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An ecological trajectories architecture for use in the Murray-Darling Basin

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Abstract: Tracking the progress of water management actions against Basin Plan objectives in the Murray-Darling Basin requires an ability to forecast the condition of the Basin's environmental assets into plausible hydrological futures. Understanding and modelling how asset condition changes through time is referend to as trajectory modelling. Asset trajectories originating from a particular starting condition are bound by a range of possible future conditions. This range increases through time in association with different sequences of environmental conditions (created through the flow regime), and is bound by the rate of response of the environmental asset. This rate of response is associated with factors largely intrinsic to the different environmental assets, for example, the rate at which generation of biomass is associated with vegetation recovery. Tracking ecological outcomes through time requires understanding and quantifying environmental water needs, responses to event sequencing and antecedent condition within a broader systems framework. Many factors are likely to influence the extent to which environmental watering can achieve Basin Plan objectives. These include natural variability in the flow regime, strategic (long-term) water management decisions, short-term prioritisation of environmental water and other threats and influences outside of water management (such as multi-species interactions). Throughout the record of historical flows, natural variability has been a major cause of change in environmental condition. Short-term incremental decision-making (or prioritization based upon annual objectives and opportunities) and the uncertainty of future conditions influence the ability to achieve longer-term objectives.

The Murray-Darling Basin Authority (MDBA) currently uses a range of ecological modelling tools and methods to inform water management priorities and decision-making within the Basin. In this paper, we outline the development of a method that builds upon existing frameworks and methods used by MDBA and integrates them into a trajectories modelling architecture. The trajectories architecture uses an automated workflow to incorporate the variability of historic flow regimes combined with scenario analyses that are linked to eco-hydrological models. The goal is to develop methods to inform possible outcomes of water management over periods amenable to both long- and short-term decision making processes and align with timelines for Basin Plan objectives and beyond. We demonstrate the architecture using a case-study of woody floodplain vegetation.

Keywords: *Trajectories, environmental outcomes, ecology, ecological response, Basin Plan, response modelling*

1. INTRODUCTION

The Murray-Darling Basin Plan establishes objectives for managing the Basins water resources including specifying high level environmental objectives (Murray-Darling Basin Authority 2012a). The Basin Plan environmental objectives include a range of outcomes including: to protect and restore water-dependent ecosystems and ecosystem functions of the Basin; to ensure the coordinated management of environmental watering; and to ensure the resilience of environmental assets to climate change and other risks (Murray-Darling Basin Authority 2012a). Supporting the Basin Plan, is the Basin-wide Environmental Watering Strategy (BWS) (Murray-Darling Basin Authority 2014). The BWS sets out the expected environmental outcomes that should be achievable over the longer-term with the available environmental water. The BWS outlines this at a whole-of-basin scale for Basin themes including native vegetation, waterbirds and native fish (Murray-Darling Basin Authority 2014). The BWS objectives for each theme describe a range of outcomes sought, such as, changes in population size, distribution, diversity or population structure (Murray-Darling Basin Authority 2014).

Annual planning of water for the environment across the Basin is guided by the Annual Environmental Watering Priorities (hereafter 'the priorities'). The priorities recommend the type of implementation actions needed to achieve the long-term environmental outcomes outlined in the BWS under different annual water availability conditions. To support this, Resource Availability Scenarios (RAS) are released and updated, often sub-annually, and provide the climate context under which different annual actions should be sought. Priorities can include maintaining drought refuge under a low RAS, or providing flows to support breeding and recruitment events under a high RAS. The priorities recognise that different climate contexts will influence the types of actions taken in any given year, and that in order to achieve some longer-term environmental objectives, the need for a multi-year consideration of environmental watering is required (Murray-Darling Basin Authority 2017).

The Basin Plan establishes review periods in which the environmental outcomes are to be assessed against the targets specified in the BWS (Murray-Darling Basin Authority 2014). While water recovery, changing circumstances, other natural resource management activities, increasing understanding of asset water requirements and understanding environmental response are ongoing processes, there is much that can influence the ability to achieve the specified environmental objectives of the BWS. This includes lag effects in environmental response and normal climatic variability resulting in different annual flow characteristics (Murray-Darling Basin Authority 2014, 2017). Lag effects in environmental response may include the length of generation time for breeding to result in population growth, or the time taken for vegetation to generate new biomass. Different environmental assets intrinsically have different response times, for example, some fish species may improve condition at a faster rate in comparison to some vegetation communities. The outcome of these intrinsic lag effects are often highly dependent upon the occurrence of multi-event sequences and the sequencing of events, where an 'event' is defined as a flow which achieves a target sought to support an environmental outcome (Murray-Darling Basin Authority 2012c, Overton et al. 2014).

Tracking an environmental condition through time, based upon the sequencing of environmental events requires an understanding of the assets' water requirements (for example as flow thresholds), rate of response and how the likelihood and sequence of events influences environmental outcomes. There are however, many other factors that influence condition of environmental assets, and hence the ability to achieve BWS targets. These include natural variability between different habitats, other water sources such as rainfall that are not represented in hydrologic models, and other threats and influences outside of water management. Biological factors include interactions among species, natural variability between populations, colonisation and local extinction processes. While there is often large uncertainty associated with complex environmental systems (see Peeters et al. (2016) for a review), the focus of this work is in providing a method to assist planning and management of water resources based upon best available science and drawing upon the existing frameworks and tools currently in use within the Basin.

Within the Basin, a range of modelling tools and methods have been used to inform policy decisions, water management and to set annual priorities within the Basin. Some of these tools and methods include hydrological and inundation models (e.g. Murray-Darling Basin Authority (2012c)), the Environmentally Sustainable Level of Take method (ESLT) (Murray-Darling Basin Authority 2012b); the Hydrological Indicator Site method (HIS) (Murray-Darling Basin Authority 2012b) and the Ecological Elements method (EE) (Overton et al. 2014). To date, the use of these models has largely been based upon assessing daily flows from long hydrological time series (e.g. 114 years). These time series can be created using calibrated river system models with historical climate inputs (Murray-Darling Basin Authority 2012b, c). In application, this long time series facilitates exploring a range of different flow conditions based upon the variability within the historical series. Importantly, these long time series provide a robust comparison for scenario analysis, for example, by developing scenarios that incorporate new management options in the river system model or by scaling climate inputs to represent climate change. Scenario analysis uses these synthetic flow time series to test the sensitivity and relative change in environmental outcomes in comparison to a baseline.

Trajectory modeling considers how environmental asset condition changes through time in response to flow for forecasting a plausible range of probabilistic future environmental outcomes into a projected future. Advances in ecological modeling approaches used within the Basin, with the development of methods that represent temporal dynamics of environmental change, facilitate the exploration of forecasting trajectories of change. However, practices of using a single long time series as a model input has limited ability to quantify the probability of specific flow events into the future, and hence, environmental outcomes out to different time periods.

2. THE ECO-HYDROLOGY PARTNERSHIP PROJECT

The aim of the trajectories project of the MDBA-CSIRO Eco-hydrology partnership is to develop a modelling approach to predict trajectories of ecological change as a result of water management, climate variability and climate change (hereafter ‘trajectories’). The partnership project aims to develop a software tool to guide the MDBA in their water management strategies for a sample of representative environmental assets from different Basin Plan themes (fish and vegetation). The software tool will demonstrate sufficient generality to facilitate incorporation of a sample of ecological modeling approaches.

2.1. What are trajectories?

Trajectory models have been used in ecology to model the process of ecological restoration, bringing in theories of succession, ecosystem condition and changes through time. Trajectory models have emerged out of a literature on disturbance, and how ecosystems change as a consequence of changes in environmental regimes. Flow ecology and stream ecosystems have long been presented in the literature as being characterised by the disturbance regime of the habitat (Resh et al. 1988). In the context of river systems, some of these disturbances are represented, for example, as drought or floods (Biggs 1995). Species populations and communities are shaped as an outcome of responses to the hydrological regime. Flow regulation in turn disrupts these regimes by modifying the frequency or intensity of which these disturbances occur (Ward and Stanford 1995).

For the purposes of the MDBA-CSIRO Partnership project, we seek to use trajectory modelling to explore the role of the current and/or antecedent condition of an environmental asset and forecast the change in condition (the trajectory) into the future (Figure 1). To do this, the method needs to consider the assets watering requirements, the antecedent and current environmental state, how the asset condition transitions through different event sequences and the probability of various climate and hydrological conditions into the future. The consideration of these aspects define the trajectories architecture.

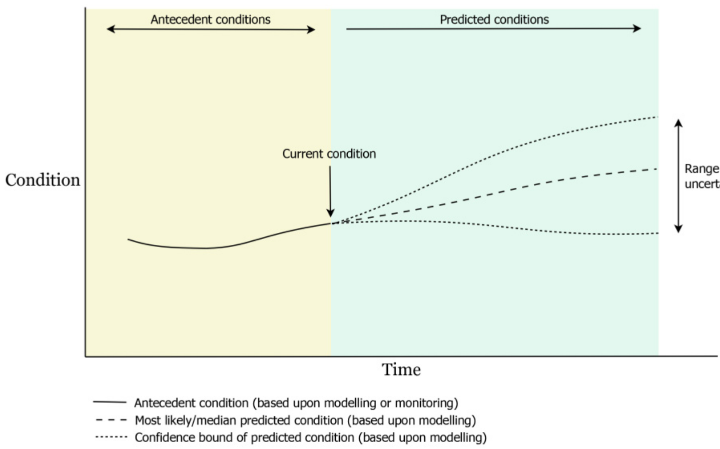

Figure 1. Representation of a trajectories concept showing modelled condition scoring over the historical period and projected condition based upon potential hydrological futures. While multiple sources of uncertainty exist, the modeled environmental condition represents the best scientific understanding of environmental asset condition and response through time

In trajectory modeling, assets with a condition originating from a particular point are bound by a range of possible conditions into the future. This range increases though time in association with the different possible future hydrological sequences, but is limited by the rate of response of the environmental asset. The ability to achieve objectives is hence dependent upon the starting condition of the asset and the range of future hydrological conditions.

Ecological trajectory modelling incorporates multiple shorter sequences of the historical flow regime as inputs, sampled to maintain important event sequencing and frequency attributes of the longer-term historical flows. Such an approach formalises the probability of future environmental conditions based upon past observed variability. Using a resampling framework, the trajectories architecture offers the ability to model plausible hydrological futures through time, and incorporating a forecasting element and the ability for assessment of climate variability and change. Climate and hydrological forecasting products (such as BoM products) provide a means to narrow the range of possible hydrological conditions in the near future (for example over the first 12 months). While historical variability provides the probability bounds for future conditions with climate change GCMs and associated modeling incorporating the longer-term prediction for changing conditions.

The length of the hydrological sequences can be used to consider plausible environmental outcomes out to several years or decades, with uncertainty and confidence increasing through time. Different time periods for modelling can range from short-term (e.g. 1-2 years), medium term (e.g. 4-5 years) and longer term (e.g. 15-40 years). The selected period of time will need to consider the objectives of the modelling and the level of associated uncertainty. Identifying watering priorities for the next few years requires a shorter assessment period compared to assessing outcomes out to periods of Basin Plan review.

2.2. Application in the Murray-Darling Basin

The Basin Plan provides a foundation for the Commonwealth and the Basin States to sustainably manage the Murray-Darling Basin's water resources. It was legislated in 2012, and is not expected to be fully implemented until after 2019, following the legislation of Water Resource Plans in each Basin state.

Chapter 8 of the Basin Plan contains an environmental water management framework (EMF). This provides long-term environmental objectives for the Basin and the adaptive policy mechanisms to achieve them. Mid-term objectives and targets are also specified (in Schedule 7 of the Plan) for assessing changes in condition towards BWS objectives in birds, fish, vegetation and macroinvertebrate communities (Murray-Darling Basin Authority 2012a).

The EMF uses three planning horizons to achieve the Basin Plan's environmental objectives: Long-term Environmental Watering Plans (States; updated every 10 years); the Basin-wide Environmental Watering Strategy (MDBA; updated every 5 years); and Basin Annual Environmental Watering Priorities (MDBA; released every year). Through these instruments, Basin and local-scale environmental objectives and targets are quantified and pursued by environmental water holders, while integrating new information generated by monitoring and evaluation programs. The MDBA is responsible for leading the monitoring and evaluation program contained in Schedule 12 of the Basin Plan, in partnership with Basin governments.

This project seeks to develop the capacity to generate ecological trajectories in a modelling environment, and formalise a trajectory modelling architecture and approach for linking climate forecasts, river hydrology and ecological response. Trajectory modelling is expected to support a variety of management applications (i.e. environmental watering planning, river operations etc.) including the ability to forecast ecological responses across a variety of plausible climate futures and alternative environmental watering strategies. This will not only aid long-term environmental water planning, but also enable managers to adapt and adjust the Basin annual environmental watering priorities each year to progress towards the BWS targets. This is achieved by understanding current environmental condition of the asset, the future environmental water requirements needed to improve or maintain condition, and the probability of these events occurring in the future based upon forecasting methods.

2.3. Understanding the need for a trajectories product

To better understand how the MDBA is likely to use a trajectories modelling architecture, several informal discussions and a workshop were held between CSIRO and the MDBA. The outcome of these discussions and workshop identified a broad range of inquiries that could be supported by a trajectories architecture and different ways in which the architecture could be used and incorporated into current MDBA modelling approaches and planning. Some of the questions or possible goals for environmental and ecological trajectory modelling raised during the joint discussions included:

- tracking how trends are progressing towards objectives (for achieving targets)

- how to consider the management decisions that are available to shift current trajectory closer to targets (including interventions)
- consideration of medium to long-term variables e.g. significant drought and/or significant wet years
- capturing the incremental effects of MDB water management
- providing an input into understanding outcomes of rolling priorities/multi-year decisions
- informing how themes could be considered together ('optimisation' and the 'long game')
- understanding how the range of error/uncertainty increases with forecast length
- considering long term risks/probabilities of these risks, and outcomes associated with different climate regimes or shifts in the long term climate change
- considering influences beyond water management

A key message was the desire for a method of forecasting environmental outcomes by considering outcomes of different management actions or water scenarios against a baseline scenario (see more information regarding scenario analysis in Section 3.1). Possible scenarios for assessment include different climate scenarios and alternate water recovery targets or diversion limits, and intervention or prioritization actions. Another key feature was the ability to apply the method to environmental assets from the different Basin Plan themes and be able to include other functional groups or species as desired.

A key goal of the trajectories project is to develop an architecture that defines a structured and standardised approach to develop ecological trajectories. The architecture would prescribe the type of data required and a method for collating and transforming the input data to create the desired model outputs. An important component to the architecture development is the design of outputs and the consideration of how information is represented in them. A simplified workflow for creating trajectories is shown in **Figure 2**. In this example, the hydrology (which is the primary environmental driver) is influenced by both climate and water management.

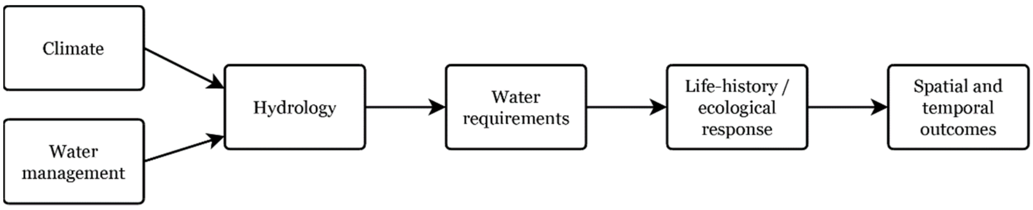

Figure 2. Simplified and general trajectories workflow

3. DYNAMIC RESPONSE MODELLING

There are various approaches used to specify and assess ecological targets for the environmental assets and taxonomic groups across the Basin. For example, environmental water requirements have been identified for some parts of the Basin (e.g. the Coorong; Lester et al. (2011)) and preference curves can be used to relate aspects of hydrology and/or habitat to ecological outcomes such as abundance and reproduction for target species (e.g. MFAT). Other common endpoints in use include site-specific flow indicators (e.g. the ESLT method) that describe necessary flow events in terms of duration, magnitude and timing. These often report the frequency at which these thresholds events occur across a flow time period. However, measures of frequency fail to transpire into understanding of how assets change condition as a dependence upon aspects of regime and sequencing. This is the benefit afforded by dynamic response modeling or transition modelling methods.

Ecological response models exist for some species (e.g. *Ruppia tuberosa*) and some ecosystems (Lester et al. 2013) providing model-specific endpoints. Ecological Elements (Overton et al. 2014) however provides one method for assessing changes in environmental condition though time with a ability to consider sequencing of water events, represented through recovery and decline pathways as a consequence of wet and dry years (Figure 3). Population models, such as those used for fish (Todd et al. 2004, Stratford et al. 2016) provide a further method which considers change through time. This aspect of response modeling is important for considering trajectories of change.

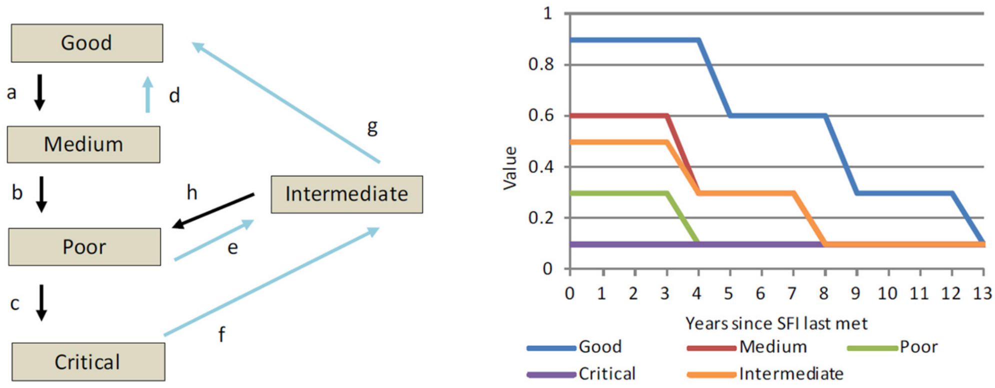

Figure 3. A) Conceptual underpinning of the Ecological Elements model for the river red gum, and B) the response curve for decline in condition showing transitioning. See Overton et al. (2014) for more information

3.1. Scenario analysis and uncertainty

The need for the architecture to be able to facilitate comparisons among different scenarios was raised during collaboration discussions and is commonly known as scenario analysis. Scenario analysis provides an objective, transparent and repeatable method for exploring the potential outcomes of management and the relative benefit of different management actions to be considered (Sutherland 2006). The MDBA has long used scenario analyses to investigate the effect of management decisions, infrastructure and climate on hydrology within the Basin (e.g. via BigMod) and are increasingly using the same approach to assess ecological outcomes.

In many parts of the Basin, climate and other types of natural variability (e.g. the timing and frequency of weather systems) create significant sources of uncertainty around the ability to meet management objectives. While this is increasingly being recognised and incorporated into planning, there is a need to quantify this uncertainty where possible, to ensure that its magnitude and potential impact are understood. Possible use scenarios for the architecture include the exploration of different types of uncertainty and identification of their relative importance. For example, previous work in the Coorong illustrated that climate change had a much smaller impact on ecological outcomes than on river flows and identified magnitudes of environmental flows that could alleviate climate-related impacts, highlighting the ability of managers to influence those ecological outcomes (Lester et al. 2013). Additional work has also highlighted the sensitivity of the Coorong hydrodynamics to the method of delivery and timing of barrage flows and to the impact of local weather systems on nearby sea level in Encounter Bay (Lester et al. 2012). Consideration of such factors is clearly important when considering the most appropriate approach to environmental watering and are thus likely to affect the ability to meet ecological objectives.

4. DEVELOPMENT AND DEMONSTRATION OF THE WORKFLOW

This project will demonstrate a trajectories workflow and scientific architecture for modeling ecological trajectories. A workflow is a structured process in which operations are sequenced to transform inputs into outputs. Scientific analysis of natural systems require large datasets and models to be integrated. The large output datasets generated are processed to produce visualisation (i.e. via graphs and plots) that help to illustrate trends and behaviours of a system. As the workflow needs to accommodate a range of pre-existing tools to generate trajectories of ecological change this sequential process will be run in, the open source "notebook system", Jupyter, which allows the creation of documents that contain live code and visualizations.

Our initial demonstration explores a use-case for forecasting possible vegetation outcomes under different hydrological scenarios. This use case demonstrates the condition of river redgum and blackbox vegetation assets based upon the EE method (Overton et al. 2014). These models include asset water thresholds, response curves for representing change in the asset condition through time (Figure 3). The response curves include both condition recovery and decline pathways as responses to the occurrence and sequencing of annual watering events (e.g. multiple sequences of successful watering lead to improvement in asset condition). Annual watering events are based upon RiM-FIM (Overton et al. 2006) inundation bands of 1000 ML/day flows between 3000 and 100,000 ML/day intersecting with river red gum and black box vegetation mapping from Cunningham et al. (2013).

While there is substantial uncertainty with forecasting weather patterns and flow events into the future, the probability of wet and dry sequences can be explored through using historical conditions. The occurrence of different flow events (e.g. prolonged drought) will have a strong influence on the ability to achieve the BWS objectives. Modelled flow scenarios such as climate change scenarios or various water management strategies can be incorporated into the workflow from existing modelling (e.g. Sustainable Yields or Basin planning scenarios) to enable the comparison and relative difference between a scenario and a baseline. Scenario analysis such as this can enable the relative benefit of different management actions or the relative risk of different climate scenarios to be considered within a probabilistic trajectories architecture.

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