CENTRE FOR REGIONAL AND RURAL FUTURES

Architecture design for the Climate Adaptation toolkit workflow

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

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EXECUTIVE SUMMARY

The impacts of climate change will affect the social, economic, environmental and cultural values of the Murray-Darling Basin. Some elements will be more vulnerable to climate change than others. There will be myriad options for ameliorating, adapting or avoiding these impacts that could be implemented and trade-offs, synergies and uncertainty associated with each.

To enhance the ability of the Commonwealth and stakeholders to assess likely future impacts of climate adaptation across social, environmental, cultural and economic values in the Basin, we will develop a toolkit of new and existing information, knowledge and models. This will enable transparent, repeatable assessments of impacts and adaptation to future climates. The toolkit will enable end-users to select appropriate future climate scenarios, identify possible adaptation options and then model flows associated with those scenarios. These will then be used to understand the resultant response of identified values, be they social, cultural, environmental or economic. This will develop new capability, enhancing the ability of the Commonwealth to account for the impacts of future climate change on water supplies and Basin assets in water planning and support non-flow related decisions. This report outlines the architecture underpinning the toolkit.

For the toolkit, identified key functionality includes:

- Scenario assessments and comparisons
- Assessments across social, cultural, economic and environmental values
- Present outcomes in a useable way
- An extensible approach that can be developed and built upon
- Transparency to enhance trust in the process and the toolkit.

To achieve this functionality, three major work components have been identified. These include: 1. Develop the ability to analyse and run scenarios (ModelArch), 2. Module development, and 3. Causal network development.

The first activity, to develop ModelArch, is the backbone of the toolkit. ModelArch, as the foundational architecture for the toolkit, will accept inputs, undertake a number of functions and provide outputs. ModelArch will be developed as a series of elements to undertake those functions: the Scenario Controller, Indicator Assessor, Objective Translator, Aggregator and Comparer. Sitting within ModelArch will be modules describing responses of each of social, cultural, economic and environmental values. The second activity will develop these modules to enable a repeatable method for defining the response of values and assets to hydrology and climate. The final activity, casual network development, involves the capture of rationale for links between hydrology, climate and the response of values and assets. The causal networks will identify synergies and trade-offs among values and assets and assist with developing methods to scale responses in space and time.

For each activity, a clear path to build is provided, along with a description of the demonstration to be developed by June 2022. This will include a demonstration of ModelArch for a selected site using existing tools for assessing response of environmental values. The demonstration will include minimal but functional components of each element of the architecture, example outputs, a demonstration of a causal network for that site and capture links between environmental objectives and indicators for NSW. In each case, a plan for the next steps of development will also be developed.

This architecture describes a feasible pathway to develop a toolkit to assess the impact of climate adaptation measures on social, cultural, environmental and economic values and assets in the Murray-Darling Basin and will provide the foundation for populating that toolkit over the lifetime of the Murray-Darling Water and Environment Research Program.

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3 INTRODUCTION

The impacts of climate change will affect the social, economic, environmental and cultural values of the Murray-Darling Basin. Some elements will be more vulnerable to climate change than others. There will be myriad options for ameliorating, adapting or avoiding these impacts that could be implemented in isolation or in combination. There will be trade-offs, synergies and uncertainty associated with different adaptation options and the resulting outcomes on Basin values and vulnerabilities. Many impacts and adaptation options will be outside Commonwealth control – with States, industry and communities all playing important roles. Thus, the task of assessing the potential impact of climate change on a healthy, working Basin is complex.

As a part of the Murray-Darling Water and Environment Research Program, this project is intended to enhance the ability of the Commonwealth and other stakeholders to identify and assess the likely future impacts of climate change across social, environmental, cultural and economic values in the Basin, and to identify potential adaptation options and assess the outcomes associated with adopting them. This will involve developing a toolkit of new and existing information, knowledge and models to enable transparent, repeatable assessments of impacts and adaptation to future climates. This toolkit will enable end-users to select appropriate future climate scenarios, model flows associated with those scenarios and incorporate other relevant information to understand the response of identified values, be they social, cultural, environmental or economic. Users will then be able to access simulations of a range of possible adaptation options and assess their impacts on those values. The toolkit will be applied to a series of adaptation investigations across the Basin. This will result in new capability, enhancing the ability of the Commonwealth to account for the impacts of future climate change on water supplies and Basin assets in water planning; and to support decision makers involved in non-flow related decisions.

The purpose of this report is to outline the architecture that will underpin the toolkit, including the functionality needed, the components identified to create that functionality and the plan to develop each. Where required, we have documented the rationale for the choices that have been made. In addition, we have also defined the components of our next step – a demonstration of this toolkit, which is deliverable in June 2022.

4 TOOLKIT CAPABILITY

The purpose of the toolkit is to enhance the ability to identify and assess likely future impacts of climate change and potential adaptation options across social, environmental, cultural and economic values in the Basin. In order to achieve this, the toolkit requires particular functionality. At a broad scale, the toolkit needs to enable:

- Scenario assessments and comparisons

The capability to assess scenarios will enable users to investigate plausible future climate sequences but also adaptation options. This is a key component to compare alternatives, both in terms of what the future might look like, but also how various actors can respond to that plausible future, so as to assess how effective those responses may be.

- Assessments across themes

Past assessments have tended to focus on a single theme at a time – one of environmental, social, cultural or economic responses – although there are exceptions. This toolkit needs to include functionality to undertake assessment across themes so as to enable explicit assessment of trade-offs and synergies among values. A standardised approach to assessment among themes is valuable as it enables robust comparisons of trade-offs and synergies.

- Present outcomes in a useable way

Assessments of multiple adaptation options for multiple objectives under multiple plausible future climates has the potential to quickly result in unmanageable amounts of output when applied across the entire basin. The toolkit will need to be able to scale local responses to larger spatial and temporal scales, and to integrate responses across multiple values. This will provide the capability to present outcomes in a manner that will contribute to planning and management in a useable way.

- An extensible approach

One of the key tenets to our approach to the toolkit development is to create a minimum viable project and to then iteratively improve that product. That is, what can we achieve now, and then what additional capability would we like to have by key dates such as the Basin Plan Review. In keeping with this notion, the toolkit demonstration will be based on the elements and capacity that is currently available, but the development will be done in a manner explicitly enabling future extension and revision. This provides a no-regrets pathway for development and enables new information, tools and capability to be incorporated as it becomes available. Thus, we will employ a cycle of iteration and adjustment to meet needs both within and following the initial demonstration.

- Trust in the process and the toolkit

Another key tenet to our approach is to ensure that the method and information included is documented, transparent and that key collaborators and stakeholders have the opportunity to contribute to, and provide feedback on, the research approach, direction and methods. This will assist to build trust in the process and the toolkit and increase the utility of the toolkit itself as well as outputs arising from it.

5 PROGRESS TO DATE

The toolkit was initially conceived as a broad range ‘catch-all’ for existing tools and to incorporate new tools – i.e. a meta-tool or umbrella tool. As a part of that conceptualisation, we conducted a scan of the many tools currently available. Our scan of existing tools and workflows elicited responses from within MDBA, the CEWO Flow-MER program and ABARES. Since, we have also identified work that is currently occurring to quantify the water needs of cultural sites based on Aboriginal Waterway Assessments (see MDBA, NBAN & MLDRIN n.d.).and economic modelling that was undertaken for MDBA (KPMG 2018). The scan highlighted that tools within the MDB are in various states of useability, with most not being particularly useful in the short term for the purpose of the toolkit (i.e. for inclusion in the demonstration and no-regrets case study). Various tools use different interfaces and languages and have different provenance. The overall landscape is therefore highly complex.

This highlighted the risk that the toolkit demonstration could devolve into a software development project focused on code to enable these tools to be interoperable. This would divert resources from core research related to expanding capacity to assess likely response to future scenarios and adaptations. Instead, to maximise the value of those tools and the resources invested, we rescoped the toolkit to develop a core product. This will focus on using available tools to deliver essential capabilities via metrics and indicators across the four themes. This structure is conceptualised as an environmental water requirements (EWR)-style framework, similar to the tool developed by MDBA, and provides a no-regrets pathway to commencing development (*Figure 1*). This approach will allow the integration of outputs from disparate tools into a common framework. Development will still be required to distil the data, relationships and information captured in each tool into indicators suitable for inclusion in each module, but this is likely to be more tractable than including each model in its native format.

The prioritisation of existing tools continues. Knowledge of additional tools continues to develop and, as that occurs, prioritisation can change. During the scan, we identified a number of groups who are continuing to develop tools or capability that has relevance to the toolkit where we could collaborate. A key element to prioritisation is a detailed set of metadata and prioritisation criteria. Development of each has commenced and will continue. The primary criteria for inclusion in the toolkit demonstration and no-regrets case study are availability and interoperability. Additional criteria will be refined and included in the toolkit demonstration.

The rescope of the toolkit explicitly includes plans for it to be extensible. Importantly, this prioritisation of indicators does not preclude future development to integrate specific additional tools into the toolkit, should that be desirable. As such, the method selected to implement the demonstration does not prevent additional functionality from being included in the future. Consistent with the over-arching ‘integrator’ role of the Climate Adaptation theme, this toolkit architecture has been designed to incorporate appropriate flow-to-outcome information from all four WERP themes over the coming four years.

CLIMATE ADAPTATION TOOLKIT ARCHITECTURE

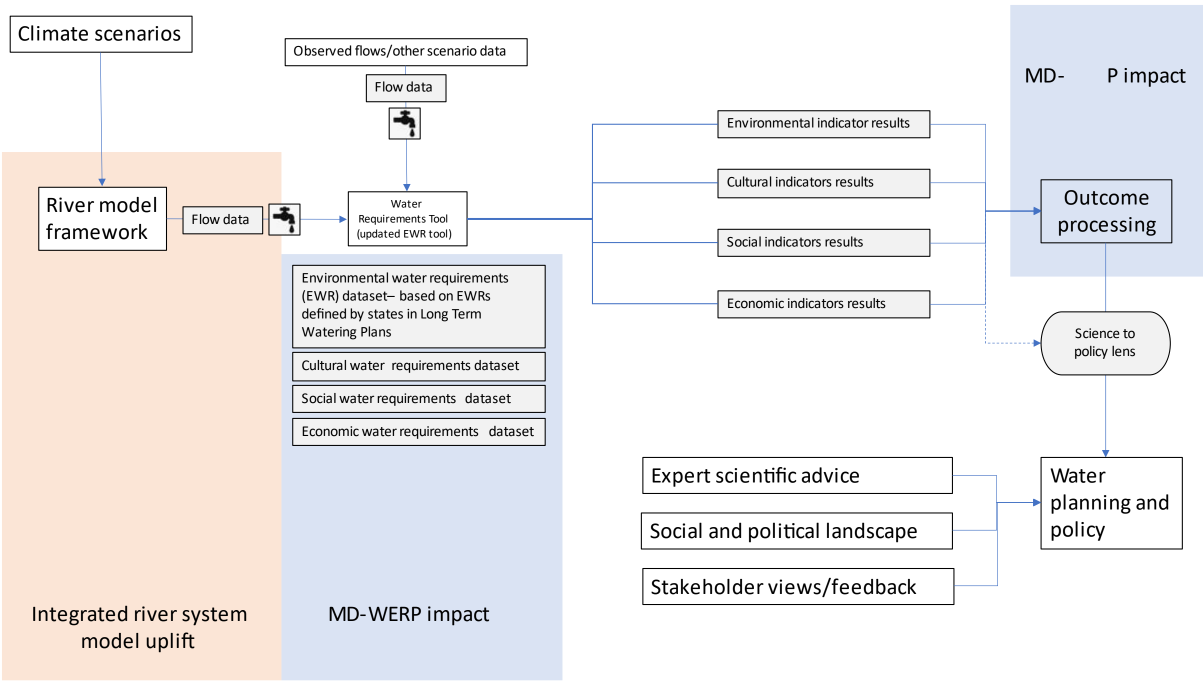

Figure 1. Critical toolkit elements identified by MDBA, including proposed linkages between each and possible funding pathways for each where relevant.

6 MAJOR WORK COMPONENTS

The toolkit architecture that we have designed has three major components that will be the focus of the next stage of development. Each of these has additional internal divisions but have been defined in this manner because they are highly inter-related, conceptually distinct and able to be developed in parallel. It is important to note that the various work components are not equal in terms of how complex or time consuming each is.

The identified major work components are:

1. Develop the ability to analyse and run scenarios (ModelArch)

   This work component is the backbone of the toolkit. It provides the functional architecture for the toolkit and ensures that scenarios are assessed in repeatable ways that use each of the components in the toolkit, and can then be scaled, compared and assessed. Creating the ability to analyse and run scenarios is predominantly a code-building task but will also include significant development of the science that is captured by that code.

   Given that ModelArch accepts inputs, undertakes a number of functions and then provides outputs, it is best conceptualised as a model itself. As a result, modelling terminology such as ‘running’ scenarios will be used in this document and others relating to the toolkit. It is important to note that ModelArch will ingest outputs from a hydrological model rather than incorporating the hydrological model itself. These outputs will then be run through the workflow described in this document to model their impact on social, economic, environmental and cultural outcomes. These outcomes will then be used to assess the effects of various adaptation options and comparisons among those scenarios as the final output.

2. Module development

   This work component focuses on defining the responses of values and assets to hydrology and climate. These responses will be defined based on the best available science and using formats usable for assessment by the ModelArch component. Each of the four themes will be represented; although, to date, the flow-to-outcomes science for some themes are much better developed than for others. Similarly, economic and social outcomes may be inferred from model outputs that are not river flows (e.g. diversion patterns), and this will need to be enabled by the modules. Initially, the focus of this work will be adding needed functionality to existing tools defining relationships between hydrology and outcomes (e.g. EWRs), while developing these relationships for other themes (social, cultural and economic). Reflecting the state of the hydrological modelling, these will initially reflect responses to hydrology alone, but may be extended to include other impacts influenced by future climate (e.g. heatwaves, bushfire risk, water quality, etc).

3. Causal network development

   This work component captures the causal relationships between climate, adaptation options, and outcomes for environmental, cultural, social, and economic values and assets. The focus will be on those relationships described by the modelling but others may be included as well, aiding in the identification of blind spots. It identifies and demonstrates those relationships and captures characteristics such as the degree of certainty associated with each link. It has the capacity to do this in a spatially explicit manner. This work component will be a tool for ensuring model appropriateness internally and to aid communication of the approach externally.

Each work component is illustrated in *Figure 2*, including the various links among components. Our approach to tackle the overall body of work will be to develop each component in parallel, focusing on initially having a functional structure and then iterative improvement. No single component will need to be complete for others to proceed. For example, we are able to build ModelArch based on the existing EWR tool, without needing to develop other modules first. Similarly, updating the EWR tool or adding new modules will require new runs to obtain updated output values, but would not rely on fundamental changes to a basic ModelArch.

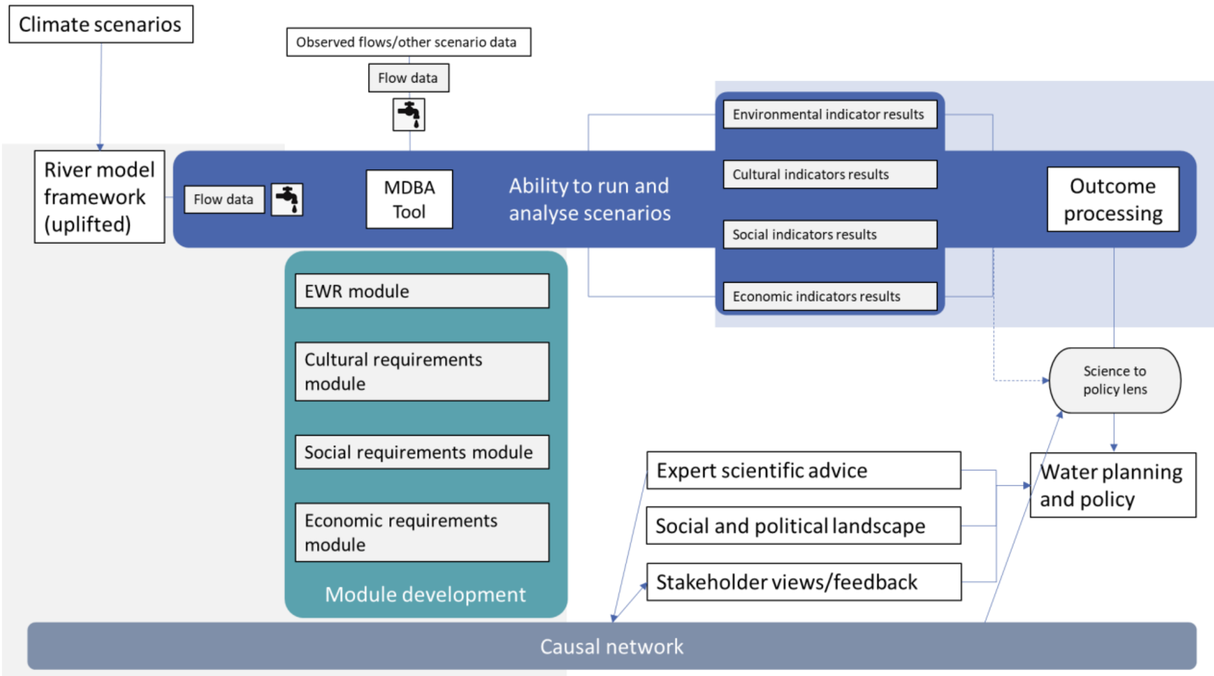

Figure 2. Conceptualisation of the near-term components of work in the WERP toolkit (filled boxes). This sits downstream of the climate scenarios, adaptation option definitions, and hydrological modelling, and feeds out results in a format useful for the science to policy lens.

6.1 Rationale

Developing the ability to analyse and run scenarios (via ModelArch) represents the core functionality of the toolkit (shown in blue; *Figure 2*). This element enables users to model the links from climate and adaptation options to outcomes presented in a useable manner. This component will take many scenarios (e.g. climate or hydrology), feed them to a driver-indicator-response model (such as the existing EWR tool), report outcomes and enable comparisons among scenarios.

The second major component is module development (shown in teal; *Figure 2*). This component will capture the relationships that infer the outcomes from hydrology across the quadruple bottom line represented by the four themes. This component is essential for ModelArch as it creates the basis of the driver-indicator-response model.

Finally, the third major component is the causal network development (shown in grey; *Figure 2*). This component creates a visual representation of the complex inter-relationships between river-related outcomes that are represented in the toolkit. This aids transparency, reducing the risk that the toolkit becomes a 'black box' and improves communication about the toolkit and its outputs. Each of these components is discussed in further detail below.

7 RUN & ANALYSE SCENARIOS (MODELARCH)

The primary aim of the toolkit is to assess responses of four themes (Environmental, Cultural, Social and Economic) to climate and possible climate adaptation options. To do this, we require capability to run and analyse scenarios of climate and climate adaptation. In many cases, climate and adaptation options will be analysed by assessing outputs from scenarios in river system models. These analyses must be scientifically robust, and the outcomes must be interpretable and usable for MDBA at the science/policy interface. The ModelArch component of the toolkit provides the core modelling functionality for the toolkit project to achieve these needs.

The ModelArch component consists of a series of modelling modules that step through from hydrology scenarios to local outcomes at the theme levels to processing those outcomes for presentation and use. Each of these modules will capture specific steps in the process and be based on best-available science and needs. Each step in the process includes uncertainty, from the climate scenarios themselves through to the effects of local changes on larger-scale outcomes, and so the ModelArch components will be developed to propagate this uncertainty through, in order to assess the confidence in the final comparisons among scenarios.

The modular approach outlined here allows each step in the modelling process to be developed as a discrete element, simplifying and clarifying development. Each component will incorporate the best-available relationships defining that particular step. Updating a module would not therefore require re-development of the architecture itself or other modules. The toolkit would only need to be re-run to obtain updated outputs. This approach allows iterative improvement in terms of the knowledge captured, capability enhancement, and the output needs. For example, adding new theme responses, changing aggregation statistics, or producing new visualisations of the results will all be straightforward.

7.1 Overview

Taken holistically, the architecture is comprised of four modelling components and the links between them, along with hydrological inputs.

The architecture will ingest flow timeseries at a location. For example, in the case of the EWRs, these are in the form of hydrographs at a gauge, but other model outputs will be able to be used. Climate and adaptation scenarios will be represented by different hydrographs for each scenario, developed and specified outside the toolkit architecture described here (e.g. in hydrological models).

1. Each scenario at each location will be fed into an indicator module. This module will check the hydrograph against a database of flow requirements for each theme to determine which, if any, are met.
2. The hydrological indicators are defined because they have causal relationships with theme-based objectives (e.g. bankfull flows of a given duration are needed for successful fish breeding). Taken with step 1, these represent simple threshold models for a range of local theme outcomes dependent on hydrological conditions. Thus, the outcomes of the flow indicators are mapped back to these theme-based objectives.
3. Local outcomes from each location will be scaled up to larger areas (and timesteps) to meet user needs. The spatial scale at which results are needed is likely to vary, depending on MDBA needs, but will often be larger than a single gauge, encompassing perhaps a valley or statistical area. This scaling will use a range of methods tailored to the specific indicators and the use case.

4. Finally, aggregated outcomes will be compared among the scenarios. These comparisons will allow visualisation and assessment of the differences among adaptation options and climate trajectories. The method of comparison will be tailored to the specific use case and required types of outputs.

The development of each of these components are described in more detail below.

All components will be version-controlled, including current software environments to ensure repeatability of all steps of the toolkit workflow. Strict reproducibility is significantly more difficult but archiving of foundational data (to the extent possible) combined with versioning at major analyses will provide near-reproducible results. Unit tests with minimal standard data will be used to ensure repeatability and expected behaviour, particularly across versions with updated functionality.

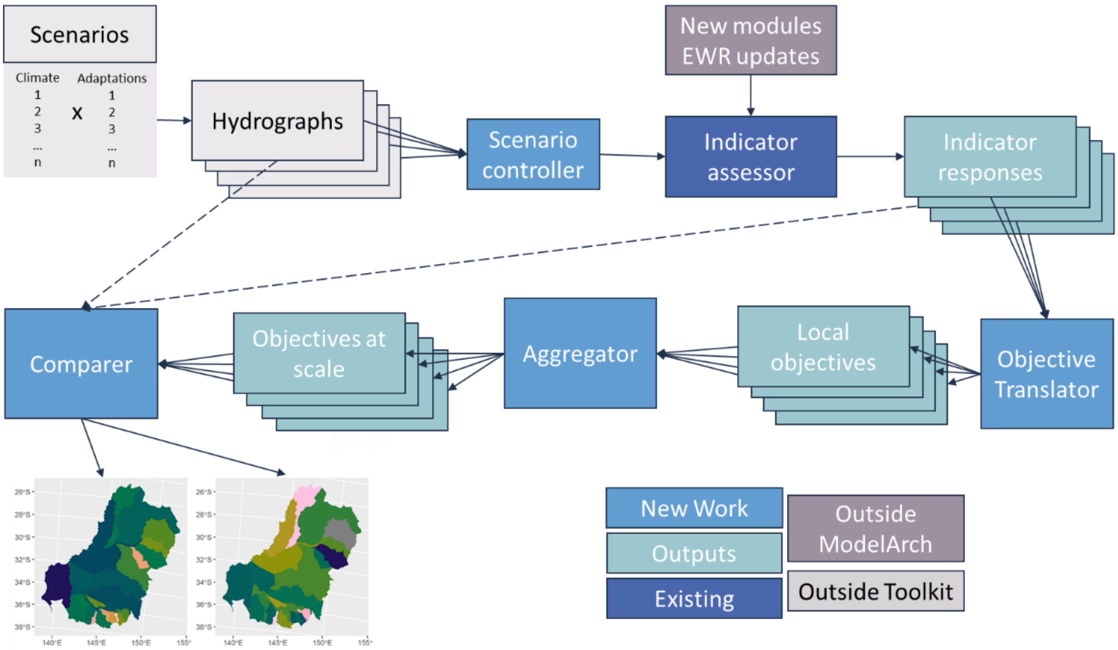

Figure 3. Flow of the ModelArch. This piece of work provides the modelling functionality for the toolkit. The goal is to produce useful analyses and comparisons of how climate scenarios impact the four themes. To do so, the architecture ingests scenario hydrographs, tests whether they meet hydrological thresholds, translates those hydrological thresholds into local management objectives relevant to the themes (e.g. bird breeding, cultural values), then aggregates the results to a desired scale and compares the scenarios in a way that is useful for MDBA science-policy interface.

7.2 Scenario Controller

Assessments of the effect of adaptation options under climate change frequently require many scenarios. These scenarios each represent one adaptation option, one example future climate or build understanding of stochastic variability. To effectively manage many scenarios, a Scenario Controller is needed.

The Scenario Controller is the interface between the externally generated hydrographs defining the scenarios and the toolkit architecture described here. Specifically, its function will be to take those hydrographs and systematically provide them to the indicator modules for modelling their impact on the quadruple-bottom-line outcomes.

The Scenario Controller will need to identify the location of relevant hydrology scenarios, load them (or point to them) and feed them to the indicator modules. To accomplish this, a user will need to be able to define the scenarios and their locations, as well as potentially control which indicator modules to run. The core functionality will be delivered via a lightweight script and simple functions that loop over those scenarios and call the indicator modules.

The Scenario Controller will provide a record of each run and its setting to enhance repeatability, ensure correctness and increase human comprehension. This will include the run-specific setup of the Scenario Controller itself (e.g. the files called). In addition, the Scenario Controller will also include metadata explicitly, attaching information about the scenarios that will be carried through the architecture. This will ensure that outputs at every stage are tagged with information about the run that created them. Further, the Scenario Controller will set up standardised output locations including records of the run settings to aid recordkeeping and future usability of assessments.

The implementation of this component will include a user-editable notebook in a Jupyter or R notebook to define the scenarios and make any other necessary settings. A notebook is an interface that combines text, code and output and enables user input, and is able to be version-controlled. Once edited, the notebook will then call a small set of standard functions to tag the run with metadata and control sending the hydrographs to the indicator modules. There is clear opportunity to enable these functions to send scenarios in parallel to improve processing of many scenarios simultaneously.

Further development may include additional inputs beyond hydrographs; for example, if the indicator modules are expanded to include factors (other than hydrology) that define response, such as temperature or local socio-economic status. As testing and development progresses, this interface may also be used to define the analyses performed on the output, making the user-editable interface of this component an overall controller for a particular set of scenarios.

7.2.1 Plan to build

The core functionality of the Scenario Controller will be developed using existing hydrographs and the EWR tool for development, testing and demonstration. These existing components will provide well-defined start and end points for the Controller. Thus, building the Scenario Controller does not depend on new work either within or external to the toolkit.

The build will consist of identifying the components that need to be in the user-editable interface and then developing that interface, while also developing functions to send the hydrographs to the indicator modules and attach run information. This may involve modifying the existing user interface in the EWR tool if possible. Enabling storage and accessibility of assessments will also be addressed. Each of these tasks are likely to proceed iteratively as we test and add functionality.

7.3 Indicator Assessor

The impact of adaptation options and climate on theme outcomes will be assessed based on whether specified requirements (e.g. water requirements via hydrological indicators) are met for a given scenario. Initially, hydrographs for each scenario need to be assessed to determine whether those requirements are met. This will be extended to include non-flow outputs as further development, but the Indicator Assessor will perform this task.

The existing EWR tool already fulfills the purposes of the Indicator Assessor tool. There will likely need to be some minor modifications needed as we add requirements beyond the environmental theme but expect the structure to remain the same.

Currently, the EWR tool is built around pass/fail indicators that link hydrological conditions to environmental objectives, and so this is the format that will be used in the toolkit demonstration. Improved driver-response models may be available in the future, where fish abundance depends on the duration of bankfull flows, for example. Newly developed modules may incorporate these sorts of quantitative relationships at the outset. Handling these sorts of relationships will require minor changes to the Indicator Assessor, but its structure would remain fundamentally unchanged. It would still ingest hydrographs and calculate relevant hydrometrics, and return a value (e.g. duration of bankfull flows) rather than a pass/fail.

The indicator modules themselves are the databases defining water requirements for quadruple-bottom-line objectives. The development of these water requirements is described below (see *Module Development* section). The Indicator Assessor tool is the software that ingests these databases and the hydrographs, calculates the necessary hydrometrics and checks whether each requirement was met. That assessment for each of the hydrological requirements is then sent to the Objective Translator module to understand the implications for the theme objectives. The Indicator Assessor will run for each scenario, likely in parallel as controlled by the Scenario Controller.

7.3.1 Plan to build

For the ModelArch demonstration, the existing EWR tool is sufficient. As new theme requirements are added or updates made, they will be incorporated and tested. Presuming that the inputs are hydrology and outputs are whether requirements pass, the structure of the ModelArch will be unaffected. Likewise, if extended capabilities are developed to return hydrometrics rather than just pass/fail, the basic structure will remain the same. This will facilitate building the ModelArch workflow.

There may be modifications needed during the initial ModelArch build to ensure that the EWR tool works well with the Scenario Controller and Objective Translator, but we expect these to be minor.

7.4 Objective Translator

Objectives are defined based on the environmental or other values and are modelled based on hydrologic indicators. To determine the impact on those objectives, translation of those hydrologic indicators is required. The Objective Translator links hydrological indicators to the expected requirements of ecological (or other) groups.

Indicator modules define the hydrological indicators (e.g. bankfull or cease-to-flow requirements), and the Indicator Assessor checks whether these are met. These requirements are defined by their causal relationship to objectives (see *Causal Network Development* section below). For example, Long Term Water Plans (LTWP) set hydrological indicators based on the expected requirements of ecological groups. The Objective Translator makes these links, taking the pass/fail of the water requirements at each gauge into the theme-based objectives (e.g. no loss of native fish species).

The Objective Translator will be similar to the Indicator Assessor. It will ingest a database (here, matching water requirements to their respective objectives) and the outputs of the Indicator Assessor tool that give whether each of those requirements was passed. The Outcome Translator then returns whether each objective was met based on whether the underlying water requirement was met.

Some objectives (e.g. no loss of native fish species) have multiple water requirements (e.g. cease to flow requirements and bankfull) at a single gauge. Aggregating these into a single native fish assessment will occur in the Aggregator tool; the Objective Translator will return whether each separate water requirement for that objective was met. This approach keeps the functions of the two tools separate and ensures that each is doing one task to increase the clarity, robustness, and modularity of ModelArch. The casual network design and structure will assist at this step.

During development, the Objective Translator may merge with the Indicator Assessor. The water requirements and objectives that determine them will necessarily be defined together (e.g. in the existing LTWP for environmental objectives, as this defines the model relating hydrology to outcomes). Moreover, the Objective Translator directly takes the output of the Indicator Assessor to map to these relationships between requirement and objectives. While checking the water requirements and mapping to objectives are two distinct steps, whether these are separate tools will be determined by how complex that second step is, and whether it makes sense from a code clarity perspective (i.e. based on the principle that each tool should typically do one specific thing).

7.4.1 Plan to build

There are two primary needs: develop a database matching the objectives to the water requirements and develop the Objective Translator tool that matches the two and returns the outcomes.

For the database construction, the first stage will be to extract objectives matching the EWRs that already exist, likely targeting just the demonstration location. This will likely involve matching table rows from the LTWP, depending on initial testing. As new modules are created, objective mapping can be incorporated from the initial build and so database creation can occur simultaneously for both water requirements and objectives.

We expect the Objective Translator tool to be lightweight, providing the capability of ingesting the water requirement outcomes from the Indicator Assessor, matching them to the objectives, and returning pass/fail for each objective at each gauge. The tool will, at its core, be something like a database query or table matching, with some data organisation to return the appropriate results for the next stages of ModelArch.

The construction of the ModelArch workflow demonstration depends on having a small number of objectives in the translation database, and the tool to match them to whether their respective water requirements were met. Once this minimal functionality exists, later components of ModelArch can be developed. Further updates to the objective mapping will then increase ModelArch capability but will not alter how the architecture works.

7.5 Aggregator

One of the key tasks for the toolkit will be to aggregate responses in space, time and across environmental objectives (or multiple species). Best available science indicates that a flexible approach to aggregation is needed. Specific objectives are best combined in different ways, depending on the intent of those objectives and a standard approach to all objectives could produce misleading results. As a result, we will build a number of options for aggregation and the ability to tailor new aggregation options by users. This will enable users to select how best to aggregate in three dimensions: space, time and across objectives.

To illustrate the need to develop a flexible approach to aggregation, an example is useful. Consider two different environmental objectives, ‘no species loss’ and ‘successful bird breeding’. The most appropriate method to combine each is likely to be very different. To meet the ‘no species loss’ objective, all species must persist in all locations at all times. From an aggregation perspective, this means that locations, time steps and species cannot compensate for one another and species loss at any point would cause the overall objective to fail. This means that taking a minimum response is likely to be the most appropriate method of aggregation. In contrast, ‘successful bird breeding’ should be aggregated using quite a different approach. Here, different species will have different requirements regarding a minimum interval between breeding events. These might range from 1-5 years, for example. Successfully breeding within that interval once would qualify as success, and so breeding is not necessarily required in all years. Different degrees of spatial aggregation will likely be reasonable. For some species, successful breeding at one location in the Basin will be sufficient. For others, more localised breeding is likely required (perhaps regionally). As for the 'no species loss' objective, it is unlikely that successful breeding individual species can compensate for a lack of breeding in other species. Thus, no compensation is possible across species, but success in some locations and some time steps can compensate for a lack of success at others. As a result, a maximum could be an appropriate aggregation method for the identified spatial extent and time frame for breeding, with each tailored to the relevant species requirements. Following this spatial and temporal aggregation, a geometric mean may be a useful way to combine species into a single aggregated 'successful bird breeding' objective.

To reduce complexity for users, we will develop a decision tree to assist with the selection of aggregation methods in space, time and across objectives. Worked examples for common objectives will also be provided as default options but we will ensure sufficient flexibility that other bespoke aggregation methods will be possible.

From a technical perspective, the core of the Aggregator will be a function that takes the objectives, spatial polygons, time frame, and an aggregation statistic (e.g. minimum or geometric mean in the example above), and returns an aggregated outcome. Surrounding code will need to prepare those polygons and statistics. Initially, we propose to have a set of default spatial units (perhaps catchment boundaries, the Basin boundary, and ABARES Statistical Areas, for example), and a default set of mappings between objectives and appropriate statistics. The Scenario Controller component would then set which of the spatial units to use and could make any changes to the default set of statistics to use. There is clear scope to do the aggregation processing for each objective in parallel, and so achieve massive speed improvements.

The need for the Aggregator arises because of the way the objectives are defined. For example, the LTWPs define local environmental objectives at each gauge because that is as close as possible to the scale of the causal relationships with hydrology. Parallel modules for other themes (social, cultural, and economic) are expected to be similar. Many uses of the toolkit are expected to require aggregation from the scale of the causal drivers of the objectives to some larger scale, whether the whole Basin, individual catchments, or statistical areas. The particular scale of this aggregation will depend on the specific use of the toolkit, as well as the objectives themselves (as described in the illustration above). For example, economic or social objectives may best be assessed at the statistical area level, while environmental objectives may be more appropriate to consider in catchments. Work related to the Basin Plan may aggregate to the entire Basin, while community engagement might require assessing responses at the scale of catchments or culturally important sites.

Objective aggregation is also valuable. For many objective types (e.g. maintaining populations of native fish), multiple water requirements are defined (e.g. bankfull, low flow). Aggregating these into a single local objective outcome for native fish populations would be ideal but requires understanding the causal relationships driving each of those water requirements in detail. As illustrated above, the most appropriate method of aggregation is linked to the objectives themselves and whether compensation is possible. To illustrate, for maintaining populations of native fish, a bankfull requirement may provide spawning opportunities while a low flow requirement may ensure refugia during drought. Aggregation would require assessing how these relationships fit together to affect fish populations – if all adults die because there are no refugia, then subsequent spawning opportunities are moot. There are several potential pathways, with a strictures and promoters approach (Lester *et al.* 2020) being particularly well-suited as it captures dependencies between the requirements (typically related to life cycles, though these could be economic, cultural, or social) but does not require complex models. Another approach is a multi-criteria decision analysis-style of assessment. Similarly aggregations across Themes may be valuable for decision making. Because there are complexities and multiple options for aggregation, the toolkit will also be able to provide non-aggregated outputs for transparency. For the purposes of a toolkit demonstration, the necessary detail for this sort of aggregation does not exist in the LTWP. Thus, the Aggregator component developed here will focus on the separate local objectives, while ensuring that future aggregation of those objectives is readily able to be integrated.

Finally, to ensure robust aggregation and reduce bias, we aggregate the responses (local objectives), not the drivers (hydrology). By scaling the responses, we avoid the large potential biases created by nonlinear relationships between drivers and responses (Jensen's inequality; Ruel and Ayers 1999). This approach is particularly important when using pass/fail outcomes because this is an extreme sort of nonlinearity and so is particularly susceptible to large errors. Thus, the purpose of the Aggregator is to scale from individual objectives at local gauges to a flexible set of larger scales in a robust, general way that introduces minimal bias in the outcome.

7.5.1 Plan to build

Building the core aggregation function requires the ability to take spatially referenced data, an aggregation unit, and aggregation statistic as the first step. This function can be built and tested using the EWRs as they exist, replacing them with the objectives or quantitative outcomes once the Objective Translator is working. We will utilise spatial aggregation functions in existing spatial packages but incorporate additional error-checking and data handling to tailor inputs and outputs to our needs, as we have done in the past.

The objective inputs will come from the Objective Translator, but the polygons into which the outcomes will be aggregated and statistics to do so will need to be specified. Initially, both the polygons and statistics will be chosen as a default set for development. A single set of polygons (likely catchments) will be the starting point, with lightweight code to obtain the polygons, clean them for use by the next phases of the Aggregator (e.g. checking coordinate systems), and pass them on. As the toolkit progresses, additional code will be developed for other sets of polygons, allowing the overall toolkit to switch between these polygon sets using the Scenario Controller.

Likewise, the statistics will initially be set at conservative defaults, using a standardised format to match the statistic name to the objective, and these will be targeted at the existing pass/fail environmental objectives. As the toolkit progresses, we will develop different dictionaries matching objectives to statistics that can be used for different purposes (e.g. minimise harm *vs.* assess expected outcomes) or to handle different sorts of outcomes (e.g. quantitative responses) and these will be able to be chosen by the Scenario Controller.

A subsequent step will be to develop code to parallelise the aggregation process. This code will manage the set of objectives to aggregate and their statistics, feeding them in parallel to the aggregation function and processing the results, including checking that the spatial information is correct post-aggregation.

The resultant spatially-referenced aggregated outcomes will then be output for use by the Comparer component.

7.6 Comparer

Comparisons are essential to assess climate scenarios and adaptation options. The Comparer is designed to make comparisons between scenarios, allowing assessment and visualisation of their differences. Each comparison will characterise the simulated impact of adaptation options under given climate scenarios. The best method for comparing will vary depending on the intended use of the comparison so, as for the Aggregator, a number of common default options will be developed, with flexibility to enable users to define alternatives.

Comparisons provide distinct advantages over reporting absolute values from modelling. Difficulty in accurately simulating a complex system means that comparing the relative outcomes between scenarios is an effective way to identify differences between them. Any bias in the baseline assumptions applies to both, for example. In short, it is safer to say that scenario *a* is twice as beneficial as scenario *b* than to specify the absolute level of benefit for both. The relative importance of differences must also be considered. Differences may exist that are not likely to be ecologically (or other) meaningful (e.g. because statistical significance is, in part, dependent on sample size) and so the real-world impact of differences needs to be considered in addition to any statistical significance.

As for aggregation, comparison can occur in many ways and the particular method should be selected based on intended use and the underlying data being compared. Example options include using a mathematical difference (i.e. subtraction), multiplicative differences or change relative to a baseline, among others. To illustrate, multiplicative differences can be particularly useful when comparing disparate objectives (e.g. birds increased 3x while fish declined 5x) while a mathematical difference between scenarios is better when large changes in small areas may obscure larger-scale patterns. Investigation of the effect of adaptation options at a catchment scale is likely to best occur via assessing multiplicative change from a baseline (because it eliminates the effect of catchment size). As for aggregation, we will develop a decision tree with worked examples to assist end users.

Presentation and visualisation of comparisons can include maps, graphs, tables and narrative descriptions. Just as the values within scenarios must be chosen depending on the underlying data and the intended use, the form of presentation will vary as well. For example, maps are particularly useful for visualisation of geographic patterns, but can be difficult to interpret if changes are small or have a temporal component. Tables and graphs typically provide more precise ability to assess values but lack the ability to clearly show geographical relationships. Timeseries plots, particularly those relative to a historical baseline, are particularly useful for visualising climate trajectories but are most useful for quantitative data without too many locations. Different uses will require different sets of outputs (e.g. community engagement *vs.* internal planning).

Each of the preceding steps in the ModelArch is designed to generate those outcomes for a single scenario in a scientifically robust way in the most useful format. The Comparer will then make the comparisons between scenarios, allowing assessment and visualisation of their differences. The Comparer module will include two major components to enable flexibility; a set of functions that yield different sorts of visualisation outputs; and a user interface notebook that allows choice as to which outputs to generate for a particular use. Separate scripts will be developed for common analyses and use cases, with careful version control to ensure repeatability of analyses. Visualisations and output types will be built iteratively, starting with those most relevant to the demonstration, and extended to include others identified in consultation with end users. Comparisons will incorporate uncertainty, allowing assessment not only of the expected differences, but also how confident we should be in those assessments and how likely the outcomes are.

7.6.1 Plan to build

We will identify a set of initial data presentations to develop, including maps, timeseries, bar charts or similar, and tables. The set of initial presentations will be chosen to capture a range of potential uses, including accentuating different scales, geographic information, or temporal trends. Eventually, these presentations will depend on the outputs from the Aggregator, but data from earlier in the workflow will likely be similar enough to allow developing these functions prior to completion of the Aggregator. Example outputs will be circulated early and often to allow iterative improvement, using best practices from data visualisation and in targeting MDBA needs and uses.

The interface to determine which outputs to produce will likely be a user-editable notebook (Jupyter or R), similar to the Scenario Controller. The Scenario Controller controls the running of the workflow for a single set of scenarios, while any given set of scenarios may have several associated Comparer notebooks, creating multiple outputs that target different uses or audiences. For wider use, outputs will be saved as universally readable files (e.g. JPEG, PDF) able to integrate into reports or presentations. Future development may include shifting the notebook format into a dashboard or auto-generation of reporting.

8 CAUSAL NETWORK DEVELOPMENT

The aim for this component is to identify and characterise the causal links from climate through to outcomes. Capturing a network of those causal links turns the toolkit from a 'black box' to a transparent assessment of specific processes that link climate to outcomes for valued assets in the Basin. This network provides a visual and conceptual representation of the relationships modelled in the ModelArch component. The network is therefore the rationale that underpins the toolkit.

For example, during a dry period, overbank flows are likely to be less common. This may make floods of a given magnitude less frequent, which may result in less extensive floodplain inundation. Floodplain inundation may be required to cue recruitment in some vegetation species (e.g. river red gum) and so recruitment may decline for those species. Rationale such as this will be captured within the causal network. Thus, for the toolkit, capturing causal links involves characterising how water availability or elements of the hydrograph lead to the state of defined indicators, and then how the states of those indicators lead to specific outcomes.

Finally, the causal network will also need to characterise how local scale outcomes can lead to larger scale outcomes or can be synthesised with other groups of outcomes to provide holistic assessments.

The casual network concept aims to create a network representation of cause-and-effect relationships to illustrate likely relationships between activities (here, adaptation options and climate change) and environmental impacts (or responses) (Peeters et al. 2022). An example is illustrated in *Figure 4*.

The causal network concept was developed in response to common challenges in environmental impact assessment (Peeters et al. 2022). Specifically, issues of completeness and dealing with interacting drivers and stressors were addressed. Many of the same challenges are relevant for assessing the potential impact of climate change on Basin values, and the possible efficacy of proposed adaptation options.

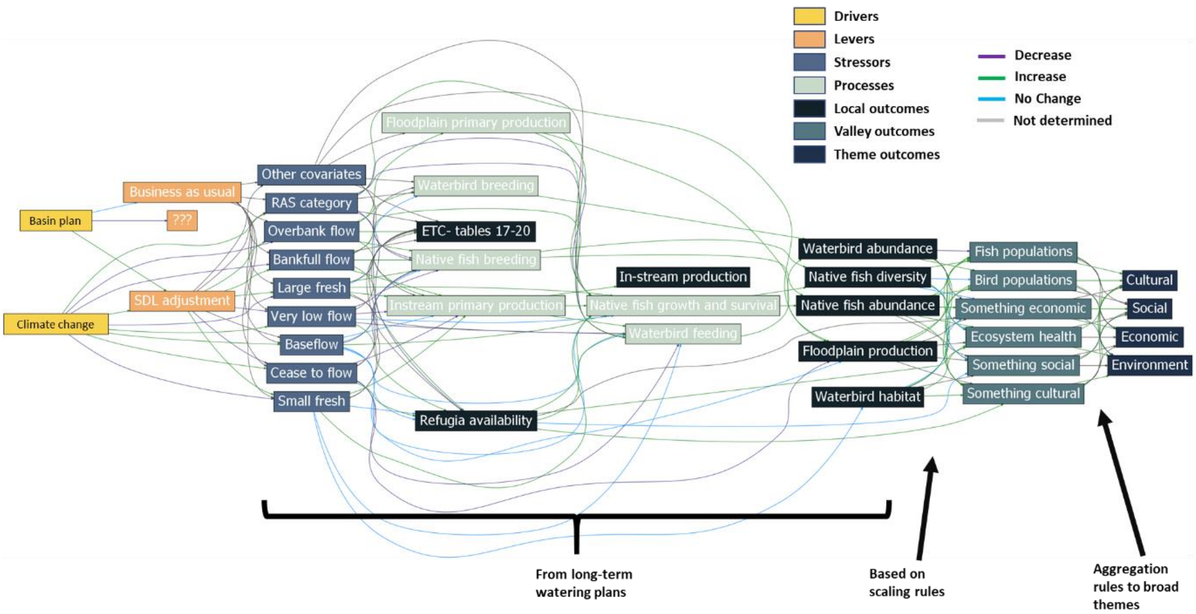

Figure 4. Example causal network capturing links from climate drivers (yellow) and MDBA responses (orange) to hydrology (indigo) to ecological processes (sage) to local objectives for the outcomes of those processes (black) to valley-scale aggregations (blue-green) and finally theme-scale outcomes. Link colours indicate directionality, but are only illustrative at the moment. This example built from a small subset of the NSW LTWP.

The network is based on a graphical representation of pathways represented by nodes connected by links (i.e. in a conceptual model). The nodes represent the drivers, levers, stressors, processes and outcomes at multiple levels in the system. The links represent the causal relationships among the nodes. Each node is clearly defined in terms of the current knowledge base, relevant knowledge gaps and key assumptions, to provide transparency.

Once the network is developed, it is subjected to analysis for internal consistency and completeness. A structured process is used to analyse the network, assess the plausibility of each link, its strength and importance, and the degree of confidence in that link. The analysis is spatially explicit and may be implemented in the toolkit at gauges, for example. The main limitations of this approach are that 1) it only considers monotonic relationships (e.g. cannot incorporate optimal relationships), 2) neglects a temporal component and 3) is a qualitative assessment. Each limitation will be assessed during the toolkit demonstration.

Documenting the network in this way will capture the structure of the models used, with rigorous, structured identification of the causal links. This creates transparency and enables causality to be assessed, challenged and updated as needed. Rationale for the inclusion of each model and causal pathway will be included along with the degree of confidence in their ability to capture relevant processes. Processes and links that are not captured in ModelArch will also be clearly identified.

One of the major benefits for WERP and the toolkit will be the ability to identify and define links between outcomes and value types. For example, within this structure, it will be possible to identify links between increased production and increased fish diversity or abundance. Similarly, increased bird abundance could be linked to increased cultural outcomes, if that species has cultural significance.

Another major benefit of this approach is its inherently visual nature. Visualisation of the casual links within ModelArch ensures that it is built explicitly to capture causality. The visual nature of the tool will be of value both within the project team and for external communication and engagement. Internally, the conceptualisation tool assists to define model components, for example. Externally, it can be used as a tool to develop trust in the toolkit and for engagement purposes.

8.1 Plan to build

To demonstrate the causal network approach, we will utilise the LTWPs developed by each state. These are already based on causal links between watering events and environmental outcomes. Additional development within MDBA with Traditional Owners is underway to explore opportunities to extend the tool to include cultural outcomes. Should this be appropriate, those cultural relationships could be included (i.e. provided Traditional Owners agree and see value in that approach).

The relationships contained within those LTWP will be used to develop causal pathways for the demonstration location as a starting point, to demonstrate the methodology of constructing and analysing the pathways.

During the demonstration, the emphasis will be to establish a process for drafting the causal networks, so as to identify and define the meanings of nodes, links and their classification within the framework set out by Peeters et al. (2022). There are two components, in particular, that will be key focal points: establishing mechanistic causality, where the causal links between watering (and other levers) to environmental, cultural (and potentially economic and social) outcomes is established; and scaling causality, where methods are developed to combine local responses to catchment and Basin-scale responses, through time and across multiple biological groups, or outcome types.

9 MODULE DEVELOPMENT

The aim for module development is to construct new or improve existing indicator models capturing the dependence of outcomes to hydrologic conditions across each of the four themes, following the approach of the EWRs.

The modules developed (new or based on existing indicators) will comprise databases of flow requirements that will pass or fail if specified hydrological conditions are met (*Figure 5*). These flow requirements (indicators) listed in each module will be mapped directly to outcomes – the condition of assets and values in each theme. For example, meeting a specific flow indicator may improve waterbird diversity, maintain a defined cultural value or support an economic activity. This means that the flow indicators must reflect a causal relationship to desired outcomes. For environmental water requirements, these links are captured in the LTWP. This explicit link to outcomes will be captured in the causal networks described above.

For clarity, the modules here refer specifically to that list or database of indicators and their associated outcomes. The EWR tool developed by MDBA, in contrast, provides a mechanism for assessing whether those indicators are met under a given hydrologic sequence or scenario (i.e. checks the EWRs for pass/fail). This is equally important but is a separate component of the ModelArch (see *Indicator Assessor* section above).

Four sets of indicators will be developed or improved, one for each theme. Where possible, these will be based on existing tools, but new indicators will be included where nothing currently exists. Each set is at a different stage of development and so the amount of work required, the timelines and the stage of planning is variable (as outlined below). Existing approaches will be prioritised, even where those approaches have limitations, as the focus of the toolkit demonstration will be to illustrate the ability of ModelArch to include diverse indicators, rather than to develop extensive sets of new indicators. We anticipate that other parts of WERP (e.g. values and vulnerabilities work, Theme 4) will be able to assist to develop indicator sets and associated causal networks in subsequent years. Future development may also shift these modules from pass/fail indicators to quantitative relationships if better models are developed during WERP.

There is also an opportunity to capture cross-theme inference that may assist for themes where the indicators are less well developed. For example, in some circumstances, greater fish yields for a culturally significant species may yield cultural and social benefits, and the flow-related requirements of the fish may be understood and captured. Similarly, higher production may also lead to increased economic benefits. Such inference will need to be undertaken with care. Given that environmental indicators are perhaps the best developed, it may be easy to give the impression that all values are linked to environmental outcomes. This is reductionist and unlikely to be true, so we will need to frame any such inference appropriately.

We will use the existing EWR tool to begin development of the ModelArch and causal networks, while proceeding with the development of other theme modules in parallel. Care will be taken to allow flexibility in the modules in case inputs and outputs vary across themes. Those themes will utilise the environmental module as a template and additional functionality will be added if required.

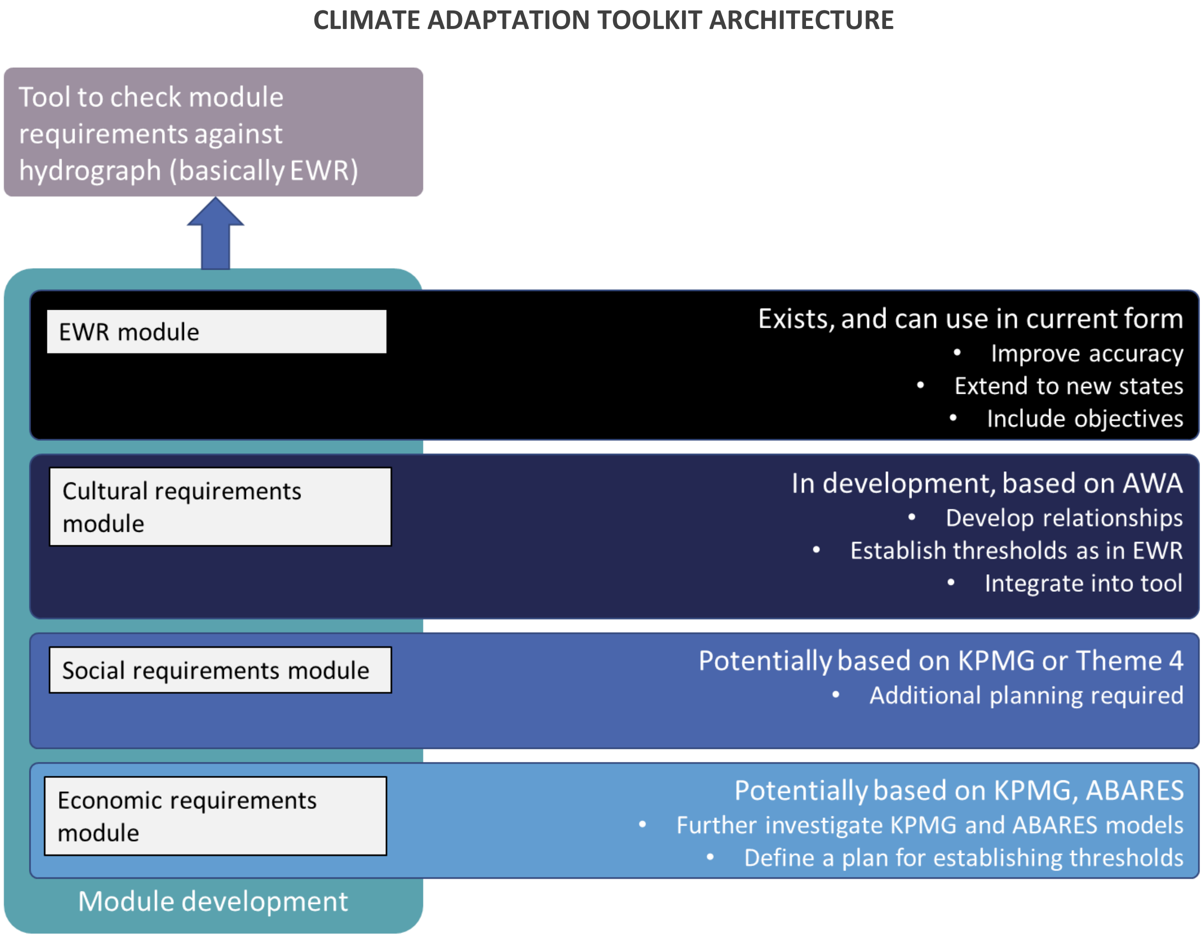

Figure 5. Structure of the theme modules and tool, with indications of work required.

9.1 Environmental requirements (EWR)

Environmental requirements are already well described. As noted above, the database used by the EWR tool captures environmental requirements in a format that can be used as the basis for the toolkit.

In the existing EWR indicator database, environmental indicators are based on the NSW LTWP. Indicators are automatically extracted from that LTWP, which are subsequently checked and amended by MDBA staff. Other states' LTWPs are compiled in a database taken from PDFs. The code utilised to extract NSW EWRs will need to be modified for each state as each LTWP varies in format and structure. For the demonstration, we will use the existing NSW set. Additional work to automate the compilation of EWRs from LTWPs will progress in parallel and beyond the timeframe of the demonstration.

9.1.1 Plan

The plan to develop the environmental requirements module will vary between NSW and other states. For NSW, additional work to improve the code to automate the extraction of EWRs is needed. EWRs change with new iterations of the LTWPs so, in the long term, having the ability to extract them automatically is advantageous. For other states, additional work will be required. Beginning with case study locations, we will evaluate the EWRs and develop a database of indicators.

The final element of the environmental requirements module is a list of relevant objectives for each indicator. Here, we will map the environmental objectives across each of the indicators, so that specific hydrologic sequences can be assessed against their ability to meet the requirements for relevant environmental values.

9.2 Cultural requirements

No tool exists to use as the basis for a cultural requirements module. Aboriginal Waterway Assessments (under the program described in MDBA, NBAN & MLDRIN [n.d.]) have been undertaken for some areas in the Basin, but these remain the property of the respective Traditional Owner group and engagement with those groups is needed before any approach could be developed that uses information contained within those assessments.

MDBA and individual Traditional Owner groups have been collaborating to pilot the development of quantitative flow requirement for cultural sites. This presents a possible opportunity to develop a demonstration of a cultural requirements module. Consultation with the relevant Traditional Owners about such an opportunity, with appropriate attribution, protection of Indigenous Knowledges and resourcing, will be undertaken. If there would be value in that for the Traditional Owners, additional work would need to be undertaken to capture the causal pathways and the links between specific indicators and objectives to enable the existing structure to be utilised. If that is not appropriate, other options will be explored. There may also be an opportunity to leverage the existing EWRs where they describe species or other environmental outcomes that also hold particular cultural value. Care would be needed to ensure that the context of such indicators was clear – they are unlikely to represent a comprehensive list of cultural indicators and so cannot be interpreted as such.

9.2.1 Plan

The first step in the development of a cultural indicator module is to engage with Traditional Owner groups to identify a suitable location and format for such an indicator. MDBA staff are currently collaborating with specific Traditional Owners to develop cultural water requirements for individual sites. We will engage via that team to determine whether a tool such as this is a suitable mechanism for incorporating such water requirements into future planning and, if so, how best to collaborate with Traditional Owners at a demonstration site. We will be guided by Traditional Owners and adapt our plan to meet their needs and preferences. One option would be to produce some demonstration outputs to illustrate the intent and capability and enable broader consultation as to the appropriateness of the approach. A discussion regarding future expansion of any approach into a broader spatial area would then follow.

9.3 Economic requirements

As for cultural requirements, there is no single tool that currently exists that captures causal relationships between flow (or other river system model outputs) and economic outcomes. Thus, an example module will need to be created to capture those relationships. Previous work has been undertaken by ABARES and KPMG that may be suitable as a starting point for the purposes of the toolkit demonstration.

The KPMG work (KPMG 2018) has, in the past, been criticised for being an overestimate of impact, as it does not account for adaptation. Given that ModelArch is specifically designed to include adaptation, this may make the KPMG model more appropriate for inclusion than it initially appeared. Another option is to leverage the EWRs to the extent that they can be linked in a causal manner to economic outcomes. A demonstration may be possible, but this is unlikely to be comprehensive. As for the environmental and cultural modules, causal links and specific outcomes for each indicator will need to be mapped. Once a database exists (even for a demonstration subset of indicators), this will be able to be used by the same Comparer to assess specific hydrologic sequences.

9.3.1 Plan

To progress the development of an economic requirements module, we will continue to investigate existing ABARES and KPMG work and identify whether they are suitable to provide the basis for the module. If so, a demonstration will be developed. In parallel, the existing collaboration with ABARES will be pursued to explore the development of a more comprehensive module.

9.4 Social requirements

Further assessment is needed to determine what exists that can be built upon as the basis for a social requirements causal network and relevant indicators. Initial assessment of the KPMG model suggests that it includes some social outcomes, and so this may be the most appropriate starting point for a social module, but further liaison is needed with Theme 4 as their activities commence. As for other modules, every effort will be made to leverage indicators from other themes that may also have causal links to social outcomes (e.g. fish populations and recreational fishing).

9.4.1 Plan

To progress the development of a social requirements module, we will revisit discussions with Theme 4 as their activities commence. We will also investigate existing indicators in other themes for inference and assess the KPMG model for appropriate indicators.

10 TOOLKIT DEMONSTRATION

To summarise the above, the toolkit demonstration, to be completed in June 2022, will comprise the following components. Additional work to continue to develop elements of the toolkit (as outlined above) will continue beyond the toolkit demonstration milestone into Year 2 of WERP. This will include an assessment of what will be feasible for development within WERP. For example, not all elements will be able to be implemented at a Basin scale during WERP. Where this is the case, assessment of resources required to extend that scope, or opportunities for outsourcing, will be developed.

ModelArch development

- For the demonstration site and using existing EWR module, develop minimal functioning components for each element in the ModelArch workflow: Scenario Controller, Indicator Assessor, Objective Translator, Aggregator, and Comparer
- Demonstration of several types of output, e.g. maps, timeseries
- Plan for next steps: identify priorities for improved functionality, needed changes to the workflow or methods, module inclusion, or output types
- Criteria for metadata and prioritisation of additional tools
- Additional: If time permits, documentation of workflow and toolkit: how to use the architecture and reasoning for decisions made
- Additional: If time permits and module development is sufficient, include additional themes
- Additional: If time permits, develop aggregation of multiple indicators per objective at single gauges

Causal network development

- For the toolkit demonstration site, capture the environmental water requirements outlined in the LTWP in a causal network for the site. The causal network will capture the identity and meaning of nodes, lines and their classification, as well as the relationships with flow and outcomes at broader scales (as plausible given the local scale of the demonstration).
- Develop a methodology for the future creation of additional causal networks for other locations and other themes
- Additional: If time permits, capture cultural outcomes for the toolkit demonstration site, provided Traditional Owners approve of the approach

Module development

- Develop indicators from NSW EWRs as an example module
- Capture the objectives associated with environmental indicators for NSW
- Capture of causal relationships between flow, indicators and outcomes in a causal network, with a documented process for use by other modules
- Include modified and updated EWR tool code to check indicators against hydrological sequences to assess the pass/fail of each indicator for each sequence and the ability to pass these outcomes to the next element in ModelArch
- Additional: If time permits, capture EWRs and related objectives from states other than NSW

- Additional: If time permits, develop indicators for cultural, social and economic values based on the Aboriginal Waterway Assessments (if appropriate) and KPMG and ABARES models
- Additional: If time permits, develop inference among themes for indicators which link multiple themes (e.g. culturally significant species or economically significant environmental indicators).

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