at least two decades. Over this timeframe, opportunities to deliver environmental water to individual wetlands and broader wetland complexes have increased via engineering works and measures, and are foreseen to increase in the future.

This project aimed to evaluate floodplain tree response to environmental watering actions using data from visual assessments of tree crown condition collected using the method outlined in Souter et al., (2010) from approximately 2009 to 2018.

This study was delivered in two phases. Phase 1 was a preliminary data scoping and project refinement phase that considered a series of draft evaluation questions that were proposed by project partners and stakeholders.

The following was adopted as the key evaluation question to be assessed in Phase 2 of the project:

> *Are the trees at sites that received managed environmental water in the years preceding and between unregulated high flow, in better condition than those sites that only received water during unregulated flows?*

The analysis aimed to group and compare sites that, over the last decade, were inundated by:

1. only the two unregulated floods that occurred in 2010-11 and 2016-17
2. the unregulated floods in 2010-11 and 2016-17 and a series of smaller follow-on unregulated flows in 2011 and 2012
3. unregulated floods (2010-11 and 2016-17) + high flows AND inundated by pumping
4. unregulated floods (2010-11 and 2016-17) + high flows AND weir pool manipulation

This report presents the analysis and findings from the Phase 2 assessment of this evaluation question.

Key findings were that:

1) in a survey year preceded by multiple dry years (no unregulated flooding for three years), trees that had received environmental water during the inter-flood dry phase were in better condition than trees that did not receive environmental water.
2) in a survey year following unregulated high flows, there was a convergence in tree condition, with trees that had received environmental watering during the inter-flood dry phase not being in better condition than trees that had not received environmental water.

The study supports delivery of environmental water as a means to improve tree condition and to maintain trees through dry inter-flood periods. These results are only valid for trees with comparable long-term hydrological

regimes. A range of site and programme-specific factors that limit the generalisation of these findings are documented, along with additional points of interpretation in relation to these key findings.

1 Introduction

1.1 Strategic context

This project has been funded through The Riverine Recovery Project (RRP). Operationally, RRP undertakes works and measures to enable hydrological management to reinstate a variable hydrograph for pool-connected wetlands, deliver environmental water to temporary wetlands, and improve flow and fish passage through priority anabranches and creeks. In addition, RRP has funded investigations, such as this project, to improve knowledge that can be applied to enhance the outcomes of wetland management.

The historic tree condition data evaluation project was initiated to utilise previously collected tree condition data to make recommendations about future data collection, and to inform hydrological management for floodplain tree outcomes. The Department for Environment and Water (DEW) has monitored the condition of trees at River Murray wetlands and floodplains for at least two decades. Over this timeframe, opportunities to deliver environmental water to individual wetlands and broader wetland complexes have increased via engineering works and measures, and are foreseen to increase in the future. This brings a requirement for prioritising and delivering environmental water in the most efficient and effective way to maximise ecological outcomes from a given available volume of water.

1.2 This study

This project aimed to evaluate floodplain tree response to environmental watering using data from visual assessments of tree crown condition collected using the method outlined in Souter et al., (2010). The available data ranged in date from approximately 2009 to 2018. The study follows a review of understorey vegetation response to RRP wetland management (Muller et al., 2017) which recommended a review of tree condition response, given the emphasis on tree condition in wetland management.

A measurable successional understorey response is expected at the scale of a single watering event (within longer term population scale and species diversity patterns in response to watering *regime*). In contrast, trees are anticipated to respond over longer timescales (decadal scale) that may not be well represented in the monitoring data available for the RRP wetlands, some of which only have a single year of data collection. For this reason, all past tree condition monitoring data from River Murray floodplains (not just data collected for RRP) fell within the original scope of this project.

This study was delivered in two phases. Phase 1 was a preliminary data scoping and project refinement phase that considered a series of draft evaluation questions proposed by project partners and stakeholders. A summary of the draft evaluation questions, and the consideration applied to focus the analyses and support selection of a final evaluation question is presented in Appendix A. Phase 1 determined that evaluation of some of the draft questions would:

- be precluded for lack of data, particularly lack of *co-incident* hydrological record and tree condition monitoring data
- have been dealt with/covered in recently completed or forthcoming related projects
- be unlikely to be validly addressed by data-mining and more appropriately investigated through dedicated intervention monitoring

At the conclusion of Phase 1 a project advisory group were presented with several options to progress refined versions of the remaining draft questions. The following was adopted as the key evaluation question to be assessed in Phase 2 of the project:

Are the trees at sites that received managed environmental water in the years preceding and between unregulated high flows, in better condition than those sites that only received water during unregulated flows?

The analysis aimed to group and compare sites that, over the last decade, were inundated by:

1. only the two unregulated floods that occurred in 2010-11 and 2016-17
2. the unregulated floods in 2010-11 and 2016-17 and a series of smaller follow-on unregulated flows in 2011 and 2012
3. unregulated floods (2010-11 and 2016-17) + high flows AND inundated by pumping
4. unregulated floods (2010-11 and 2016-17) + high flows AND weir pool manipulation

This report presents the analysis and findings from the Phase 2 assessment of this evaluation question.

2 Methods

2.1 Tree condition assessment method and data format

Prior to 2008 a wide variety of visual assessment approaches to tree condition assessment were in use throughout the Murray-Darling Basin (MDB). To address this, a standardised method specifically for assessing changes in condition of floodplain trees in the MDB was collaboratively developed in 2008 and iteratively improved (Souter *et al*., 2010). Since 2008, floodplain tree condition data throughout the MDB has primarily been collected using this, *The Living Murray* (TLM) method (Souter *et al*., 2010). There was no concerted effort by this project to source data that was collected using preceding methods that are unlikely to be used again in the future. Therefore, the data collated for this project ranged in date from 2009 to 2018. The three most abundant floodplain tree species in South Australia that are routinely assessed using the TLM method are River Red Gum (*Eucalyptus camaldulensis*), Black Box (*Eucalyptus largiflorens*), and River Cooba (*Acacia stenophylla*). In brief, the TLM method assesses two attributes: crown extent (CE) and crown density (CD). CE is defined as the percentage of all existing tree branches (alive or dead) with live leaves, and CD is defined as the percentage of skylight blocked by those portions of the crown containing live leaves). Assessment transects consist of 30 trees that had a diameter at breast height (dbh) greater than or equal to 0.10 m at the time of transect establishment.

A limitation of Souter *et al*. (2010) is that little guidance is provided on how to convert field data into a readily interpretable index of crown condition. Consequently there is a variety of approaches currently in use throughout the Murray-Darling Basin. Wallace et al (2018a) reviewed the utility of six existing approaches to generating tree condition scores from the TLM field data for CE and CD, and used existing multi-year data sets to increase understanding of likely responses of floodplain eucalypts to wetting and drying phases. Those authors make clear recommendations on standardised approaches to analysing and interpreting both low frequency (annual condition) and high frequency (intervention monitoring) survey data, along with a revised conceptual model of tree decline and recovery.

Presently, within South Australia, site and environmental asset-scale ecological targets (DEWNR, 2017a, 2017b, Kilsby & Steggles, 2015, Wallace et al., 2014) are based on a tree condition index (TCI) scoring system (Wallace, 2015) that bins the CE and CD field data into the category defined by Souter et al. (2010), obtaining a value for CE and CD respectively ranging from 0-7 (Table 2-1), then sums the two values to generate a tree condition index (TCI) score with a possible range from 0-14. The score system index is supported by an interpretative framework (Wallace, 2015, 2016) to provide management guidance on the requirement for environmental watering actions (Table 2-2). The TLM field data, interpreted within the TCI score system (Table 2-2), represents a robust and easily interpretable approach for low frequency (i.e. annual) monitoring surveys where trends and trajectory in condition against ecological targets and management triggers are the primary factor of interest. A recent review of data from managed sites (Wallace et al., 2018) suggests some minor adaptations to the framework, specifically in relation to the duration of the recovery period for heavily stressed trees (e.g. TCI 5 and 6).

The TLM tree condition assessment method (Souter et al., 2010) also includes guidance on visual classification of six other secondary attributes of floodplain trees (new-tip growth, reproduction, epicormic growth, leaf die off and mistletoe infestation, and bark condition). Data on these attributes has been collected at some South Australian River Murray wetland and floodplain sites since the field protocol was originally developed in 2008-09. Souter *et al.* (2010) does not include a scoring system to combine the data on all potentially recorded attributes into a multi-parameter condition index. Various authors have explored the use of multi-parameter indices (e.g. McGinness et al., 2018, Souter, 2018, Horton et al., 2011) to assess and report on eucalypt condition. However, the secondary attributes identified by Souter *et al*. (2010), respond to different stressors-drivers and at different temporal scales than crown extent and crown density. Consequently, it is problematic to combine the primary attributes (CE and CD data) with the secondary parameters into a "one-size fits all" ecologically defensible and easily interpretable index of condition (Wallace et al., 2018). Furthermore, the final data-set did not include observations of these secondary attributes.

The selection of tree condition data to support analysis of the evaluation question was heavily influenced by the availability of hydrological data to enable classification of transects by watering history (Section 2.2).

Table 2-1: Categories for reporting crown extent and density (modified from Souter et al, 2010)

Score	Description	Percentage of CE / CD
0	None	0
1	Minimal	1 – 10
2	Sparse	11 – 20
3	Sparse – medium	21 – 40
4	Medium	41 – 60
5	Medium – major	61 – 80
6	Major	81 – 90
7	Maximum	91 – 100

Table 2-2: Score system for TCI and corresponding condition description (Wallace, 2016)

TCI score	Condition Description	
0	Non-viable	Tree may be dead or very near to the critical point of loss. A small proportion of trees may respond to delivery of water, but are likely to be in a precarious position i.e. response may not be sustained and tree may not recover
2-4	Very poor	Tree viable but in very poor condition and in a precarious position i.e. continuation of dry conditions is likely to lead to death. Trees with low TCI scores have a slow response. A single watering may stabilise condition. Multiple, back to back watering will be required to achieve "good" condition
5-7	Poor	Most trees would be expected to respond positively to watering. Inundation may stabilise condition or result in an improvement. Trees may be at the edge of the resilience period, i.e. continuation of dry conditions is likely to lead to a marked loss of condition. Multiple, back to back watering is likely to be required to achieve "good" condition
8-9	Moderate	Trees in this grouping may receive high scores for crown extent but low scores for crown density. Most trees with TCI scores ≥ 8 would be expected to respond positively to watering and increase to the next condition class. Trees are likely to be approaching the edge of the resilience period, i.e. continuation of dry conditions is likely to lead to a marked loss of condition.
10-12	Good	Trees are expected to have a moderate degree of resilience and should be able to withstand a short dry period with minimal loss of condition. However, under dry conditions, some proportion of these trees may decline to the next class within the next 12 months. Most trees would be expected to respond positively to watering and increase to the next condition class.
13-14	Excellent	Trees are expected to have a high degree of resilience and should be able to withstand a short dry period with minimal loss of condition

2.2 Data availability

At the project outset, all River Murray floodplain tree condition data collected over the past decade was potentially available to support analysis of the evaluation question. However, assessment of the evaluation question required knowledge of the history of unregulated flows and managed watering at locations where tree condition monitoring data was available. Spatial and temporal co-occurrence of reliable watering history and tree condition monitoring data was therefore a primary consideration for selecting a sub-set of tree condition data for analysis. Further criteria for selecting a sub-set of tree condition data included (i) the availability of repeat measures over time, (ii) a range of tree condition transects that could be assigned to the watering history groups identified in the evaluation question, and (iii) constrained by additional factors that were deemed important for data coherence and validity of data amalgamation. These additional factors included a constrained spatial extent to minimise variation in some environmental parameters (e.g. rainfall, groundwater salinity) and selection of transects from within programme/s to ensure transect establishment was consistent.

The first stage of this project focussed on data profiling. Tree condition data collation (Section 2.2.1) and an evaluation of methods to reconstruct watering history (Section 2.2.2) were undertaken in parallel to support final selection of a sub-set of data for analysis of the evaluation question (Section 2.2.3).

2.2.1 Tree condition data profile

The central authoritative data store for tree condition data is the Biological Survey Databases of South Australia (BDBSA).

A data load template was developed for loading tree condition data into BDBSA in 2017. This template includes all of the attributes potentially collected under the TLM tree condition monitoring method. The data load template ensures that each tree is assigned a unique identity with spatial coordinates and that subsequent observations can be associated with the same tree. It also ensures that a minimum level of associated data and meta-data is recorded and retained, such as date of observation and observer names, for example. The key data fields available for use by this project were date, location represented by GPS coordinates, species (*Acacia stenophylla*, *Eucalyptus largiflorens* or *Eucalyptus camaldulensis*), raw field data for CE and CD (5% increments) CE and CD category scores (an integer from 0 to 7) and TCI (an integer from 0 to 14).

Scoping at project initiation revealed that there was tree condition data yet to be submitted for upload to BDBSA, data staged for upload to BDBSA, as well as the data within BDBSA.

An initial extract of tree condition data taken from BDBSA for this project in early September 2018 yielded 2 938 observations. Subsequent to the initial data extract, the Riverine Recovery Project provided a database of tree condition data to be uploaded to BDBSA. A large volume of tree condition data collected by the NR SAMDB wetlands team was also provided and loaded into BDBSA. Additionally, upload of a number of other tree condition data-sets that had previously been queued was expedited to service this project. Collation of all available tree condition data via upload to BDBSA provided benefits such as utilisation of existing quality control processes, corporatisation of the data, and support of data extraction in a format that is utilisable in a GIS environment (fundamental to the evaluation question). At the conclusion of this project there were 24 722 records of tree condition for SA River Murray wetlands and floodplains in BDBSA. Key features of the data were:

- 6 139 monitored trees
- 2 921 trees that had only been visited once
- Considerable geographic skew in survey effort:
    - 14 614 records from above lock and weir 6, mostly from within the Chowilla anabranch and floodplain system
    - 835 records from the floodplain adjacent to weir pool 5
    - 1 919 records from the floodplain adjacent to weir pool 4, dominated by observations from Pike Floodplain
    - 3 301 records from the floodplain adjacent to weir pool 3, dominated by observations from Katarapko Floodplain
    - 597 records from the floodplain adjacent to weir pool 2
    - 703 records from the floodplain adjacent to weir pool 1

- 992 records from below lock and weir 1

- Unequal survey effort (or data corporatisation) through time, with recent year's data likely yet to be submitted:
    - 2 614 records from 2008
    - 4 072 records from 2009
    - 1 505 records from 2010
    - 1 522 records from 2011
    - 2 627 records from 2012
    - 2 648 records from 2013
    - 401 records from 2014
    - 4 970 records from 2015
    - 1 943 records from 2016
    - 436 records from 2017
    - 1 984 records from 2018
- A paucity of data collected from reference sites, i.e. the majority of these data were collected from sites that have been subject to hydrological management actions

2.2.2 Watering history data

The utility of a variety of information sources for assigning monitoring transects to watering history group was reviewed. Sources of hydrological information that were potentially available to support this study were:

1. Spatial inundation extents referenced to flow at the SA border or to adjacent Murray River weirs, derived from hydrological models. This included floodplain inundation models for Chowilla, Pike and Katarapko Floodplains, weir pool manipulation inundation extents, and border to the mouth floodplain inundation extents for QSA of 60 and 80 GL.day^{-1}.

2. Water Observations from Space (WOfS), a remotely sensed product that provides a spatial record of presence and persistence of surface water across Australia developed from 27 years of satellite imagery and ancillary validation data-sets (Mueller et al., 2015, https://www.ga.gov.au/scientific-topics/hazards/flood/wofs).

3. DEW records of volume of water pumped and time periods for operation of regulating structures for many of the managed wetland sites.

4. Potential to reconstruct individual wetland water levels using purpose-built SWET models (e.g. Muller et al., 2017).

Criteria used to assess the utility of these options included:

1) Co-incident spatial extent of products with available tree condition data

2) Likely accuracy of:

    a) modelled inundation extents, based on consideration of the inherent precision at which models were constructed and the extent to which they have been validated via calibration with field data

    b) WOfS, based on reported error rates within imagery and geographic sampling intensity of imagery for the study region

3) Availability and total resources required for construction of new purpose-built products, including SWET models and WOfS derived hydrographs versus the number of case studies which could be developed within the available resourcing.

It was concluded that the modelled inundation extents produced using an existing hydrological model for Weir Pool 3 offered the most resource efficient option with the potential to utilise data from up to 63 transects at Katarapko Floodplain. The Weir Pool 3 model provided inundation extents for flows at Weir 4 in 5 000 $ML.day^{-1}$ flow bands, sufficient to assign the 63 transects to the watering history groups described in the evaluation question. There were data from six transects monitored at pumped wetlands – Piggy Creek and Carparks Lagoons, as well as transects spanning the inundation flow thresholds. The model has been subject to calibration commensurate with its design purpose to support the substantial investment currently being made in environmental watering infrastructure at Katarapko floodplain (McCullough *et al.*, 2017).

2.2.3 Assignment of watering history group

The watering history groups were defined in the evaluation question as transects inundated by:

1) only the two unregulated floods in 2010-11 and 2016-17
2) the unregulated floods in 2010-11 and 2016-17 and a series of smaller follow-on unregulated flows in 2011 and 2012
3) unregulated floods (2010-11 and 2016-17) + unregulated high flows (as for Group 2) AND inundated by pumping
4) unregulated floods (2010-11 and 2016-17) + unregulated high flows (as for Group 2) AND weir pool manipulation

There are no sites in the floodplain of Weir Pool 3 that have received water from weir pool level manipulation (i.e. no “Group 4” sites).

The tree condition data available for Katarapko Floodplain were collected in 2015, 2016 and 2018. The tree condition transects were assigned to one of the watering history groups by intersecting tree coordinates with the modelled inundation extents within a Geographic Information System (Figure 2-2). The final groups are described by Figure 2-2 and Table 2-3. Two additional watering history groups were defined for transects that were (a) never inundated over the study period (”Group 0”) and (b) transects that were within 50 metres of a permanent anabranch where trees may have permanent access to water (”Group 5”). Group 5 was defined as a new group due to the inherently complex topography along the riparian corridor and as an artefact of the riparian corridor being a boundary zone where a 1D (channel) and 2D (floodplain) model have been ‘joined’ within the inundation model. The consequence of these real and modelled conditions are that transects located here would have individual trees assigned across multiple watering history groups if not separated as a group defined by lateral distance to permanent water rather than inundation threshold. Published estimates of lateral distance over which trees may be able to access bank stored water from permanent anabranches range from 50 (Holland et al., 2006) to 120 metres on the main River Murray channel (Doody et al., 2014) and is accepted to be highly dependent on soil type and site specific landform. Five floodplain transects were discarded at this stage of the assessment due to having trees scattered across a wide elevation gradient and therefore being unable to be assigned within a category of inundation threshold.

The distribution of transects by species and survey year of the 58 transects that were assigned to a watering history group is provided in Table 2-4.

The number of transects listed as surveyed in 2018 is inclusive of the 26 transects surveyed in 2015 and 2016 (i.e. the monitoring programme was substantially expanded to include 40 new transects in 2018), which directly addressed the data requirement of repeated sampling

The history of delivering pumped e-water to Carparks Lagoons and Piggy Creek (i.e. Group 3 sites) is provided in Table 2-5. Carparks Lagoons received e-water four times over the study decade and Piggy Creek received e-water in two consecutive years starting in 2015, the first year for which tree condition data was available.

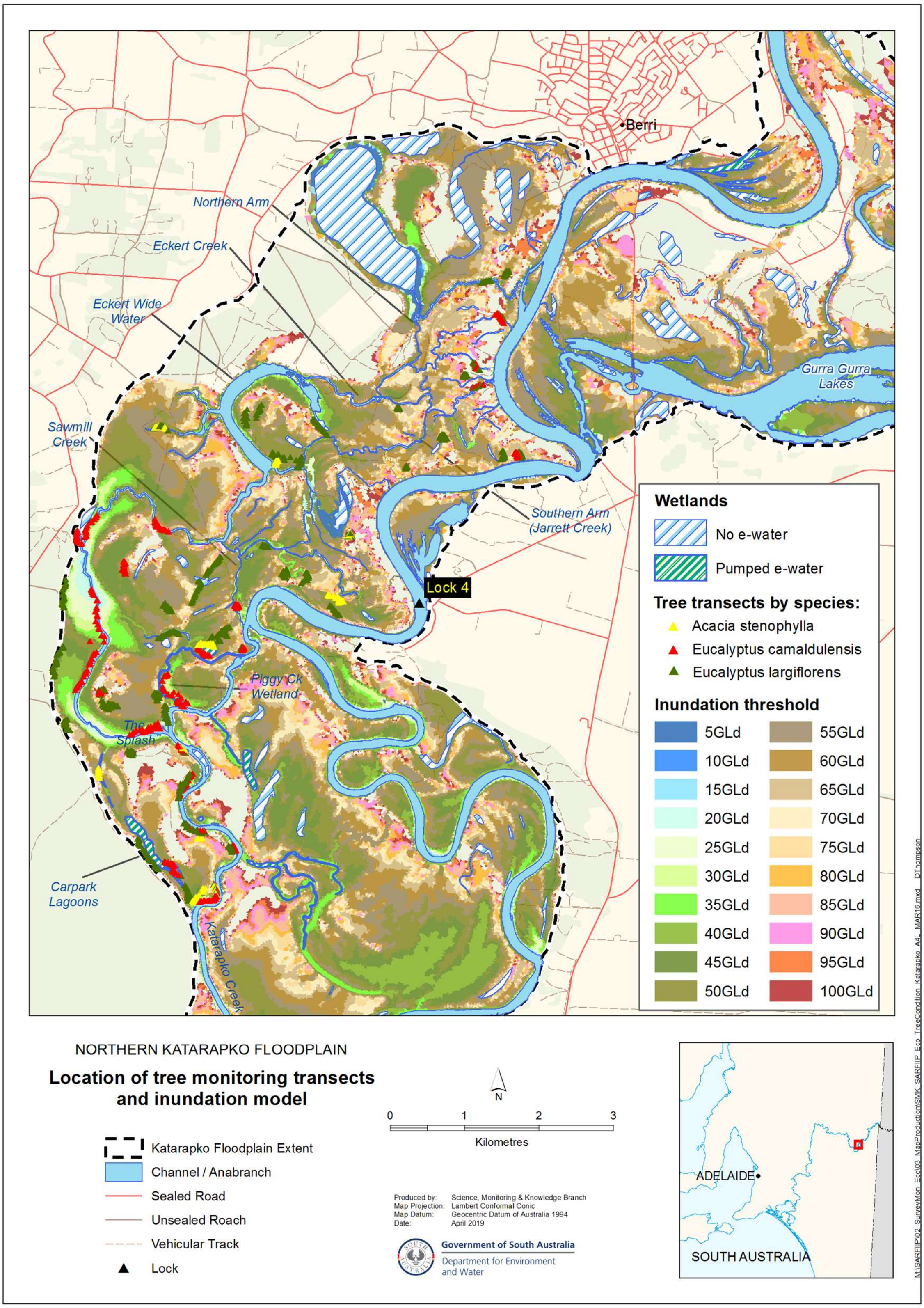

Figure 2-1: Tree monitoring transects at Katarapko Floodplain. A total of 58 transects are represented.

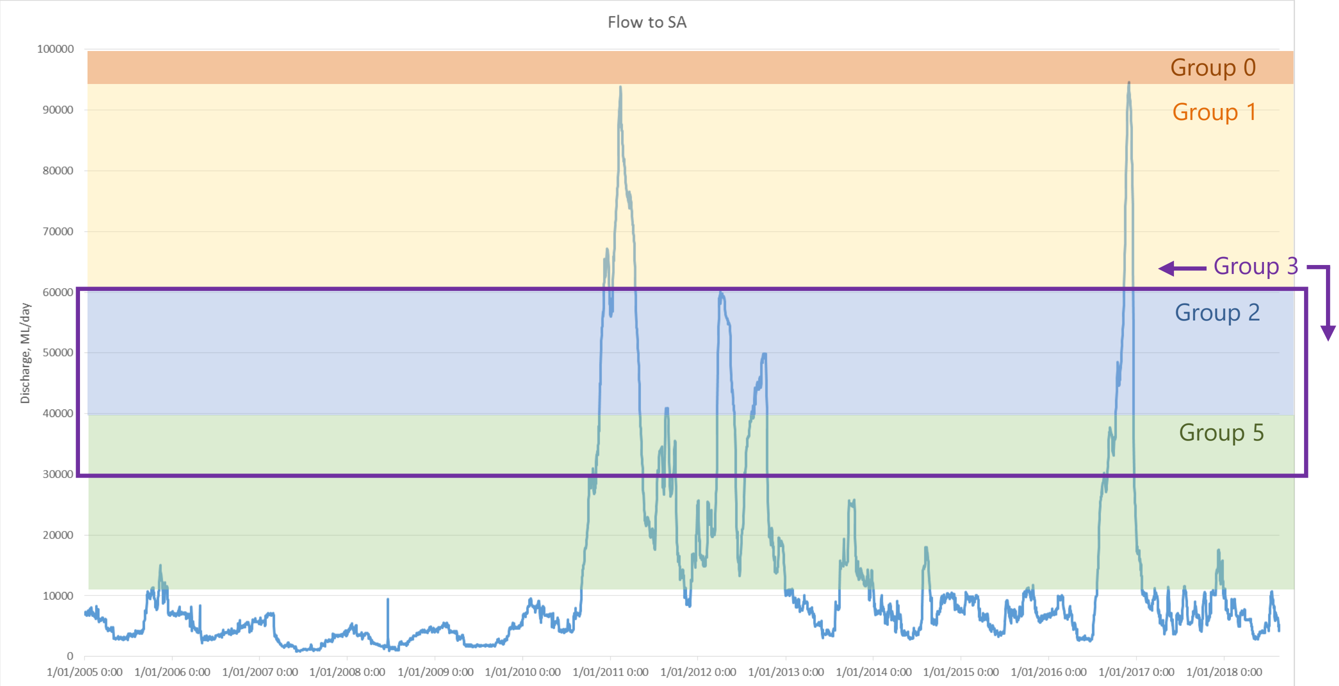

Figure 2-2: Flow to South Australian River Murray showing inundation thresholds used to classify tree condition transects.

Table 2-3: Description of inundation history for watering groups.

Group 0	Not inundated 2009 – 2018. Require flows >95 000 ML.day^{-1} for inundation
Group 1	Inundated 2011 (x1) and 2016 (x1). Inundated at flows 60 000 – 95 000 ML.day^{-1}
Group 2	Inundated 2011, 2011/2012, 2012, 2016 (total of 5 events, consisting of follow up flows for 2011 major event, and 2016 event)
Group 3	Pumped wetlands (otherwise inundated at flows 30 000 – 60 000 ML.day^{-1})
Group 4	Subject to weir pool raising. No sites.
Group 5	Within 50 m of permanent anabranch (inundated at flows 5 000 – 40 000 ML.day^{-1})

Table 2-4: Transects by tree species, year of survey and watering history group.

	Floodplain tree species				Survey years	
	River Red Gum	Black Box	River Cooba	Mixed species	2015 and 2016	2018
Group 0	-	3	-	1	0	4
Group 1	1	19	1	3	7	24
Group 2	2	6	2	1	5	11
Group 3	3	2	2	-	5	7
Group 4	-	-	-	-	-	-
Group 5	7	1	-	4	3	12

Total	**13**	**31**	**5**	**9**	**20**	**58**

Table 2-5: History of environmental water delivery at the Group 3 transects

Location	2008/2009	2009/2010	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	2015/2016	2016/2017	2017/2018
Carparks Lagoons										
Piggy Creek										

2.3 Analysis workflow

All data analysis and report writing was done in a single scripted workflow (script file: Report.Rmd using the programs 'R' and 'R-studio'.

R (R Core Team 2017a) is an open-source platform which makes available a library of packages that can be used and modified as necessary. R-studio provides a range of user-friendly features to facilitate interaction with R. The packages used are listed in Appendix B: R packages used.

All data, code and outputs are stored on DEW corporate data systems (R:/IST/SRC/MonSurv/MERF/DocWorksp/RC/projects/fpTrees).

2.4 Model

Trend in TCI was analysed using a Bayesian generalised linear mixed model. A Bayesian modelling approach provides the capability to prepare a posterior probability distribution that is amenable to re-sampling and interrogation that would not be possible using frequentist or 'classical' approaches to statistical analysis. This particularly useful when asking questions of the data such as, 'what is the likelihood that treatment 1 has higher values than treatment 2 at time x'.

The analysis was run using the rstanarm package (Stan Development Team 2016) in R (R Core Team 2017b). Transect was treated as a random effect in the analysis. Its inclusion as a random effect recognises the possibility that trees in the same transect may be more similar to one another than to trees in other transects. Each tree was then assumed to provide an independent data point for the analysis. A time field was generated as \(time = min(Year) + (max(Year) - min(Year))/2\). The model specification was:

cbind(TCI, 14 - TCI) ~ time * Species * HYDRO_GP + (1 | Transect)

2.5 Final data-set

The original data-set proposed for analysis included trees from all transects described in Figure 2-1 and Table 2-4, comprising 1 740 trees in total, 600 of which had been observed in three years and 1 140 of which had only been observed in 2018.

Through iterative model processing and review of interim results, the trees that were monitored in only 2018 were discarded from the analysis. Preliminary processing suggested that the condition of trees in the transects that were set up, and therefore only monitored, in 2018 was not representative of the condition of trees in transects that were set up in 2015 (indicated by poor model fit). Subsequent re-inspection of transects in the field indicated that the initial (2015) monitoring design was likely to have intentionally excluded defoliated trees, whilst the transects set up in 2018 included defoliated trees. Furthermore, the monitoring set up in 2015 did not necessarily sample nearest neighbours along transects, with the rationale for this being unknown. Discarding the transects that were only monitored in 2018 resulted in there being no transects representing watering history group "0" (no inundation during the study period), and a final data-set that included only 20 transects, representing 600 trees.

3 Results

Results pertaining to the evaluation question are presented here. A selection of model diagnostics (i.e. that describe the model performance) are provided in Appendix C.

3.1 Tree condition index (TCI)

The TCI distributions for each tree species in each year are summarised graphically by watering history group in **Error! Reference source not found.**. This shows a shift to higher condition scores over the three monitored years, with the exception of transects in Group 5 where TCI was stably 'good' (median TCI score of 11) in all three monitored years. The median estimates for TCI from this analysis are provided in Table 3-1.

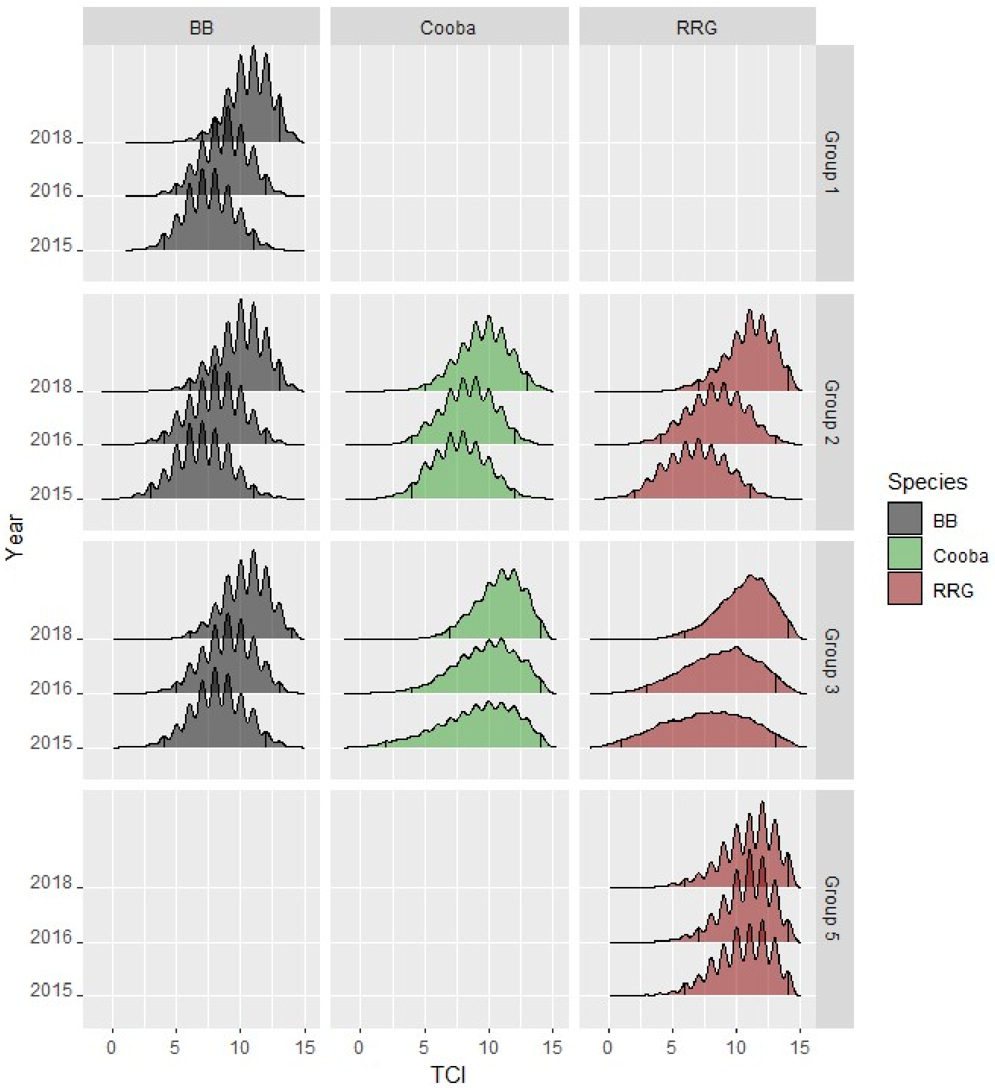

Figure 3-1: Distribution of TCI values. Vertical lines on each distribution represent 95% credible intervals. Groups 1 to 5 are watering history groups, described in Table 2-3.

Table 3-1: Median estimate for TCI

Watering history group	Year	Black Box	River Cooba	River Red Gum
Group 1	2015	8		
	2016	9		
	2018	11		
Group 2	2015	7	8	7
	2016	8	9	8
	2018	10	10	11
Group 3	2015	8	10	8
	2016	9	10	9
	2018	10	11	11
Group 5	2015			11
	2016			11
	2018			11

The credible range (i.e. Bayesian equivalent of the confidence interval) within which 95% of TCI scores occur for each species, in each year, by watering group is provided in Table 3-2. With the exception of mid floodplain elevation (Group 2) River Cooba and near anabranch River Red Gums (Group 5), the range in TCI scores reduced over the three years of monitoring. The widest variation in TCI occurred in the transects at managed wetlands (Group 3) in the first two years.

Table 3-2: 95% credible interval range for TCI

Watering history group	Year	Range in TCI (and lowest and highest TCI in range) Black Box	River Cooba	River Red Gum
Group 1	2015	7 (4 to 11)		
	2016	6 (6 to 12)		
	2018	5 (8 to 13)		
Group 2	2015	7 (4 to 11)	7 (4 to 11)	8 (3 to 11)
	2016	6 (5 to 11)	7 (5 to 12)	8 (4 to 12)
	2018	6 (7 to 13)	7 (6 to 13)	6 (8 to 14)
Group 3	2015	7 (5 to 12)	9 (4 to 13)	11 (2 to 13)
	2016	6 (6 to 12)	8 (5 to 13)	9 (4 to 13)
	2018	6 (7 to 13)	7 (7 to 14)	7 (7 to 14)
Group 5	2015			7 (7 to 14)
	2016			7 (7 to 14)
	2018			7 (7 to 14)

3.2 Difference in tree condition between Group 2 and other watering history groups

An assessment was made of the likelihood that TCI was higher in transects of Groups 1, 3 and 5 compared with TCI in Group 2 transects, in each monitored year. This comparison was undertaken to directly assess the evaluation question, i.e. are the trees in transects that received environmental water in better condition than the trees in transects that did not receive environmental water? All comparisons are made to Group 2 because Group 2 transects are inundated across a range of river discharge that is broadly comparable to the range of discharge that inundates the Group 3 managed wetlands (the key group of interest that received environmental water) under unregulated flow (see Figure 2-2 and Table 2-3).

In order to better understand how the data and resulting model are able to inform management, a number (4000) of simulations were made based on the model results (strictly, draws were made from the posterior predictive distribution). Each simulation generated a prediction based on a single draw of the model parameters from their predicted distributions. Thus, for each simulation a predicted value for each species, watering group and year were available. For a species within a year, the difference in TCI for each simulation was based on the difference between Group 'x' and Group 2 (i.e. for a species in a year, Group X TCI – Group 2 TCI). Thus, a value of greater than 0 indicates the simulation predicted Group X TCI as higher than Group 2 TCI. The result of doing this 4000 times gave the distributions shown in Figure 3-2. The red dashed line in the centre of each plot marks zero, or no, difference between Group 2 TCI and Group 1, 3 or 5 TCI. Negative and positive values for the difference between Group 1, 3 or 5 TCI and Group 2 TCI are distributed to the left and right of this line. These distributions are summarised in Table 3-3 as the likelihood that Group X had a higher TCI than Group 2 (i.e. 100 * count(differences>0)/4000). Note that this summarised value does not provide any information regarding the magnitude of any difference.

3.2.1.1 Summary for 2015

In 2015 the Group 2 and Group 3 transects had not been inundated by unregulated high flow since Spring 2012. The Group 3 transects had received environmental water during this period and Black Box and River Cooba were somewhat likely to be in better condition (have a higher TCI score) than trees in Group 2 transects (Table 3-3, 61.5% and 62.7% of results respectively). The likelihood of a higher TCI score for River Red Gums in the watered transects was less compelling with 54.5% of the results being positive values (higher TCI score). For River Red Gum in Group 5 (i.e. close to permanent creeks), TCI scores were likely to be higher (84.2%, Table 3-3) than for trees in Group 2 transects. The results showed essentially the same (i.e. 51.1% likelihood of TCI being higher, Table 3-3) TCI scores for Black Box in Group 1 transects as Black Box in Group 2 transects.

3.2.1.2 Summary for 2016

In 2016, Black Box and River Cooba in the watered transects (Group 3) remained more likely to be in better condition than Black Box and River Cooba in Group 2 (Table 3-3, 58.2% and 62.4% respectively). River Red Gums in Group 3 were as likely to score higher as to score lower than Group 2 River Red Gums in 2016. The Group 5 River Red Gums adjacent permanent anabranches remained in better condition than Group 2 mid-elevation floodplain River Red Gums. Again the results showed essentially the same (i.e. 52.5%, Table 3-3) TCI scores for Black Box in Group 1 transects as Black Box in Group 2 transects.

3.2.1.3 Summary for 2018

Neither Black Box nor River Red Gum at watered transects (Group 3) or near anabranch transects (Group 5) were likely to have higher TCI scores than Group 2 transects in 2018, just over a year after high unregulated flows that inundated the majority of the floodplain.

The likelihood of River Red Gums in Group 3 and Group 5 transects having higher TCI scores than Group 2 River Red Gums was 35.1% and 40.3% respectively (Table 3-3).

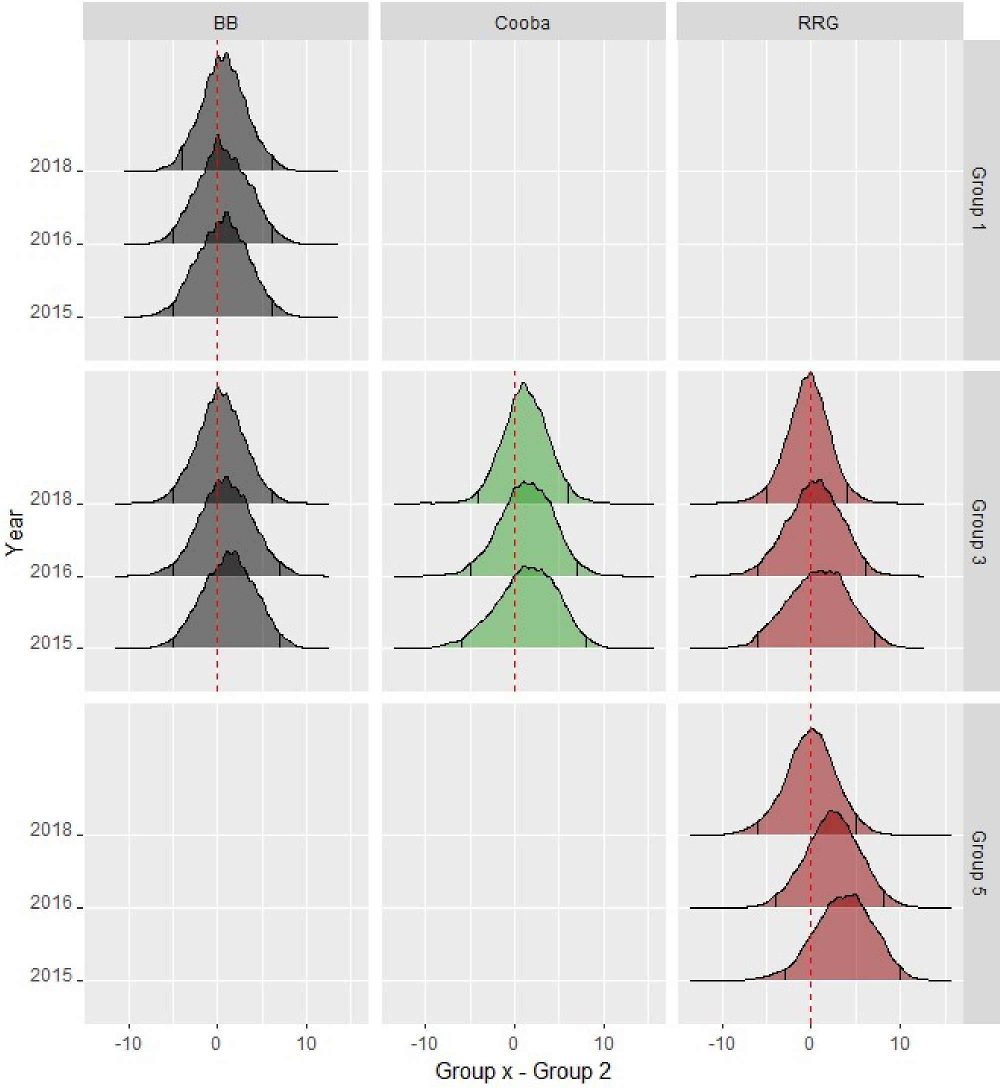

Figure 3-2: Distribution of credible values for the difference in TCI between Group 2 and other transects. Vertical lines on each distribution represent 95% credible intervals.

Table 3-3: Likelihood of higher TCI in each Group compared to Group 2

		Percent likelihood of higher TCI for tree species		
Watering history group	**Year**	**Black Box**	**River Cooba**	**River Red Gum**
Group 1	2015	51.1		
Group 1	2016	52.5		
Group 1	2018	50.5		
Group 3	2015	61.5	62.7	54.5
Group 3	2016	58.2	62.4	49.6
Group 3	2018	45.9	62.2	35.1
Group 5	2015			84.2
Group 5	2016			74.7
Group 5	2018			40.3

4 Summary discussion

4.1 Key findings

Using these particular data the analysis suggests that at Katarapko Floodplain:

1. when comparing areas with similar unregulated flooding history, TCI was likely to be higher during dry periods at tree transects that had received additional environmental water, compared with tree transects that had not received additional environmental water
2. tree condition across transects with varying watering history can converge following a large unregulated flow
3. trees adjacent permanent waterbodies are more likely to maintain better condition and their condition is less variable over time compared with the condition of trees at temporary wetlands and floodplain transects

These are general patterns of change and difference between watering history groups that are plausible with reference to our conceptual understanding of tree response to changes in soil moisture and with reference to knowledge of the study site.

There are, however, limitations in the data coverage and distinctive site-based characteristics of this particular data-set that imply that the results should not be generalised. In addition, causal explanation of observed patterns is challenging where analysis of historical data seeks to answer evaluation questions that the data were not originally intended to address.

4.2 Key limitations

Whilst the hypothetical ability to utilise a large volume of data is a potential advantage of pooling historical tree condition data, many knowledge gaps can only be validly examined through a well-designed intervention monitoring programme.

The data analysed here span only three years and the surveys were conducted at different times for each survey, ranging from late Winter (2016), Spring (2015) to Autumn (2018). Changes in crown condition may occur over multiple years in response to a series of inundations, rather than as a response to a single watering event. The varied seasonality of data collection and unequal inter-survey timing within so few surveys may exaggerate an apparent directional change in condition over a short period of time, and could create "noise" in the long-term trend/trajectory due to normal seasonal variability in condition. The actual magnitude of inter-season variation is currently an "unknown" and could be very difficult to untangle in highly stressed systems where water availability will decline markedly during inter-flood periods, and/or improve markedly at actively managed sites. It is likely that site specific changes in soil water potential will have more impact on driving observable short-term changes in crown extent and density than variability in seasonal timing of assessment.

None of these data were collected prior to the environmental watering intervention, precluding direct assessment of change in the condition of the watered trees. Using transects inundated at similar flow thresholds as 'reference sites' has supported meaningful comparisons. However, the transects treated as reference sites (Group 2) cannot be considered to have been subjected to an 'equivalent' unregulated inundation history as the Group 3 managed sites. The Group 2 and 3 transects have varying inundation thresholds for unregulated flow, and the watered sites, Carparks Lagoons and Piggy Creek, have different pumped watering histories to one another.

Importantly, the decision to deliver environmental water will not have been made independently from (i) the initial condition of the trees, and (ii) the engineering feasibility of delivering and retaining environmental water at these locations.

The most up-to-date conceptual models (Wallace et al 2018, Bond et al., 2018) highlight that tree condition responses to watering will be dependent on antecedent conditions and prevailing condition of trees; trees at the low and high end of the condition range are expected to respond markedly differently to trees in the middle of the condition range. This is an important consideration when interpreting Key Finding #2. The results indicate that in 2018, River Red Gum in Group 3 (received environmental water through pumping) were unlikely to be in better condition that trees in Group 2 (did not receive additional water). This counter-intuitive result may be due to a number of factors. For example, the environmental watering may have supported an initial improvement in condition from a "poor" pre-watering baseline, and thereby facilitated further improvement in condition following the 2016 high flows. However, if these trees were watered on the basis of being in "poor" initial condition, they may have been approaching the high to maximum achievable CD scores in 2018, but limited CE scores due to the some sections of the existing branching structure not having any live sapwood to support foliage (i.e. pre-watering drought stress and loss of sap-wood may have created an enduring limitation that precludes some of the trees in Group 3 achieving an equivalent or higher TCI than trees in Group 2.

It is important to recognise that it is the sequence of inundation events and their effectiveness at maintaining soil water potential (soil moisture availability) in the range conducive to tree recovery and continued growth, rather than the "type", or mechanism of delivery, of watering that is expected to influence tree condition outcomes. The unregulated flows in 2010-11 and 2016-17 inundated the majority of floodplain and wetland transects. In contrast, at watered wetland sites pumping may not have inundated all trees in the transects, simply due to the managed delivery of water achieving lower water levels than those attained during large unregulated flows. As a result, some Group 3 trees may have experienced a watering history closer to trees in Group 2 transects.

The ecological targets for floodplain trees under a range of environmental management programmes operating in the South Australian Murray-Darling Basin include targets for tracking tree loss as well as crown condition (DEWNR, 2017a, 2017b, Kilsby & Steggles, 2015, Wallace et al., 2014). The initial transect set-up at Katarapko Floodplain did not include defoliated trees and may not have sampled closest neighbours, with the original rationale for excluding some trees unknown. The distribution of trees scoring "0" (defoliated, likely to be dead) was not able to be analysed due to the incompatibility of set-up between the 2018 and earlier established transects. Hence, the effectiveness of environmental water in preventing tree loss during extended dry periods, a crucial outcome sought from environmental watering, was not able to be investigated. However, the results of the study do suggest that environmental watering does have long-term benefits in providing maintenance flows.

The good condition of trees adjacent permanent anabranches (Group 5) in this study is consistent with a conceptual assumption that they may have access to a permanent fresh water source. This is not representative of trees situated in a similar landscape position at floodplains influenced by shallow saline groundwater.

5 Conclusions and recommendations

In response to the evaluation question *Are the trees at sites that received managed environmental water in the years preceding and between unregulated high flows, in better condition than those sites that only received water during unregulated flows?* this study found that:

1. in 2015, a year preceded by multiple dry years (no unregulated flooding since 2012), trees that had received environmental water during the inter-flood dry phase were in better condition than trees that did not receive environmental water.

2. in 2018, following unregulated high flows in 2016-17, the trees that had received environmental watering during the inter-flood dry phase were not in better condition than trees that did not receive environmental water.

These results are only valid for trees with comparable long-term hydrological regimes. There are a range of site and programme-specific factors that limit the generalisation of these findings (documented, along with additional points of interpretation regarding these key findings in Section 4).

The modelling approach to predict the posterior distribution of TCI has potential to be further developed as a tool to model theoretical reference condition for groups of trees. This could support assessment of observed versus expected tree condition at sites with known watering history (depth and duration of inundation at the specific location of trees within transects) and geophysical (e.g. soil type, soil salinity, groundwater salinity, soil water potential) and other location specific characteristics including rainfall and evaporation. This would require coupled hydrological data for reference and monitored sites of interest, and is not a trivial exercise, primarily because such data only exists for an extremely limited number of sites.

Lack of coupled, detailed watering history for sites where tree condition has been monitored was a major obstacle to assessing many of the evaluation questions initially proposed under this project. The inability to rapidly reconstruct detailed hydrological information for tree monitoring transects across numerous sites prevented the initially proposed 'big data' approach to this project. The capacity to track tree condition over time in relation to environmental watering actions and unregulated flows should be considered a strategic priority to enable evaluation of the Department's environmental watering programme and to meet evaluation and reporting obligations under the Basin Plan. There will be an on-going need to evaluate the influence of environmental watering actions, including the ability to associate watering actions with transect-scale monitoring observations. This information cannot readily be extracted from existing corporate databases and it is recommended that opportunities to integrate information from BDBSA and the Management Action Database (MAD), or develop a purpose-built information management solution, be investigated.

A simple and efficient supply chain that results in corporatisation of tree condition monitoring data at the completion of projects must be maintained. Whilst this project has directed resources to transforming the format of some data captured in the past, the recent development of a data load template for TLM method tree condition observations should improve the standardisation and ease of retrieval of this data from BDBSA.

6 Appendices

A. Phase 1 evaluation question refinement

Tables A-1 to A-8 document the rationale behind refinement of the evaluation question and the identified obstacles to pursuing some of the draft questions.

Table A-1. Draft evaluation questions that related specifically to data profiling and that were partially or fully addressed through Phase 1 and therefore did not need to be pursued in Phase 2.

Draft evaluation question	General comments/queries in response to evaluation question
What overstorey tree condition data do we have/are we collecting?	These questions have been addressed through data profiling in Stage 1, including facilitating the corporatisation of tree data and entry into BDBSA (section 3)
Where are the tree data?	
What periods do we have repeated measures for?	
Do we have watering data for the same periods as the tree condition data?	There is generally no surface water information collected in association with the tree condition monitoring. There are records of duration of management actions, such as pumping, kept for water accounting, planning and evaluation and reporting purposes. In the field, some observers have recorded whether a site was in a dry, falling or rising limb stage. However, actual water level or whether individual trees are inundated is not generally recorded. If required for analyses, detailed watering history will need to be reconstructed from hydrological models and flow records from the River Murray weir closest to the relevant wetland or floodplain. Ability to reconstruct watering history from satellite imagery is limited (see section 4)
Where can we add water? At what flow bands?	Essentially addressed via the compiled data profile which identifies which sites may have been influenced by weir pool raising and lowering, which sites have been actively managed (managed drawdown, gravity based deliver, pumping) operation of the Chowilla Environmental Regulator, potential inundation extents for the planned infrastructure at Pike and Katarapko.
Are we collecting tree condition data in the right places at the right times?	Annual condition data for what purpose? As a key input to managing individual wetlands/weir pools/ floodplains, or for reporting on condition at the whole of SA PEA scale? This is a very open ended question that requires more clarity.
What is the watering history?	Requires reconstruction of hydrology. There are a number of potential approaches to this, each of them have challenges/limitations. See section 3 for more information.

Table A2. Draft evaluation questions that relate specifically to current state of knowledge on drivers of tree condition

Draft evaluation question	General comments/queries in response to evaluation question
Do our conceptual models need updating? i.e. were the changes in condition what we expected under particular hydrological conditions?	There have been several recently released versions of updated conceptual models e.g. Bond et al., (2018), Wallace et al., (2018) that represent the most up-to-date understanding. Hence this is not likely to be a major task requiring substantial attention in the near future
What have we learnt about environmental water management and responses of overstorey vegetation condition?	There has been a very large improvement in knowledge on (i) tree responses to delivery of water to stop/reduce the death of trees after an extended dry period, and (ii) recovery of heavily stressed trees as environmental water availability and ability to deliver it has improved. There is still a very large gap in understanding of medium to long-term maintenance regimes, as few sites have made the transition from completion of the “recovery watering” phase to being in the “maintenance watering” phase.

Table A3. Draft evaluation questions that relate specifically to updating Environmental Water Requirements

Draft evaluation question	General comments/queries in response to evaluation question
What does this mean for EWRs ?	EWR’s are a simplification of ecosystem water demands developed using data on ecological response to hydrological regime. They are extremely useful for long-term planning, but trees do not respond directly to discharge at the individual or stand scale. Whilst estimates of return interval to maintain the condition of floodplain trees converge on ranges that provide guidelines for hydrological management, site-scale and geographic variation between studies is found (e.g. Casanova, 2015, Rogers and Ralph 2011, Roberts and Marston, 2011). This is because tree condition and trajectory is driven by a much more complex interaction of factors that vary spatially and temporally. i.e. return interval and duration of inundation are only a sub-set of the key drivers of condition and trajectory. Furthermore, EWRs assume trees are good starting condition. Hence using EWR’s as the key input to determine the need/priority of watering is not valid where (i) initial condition is poor and management actions need to facilitate recovery, or (ii) there are additional location specific stressors that do/did not occur under unregulated river conditions.

Table A-4. Draft evaluation questions that related specifically to ability to report against existing ecological targets

Draft evaluation question	General comments/queries in response to evaluation question
Were changes in tree condition apparent?	This question is already answered *via* existing annual reports for respective sites (or groups of managed sites). There is opportunity to compare the ability to detect change using a system that bins field data into categories (e.g. TCI) compared to a method that retains the full resolution of the field data (e.g. mTCI). It is important to note that the purpose behind this would need to be made very clear to justify the effort. Where there is a need to detect small changes in condition, this should be addressed through intervention monitoring programs with repeat surveys at short (e.g. monthly) intervals, *not annual condition monitoring surveys*. Annual monitoring reports for Chowilla, Pike and Katarapko have already demonstrated that the TCI system is effective at detecting trends in condition and providing managers with easily interpretable data to underpin management decisions. In addition, Wallace et al., (2018a) recently reviewed different methods of combining field data into a tree condition index and made clear recommendations that TCI is effective for low frequency (e.g. annual) sampling.
Are we meeting our targets for overstorey vegetation at the site scale?	Site scale targets are already reported on annually for the large floodplains. Existing reporting at the large sites (Chowilla, Katarapko) is effective, and demonstrates that intensively managed sites are meeting the Ecological Targets.
If we are meeting the targets at the site scales, what is the level of achievement of targets at the system scale?	Reporting at the reach or system scale is incomplete. The data profile demonstrates that there is substantial skew in the spatial distribution of data that does not adequately support system scale summaries. Summaries could be split by reach for increased transparency regarding the volume of data available along the River. The available data for the river channel and floodplain PEA is being assessed through Matter 8 reporting, and hence this does not fit as a priority task for this project
If no tree condition response is demonstrated by analyses using TCI, investigate whether a response is demonstrated by RCI	RCI is a proposed method that is not currently in use. The RCI method does not provide a score system compatible with the existing ecological targets. RCI will not provide a higher level of resolution of changes in CE and CD, as the field scores for those attributes are binned into the same categories as the TCI method. In addition, the RCI method weights and combines the scores for CE and CD with six secondary attributes. The weighting and consolidating of primary attributes (CE and CD) that change over months-years, with secondary attributes that respond rapidly (weeks) to improved soil moisture availability and secondary attributes that respond to seasonal and antecedent conditions or reflect habitat utilisation by transient biota confounds interpretation of which attributes are changing. See section 2.

Table A-5. Draft evaluation questions that related specifically to hydro-ecology for which there was not sufficient data to facilitate investigation in Phase 2

Draft evaluation question	General comments/queries in response to evaluation question
Are there differences in tree condition as a result of their position in the landscape? i.e. is there evidence that trees higher on the elevation gradient have a different biotic watering requirement? Can this be quantified?	Tree condition will vary with elevation gradient, but this will be due to a complex interaction of interrelated factors including changes in soil type, depth to groundwater, groundwater salinity, rates of evaporation and transpiration, effective vertical infiltration, and possible lateral infiltration via hyporheic flow paths. Sufficient data to pursue this is not available
Do short inundation events (e.g. 7-days) improve tree condition?	What magnitude of improvement and what measure of condition is of interest? It has been demonstrated that floodplain eucalypts respond physiologically (improved pre-dawn shoot water potential and increased transpiration) in response to rainfall. It is also acknowledged that in circumstances where trees are overlying saline groundwater and are not frequently inundated, they are persisting on rainfall. It is intuitive that short duration floods will deliver more water to the soil profile than a rain event, and hence an improvement in tree water status (physiological condition) would be expected as a response to short inundations, but there may or may not be a recordable increase crown extent and crown density (visual condition). There may be increases in some secondary attributes such as new tip growth (see section 2). Failure to record an improvement in TCI does not mean that the watering was not beneficial. Data on tree water status and soil water availability is scarce outside of specifically target intervention/research projects, and data on visual condition (TCI) is not collected annually at all sites. Responses will be highly site specific and dependent on the antecedent conditions of the unsaturated zone including soil moisture, soil salinity, soil water availability (total water potential), and localised variability in vertical and lateral infiltration. Also requires detailed reconstruction of hydrology
Are there differences in tree condition as a result of the type of wetland – e.g. temp vs pool level permanent wetlands managed with infrastructure to enable wetting and drying	Tree condition may vary between these types of wetland, as the hydrology is fundamentally different between three wetland "types". Type 1 is normally dry (laterally disconnected from the river channel at normal weir pool levels by elevation), with water being added via pumping to provide wet cycles. Type 2 is normally wet (laterally connected to the river channel at normal weir pool level, with a regulator being closed on a planned cycle to facilitate a dry phase *via* evaporation /seepage of the water held within the wetland. Type 3 is normally dry, (laterally isolated from the river channel at normal weir pool level via a regulator that is closed), but the regulator is opened on a planned cycle to facilitate a wet phase, and then closed to reinstate a dry phase. The differences in imparted regimes (long dry with intermittent wet v's long wet with intermittent dry) may produce different outcomes. However, interpreting outcomes will be very complex due to differences in imparted wet/dry regime with interactions/feedbacks loops driven by changes in soil type, depth to groundwater, groundwater salinity, rates of evaporation and transpiration, and magnitude of effective vertical infiltration, and possible lateral infiltration via hyporheic flow paths. This type of data is extremely scarce.
Can we demonstrate a tree condition response to the operation of Salt Interception Schemes	There are very few examples where there is existing data that is paired (tree condition, groundwater) within the influence of the SIS schemes (see section 6).

Table A-6. Draft evaluation questions that related specifically to key knowledge gaps in hydro-ecology that could have been pursued in Phase 2, but were unlikely to be answerable due to lack of appropriate data and/or the logistics involved (project time frame, finances, human resources) were prohibitive

Draft evaluation question	General comments/queries in response to evaluation question
What is the watering history?	Requires reconstruction of hydrology. There are a number of potential approaches to this, each of them have challenges/limitations. Reconstruction of hydrology may be “relatively easy” for most sites, if the level of resolution required is only to understand if a site received water in a month(s) of a given year (e.g. Tables 4 and 5). However, generating site specific data on water level, duration of inundation, if individual trees were inundated, or if trees were within a specified distance from the wet edge (e.g. <50 m) is very challenging and may not be achievable for many sites (particular managed wetlands). Sites with calibrated and reliable inundation models built for operation of large environmental regulators (Chowilla, Pike, Katarapko) have the most potential for reconstruction of hydrographs at a relatively detailed level. See section 3 for more information on reconstructing watering history (hydrology).
Are there difference in condition / responses due to starting condition of the trees?	That the duration of the “recovery period” is markedly affected by starting condition has been clearly demonstrated by a recent review (Wallace et al., 2018a) of data from Chowilla, Lindsay-Mulcra-Wallpolla and Hattah Lakes. Those authors demonstrate that trees with TCI scores of 5 require a very long period (>10 years) of high intensity watering to facilitate recovery. In comparison, trees with TCI scores of 8 or 9 attain the Ecological Target in a markedly shorter period. A similar review of data from other managed sites could be undertaken, but outside of Chowilla, the number of areas e.g. wetlands/depressions or creek reaches with multiple transects is very limited and therefore there is likely to be very low numbers of trees in the respective starting conditions. This is exacerbated by the fact that many sites have had water delivered on one or more occasions before tree condition data was collected (Table 3), so at many sites the condition of trees prior to intervention (true “starting” condition) is not known. Pooling data from multiple sites to attain sufficient replicates of trees in different starting conditions is problematic, as each site will have nuances in the hydrological regime (e.g. timing, duration, return intervals), site specific soil and groundwater conditions, and climatic conditions (rainfall, evaporation and transpiration) that will confound interpretation (pooling data is not recommended). Hence there may be limited gains in knowledge from investing into this question.

Table A-7. Draft evaluation questions that related specifically to hydro-ecology that could have been pursued, and were refined as potential options to be analysed in Phase 2

Draft evaluation question	General comments/queries in response to evaluation question
Do 'managed' inundation events generate a different response in tree condition than inundation via connected high flow events?	As changes in tree visual condition are known to occur in response to cumulative events, an analysis of condition monitoring data (i.e. annual surveys) that is collected in the year "before" and year "after" individual watering actions has limited ability to infer which events are driving the observed changes. In addition, tree responses occur as a result of cumulative improvements in conditions over a multi-year period. For visual condition of heavily water stressed trees to improve in response to improved soil water availability, it is likely that they will first need to rebuild their roots and sapwood in order to access and transpire more water to facilitate supporting a larger crown. This may take many months or years. Hence, at the end of an extended dry period, the first watering(s), irrespective of method of delivery (managed delivery or unregulated flood) set up the capacity for trees to respond to subsequent events. Therefore where managed sites have had water delivered via a combination of managed inundations and unregulated flooding, it is not a trivial exercise to ascertain which inundation type is more effective, and there is a major risk of misinterpreting the results.
Are there differences in tree condition as a result of watering frequency/duration? (where watering includes both high natural flows and managed events such as pumping/infrastructure operation)	The condition of trees responds to changes in soil moisture availability in the unsaturated zone. Hence the only reason to anticipate a different response in tree visual condition is if one type of event (e.g. connected high flows events) is more successful in emplacing low salinity water into the unsaturated *via* vertical and lateral infiltration than the other (e.g. managed inundation). High river stage may be more likely to drive temporary increases in lateral freshening (increasing the lateral flux of water from the creek into the near bank soil profile and aquifer) than delivering water into relatively small, disconnected waterbodies. It is unlikely that there would be marked differences in vertical infiltration where the same area is inundated to the same/similar depth by managed inundation or unregulated flooding, unless there are marked differences in duration of inundation that would allow for increased infiltration (hence the events would not be comparable). Direct analysis to robustly answer this question requires detailed information on groundwater and soil conditions pre- and post- both types of events, data which typically does not exist. A refinement of this question that would be relevant to management of floodplain trees is *are sites that received managed environmental water (via pumping, weir pool raising etc) in the years preceding and between the unregulated high flows that occurred 2010-11, 2012, 2016-17, in better condition than those sites that only received unregulated flows?* This question could be expanded to comparing (i) sites at low elevation with good connection to the river that also experienced inundation during periods of moderate flow (e.g. 2012) in between 2010-11 and 2016-17, and/or (ii) separating those sites inundated by pumping and by weir pool manipulation. Data from 2017 and 2018 surveys would need to be sourced. The analysis could include the difference in (number of) condition classes between sites with/without management intervention. Providing there is sufficient data available to do so, a degree of control for tree starting condition can may be achieved by separately assessing the recorded change in condition between surveys for response of trees in different starting categories. However, given that many sites only have one transect, this may not be possible. Pooling data from multiple sites to attain sufficient replicates of trees in different starting conditions is problematic (Table 1F). Consequently it is recommended that sites should be considered separately. Identifying which sites fall into which categories, and the hydrological regime for most sites has already been identified as a major logistical challenge.
Do tree condition responses relate to watering history?	

Table A7 cont...

Draft evaluation question	General comments/queries in response to evaluation question
Is it possible to better describe a threshold for duration (i.e. minimum duration to generate an improvement in condition) and frequency (i.e. maximum interval between inundation events before a decline in condition becomes evident)?	If the focus is "duration of inundation" and "return interval" in the classic sense of EWR's (e.g. 30 days once every 2 years) then the question is not phrased in a manner consistent with understanding of tree response to inundation. The condition of trees responds to changes in soil moisture availability, not duration of inundation, or frequency of return events. If trees have access to sufficient soil moisture in the unsaturated zone *via* rainfall or low salinity groundwater, they do not need to be inundated at all to achieve or maintain good condition. Tree condition does not decline after a set period post inundation (e.g. 2 or 10 years); condition will decline when soil moisture availability falls to a level where transpiration is restricted, not after XXX number of elapsed days since last inundated. The duration for soil moisture availability to fall to where transpiration is limited, will be highly spatially and temporally variable, driven by variability in soil type (clay type or sand type), depth to groundwater, groundwater salinity, evaporation and transpiration from the unsaturated zone and the saturated zone, and rainfall. It is also important to define what magnitude of decline is of management concern. Using the standardised TLM field method, a decline in crown extent or density of 5% can be detected, but this may not require management intervention. If trees are "functioning" in a natural manner, small fluctuations (improvements and declines) in condition should be expected. It is when the magnitude of decline experienced during a dry phase requires a long-recovery period, or facilitates a deterioration of ecological function (ecosystem services) that management intervention is required. A threshold for management action of "*Within the area that can be influenced by management action(s), more than 10% of established viable† trees (river red gums, black box cooba respectively) with DBH > 10 cm receive TCI scores ≤8*" has already been adopted and implemented at Chowilla floodplain and within the draft monitoring programs for Katarapko and Pike floodplain. Questions relevant to management of floodplain trees are: *"what is the duration of inundation required to drive an ecologically meaningful improvement in soil moisture availability* *"post inundation* how long is soil moisture availability maintained within the range conducive to active growth of trees" The answers will be dependent on the antecedent conditions of the unsaturated zone including soil moisture, soil salinity, soil water availability (total water potential), and localised variability in vertical and lateral infiltration.
What is the frequency (or maximum interval between inundation events before a decline in condition becomes evident?	

Table A-8. Draft evaluation questions that related specifically to key knowledge gaps in knowledge of drivers of tree condition, that could have been pursued in Phase 2 but would not have focussed on "data mining" existing tree condition data

Draft evaluation question	General comments/queries in response to evaluation question
What remains as the critical knowledge gaps and improvements required to inform out management decision-making processes?	Critical knowledge gaps revolve include, but are not limited (i) processes required to make ecologically meaningful improvements in soil moisture availability, (ii) the duration of persistence of sufficient soil moisture availability in different settings, (iii) development of low cost, low invasive techniques to measure soil water availability, (iv) understanding of rates of ET and how they will change, and salt accumulation in the unsaturated zone will change in response to changes in groundwater level associated with managed inundations and proposed floodplain groundwater management schemes
Can the biotic watering requirements of trees in the lower Murray be better quantified?	Refining knowledge of biotic watering requirements requires separating geo-physical from biotic parameters, and therefore requires monitoring data on soil condition, tree physiology such as transpiration. This type of data only exists for a very small number of sites over discrete time periods, and what does exist has already been published by the relevant researchers. This is a key knowledge gap that requires targeted research
Are there differences in condition/ responses to watering that can be attributed to soil or groundwater conditions?	Site specific physical characteristics such as soil type and groundwater regime will be key drivers in response. Intrinsic factors such as genetic variation between tree populations, tree form and tree density may also be strong influences on observed responses. However, there is little systematically collected and co-located soil, groundwater and vegetation monitoring data available for use in assessing this question. Wallace et al (2018 b) compared tree crown condition (TCI) with tree physiology (pre-dawn shoot water potential, tree transpiration), groundwater depth and salinity, and soil condition (pH, EC, gravimetric water content, total soil water potential) relative to known/perceived thresholds to address a number of key knowledge gaps in the links between *soil water availability* ↔ *tree physiology* ↔ *tree visual condition*, and the decision making process for prioritising sites for management action. This evaluation question could be refocused to "*Post inundation, does plant condition decline at a faster rate in areas underlain by saline groundwater when compared to areas underlain by fresher groundwater*" This could be investigated using 3- monthly Landsat products that describe green vegetation cover. A grid of points could be used to extract data from the underlying AEM (as representative of groundwater salinity) and vegetation ecotype layers (which will support stratification by other factors). Reported metrics could include duration of time to maximum green cover following watering; duration of time to return to a defined 'baseline'; comparison of perennial versus annual/short-lived plant response. Separation of the response from ephemeral growth may be used as indicative of drying of the top of the soil profile.

B. R packages used

R (R Core Team 2017a) packages used in the production of this report:

Package	Citation
base	R Core Team (2017a)
bookdown	Xie (2018a)
DataExplorer	Cui (2018)
dplyr	Wickham *et al.* (2018b)
DT	Xie (2018b)
forcats	Wickham (2018a)
ggplot2	Wickham *et al.* (2018a)
ggridges	Wilke (2018)
gridExtra	Auguie (2017)
knitr	Xie (2018c)
lubridate	Spinu *et al.* (2018)
mgcv	Wood (2017)
purrr	Henry and Wickham (2019)
readr	Wickham *et al.* (2017)
readxl	Wickham and Bryan (2018)
rstan	Guo *et al.* (2018)
rstanarm	Gabry and Goodrich (2018)
stringr	Wickham (2018b)
tibble	Müller and Wickham (2019)
tidyr	Wickham and Henry (2018)
tmap	Tennekes (2018)

C. Model diagnostics

TCI vs residuals

Figure B-1 shows residuals plotted against TCI. Ideally these residuals will show no pattern - i.e. randomly distributed about zero. However, in this case, at low values of TCI the model is under-predicting (negative residuals) while at high values the model is over-predicting (positive residuals).

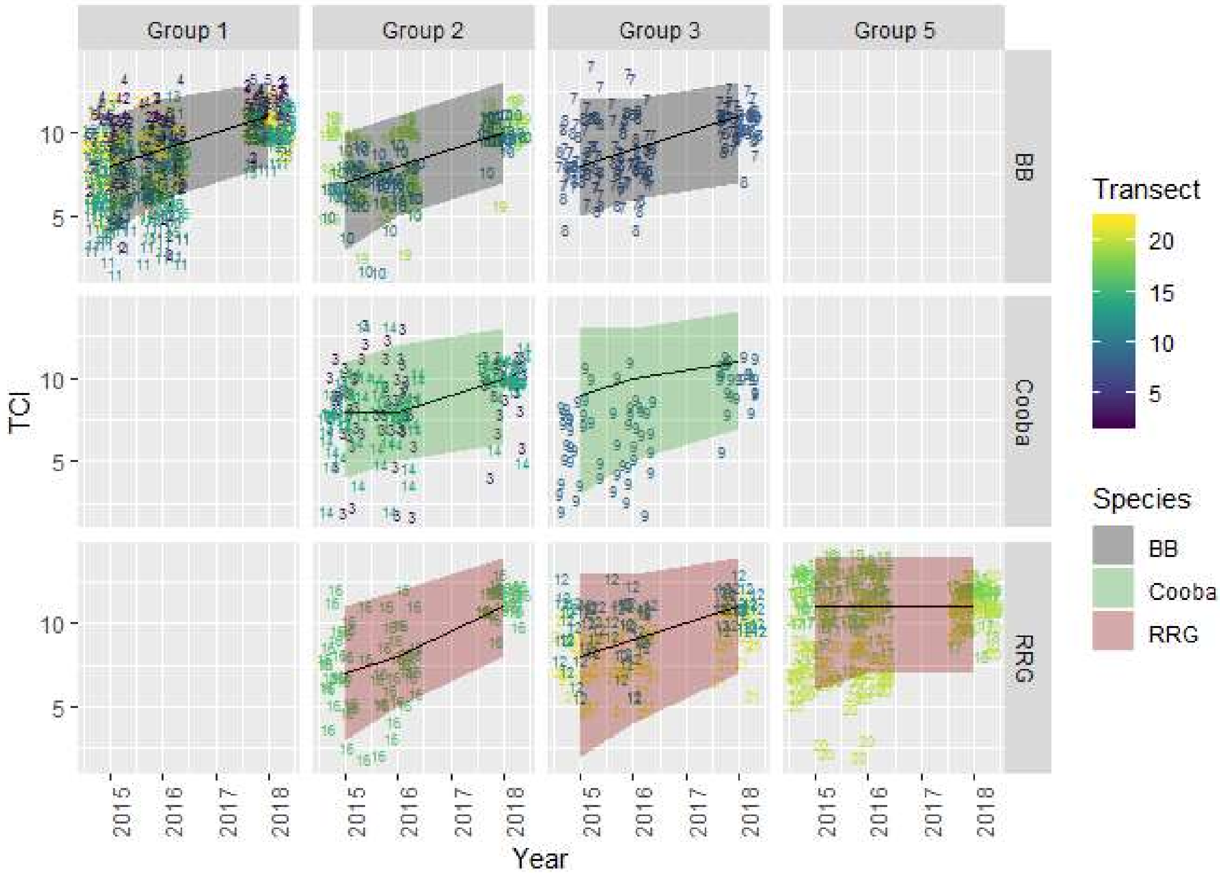

Figure B-1: Residuals

Model fit

Figure B-2 shows how a subset of the model runs (light blue lines) fit to the original data (dark blue line).

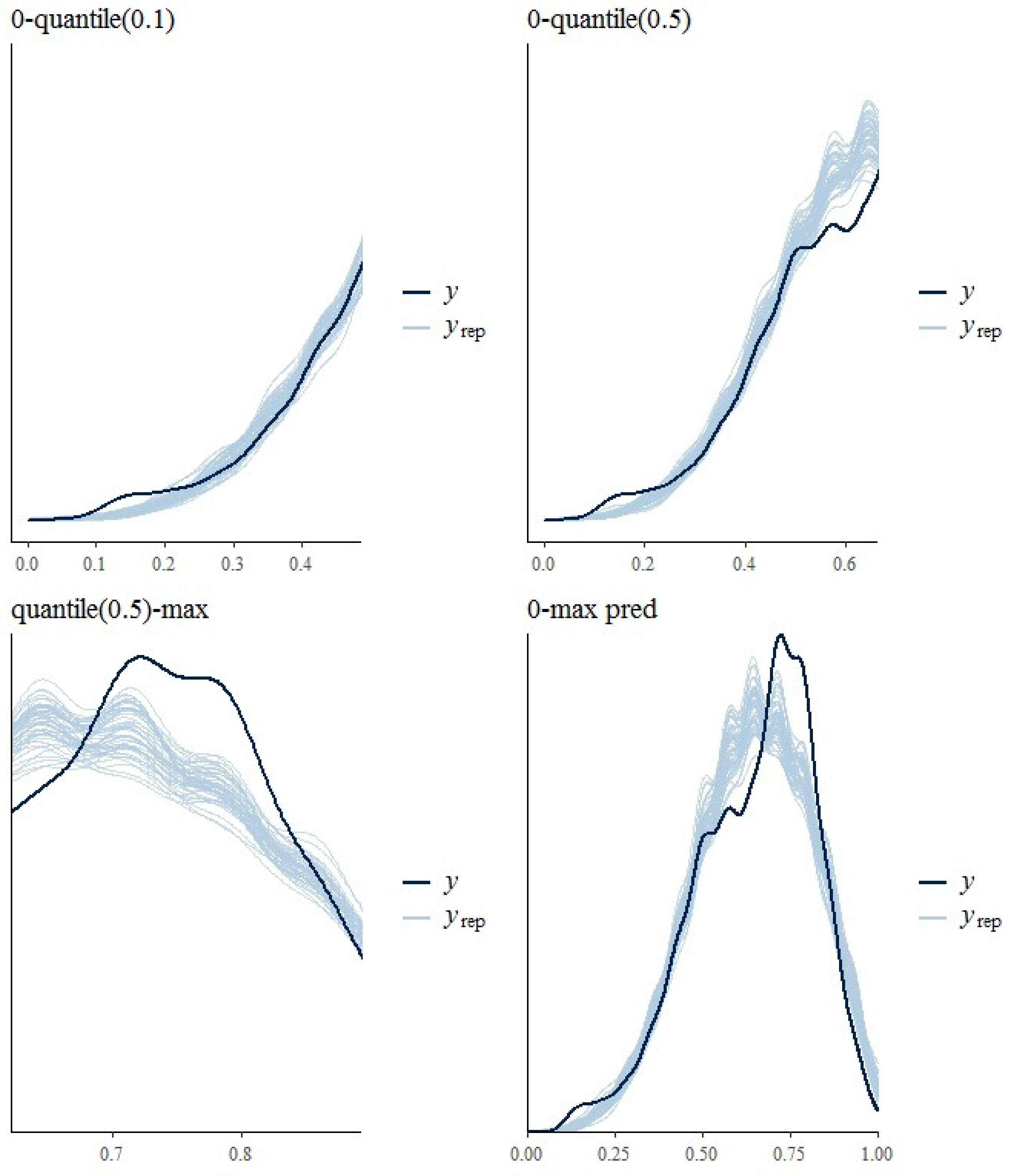

Figure B-2: Model fit

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