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Weed management on floodplains:
A guide for natural resource managers

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Introduction

Landscapes and ecosystems are composed of complex networks of interactions; consequently the effects of management actions can be unpredictable. In dynamic floodplain systems a wide range of changes, acting through a diversity of different processes, increase the abundance of weed establishment, proliferation and spread within native plant communities (Table 1). Sustainable weed control is likely to be easiest to achieve if management actions are conducted within the scope of broader floodplain management goals. The overall goal may contain a combination of the following: to restore a particular ecosystem service, production value, functional or species diversity, community structure or conservation of a particular species of concern.

Front cover photo Alison Pouliot. Above: Floodplains support unique vegetation communities such as these river red gum forests and Moira grass plains at Barmah forest. Photo Keith Ward, Goulburn Broken Catchment Management Authority (GBCMA).

Weeds as symptoms or causes of ecosystem change?

Directly targeting invasive floodplain weeds may not lead to a shift in the ecosystem to a more desirable state for a number of reasons. Firstly, the weed species may not be a causal agent of change in the ecosystem, but instead may be a symptom of underlying processes of ecosystem degradation, such as pollution and excessive water extraction (see Table 1). Secondly, the management regime itself may promote re-invasion by the same or different species. Thirdly, recovery of native vegetation may be dependent on an ecological process, such as the supply of plant seeds to suitable germination habitat. Management objectives may not necessarily involve reduction of the population density of the invasive species directly, but instead may involve alteration of the outcomes of species interactions (e.g. competitive exclusion), or manipulation of physical factors (e.g. flood regimes), to promote suitable conditions for native plant species to germinate and reproduce.

Table 1. Human-mediated changes to riparian vegetation that potentially lead to degradation, with special emphasis on changes potentially promoting the establishment, proliferation and spread of invasive alien plant species. Adapted from Richardson et al. (2007) with permission. See glossary (page 15) for terminology.

Type of change	Processes affected	Effects favouring establishment, proliferation and spread of alien plants
River regulation	• Altered flood regime • Altered propagule dispersal regimes • Altered geomorphology	• Increased availability of recruitment sites in space and time • Changes in plant competition • Reduced dispersal of native species down rivers • Altered sediment dynamics
Water extraction	• Reduced flow • Altered flood regime • Altered propagule dispersal regimes	• Alterations in plant competition • Increased availability of recruitment sites in space and time • Reduced dispersal of native species down rivers
Agriculture	• Altered nutrient cycling • Increased soil erosion • Decreased connectivity for dispersal and migration • Reduced buffering capabilities	• Alteration of sediment dynamics • Conduit for alien species dispersal • Reduced propagule pressure (native plants) • Increased edge effects
Clearing riparian vegetation	• Altered nutrient cycling • Altered disturbance regimes • Reduced bank stability • Damaged buffering capabilities	• Altered vegetation functioning • Increased space for colonisation • Altered lateral seed dispersal potential
Planting alien species	• Altered propagule dispersal (lateral and longitudinal) • Altered nutrient cycling • Altered water use and flow regimes • Reduced buffering capabilities	• Introduction of propagules (alien species) • Alterations in plant competition • Alteration of sediment dynamics
Invasion of other alien species	• Altered ecosystem functioning and successional trajectories • Increased fire risk and intensity • Reduced buffering capabilities • Synergisms (invasional meltdown)	• Alteration of vegetative communities • Alteration of sediment dynamics • Increased facilitation of alien species invasion
Pollution	• Altered nutrient cycling • Reduced fecundity and increased mortality	• Alterations in the outcome of plant competition
Grazing and trampling (local-scale effects)	• Compaction and reduced bank stability • Reduced vegetation cover • Increased nutrient input • Reduced buffering capabilities	• Altered regeneration niches • Introduction of propagules • Increased space for regeneration • Altered plant competition
Altered fire regime	• Increased mortality of native species • Altered nutrient cycling • Reduced buffering capabilities	• Alteration of regeneration niches • Alteration of riparian structure and function
Global climate change	• Altered flow regimes • Increased amplitude of flood events	• Alteration of vegetation communities • Increased long-distance propagule dispersal

Biotic strategies of resilience and disturbance

Resilience is the natural capacity of an ecosystem to recover from an alteration, or the adaptation to a regular disturbance. Disturbance is a natural or artificially imposed perturbation of the system.

Changes in the frequency, duration, depth and spatial extent of flooding are forms of disturbance that can have significant implications for wetland and aquatic habitats. Disturbance is a complex structuring mechanism, on the one hand it facilitates co-existence and maintains biodiversity by increasing opportunities for adapted natives to establish, whereas on the other hand changes to, or newly imposed disturbance, can create conditions that favour the dominance of one species over others. The effect disturbance has on species richness will vary depending on its inherent frequency, intensity, duration, timing and scale. The species that assemble after a disturbance event will also depend on the characteristics of the individual ecosystem, including the composition of the seedbank, resource availability and the outcome of species interactions.

Predicting future alterations to vegetative community composition following disturbance events, and the consequences of such alterations is a key priority for managers. Unfortunately, changes to natural flood regimes and the invasion of weeds have altered the natural pattern of species succession in floodplain communities, making prioritisation of future management plans a difficult process. In addition, climate change is predicted to alter trends in the frequency and size of future flood events in south-east Australia, with consequent effects for ecosystem functions and processes. In this context native plant species can actually become invasive under the altered conditions, as they begin to appear in areas where they have historically been absent. Understanding and forecasting changes in plant communities, ecosystem properties, and their associated services requires a mechanistic link between community shifts and modifications in ecosystem properties.

This guide describes a management protocol that aims to link the disturbance ecology of invasive weeds to management strategies, by investigating the benefits of incorporating actions that manipulate disturbance (natural or artificial) into control efforts. The factors influencing floodplain vegetation composition are discussed and conceptual models outlined, followed by a generalised framework for designing and implementing monitoring programs to assess ecological responses resulting from specific management actions, focusing on the impacts of alterations to environmental flows on floodplain weeds as an example.

Slow flows in floodplain creeks may promote colonisation by aquatic weeds such as Sagittaria. Photo Kim Pullen, CSIRO Entomology.

River channels act as dispersal conduits

Dispersal of propagules (plant seeds and vegetative units) in water is determined by the hydrological regime during seed release and transport, as well as hydrological connectivity within the landscape. River channels can act as conduits, transporting plant propagules to new locations. This is important when considering the potential success of controlling weed species, or the re-establishment of native vegetation. For example, the arrival of particular weeds in low lying catchments can sometimes be predicted from their abundance at higher elevations. This is demonstrated in Figure 1 opposite, which shows the chronological spread of *Phyla canescens* (Lippia), a low-growing plant that forms extensive mats preventing colonisation by other species. Initial records (pre-1950) show this weed had limited distribution in the north-east of Queensland and in the high elevation Alpine area on the border between Victoria and New South Wales.

Figure 1. Spatial point records of the distribution of lippia in the Murray-Darling Basin recorded over time. Photo Guy Roth.

Later records show the encroachment of the plant, southwards and westwards into the Murray system, with some early records (1951–70) occurring at the confluence of the Darling and Murray Rivers. Lippia is capable of regenerating from detached plant fragments which re-root at downstream locations following flood events. Whilst there are no records of lippia occurrence in the Darling River, it is highly probable that their absence is due to the low frequency of surveys conducted in this area, rather than true absence. The spatial patterning of the invasion over time, linked with knowledge of reproductive ability and dispersal capacity, indicate that invasion of the River Murray occurred due to the downstream transport and establishment of fragments.

The importance of hydrogeomorphic processes in creating habitat for floodplain vegetation communities

Flood disturbances can both scour substrate and deposit sediment of various sizes. Many floodplains represent a shifting mosaic of landforms created by hydrogeomorphic processes. Depending on the degree of erosion or deposition, floods can cause breakage and uprooting of plants and burial of established vegetation. This selects for plant species which can tolerate these physical conditions.

The importance of life history strategies

Plant life history strategies (e.g. growth form, seed size, dispersal mode, flowering period) determine whether, where and when a floodplain plant can colonise a site. In many floodplain communities the relative importance of sexual versus vegetative reproduction and seed banks versus seed dispersal in recruitment dynamics is poorly known. For species adapted to floodplains, opportunities for recruitment occur mostly after flood events, when new sediment is deposited or available gaps open up in the existing vegetation due to flood damage. To successfully recruit from seed in the post-flood environment, either the reproductive phenology (seasonal timing) must correspond to the flooding season, so that seeds are dispersed into a favourable germination environment, or else the species requires a propagule bank, such as a persistent soil-stored seed bank, that may be triggered following a flood or rain event.

Different types of habitat that can be expected in floodplain environments mean that plants have to be adapted to reproducing in a diverse range of hydrological conditions. Common reed photo (below) Alison Pouliot.

Post-germination fate of seedlings often explains much of the variation in species distributions. In humid areas establishment success depends on the maintenance of low water levels during germination and seedling establishment, whereas in semi-arid areas water availability and the rate of decline of the water table limit establishment. The recruitment of later successional species may be uncoupled to flood events because in these species success is contingent on life history characteristics adapted for the ability to germinate in the shade of established vegetation.

A general conceptual model to predict the organisation of plant communities on river floodplains should include the following factors and their effects on habitat characteristics and plant communities.

- the physical constraints that influence river floodplains (i.e. the scouring and depositing character of flood disturbances)
- the frequency and intensity of disturbances that limit competitive interactions and create gaps for recruitment of new individuals
- the specific life-history traits that allow plant maintenance, recruitment and colonisation in floodplains subject to differing degrees of disturbance.

Key ecological processes that potentially influence plant communities and related plant strategies are shown in Figure 2.

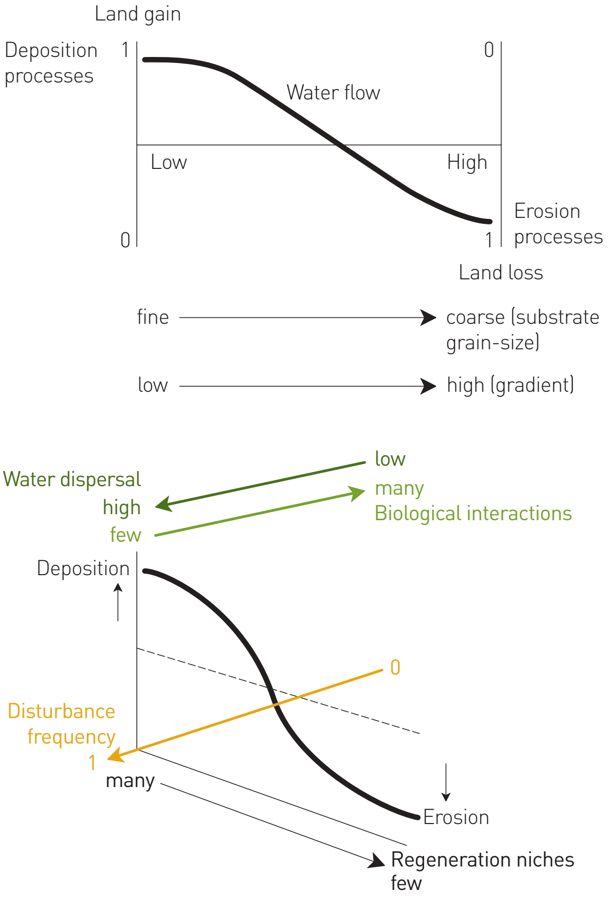


Figure 2. A conceptual model showing the hydrological and ecological processes that hypothetically control floodplain plant communities.
The top figure shows deposition and erosion processes, the two main types of process that occur in floodplain landscapes. Depending on water flow, landscape gradient and grain size, land may be either lost through erosional processes, or deposited due to sediment accumulation. The bottom figure includes ecological processes resulting from the interaction of land loss or accumulation with the frequency of flooding events (disturbance frequency). During high flood frequencies dispersal of plant propagules is high, as is the potential for seeds to recruit in regeneration niches. Biological processes like plant competition are more important when the landscape is disturbed less frequently. The model is adapted from Bornette et al. (2008).

Droughts are a more frequent occurrence in recent years. Photo Alison Pouliot.

Measuring resilience in floodplain plant communities

Floodplains are dynamic systems. Measuring resilience in terms of species composition is therefore difficult in these frequently disturbed communities and is not necessarily indicative of changes underlying ecosystem structure or function. Measures of ecosystem functions themselves are expensive and time consuming to collect. Plant functional traits (PFTs) provide an alternative ecological tool indicating plant community response to variation in ecosystem attributes and processes that is largely independent of species composition. PFTs are species traits associated with reproduction, colonisation and growth. They may include factors such as flowering period, dispersal mode, seed mass, growth form, or tolerance to inundation. PFTs are not direct measures of ecosystem function, but have previously been used successfully to infer underlying ecological processes and to examine the effects of disturbance, such as fire and grazing on plant communities. Additionally, PFTs can be compared over large and disjunct geographical regions, as well as across considerable temporal scales. Finally, using a core set of PFTs allows for widespread comparisons between separate datasets and studies. The case study on the following pages illustrates how knowledge of the PFTs of floodplain plant communities both pre- and post-degradation can be used to highlight potential changes in ecosystem function, and prioritise rehabilitation efforts.

Photo Alison Pouliot.

Barmah-Millewa forest: an iconic river red gum site. Photo Keith Ward, Goulburn Broken Catchment Management Authority.

Case study: Barmah-Millewa forest

This study was conducted in the Barmah-Millewa forest, an extensive floodplain and wetland system that historically flooded in winter/spring and dried in late summer/autumn. Barmah forest is now a remnant river red gum dominated floodplain covering approximately 25,900 hectares, located between the townships of Tocumwal and Echuca. It is reserved as State Forest (72% of the area), State Park (26%) and Murray River Reserve (2%).

Barmah-Millewa forest is part of the traditional country of the Yorta Yorta people and has great conservation, heritage and amenity value. The Murray-Darling Basin Commission has identified part of the forest as a Significant Ecological Asset, and the site is listed as a Wetland of International Importance under the Ramsar Convention.

Changes in river flow at the site are due to upstream storages and releases, as well as local manipulation of regulators, all of which collectively affect floodplain inundation. Analyses (Abel et al. 2006, VEAC 2006) have identified the following:

- reduced frequency, duration and inundation area of winter-spring floods
- altered timing of flows
- increased frequency of small summer floods
- reduced variability in flood flows.

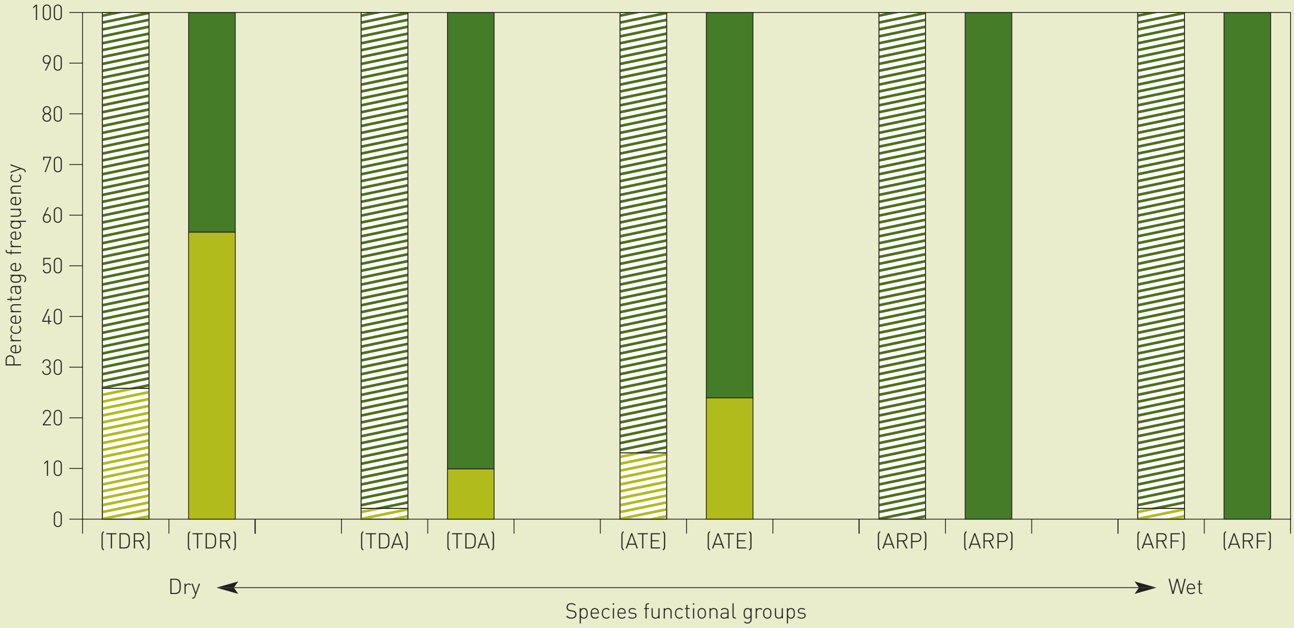
Vegetation surveys were conducted in Barmah forest in 1993/94 and 2006/07 (Ward 2007). Given that the vegetation dynamics and patterning in floodplain and wetland areas are primarily influenced by water regimes, a functional trait classification that groups species in terms of their water regime requirements for germination and establishment would be most appropriate. Ideally a vegetation classification should represent the heterogeneity of the vegetation (both species compositional and structural) at a resolution relevant to management. A hydrological classification scheme for vegetation produced by Casanova and Brock (2000) is described opposite. Exotic and native species surveyed over the 14 year time period at Barmah forest were classified under this scheme, prior to conducting statistical analyses on the results.

Results from this study indicate that a shift has occurred from native plant species in amphibious fluctuation tolerator and responder groups, which have the ability to germinate in flooded conditions and reproduce vegetatively, to exotic weed species in terrestrial dry and damp groups, which can germinate when the water table is below the surface of the soil, and mainly reproduce from seed. The ecosystem level implications of this trait shift are increased existence of durable seed banks composed of exotic species, resulting in a potentially persistent problem for site managers.

Table 2. Categories developed by Casanova and Brock (2000), from field surveys and experiments, including examples of native and exotic species found in Barmah assigned to those categories.

Primary category	**Secondary category**	**Description**	**Indicative native species for Barmah**
Terrestrial	Dry species (Code = TDR)	Species which germinate, grow and reproduce where there is no surface water and the water table is below the soil surface.	*Austrodanthonia setacea* Bristly or Mulga wallaby grass
Terrestrial	Damp species (Code = TDA)	Species which germinate, grow and reproduce on saturated soil.	*Amphibromus nervosus* Swamp wallaby grass
Amphibious fluctuation tolerators	Emergent species (Code = ATE)	Species which germinate in damp or flooded conditions, which tolerate variation in water level, and which grow with their basal portions underwater and reproduce out of water.	*Phragmites australis* Common reed
Amphibious fluctuation responders	Morphologically-plastic species (Code = ARP)	Species which germinate in flooded conditions, grow in both flooded and damp conditions, reproduce above the surface of the water and which have morphological plasticity (e.g. heterophylly — different types of leaves formed under dry or submerged conditions) in response to the surface of the water level.	*Myriophyllum crispatum* Curling water milfoil
Amphibious fluctuation responders	Species with floating leaves: (Code = ARF)	Species which germinate in flooded conditions, grow in both flooded and damp conditions, reproduce above the surface of the water, and which have floating leaves when inundated.	*Nymphoides crenata* Wavy marshwort

Figure 3. Mean changes in abundance (number of quadrats occupied) for five plant functional groups in Barmah forest between 1993/94 and 2006/07. Functional group codes are as in Table 2 above. Proportional frequency is represented by dashed lines in 1993/94 and solid colours for 2006/07. Exotic species are coloured in the light green and native species in the darker green.



Translating scientific knowledge to management processes

Due to the diversity of land uses in floodplain systems the management of invasive species is a frequent cause of conflict because perceptions of costs and benefits differ among stakeholder groups. Conflicting interests and perceptions make it challenging to develop and implement sustainable management practices for invasive species within an integrated natural resource management framework. As the range of environmental problems continues to grow, scientists and managers are forced to attempt prediction and management of only the most immediate problems that command their attention. A more structured response requires the adoption of a management framework that can encompass ecosystem change, and in some cases, pragmatic acceptance of invasive species as part of ecosystem dynamics. Such a management system must allow change within a range of predefined limits of acceptability, whilst also effectively highlighting where these limits are broken and action is required.

To successfully manage floodplain environments several issues will need to be addressed, including the control of feral animals, weeds, erosion, fire and salinity. However, most of these issues are closely related to delivery of environmental water. For example, flooding can be an efficient way of controlling the growth of weeds. In order to achieve appropriate flow regimes for a specific floodplain region five main requirements will have to be met.

- Delivery of a sufficient overall volume of water.
- Delivery of water at appropriate rates of flow.
- Ensuring that floods persist for appropriate periods of time.
- Delivery of water at appropriate times of year.
- Delivery of water at appropriate times between years.

Lack of scientific knowledge regarding the exact quantification of these five requirements in relation to ecological responses is one factor impeding effective water delivery. However, there are also a number of interacting physical, social, political and institutional impediments to achieving a flow regime which maintains the products, attributes and functions of floodplain wetlands. Stakeholders with an interest in water resource management will increasingly expect to see evidence of the environmental or ecological response of floodplain systems to implemented environmental flow regimes. Monitoring and assessment of controlled manipulations are therefore essential to ensure that a management program can be evaluated in relation to the goals that were originally proposed.

The flow diagrams on the following pages are intended to help better understand the relationship between management actions and ecological responses, including their inherent uncertainties.

- **Phase 1** involves determining the management goals (e.g. reduction of exotic weeds) (Figure 4),
- **Phase 2** involves developing a monitoring program compatible with the study design (Figure 5).
- **Phase 3** involves characterising the changes, documenting the available evidence of success (and/or failure) of management interventions and distributing the results to stakeholders (Figure 6).

In the floodplain context, a conceptual model is of benefit to provide a reference for the range of key system variables that can be considered "healthy". This step can be initiated jointly between practitioners and researchers, in order to incorporate experiential knowledge within the context of the specific geographical regions from which the knowledge was derived. This is particularly important in cases where the implicit knowledge of managers is difficult to quantify (i.e. "it works but we don't know why it works").

Connectivity and Operational Landscape Units (OLUs)

Goal setting is not a trivial exercise and care needs to be taken to ensure that the spatial scale at which goals are to be evaluated and maintained is appropriate. One approach is to attempt to identify Operational Landscape Units (OLUs), defined as combinations of landscape patches with associated biotic and hydrogeological connections (Verhoeven et al. 2008). The aim is to combine ecological knowledge on the spatial requirements of species with the spatial distributions and connections of ecosystem processes, in order to develop more effective regional conservation strategies. An OLU then represents the totality of patches in a landscape

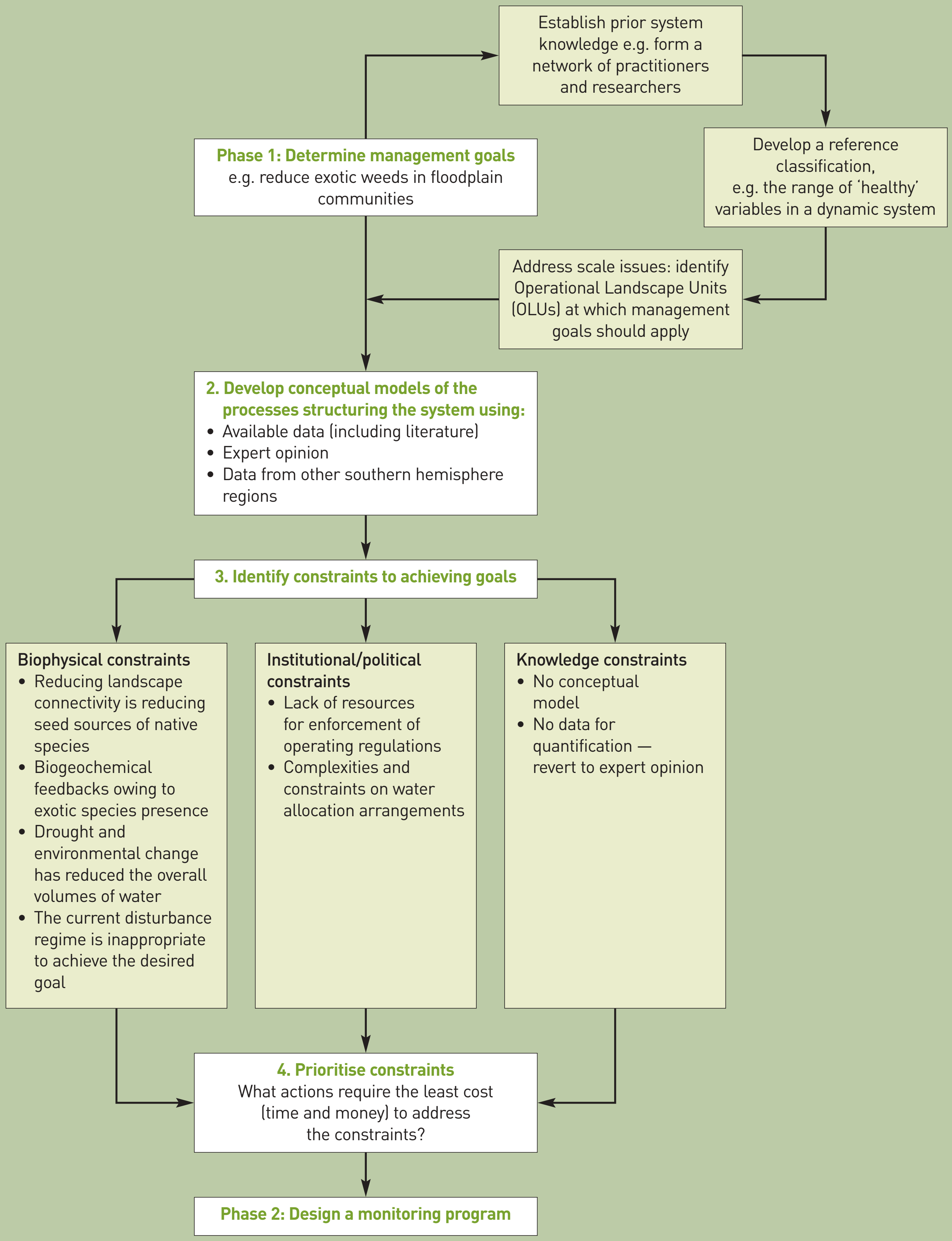


Figure 4. Decision tree for determining management goals (Phase 1)

mosaic over which the management strategy must be implemented. If data are available, a good variable to structure an OLU around is the degree of hydrological connectivity during flooding. Floodplain inundation models can be used to specify the geographic area which is inundated at specified river flows (e.g. see RiM-FIM model for the River Murray, Overton et al. 2006). Dispersal of plant propagules is facilitated by moving water and knowledge of the degree of landscape connectivity would indicate the spatial extent at which management has to be coordinated in order to restore seed sources for native species, or reduce upstream populations of exotics.

Once goals have been determined the factors inhibiting success must be examined. These constraints may be biophysical, political, or knowledge-based (see Figure 4). Prioritising constraints indicates which goals are feasible. Therefore the combination of landscape components into OLUs may differ for different conservation or management targets, depending on the nature of the flow component and the ecological processes.

Developing a monitoring program that evaluates the success of management actions

Floodplain interactions can be conceptualised in models developed from specific knowledge of the system, the scientific literature, or models relevant to similar types of rivers and floodplains. The different components and links in a model are likely to have varying levels of associated uncertainty. The level of uncertainty and the temporal scale of predicted ecological responses to changes in the flow regime are important to consider when developing a monitoring program (Figure 5). Monitoring programs must be flexible when selecting variables to measure the response to management actions, such as an alteration in environmental flows. Selection of relevant variables must also be sufficiently diverse to detect undesirable outcomes from the management action. This framework does not include specific instruction on variable selection but guidance can be obtained from resources such as the ANZECC and ARMCANZ (2000), and Baldwin et al. (2004).

Separating changes in ecological condition due to a direct management action (e.g. enhanced environmental flows) from other natural or human induced variability (e.g. stock grazing changes) requires an understanding of conditions both before and after environmental flows are delivered. In some situations "before" data are not available. In this case, establishing spatially replicated control sites allows "intervention" versus "control" sites to be contrasted over time (see Figure 5).

An important point to consider is determining the size of the ecological responses. This is the data that provides evidence that the management action delivered the predicted response. For example, if an environmental flow objective is to restore native plant communities, then measurable targets might include targets of abundance (e.g. 50% increase over three years), frequency of successful recruitment (e.g. annual) and spatial extent (range) over which the recruitment is expected. The smaller the likely effect size, the greater the sampling intensity and resources required to detect it. Therefore the challenge is to ensure the effect size to be measured is congruent with the resources available to measure it. Ecological responses are non-linear in nature (i.e. large responses may result from relatively small changes in flow regimes, or conversely, large changes to the flow regime may be required before an ecological response is detected). Additionally, uncertainty surrounding potential responses is likely to be high, emphasising the need for conceptual models and adaptive management processes.

The final phase of this process is to evaluate the success of the management action in terms of the original objectives (Figure 6). This may involve re-evaluating the conceptual models that form the basis of the monitoring and assessment program, or the constraints that are inhibiting progress towards goals. It is important that this learning step is undertaken in order to refine the program and improve understanding of flow-ecology relationships. A manager may need to compare the benefits of different potential actions within a continually shifting cost-benefit framework, so priorities require constant re-assessment in the light of new evidence.

Finally, shared insights should be documented and disseminated to help improve adoption and implementation.

Figure 5. Decision tree for developing a monitoring program (Phase 2)

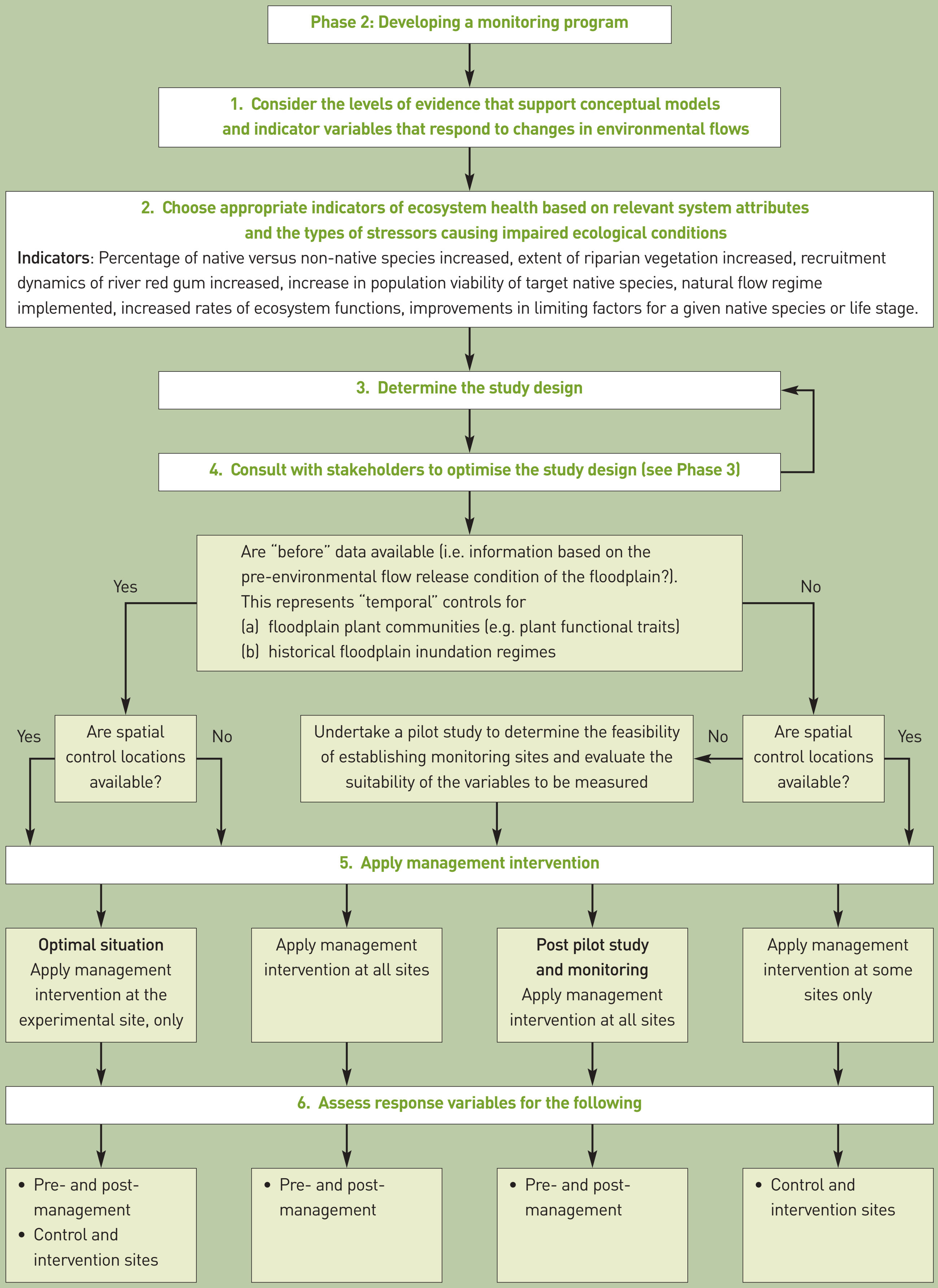
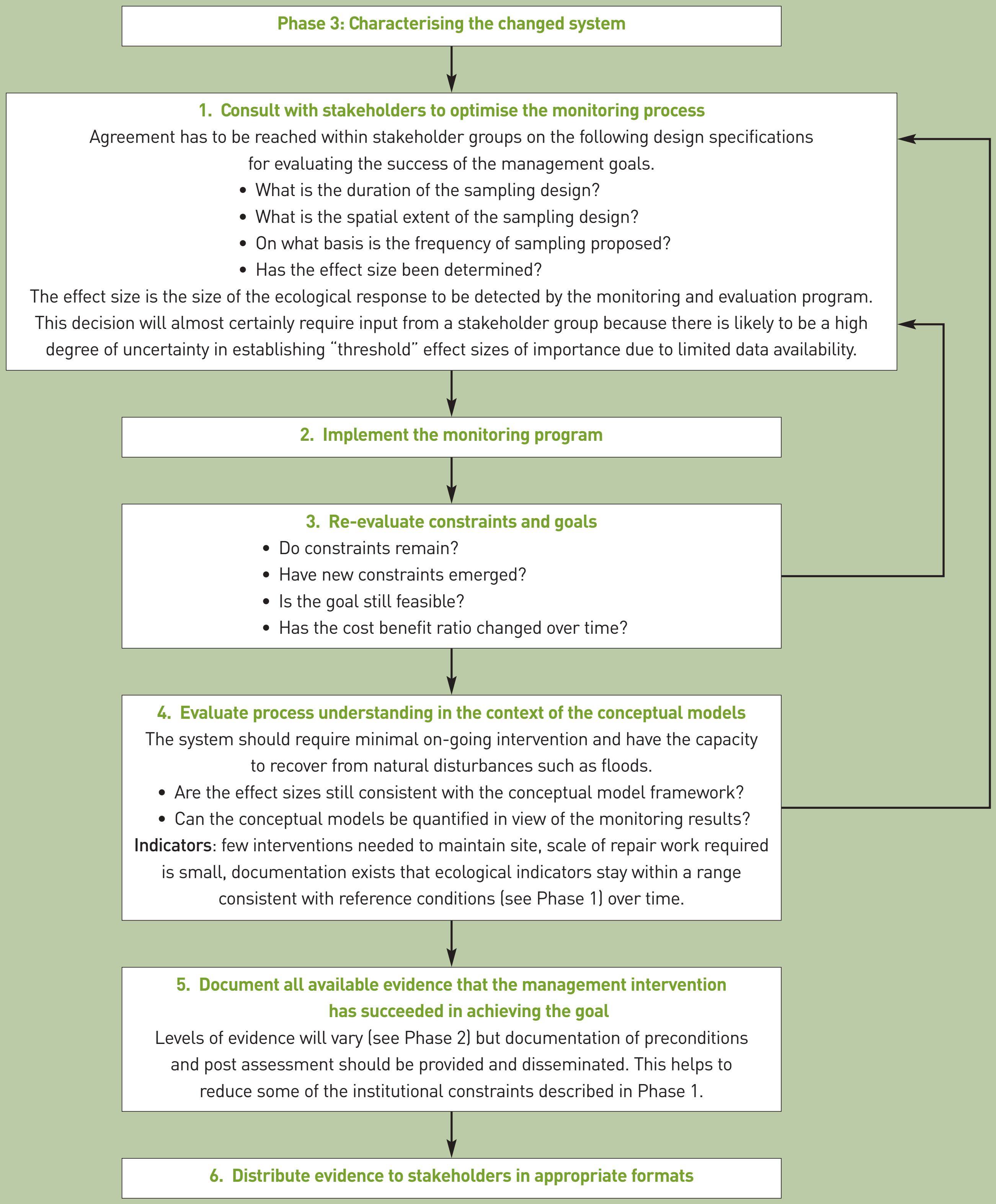


Figure 6. Decision tree for assessment of change (Phase 3)



Phase 3: Characterising the changed system

1. Consult with stakeholders to optimise the monitoring process

Agreement has to be reached within stakeholder groups on the following design specifications for evaluating the success of the management goals.

- What is the duration of the sampling design?
- What is the spatial extent of the sampling design?
- On what basis is the frequency of sampling proposed?
- Has the effect size been determined?

The effect size is the size of the ecological response to be detected by the monitoring and evaluation program. This decision will almost certainly require input from a stakeholder group because there is likely to be a high degree of uncertainty in establishing "threshold" effect sizes of importance due to limited data availability.

2. Implement the monitoring program

3. Re-evaluate constraints and goals

- Do constraints remain?
- Have new constraints emerged?
- Is the goal still feasible?
- Has the cost benefit ratio changed over time?

4. Evaluate process understanding in the context of the conceptual models

The system should require minimal on-going intervention and have the capacity to recover from natural disturbances such as floods.

- Are the effect sizes still consistent with the conceptual model framework?
- Can the conceptual models be quantified in view of the monitoring results?

Indicators: few interventions needed to maintain site, scale of repair work required is small, documentation exists that ecological indicators stay within a range consistent with reference conditions (see Phase 1) over time.

5. Document all available evidence that the management intervention has succeeded in achieving the goal

Levels of evidence will vary (see Phase 2) but documentation of preconditions and post assessment should be provided and disseminated. This helps to reduce some of the institutional constraints described in Phase 1.

6. Distribute evidence to stakeholders in appropriate formats

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Glossary

Buffering capability: the capacity of riparian vegetation to protect aquatic environments from excessive sedimentation, polluted surface run-off and erosion.

Edge effect: the difference in ecological attributes between the centre of an area of habitat and its margins, due to the juxtaposition with a different habitat.

Invasional meltdown: process by which a group of species facilitate one another's invasion in various ways, increasing the likelihood of survival and/or of ecological impact.

Lateral linkages: linkages between floodplains and the river channel.

Longitudinal linkages: linkages between upstream and downstream river sections.

Landscape connectivity: the degree to which the landscape facilitates or impedes movement among resource patches.

Propagule pressure: the frequency with which plant reproductive units (seeds or clonal fragments capable of regenerating and forming new individuals) arrive at recruitment sites.

Propagule dispersal: the distance that plant propagules are transported prior to recruitment.

Recruitment sites: spatial habitat areas providing physical sites for plant reproduction.

Regeneration niche: the component of the niche of a plant that is concerned with processes such as seed production and germination, and by which one mature individual is replaced by another.

Resilience: the ability of an ecosystem to return to its former state following a disturbance or stress, or the time required to return to its former state.

Riparian vegetation: vegetation that grows along the banks of rivers, lakes or watercourses.

Successional trajectories: the direction of changes in the composition or structure of an ecological community.

Further reading

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