Framework for evaluating aquatic ecosystem connectivity

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1 Executive summary

Over recent years there has been an increasing realisation among planners, managers and policy makers that effective management of wetlands is often hampered by the lack of a consistent framework for including connectivity in planning and management decision making. While many effective wetlands management actions can be conducted at a site level, without an appreciation of the connection of the wetland to other wetlands and to the broader landscape many site-specific actions may be of limited value. Many of the values and ecosystems ascribed to wetlands are only effective when the wetlands are part of a connected network. The aquatic ecosystem connectivity project arose to fill this knowledge gap and to develop a set of tools for evaluating and assessing connectivity within and between aquatic ecosystems for management outcomes.

This document outlines a definition of aquatic ecosystem connectivity, connectivity principles and a framework for understanding aquatic ecosystem connectivity. The definition and principles establish that connectivity needs to be understood in terms of the environmental processes which it facilitates. These processes provide the appropriate context for understanding it. The framework describes a process for systematically and transparently working through the connectivity for relevant function of an aquatic ecosystem and identifying the appropriate spatial scale for the issues identified.

The connectivity framework was developed through expert workshops involving policy makers and scientists from state, local and federal government bodies and universities, with individuals from a wide range of disciplines. It is effectively a synthesis of concepts and ideas that are currently being applied to specific connectivity problems with narrower scope. What distinguishes this framework from others is its applicability to a range of connectivity issues. Research fields have developed methods for measuring and understanding specific types of connectivity, whether it is population connectivity (genetics), floodplain connectivity (hydrological regime and tagging studies) or groundwater connectivity (hydrogeology). Each research area has a specific definition and series of methods for evaluating connectivity, and though they may share commonalities, they are rarely completely compatible and individually do not cover the depth and breadth of connections which may occur between aquatic ecosystems.

The framework developed through this project is compatible with understanding connectivity at any level of spatial scale for any outcome. It involves a transparent process for building an understanding of ecological connectivity in the context of ecosystem function in order to facilitate management activities. It can also benefit research in providing a common context and systematic method for the consideration of complex forms of ecological connectivity.

The key principles from the project are:

- There needs to be a **purpose** for connectivity linked to overall management objectives.
- Connectivity is a **mechanism that supports environmental processes.**
- **Potential connections** do not always result in **realised connectivity**.
- Connectivity must occur through the **physical environment** (air, water, land).
- **Appropriate connectivity** does not necessarily result from more connectivity**.**
- Components (the parts) and connectivity **must both** be addressed for long-term systems resilience.
- **Conceptual models of underlying processes** are essential precursors to addressing connectivity.
- **Knowledge gaps and uncertainty** must be acknowledged, but not limit decision making.
- The environmental processes should determine the relevant **spatial and temporal scale.**
- Connectivity decisions should be made within an **adaptive management** framework, which will allow for decisions to be refined as system understanding improves.

2 Definition and scope

2.1 Aquatic ecosystem connectivity - definition

Aquatic ecosystem connectivity is the mechanism that propagates environmental processes spatially and temporally.

Important points about the definition:

- Connectivity affects the components of an ecosystem through the processes they are involved in.
- Environmental processes can be physical (e.g. sedimentation and erosion), chemical (e.g. pH regulation processes) or biological (e.g. dispersal of a fish).
- Considering connectivity in reference to specific processes gives it the necessary context for ecologically meaningful evaluation.
- A connection is the pathway over which connectivity occurs or the state of being connected.

The framework includes connectivity within and between aquatic ecosystems, including freshwater (riverine, palustrine, lacustrine, subterranean), estuarine and marine. It encompasses physical, chemical and biological connections, both in and out of the water, which facilitate processes for aquatic ecosystem function. Examples of this are connections by aquatic biota which may have terrestrial life stages (e.g. frogs, aquatic invertebrates), connections between aquatic ecosystems which are not mediated by water (e.g. birds transferring nutrients, aeolian deposits) and nutrient cycling processes which may influence the aquatic ecosystem (e.g. riparian vegetation inputs, carbon cycling processes).

Effective application of the framework may require technical expertise and specialised desktop investigation skills. For more complex connectivity issues, the expertise and experience of professionals from various disciplines related to hydrology, ecology, genetics, environmental planning and management should be engaged.

Because healthy, functioning aquatic ecosystems require connectivity through land and air as well as water, the principles of the method are broadly applicable to terrestrial ecosystems and are consistent with a landscape ecology or ecological engineering approach.

For the purpose of this project aquatic ecosystems are considered consistent with the definition of wetlands.

3 Previous applications of connectivity

Research into connectivity can be grouped in many ways but for the purposes of this framework we have considered it in two broad categories:

1. Those that examine the patterns of connectivity through the environment.
2. Those that focus on the processes of how connectivity functions (see Bibliography).

In general, broadscale government planning and management projects focus on physical patterns of connectivity. These usually focus on the 'connection' provided by a contiguous physical feature of the environment (e.g. corridors, stream networks etc.), assuming this is a surrogate for other types of connectivity and that these physical connections mediate other connections. These methods have typically resulted in criticism and observations that the physical features do not capture particular aspects of connectivity (e.g. flow timing), which leads to boot-strapping (i.e. adding simple rules on top of the original physical feature in order to capture some of the dynamism of the natural system) of complexity onto the feature. The boot-strapping process then continues as more shortcomings are identified. This is a legitimate and common way of dealing with complex systems, but in its implementation in connectivity problems, it has focused on small parts or aspects of the connected system, missing the ecological relevance of the connected system as a whole.

There is some predictive capacity in the use of simple measures of physical connection (e.g. the provision of environmental flows), but it does not move us towards a consistent ecologically meaningful way of assessing connectivity. Some of the case studies run as part of the connectivity project demonstrated that solely relying on physical features has the potential to lead to inappropriate decisions (Hughes and Schmidt 2012), and that by focusing on ecological function an elegant and intuitive understanding of connectivity can be derived (DSITIA 2012). This is reflected in the scientific literature in projects which focus on ecological function and the specific connections required to support the environmental processes (see Bibliography).

4 Understanding aquatic ecosystem

Connectivity as a concept is easy to understand; and can be applied to almost any functioning aspect of an ecological system. Consider the following examples:

- Hydrology: Water flows from upland river systems, down across the lowlands and out to sea via estuaries.
- Behavioural ecology: Higher water levels allow fish to connect to more habitat.
- Genetics: Genetic diversity is maintained by fish migration between populations.
- Geological processes: Disconnection of coastlines from in-stream sedimentation processes, though the construction of large dams can alter coastal formation processes.

While these examples demonstrate that the concepts of connectivity are readily understood, without a way to systematically understand connectivity it becomes difficult to evaluate it in an ecologically meaningful way.

The system for understanding connectivity in the present framework is presented in two parts:

1. Key concepts to structure a way of thinking about connectivity
2. A framework for evaluation of ecosystem connectivity.

These provide the basis for systematically understanding aquatic ecosystem connectivity and applying it to real world scenarios.

4.1 Key concepts

A large part of the framework for understanding connectivity revolves around an understanding of the components and processes which contribute to ecosystem function. **Components** are the parts which comprise the environment (e.g. fish, wetlands, birds, carbon stores), whilst **processes** help form and maintain the system (e.g. spawning, inundation, migration, carbon cycling). Processes require particular characteristics to function properly. The characteristics may be physical (e.g. temperature), ecological (e.g. habitat availability) or other processes (e.g. recruitment cannot occur unless there has been a successful reproduction process).

4.1.1 Potential and realised connectivity

Potential connectivity refers to the appropriate physical environment required for connectivity to occur.

Realised connectivity is the successful completion of the connectivity action for the fulfilment of an environmental process.

It is important to understand that connectivity does not automatically happen because of a connection by a physical medium (e.g. just because water flows between two points does not mean fish will disperse between them). As such, connectivity cannot be evaluated by the use of a single physical metric. For long-term systems resilience, management must address both the components and their connectivity together. Appropriate physical characteristics (e.g. water flow between two points) provide the **potential** for ecological connectivity; however, the requirements for that connection to occur need to be assessed with reference to an objective. The objective will vary depending on the purpose and scale of the question being posed. The objective will likely have other requirements before the connection can be **realised** (e.g. fish require suitable habitat to disperse to). Management tends to focus on **potential** connectivity (e.g. providing corridors, ensuring watering regimes, removing blockages). Demonstrating that connections are being **realised** is important to ensure management objectives are met and will improve understanding of how ecosystems function. Appendix 2 – Dealing with knowledge gaps contains more information on techniques for demonstrating that connectivity is being realised.

4.1.2 Process-centric understanding

Because connectivity works through processes, an understanding of these processes becomes central to how to structure an understanding of the connections in an ecosystem. It is impossible to understand connectivity without an understanding of the processes within the system. These environmental processes define the:

- **medium** through which the connection functions (land, water or air) and a realisation that connections between aquatic ecosystems do not need to occur through water
- the relevant **attributes,** which define the appropriate connectivity
  - **magnitude** required for appropriate connections, e.g. zero connectivity (i.e. isolation) may be as important as complete connectivity for the ecosystem
  - level of **spatial scale** at which the connections function
  - **appropriate timings** for the connection (e.g. at what time of year, how long for and how often)
- effective **connectivity regime** - a combination of all the factors above.

The processes define how connections can be understood and set the context for how they interact with the physical environment. Each process has requirements which may be:

- a physical connection event (e.g. through water, land or air)
- physical/chemical (e.g. temperature, pH)
- another environmental processes (e.g. recruitment is dependent on a successful spawning event).

Fish spawning: An example of a process
The spawning process for a fish species will have evolved to occur under specific conditions (water quality, temperature, suitable habitat), only some of which will be related to connection (hydrological regimes). The eel-tailed catfish, *Tandanus tandanus*, requires low stable flows for successful spawning and larval development. The low stable flows are a connection event that provides appropriate conditions for the spawning process (e.g. allows nest building, oxygenation for the eggs). Appropriate flows must then coincide with the breeding season which varies with region. If this does not happen, the breeding event may be missed. The magnitude and duration of the flow must also meet the requirements of the process. If the magnitude of the flow is too high, the nest may be destroyed; if it is too low, spawning may not occur or there may be higher egg/larval mortality. Also, if a suitable flow does not last long enough for spawning and larval development, there may be high egg/larval mortality.

5 Connectivity framework

Evaluating how connectivity affects an aquatic ecosystem should be considered as part of an overall adaptive management framework (Figure 1). The framework involves understanding the ecosystem in terms of its processes as this provides a systematic structure for evaluating the ecological meaningfulness of connectivity.

At the broadest conceptual level, the framework involves:

- **Defining the issues**, considering formal policy and legal drivers, setting specific objectives and defining the spatial scale.
- Forming a **conceptual understanding of the ecosystem**, based around the components and processes and how the system functions. Determining if the level of spatial scale is ecologically meaningful.
- Developing the **spatial and temporal regime** of connections, required to deliver the objectives, from the conceptual understanding.
- **Evaluating** the connectivity regime in the real world.

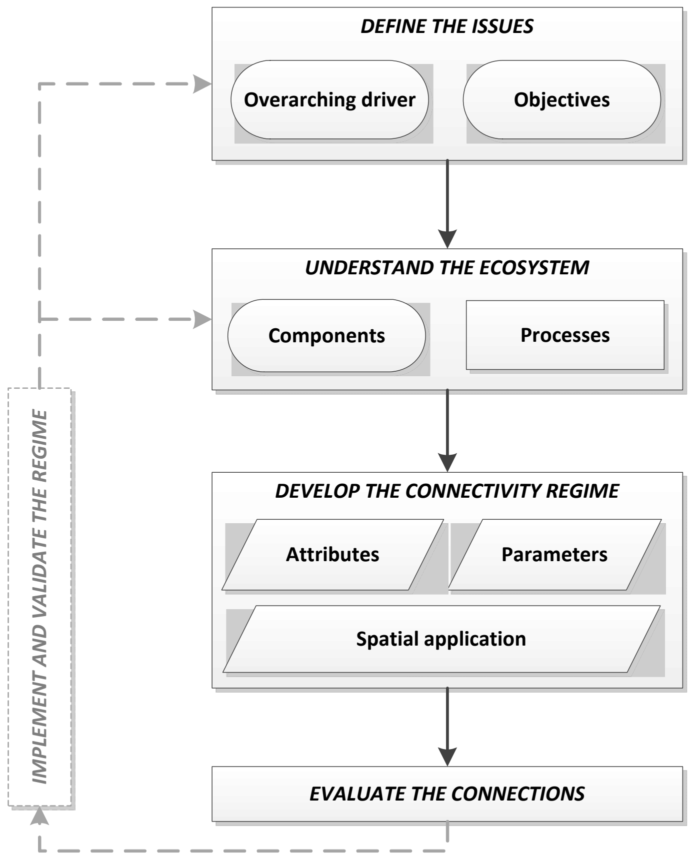

Figure 1 – Connectivity method flow chart. Parts in grey are completion of the adaptive management loop and are not covered in this document.

The process described in this document only addresses the framework for understanding connectivity. Implementing the connectivity regime in the real world and revising the understanding is an integral part of the process but is not discussed in detail in this document.

5.1 Defining the issues

Because of the complexities of connectivity, and the fact that appropriate connectivity may be achieved for one objective but not for another with the same connectivity regime, it is necessary to have a well defined purpose before attempting to begin a connectivity assessment. The purpose will limit the scope and provide focus for the assessment of connectivity. Without a well developed purpose an assessment of connectivity runs the risk of becoming either too complex, being irrelevant to the desired outcomes or too simplistic and not resulting in realised connectivity. The key point is that there is no magic 'single answer' for all connectivity objectives, something which has been attempted and is prevalent in the sole use of physical media as surrogates to demonstrate connectivity in a system.

5.1.1 Overarching driver

This is the formal driver for the connectivity assessment. It may be a legal requirement, a policy driver or the broader social or economic reason for wanting to assess connectivity. This provides context and direction to the connectivity assessment and can strongly shape the specific details for the objectives. Some legislative drivers may prevent effective connectivity analyses from being conducted by limiting the spatial extent of the assessment area (i.e. meaningful environmental processes may occur at a broader scale than the scale at which the assessment is occurring). It is important to note any factors which may reduce the ecological relevance of the assessment and bring these to the attention of those responsible for the policy or driver.

Drivers and objectives

It is important to understand the nature of the driver in shaping the objective(s). Different drivers will have been designed for different purposes and may result in subtly different objectives which may or may not be compatible. This was succinctly captured in the following example from Dale et al. 2010: 'the *Nature Conservation Act 1992* provides for the conservation of nature (Part 2, S 4). The purpose of the *Fisheries Act 1994*, which also protects wetlands as declared fish habitat areas, is "to provide for the use, conservation and enhancement of the community's fisheries resources and fish habitats" (*Fisheries Act 1994*, S 3 (1)). Although the two objectives are related and similar, the emphasis of the *Fisheries Act 1994* is on human use, promoting ecologically sustainable development, whereas the *Nature Conservation Act 1992* is primarily concerned with conservation and how to achieve this by management.'

5.1.2 Objective(s)

The objectives are defined from the overarching driver. At this stage in the assessment it is important that the objectives should not be limited to those specific to connectivity. The objectives will be used to define the scope of the conceptual understanding of the ecosystem. They should be 1-2 lines long and provide a description of the defined ecosystem including both natural state and any past current or predicted changes.

Defining and refining objectives

Without tightly defined objectives it may not be possible to structure the ecosystem understanding or define subsequent connectivity objectives. If there are problems with any subsequent stages (e.g. system understanding is too large and lacking direction, connectivity objectives are not forthcoming from the system understanding), it is likely that revisiting and refining the objectives will provide better focus.

The objectives should be specific enough to be able to set goals and targets, and give a clearly defined output and assessment criteria to frame the conceptual understanding. Consideration of ecosystem services may help in defining the objectives.

The description of the ecosystem should include both its current and desired future state, effectively answering the questions:

- How are we going to measure the outcome?
- How is the outcome going to be understood?

Some example considerations for measuring outcomes:

- Is connectivity being assessed with reference to natural condition or optimal connections given landscape constraints?
- Are critically endangered species targeted? Is biodiversity taken into consideration?
- Is the goal to maintain or improve ecological assets in the defined spatial scale? How do we measure whether this is occurring?

The following provides an example of a series of objectives applied to the outcome of **maintaining and/or restoring viable floodplain vegetation communities of a lower river floodplain system**. In developing the objectives for this outcome other aquatic components of the system**,** such as the river network**,** are not considered. Objectives for this will involve understanding:

- a delineation of the **l**ower **r**iver **f**loodplain **s**ystem, i.e. the study area extent
- the types and extent of vegetation communities within the area (as each may have different watering regime requirements)
- the condition of each of these vegetation communities across their extent, this may also contribute to understanding some fundamental management definitions such as:
  - what viable may mean for each of the communities
  - what the restoration needs and requirements are for each of the vegetation communities?
- the hydrological requirements to maintain and restore each of the vegetation communities.

This example only considers water regimes as a management tool and it implicitly assumes that fulfilling water requirements will achieve outcomes (i.e. it does not consider other threatening process such as grazing but, in saying this, the nature of the framework allows for a conceptual understanding of what components and processes may be affected by grazing).

Defining level of spatial scale

Throughout this document the term 'scale' refers to spatial scale (i.e. the spatial extent at which something occurs), as opposed to mapping scale (i.e. the ratio of the distance on a map to the distance in the real world). In order to improve management decisions it is necessary to be aware of the level of spatial scale being considered and its ecological relevance, by considering it in terms of environmental processes. It is possible that a level of scale has been prescribed that is not relevant to the environmental processes being considered (e.g. at the site level, only the processes of recruitment and spawning may be relevant, the process of dispersal usually occurs at the landscape level of scale). At the very least any discrepancy and limitations should be documented. Appendix 1 has more information for consideration of scale.

5.2 Understanding the ecosystem

Once the assessment objectives have been determined, a conceptual understanding of the ecosystem must be developed at the appropriate scale. Care must be taken as connectivity is only one mechanism supporting an ecosystem, and other components and processes supporting ecosystem function should be considered before determining if connectivity is the primary focal issue. The development of as complete a system understanding as possible is recommended, with consideration of limitations of data availability and real world application. This allows easy identification of knowledge gaps and can help reinforce future research directions.

Existing conceptual models, focusing on the processes contributing to ecosystem function and their locations and interactions in the landscape can be incorporated directly into the connectivity framework (EHP 2012c). The development of process focused models of ecosystems forms an essential base upon which to build connectivity understanding.

5.2.1 Components, processes and environmental responses

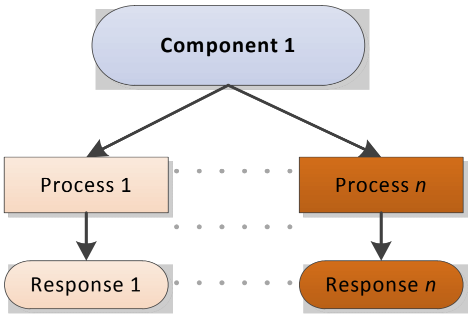

Figure 2 - Components can have multiple processes which lead to numerous responses.

The connectivity framework uses a simple approach to ecosystem conceptualisation focusing on the processes of an ecosystem, the components they influence (i.e. the constituent parts of a system) and the resulting environmental responses (i.e. the end result of processes). The processes are central to the understanding of the system as they link the components to the environmental response, and as such play a fundamental role in structuring the ecosystem. Each component may by affected by multiple processes which lead to different responses (Figure 2). Systems are built from the interactions between components, processes and responses (e.g. the recruitment process is dependent on a successful response from a reproduction process such as spawning, seeding or fawning etc.). Processes may interact with each other, and may form complex dependencies (see following example).

It is important to document the components, processes, and the interactions between them in an appropriate format (e.g. tables and flow charts).

Appendix 1 – Processes and conceptualisation contains further information regarding the development of system conceptualisations.

Examples of system conceptualisations can be found in the case studies conducted for the project (EHP 2012a).

Example: Hyriid mussels in the Georgina and Diamantina catchments

Hyriid freshwater mussels are extremely long lived (with recorded life spans in excess of 60 years) and inhabit the ephemeral river system in the Georgina and Diamantina catchments of Queensland, occupying waterholes that are disconnected for the majority of the year (Figure 3). Genetics studies have validated that the populations in the Georgina and Diamantina catchments are not related, and that the catchment is an appropriate spatial scale to conduct a connectivity analysis (Hughes et al 2004).

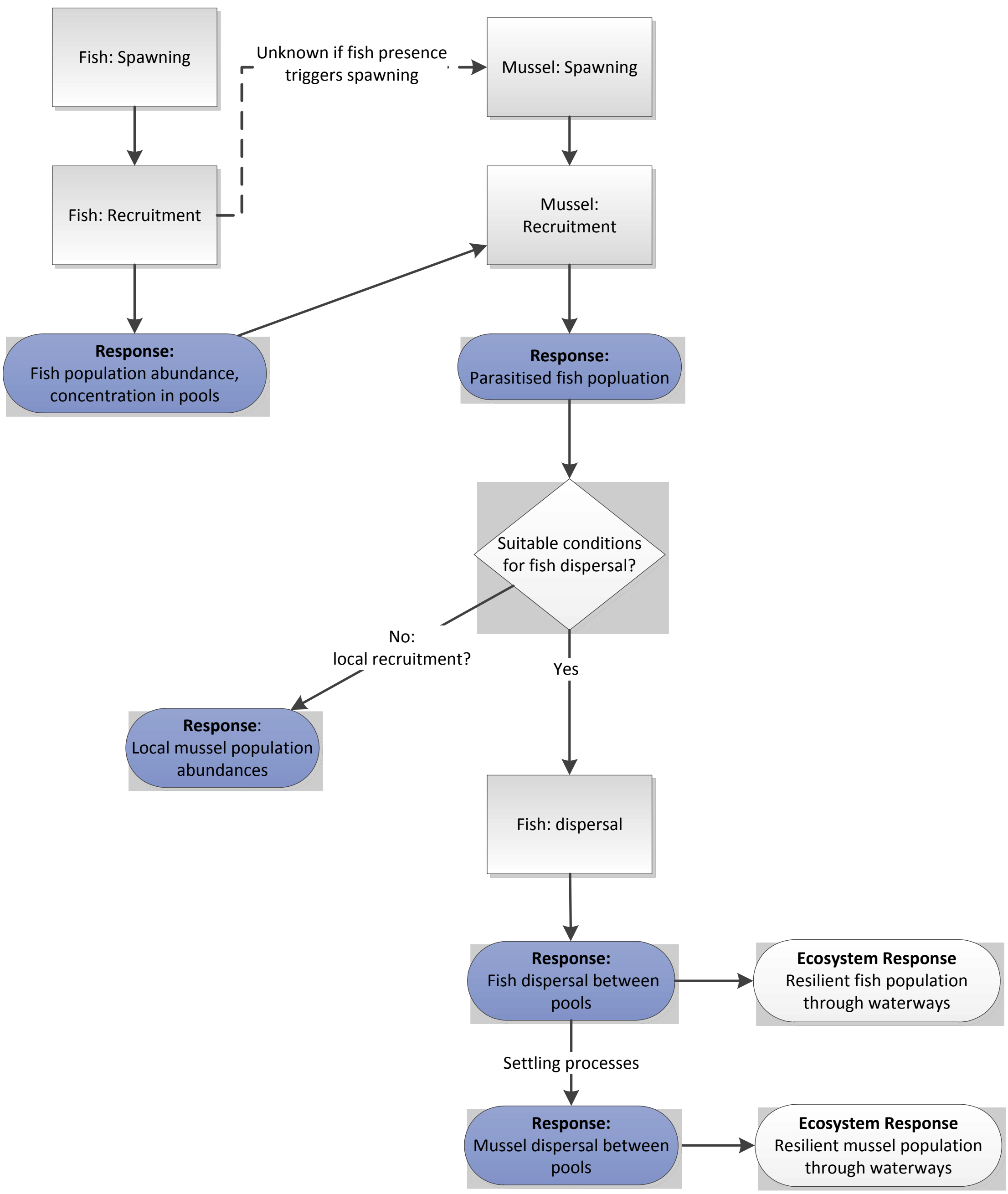

Figure 3 – System conceptualisation for Hyriid mussel population viability

Their spawning occurs when water levels in the waterholes drop enough for them to make contact with local fish species. The larvae (glochidia) parasitise the gills of the fish which is a requirement for their life cycle and also acts as a dispersal mechanism for the mussel. It is unknown what the exact triggers are for mussel spawning but they could be environmental conditions, increased contact with fish (due to higher fish density in contracting waterholes) prior to flooding, subsequently allowing fish (and larvae) to be dispersed. The following flow chart summarises the interaction between mussels and fish from a population viability perspective. It incorporates local processes (spawning and recruitment), landscape processes (dispersal), their requirements and considerations of frequency and seasonality.

5.2.1.1 Available data, knowledge gaps and uncertainty

Part of the conceptualisation process is to collate available data and information and record the knowledge gaps and uncertainty associated with these. Relevant data sources include databases, research, mapping and conceptualisations, and these should be recorded to add validity to the conceptualisation.

Due to the complexity of natural ecosystems there are likely to be significant gaps in knowledge or areas where knowledge is incomplete or unproven. Information used in conceptualisations may have varying levels of confidence (i.e. years of research into a specific topic may have validated a theory while for others there may be no direct data and only untested hypotheses). As such it is important to record the level of confidence in the information. Notation of the uncertainty can be used to identify areas of the conceptualisation which may need revision and to target subjects for future research.

Some examples of methods for dealing with knowledge gaps can be found in Appendix 2 – Dealing with knowledge gaps.

Example: Knowledge gaps
The following knowledge gaps were identified in the mussel system conceptualisation (Figure 3):
Hyrtl's catfish, *Neosilurus hyrtlii*, was used as a surrogate to determine the spawning, recruitment, and dispersal requirements for the host fish species. This species was chosen because it was known to inhabit the area and life history information was available. It may not be indicative of requirements for other fish species.

Specific mussel spawning triggers are unknown. It may be triggered by fish contact during the drying phase or by a different physical or chemical component. It is also not known whether mussels recruit locally into waterholes, though it is considered likely by experts.

5.3 Develop the connectivity regime

This step involves using the system conceptualisation to define the connectivity requirements for the realisation of each process and applying these to a real world situation. It involves finalising the list of attributes associated with the environmental processes, defining their parameters and applying this to the real world setting.

5.3.1 Attributes and parameters

Attributes, as descriptive characteristics or features, outline what is required for each process to succeed (e.g. overbank flow for recruitment, inundated habitat for access to food and shelter) and will have been partially defined in the system conceptualisation stage. Attributes have some commonality between different ecosystems, but the terminology will vary (e.g. freshwater flows in rivers are similar to tidal currents in estuaries). Because of this, specific attributes are not defined, but some examples are provided and can be found in Appendix 3 – Attributing the medium of connectivity.

Parameters define the limits of the attribute (e.g. magnitudes, thresholds, and timings) in order for the process to be delivered successfully. These must be ecologically relevant and can be generic or location specific. Generic parameterisation involves providing numerical values to a process which occurs irrespective of location (e.g. a water temperature of 28 degrees Celcius is required for the species to spawn), or a description of the process which needs to be parameterised to local conditions (e.g. requires overbank flow to maximise recruitment with the magnitude of flow required to overbank varying from area to area). Descriptions should contain assumptions which were used in setting the thresholds and levels (e.g. assume two significant dispersal events are needed per generation to maintain population resilience. The life span of the organism is 10 years. Therefore the need for a significant dispersal event occurs every five years). The descriptive parameters can be given numerical values in the context of the real world situation (e.g. in this creek system overbank flows occur at 5000 ML/day).

Example: Connectivity regime for the mussels
The original concept of mussels being distributed by fish only comprises part of the connectivity regime of the system. Other life history stages have connectivity requirements at other spatio-temporal scales that may need to be considered.

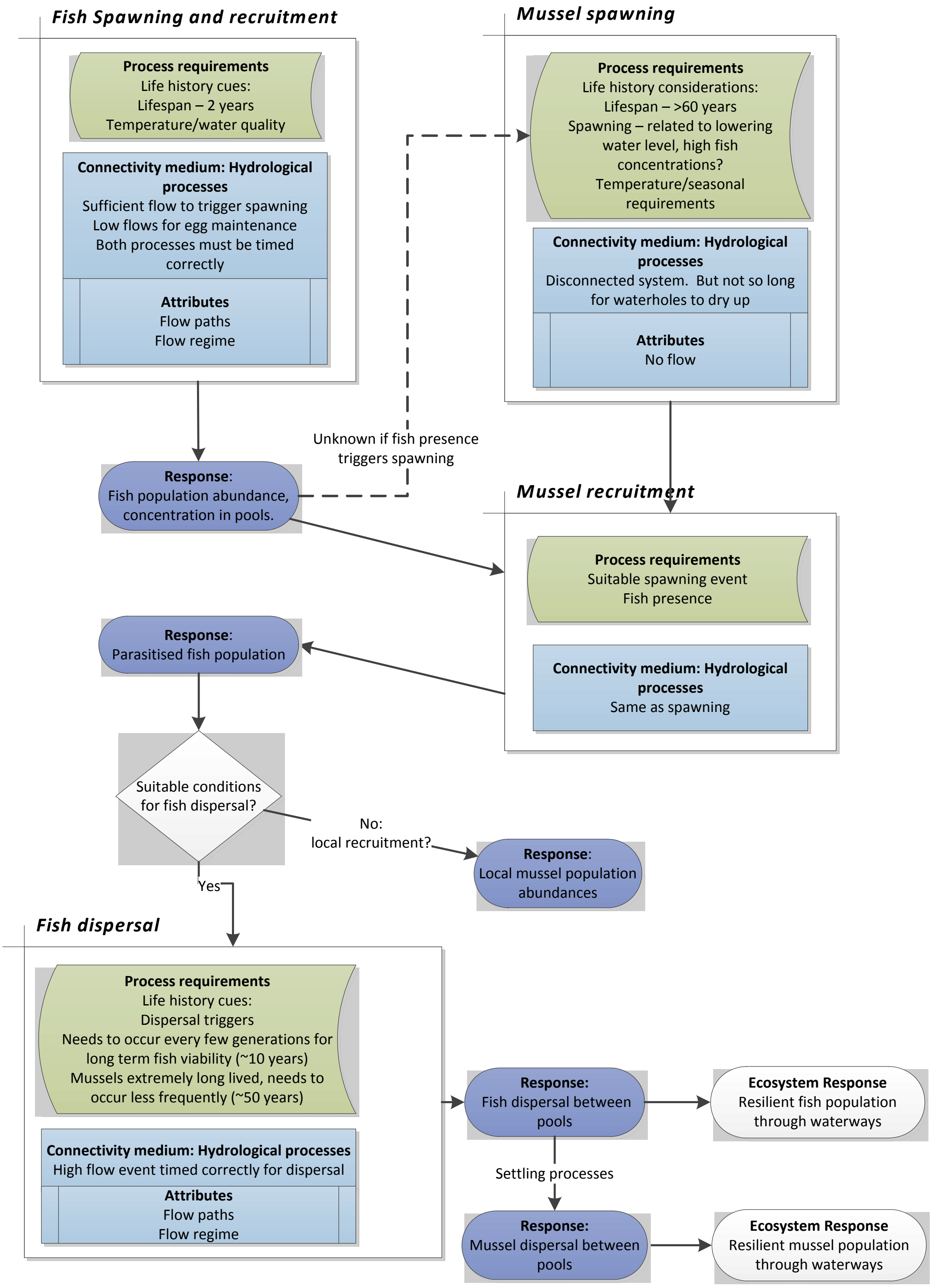

Figure 4 - System conceptualisation for Hyriid Mussel population viability with attributes and parameters

The connectivity regime in this example is primarily driven by the hydrological regime of the ecosystem. Key points relating to the hydrology to each of the life history stages are outlined below (note, timing of events is arbitrary but included for the sake of the examples):

Fish spawning and recruitment

- Flushing flows improves water quality, followed by low flow period for egg maintenance. Spawning occurs after seasonal high flows during the spring to summer months.
- Seasonal low flows and high oxygen saturation are required for significant recruitment.
- These events should occur biannually (once per generation) to ensure maintenance of the population in disconnected pools.

Mussel spawning

- Hydrological disconnection of between 6-9 months occurs during dry season to let water level drop.
- Due to long life span of the mussel this should occur every 50 years.

Mussel recruitment/parasitism of fish

- Fish must be present in disconnected pools and mussel spawning must have occurred.

Fish dispersal

- Hydrological connection through the system occurs in early spring/summer prior to spawning, it needs to occur with enough frequency to maintain genetic diversity.

5.3.2 Spatial application

This step involves the application of the connectivity regime to the real world. The previous steps have built the understanding of the ecosystem and determined the thresholds, limits and requirements for how connectivity supports it. This step takes that synthesised understanding and applies it directly to a real world context, usually through a mapping process.

The broad principle is to use the parameters of the connectivity regime to determine how well each of the processes will be delivered for the defined purpose in the defined location. It may involve testing different hydrological scenarios to determine how well a reach acts as a fish habitat or evaluating the major barriers to dispersal in a basin. The features focused on will vary depending on the objectives of the connectivity analysis, the processes being considered, and will be subject to data availability.

The connectivity analysis was applied to two real world scenario, using currently existing conceptual models: Applying Conceptual Models to Connectivity Analyses – Dewfish Demonstration Reach and the Anabranches of the Macintyre River (EHP 2012a).

5.4 Evaluation of the connections

The connectivity regime can then be used to target the crucial aspects of the system which require management. By cross-referencing the specific connectivity requirements of the ecosystem against the processes, it is possible to determine how human activities influence connections and how this relates to the objective (e.g. in the mussel example, if water is being added to the system during the dry season the mussel spawning process is likely to be at risk, or if too much water is being extracted at the wrong time of the year, the fish may not spawn. Also, developing the system understanding usually allows more general insights into management focus (e.g. due to the long life span of the mussels they are innately resistant to change, therefore management focus on maintaining fish populations is more likely to be beneficial).

Once the major connectivity issues have been defined, the implementation of the regime in the real world and validation of the connections can be considered. This will involve determining the data that needs to be collected or interrogated (e.g. if the regime defines the hydrological processes underlying fish dispersal, data on the realised connections of fish needs to be gathered to validate the regime). The knowledge gaps derived from the conceptual analysis can be used to target research to improve the conceptual understanding.

6 Conclusions and way forward

The connectivity project developed a series of foundation principles and a framework on which decisions and actions can be based. The principles indicate that current approaches in terrestrial environments are limited for understanding and managing connectivity in aquatic environments, where spatial and temporal complexity of physical connection is commonplace.

Developing a full suite of connectivity tools to be able to map high-priority areas and develop guidelines for ecological values will take time. The initial step will be the development of process based conceptual understanding, linking specific environmental processes to the physical connections they require (Figure 5).

These process based conceptualisations provide the basis for understanding how ecosystems function, are useful to current government activities and form the basis for future connectivity analyses. A suitable framework for developing appropriate, spatially linked, conceptual models is the Queensland Wetlands Program 'Walking the landscape' framework (EHP 2012b).

Some key principles of this framework that work in conjunction with the connectivity framework are to:

- develop conceptual models based around the components and processes of the environment
- link conceptual models to already existing datasets
- develop them in context to the real world
- use expert opinion to supplement data
- ensure they encompass an ecologically suitable level of scale (e.g. conceptual models of flooding should include the entire catchment).

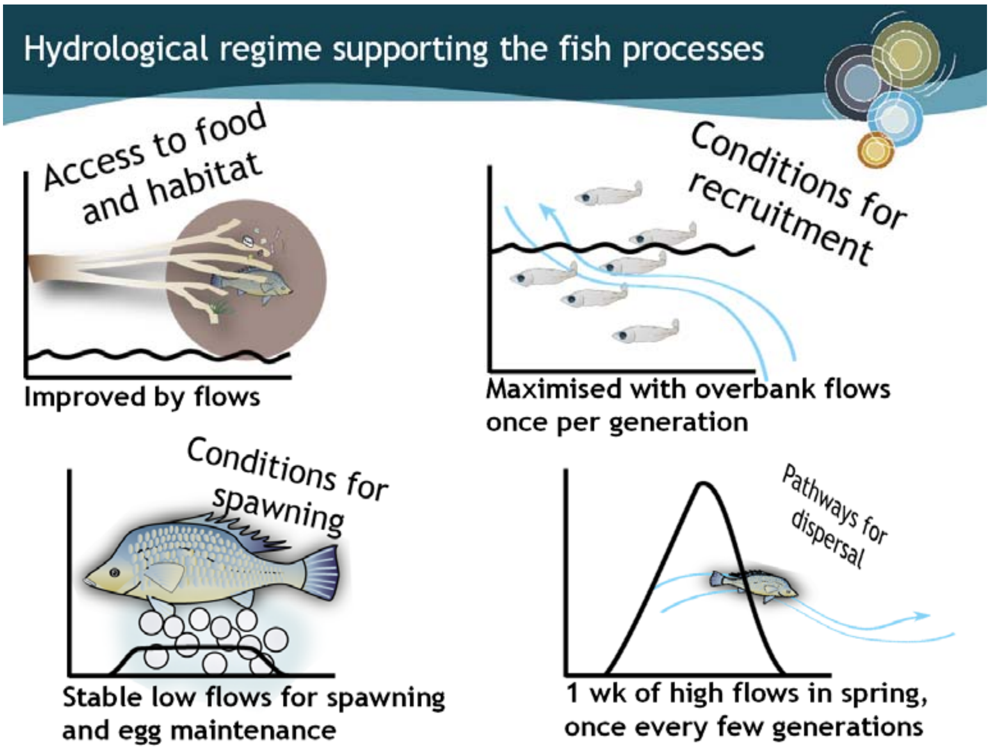

Figure 5 - Excerpt from the presentation Understanding connectivity (EHP 2012c), depicting how different environmental processes from a fish life cycle may require different magnitudes, timings and duration of hydrological connection.

As a no-regrets approach, the 'Walking the landscape' framework (EHP 2012b) describes a method for developing spatially linked conceptual models of environmental processes, that is compatible with connectivity analyses and is being applied to specific projects (e.g. Groundwater dependent ecosystem mapping and classification, Great Barrier Reef Marine Park Authority's coastal ecosystems framework, Healthy Waterways wetland and floodplain resilience). The 'Walking the landscape' framework provides the bridge between short-term outcomes for specific needs and building the foundation for holistic system understanding. In the future, the conceptual understandings developed from this framework can form the basis for integrating connectivity into standard government environmental practices, for better whole-of-system management.

7 Glossary

Definitions for technical terms use the Wetland*Info* Glossary as their primary source (EHP 2012d) (Table 1). Other, more general defininitions have been primarily sourced from the Macquarie Dictionary (2011) as per Queensland Government policy. Almost all terms had multiple definitions; in these cases the most suitable for our needs was selected (Table 2). For reference purposes the numbering in the Macquarie Dictionary has been maintained.

Table 1 – Technical definitions from the Queensland Wetlands Program Glossary

Term	Definition
Attribute	Attributes are descriptive characteristics or features.
Ecosystem	Ecosystem means a dynamic complex of organisms and their non-living environment, interacting as a functional unit.
Ecosystem components	Ecosystem components include the physical, chemical and biological parts that make up the environment. Examples could include the vegetation types at a wetland, the organisms that live in a wetland, or the wetland itself (adapted from DEWHA, 2008; MEA, 2005; Ramsar, 2005).
Environmental processes	Environmental processes include ecological, physical and chemical processes. Ecological processes include all those processes that occur between organisms and within and between populations and communities, including interactions with the non-living environment that result in existing ecosystems and that bring about changes in ecosystems over time (Adapted from DEWHA, 2008; Australian Heritage Commission 2002). In some cases it may be necessary to consider broader environmental processes that may be physical or chemical and not directly involve organisms. Environmental processes play a key role in influencing the extent, condition and biodiversity of ecosystems (Plant et al. 2012). Groups of environmental processes are sometimes referred to as ecosystem functions. Examples include the movement of water through the wetland into streams or the ocean; the decay of organic matter; the release of nitrogen, sulphur, and carbon into the atmosphere; the removal of nutrients, sediment and organic matter from water moving into the wetland; and the growth and development of all the organisms that require wetlands for life (Marjut and Gannon, viewed 2012).

Table 2 – Terms used and relevant indexed Macquarie Dictionary definitions

Term	Macquarie definition
Mechanism	2. the … means, by which a particular effect is produced or a purpose is accomplished.
Parameter	1. any constituent variable quality.
Propagate	6. to cause to extend to a greater distance, or transmit through space or a medium: to propagate sound.
Scale	9. a certain relative or proportionate size or extent.

8 References

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9 Appendix 1 – Processes/conceptualisation

9.1 Continuous improvement

This appendix presents concepts and information relevant to assessing connectivity for ecological management and planning purposes. In keeping with the principles of continuous improvement and adaptive management the information will improve over time and the documents will be updated.

9.2 Introduction

This appendix is intended to assist with ecosystem conceptualisation. It contains references to documents listing ecosystem services and processes which can be used to develop an ecosystem understanding. It also contains some common objectives and suggested processes for understanding the key connections in a system.

The case studies conducted for the connectivity project include practical applications for conceptual and applied systems and can be used as examples of the different ways that system conceptualisations have been conducted.

The following documents available on Wetland*Info* may assist in the development of the system conceptualisation:

- Pictures worth a thousand words: A guide to pictorial conceptual modelling
- Conceptual models (contains site specific, typological, regional conceptual models and a guide for making conceptual models)
- Wetland environmental values (incorporates environmental values from the Millennium Report: Ecosystems and Human Well-Being: Wetlands and Water (Millennium Ecosystem Assessment 2005) and the Environmental Protection (Water) Policy 1997).

Because of the complexity of connectivity it is easy to get overwhelmed whilst attempting to conceptualise a system. This section provides some useful ways of framing system conceptualisations.

9.3 Population viability analyses

A useful method for placing connectivity into an ecologically meaningful context is to consider connectivity within the context of flora and faunal life history requirements, i.e. what are the appropriate connections required for the long-term viability of this population? Organisms are supported by four main sets of processes for maintenance of viable long-term population across a landscape:

- **Survival processes**, e.g. day-to-day behaviours such as foraging or refuge usage. The complexity with which this will need to be defined will depend on the connectivity question. This can be used to define small-scale, high-frequency connections.
- **Reproduction processes**, e.g. spawning, egg laying, movement to reproduction areas. For small-scale connectivity processes frequency will depend on reproductive types and longevity of the organism.
- **Recruitment processes**, i.e. the survival of the juvenile population into the adult pool. Most species have juveniles which have different life history requirements than adults. These may mean that connections to specific habitat types or other resources are required for the survival of the different life stages. This can potentially be considered within survival or reproduction processes depending on the species. The scale, frequency and timings for this will depend on the organism being considered.
- **Dispersal/migration processes**—these function at larger scales and assure the long-term success of the population; they may be tied to reproduction processes or may be related to colonisation or genetic mixing outcomes. Relatively large-scale movements with low frequency of occurrence (possibly every few generations).

9.4 Processes and the concept of scale

Scale is an important consideration when examining environmental processes and defining management decision-making. Management decisions made without consideration of appropriate levels of scale may run the risk of making decisions which do not result in meaningful ecological outcomes. For example, when considering the population viability processes outlined in Figure 6 local-scale requirements (a) for survival and reproduction processes must be considered in conjunction with landscape-scale processes (b) of dispersal to produce a viable long-term population. These processes may require management at different levels of scale (e.g. by providing a watering regime for a catchment), but the first step in defining that will be to identify the level of scale at which they function. By not considering this issue adequately the management of individual wetlands as discrete entities may be limited as the process on which many of their key values exist can only be managed at the catchment scale.

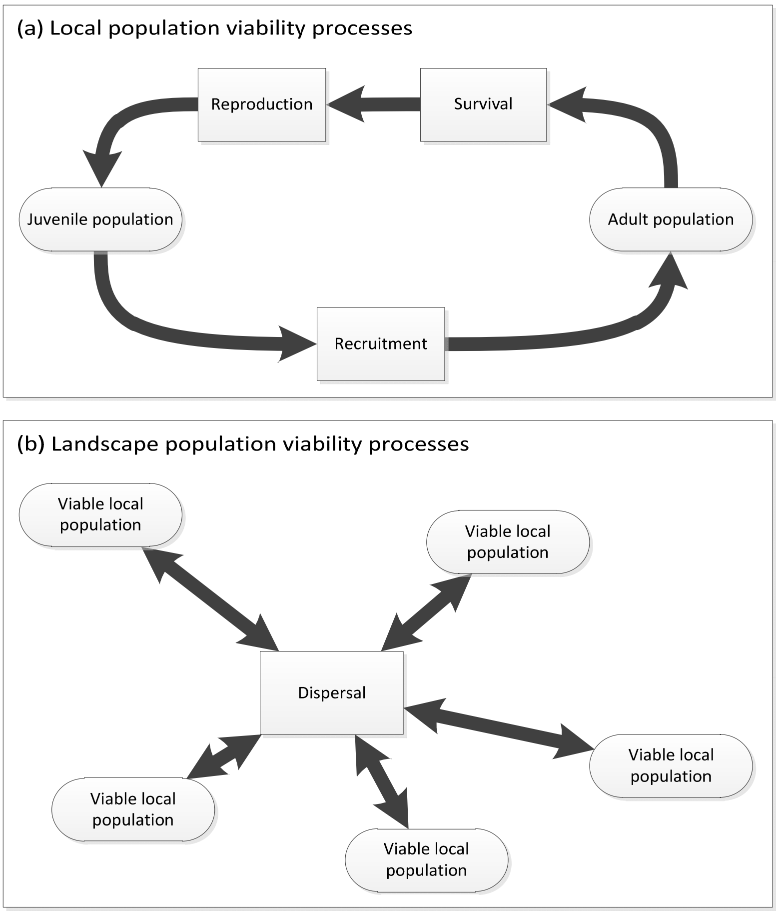

Figure 6 - Generic diagram of the processes governing local population viability (a) and how these interact to produce long-term population viability at the landscape level (b). Processes are represented as rectangles, ellipses are components. These generic models are just guides and may not reflect the real world where there may be movement as part of each of these processes (e.g. larval drift on currents as part of the recruitment process, inland migrations by juvenile barramundi).

9.4.1 Hydrological regime

The hydrological regime is the temporal variation of water flow, levels and volumes in rivers and other wetlands (modified from Macquarie Dictionary 2011). It is related to seasonal changes in climate, and can be vary depending on the location of the aquatic system and the local environmental conditions. Aquatic ecosystems in Australia have some of the most variable hydrological regimes in the world; In some parts of north Queensland rivers flow perenially, whereas in the Lake Eyre region of central Queensland long periods of drought punctuated by large floods are the norm. The organisms inhabiting these different ecosystems have evolved around the local environment and are adapted to these hydrological regimes. Even the periods without any water can be important for the function of the ecosystems.

The following contains some general prompts on how different parts of the hydrological regime influence ecosystem function. These prompts are generic and may or may not be applicable to a specific species inhabiting a specific area:

- No-flow regime—Increases in no-flow may reduce water quality, reducing the overall quality of the area as a habitat to local organisms. Extended periods without flow increase stress on organisms and may even cause extinction of local populations. By contrast, reducing or removing periods without flow tends to increase the attractiveness of an area to noxious species not adapted to the boom-bust cycles of Australian freshwater systems.
- Low flows—Low flows usually assist in maintaining water quality and may be important to spawning and egg maintenance behaviours.
- Flushes—High-flow pulses through freshwater systems can stimulate food webs by mobilisation of nutrients and sediments. They can also refresh water quality and give ecosystems a quick boost.
- High/overbank flows—These generally provide the broader ecosystem (e.g. floodplains) with access to nutrients and chemicals which have been building up in nearby systems (e.g. anabranch channels,). These flows are often associated with recruitment success, most likely due to increased carbon input into the food chain.

Analysis of changes to flow regimes will usually involve examining data from hydrological models. These models use data collected from rainfall and river flow stations to predict how much flow is expected over a period of time given different rainfall conditions. Comparison of the hydrological regime of the 'natural state' to 'current condition' models (that typically include variables such as water extraction by irrigation) can give us an idea of how an ecosystem is likely to have been affected by human activity. The methodology of the riverine conceptual models on Wetland*Info*can be used to give a broad overview of hydrological regime. For a full connectivity analysis, the method described above may have to be modified to better represent the requirements of the environmental processes.

10 Appendix 2 – Dealing with knowledge

10.1 Introduction

Knowledge gaps will always be present when attempting to build a system conceptualisation. This section contains a summary of methods for dealing with incomplete information, research tools for validating realised connections and methods for dealing with uncertainty.

10.2 Incomplete information

The construction of a perfect system conceptualisation is an unattainable goal for most ecosystems. Due to the complexity of natural systems it is probable that the information required may be unavailable or overly complex. Methods for simplifying or substituting information can be required. Table 3 summarises a number of methods which can be used to simplify a system or deal with incomplete information. The shortcomings of any methods should be incorporated into a vulnerability assessment based around the knowledge gaps.

Table 3 – Common methods for dealing with incomplete information

Technique	Description	Shortcomings
Surrogate	The use of knowledge about a specific species in lieu of detailed knowledge about other species	The species chosen may not be representative of other species.
Indicator	The use of knowledge of a particular species that has been identified as representative of a particular response for other species	This is preferred to the use of a surrogate, but there may not be any indicator species available.
Functional group/guild	The use of groupings of species which are representative of particular traits.	Groupings may be very specific to particular processes (e.g. low-flow spawning fish).

10.3 Demonstrating connectivity

The availability and resolution of data to validate connections will vary depending on the assessment (e.g. data on hydrological connection is relatively abundant, whilst data on the actual source of sediment for coastal deposition processes is much coarser), and may require specialised techniques for measurement (e.g. sediment tracing techniques, genetic analyses). The information provided by these methods is invaluable and, when tied to a suitable objective, is one of the few ways to validate whether a connectivity regime has been effective. Table 4 contains a summary of methods for demonstrating realised connectivity.

The connectivity framework provides a structure for systematically assessing connectivity in a holistic way; data on the realisation of connections are important for improving the information in a connectivity assessment in a number of ways. In general, it can be used to validate a connectivity regime and the resulting management recommendations. The following are some specific examples of how it can be used:

- to inform a system conceptualisation (e.g. Strontium isotopes in otoliths demonstrate fish movements through their life)
- to validate management scales (e.g. it is appropriate to manage these catchments separately as the populations are genetically distinct)
- to validate whether potential connections result in a realised connection (e.g. acoustic tags can be used to demonstrate that a fishway is working).

The specific method used for validation of realised connections will depend on the objective of the connectivity analysis and the environmental processes being examined. The case study byHughes and Schmidt 2012 demonstrates how information on population genetics can be used to validate the process of dispersal and inform a connectivity analysis.

Table 4 – Summary of measurements of realised connections

Name	Description
Otolith microchemistry	Examining the occurrence of particular isotope ratios in the otoliths of individuals can be used to trace their movements through their life span.
Tagging studies	There are numerous studies which involve tagging animals to examine how they move and utilise habitat. Mark-recapture methods require repeated capture of animals, can be used to gain estimates of population sizes, and determine if individuals move between different habitats. Other methods can give more continuous data on an animal's spatial location (e.g. radio, GPS, and acoustic tagging), and may require recapture of the same animal or a method to transmit data.
Genetic analyses	Genetic connectivity, using population genetics approaches, provides information about how populations interbreed.
Behavioural observations	Specific details of animal movements gained from observations, e.g. fish passage across barriers.
Stable isotope analysis	Tracking the food sources and their proportions through the food web using stable isotopes.
Sediment tracing	Sediments can be traced to particular erosion events using radionucleides to identify the spatial sources and the timing of major erosion processes.

10.4 Risk assessment

In general risk assessments are commonly used tools for prioritising management actions. A risk assessment focuses on threats to a system, evaluating the likelihood and consequences of their occurrence and using this information to prioritise management actions.

The information from a connectivity assessment lends itself to integration with risk assessment frameworks. The system conceptualisation can be used as a catalogue of the resources for the ecological system. To this end the following is a generic process for how to integrate a connectivity analysis into a risk assessment.

A generic process for risk assessment involves the following steps:

1. Use the system conceptualisation as a catalog of the resources in a system.
2. Use the knowledge gaps to identify the risks to the system.
3. Use a risk assessment process to identify which of these knowledge gaps presents the highest risk for the system if the information is incorrect.
4. Use the highest risk outcomes to:
    a. identify crucial areas that could result in system failure
    b. prioritise research to fill knowledge gaps
    c. define management options for risk mitigation.

11 Appendix 3 – Attributing connectivity

11.1 Introduction

Attributes for the various media which underpin connectivity are presented below for reference. These lists are only suggestions as the specific attributes used in any assessment will vary based on the processes considered, ecosystem structure and disciplinary preferences.

11.2 Water

Water is a more dynamic connection medium than land and the one which is considered most often in aquatic ecosystem connectivity. It interacts significantly with terrestrial ecosystems, and its patterns of flood and drought can be a fundamental factor shaping landscapes and their ecosystems. It can be used as a transport medium by biota, nutrients and debris and can shape coastlines and landscapes. Its attributes primarily are reflections of hydrological processes and refer to the components affecting the movement of water and its physical or chemical composition.

Hydrological connectivity is part of the broader hydrological cycle, and in freshwater systems it is usually considered in four main dimensions:

- **Longitudinal**, e.g. movement of water within a river channel.
- **Lateral**, e.g. for riverine systems the movement of water between the main channel and off-stream wetlands. This can include movement through anabranches (secondary channels) or horizontal seepage through porous sediments as groundwater or movement of water into non-floodplain wetlands.
- **Vertical,** movement of water between the atmosphere, the surface feature and groundwater.
- **Temporal**, the timings of flow. This includes how often they occur, how long they last for and their predictability and variability.

Freshwater and marine ecosystems have different attributes, some examples of these are:

Freshwater ecosystems

- flow paths
- flow regime
- timing
  - frequency
  - duration
  - seasonality
- magnitude
- flow direction
- water body size
- physical/chemical composition (e.g. temperature).

Marine ecosystems

- currents
- eddies
- upwellings
- physical/chemical composition (e.g. temperature).

Some broad concepts for useful measures of hydrological connectivity can be found in section 9.4.1.

11.3 Land

Land can be traversed by organisms, used as a growth medium for plants or organisms may move through it. Its attributes primarily refer to the pathways through or across its surface.

Some of the attributes influencing surface pathways are:

- altitude
- terrain
- slope
- geomorphology
- soil type
- habitat.

Attributes influencing pathways through the land are:

- soil porosity
- soil permeability
- presence of impermeable layers
- geomorphology
- slope
- habitat.

11.4 Air

Air can influence the distribution of nutrients across the landscape through aeolian depositions and is utilised by birds. Its attributes will primarily be related to wind direction and speed and its physical or chemical composition.

Attributes:

- Wind speed
- Wind direction
- Physical or chemical composition (e.g. temperature, humidity).