Estimating the Water Requirements for Plants of Floodplain Wetlands: a Guide

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Contents

List of Figures

List of Tables

Preface

Throughout Australia, the future of water resources, water-dependent industries and aquatic ecosystems is being reviewed. The principal users of river water, that is industries and ecosystems, are being identified and their respective needs are being formally recognised. Although the process of making allocations differs between jurisdictions, there is a common requirement for quantitative estimates of these needs. At present, the allocation process is faced with uneven knowledge, and ecosystem needs are inadequately articulated. This guide addresses the needs of one part of the riverine ecosystem: the plants of floodplain wetlands.

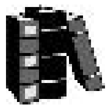
In terms of flow management, riverine ecosystems can be divided into in-channel and over-bank or floodplain. The links between in-channel ecology and flow regime are recognised and there has been considerable development in defining and quantifying the in-stream flow needs. The recent publication of wetland books, reviews and manuals shows a similar advance in understanding for single wetlands (Note A). In contrast, knowledge of the over-bank riverine environment, or whole floodplain complexes, has advanced much more slowly.

Floodplain wetlands are large and diverse, but are typically well-vegetated. This vegetation has value as habitat providing, for example, refuge and breeding opportunities; these values are not fixed but change through time. Because they support large waterbird populations after flooding, many floodplain wetlands have been listed as wetlands of national and international significance.

In this guide we aim first, to advise on how to estimate the water requirements of the plants on these floodplain wetlands, and second to inform and thus increase understanding. It is not a prescriptive manual. As a guide, it is directed at persons charged with making decisions about water allocations, persons who are not necessarily trained in all relevant areas.

The guide draws on case histories from Australia, but is not a critical review. Most of the cases are from inland rivers in eastern Australia, where the pressures of agricultural development have been most acutely felt.

Restoration has been a management goal in wetland management worldwide, but in Australia there has been a drive to restore a wetland by restoring its 'natural' or pre-European water regime. This is possible for smaller, discrete wetlands, often with the aid of structures such as regulators, but is much harder to achieve for floodplain wetlands. Rehabilitation has been the primary management goal for the in-stream environment. Rehabilitation is the reality of managing heavily regulated rivers where the goal is to obtain small improvements while working within operational constraints. Resolution of what is desirable or achievable for floodplain wetlands is within the social and political sphere, and outside the frame of this guide, which instead outlines approaches suitable for restoration and rehabilitation.



NOTE A

On wetland management

For general reading on wetland management, see the range of manuals recently produced by State agencies across Australia. Examples are:

"Wetland management; a manual for wetlands of the River Murray in South Australia" (Carter and Nicolson 1993)

"Manual of wetlands management" (Hull and Beovich 1996).

"Wetlands of the Swan Coastal Plain: their nature and management" (Balla 1994).

These focus on individual wetlands or discrete waterbodies, such as billabongs, rather than on wetland complexes.

Some manuals include sections on water management, and introduce basic hydrological concepts. Methods used for estimating water requirements of wetlands are reviewed in "Comparative evaluation of environmental flow assessment techniques: review of methods" (Arthington and Zalucki 1998): this separates 'wetlands' from 'floodplains', and focuses on wetlands only.

Note that the guide is concerned primarily with water quantity. Water quality and land management, both of which are factors that can adversely affect the condition of plants on floodplain wetlands, are not considered.

Acknowledgments

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Guide to Contents

The aim of this guide is to advise readers on how to go about estimating the water requirements of plants on floodplain wetlands. This is a multi-disciplinary task, drawing on expertise in hydrology and plant ecology. There is no reference text for this. The task is made more difficult because of the general lack of information on floodplain hydrology, geomorphology and vegetation.

Section 1: Introducing floodplain wetlands

Understanding floodplain geomorphology and hydrology is the key to understanding ecological diversity of floodplain wetlands, and to understanding the vegetation. In this section, the key features of geomorphology and hydrology are introduced, to show the diversity within and between floodplains. Floodplain water balance, which is an important part of this guide, is also introduced, and its link to water regime outlined.

Section 2: Introducing the vegetation

This section gives an ecological background to floodplain vegetation, by looking at some of the ways that water, and water regime, affect plants. First, water is considered as part of the plant environment and described as environmental gradients across the floodplain; then it is considered as a resource; and finally as a resource and as an environment that affects other resources. Vegetation attributes that are routinely used to describe terrestrial vegetation are presented, in the context of Australian floodplains. Descriptive approaches such as growth-forms and plant functional types are outlined in relation to the floodplain environment. Plant water regime and its seven main components are presented, and the value of focusing on depth is emphasised.

Section 3: A stepwise procedure

The process for determining the water requirements for plants of floodplain wetlands can appear complicated and even circular to those involved in the process, but in fact it follows a series of well-defined steps. These steps are similar regardless of political process or which floodplain wetland is being considered. This section describes the five steps in this general procedure. Only Step 3 and Step 4, both purely biophysical, are treated in detail in this guide.

Section 4: Old and new data

One of the first decisions is whether to use existing vegetation–hydrology relationships, or to develop new ones. An assumption of this guide is that existing hydrological data are likely to be adequate, so it becomes a matter of how to use what water regime is available and how to improve it. Nevertheless, it is likely that there will be few useful vegetation data, so they will have to be collected. This section discusses how to evaluate existing knowledge, then outlines options for developing new relationships, based on field studies. There is a definite role for special studies and experimental research, which tend to be overlooked.

Section 5: Obtaining vegetation data

When there is little or no previous information about water regime for relevant species, then vegetation–hydrology relationships must be established from scratch. This section describes what sort of vegetation data to obtain, and whether to do this at the level of species or community; if at species level, ways of choosing species are outlined. Different measures of vegetation are described — abundance, character and vigour — and examples given for species, community and different growth-forms. Techniques for measuring abundance, character, and health are outlined, rather than given in detail. Examples are given of Australian studies and experiments to show how these complement a field-based vegetation–hydrology relationship.

Section 6: Using water regime data

The hydrologic variable of most relevance to plants is water depth, but water depth data are rarely available for large wetlands. Depth can be obtained directly, or indirectly by water balance calculations from existing data. This section focuses on the indirect ways for obtaining depth, but recognises that water regime can be defined in other ways. Options for estimating the different components of a floodplain wetland water balance are described, with emphasis on spatial and temporal variations across the floodplain wetland. The application of water regime data for hydrological modelling is described, with current Australian examples, although these are rarely based on depth.

Section 7: Predicting vegetation responses

The general procedure advocated in this guide is to use vegetation–hydrology relationships to predict the likely future state of floodplain wetland vegetation as a result of proposed changes to water regime. The process of making these predictions is referred to as modelling. While modelling may be as simple as expert predictions based on a conceptual model, in general it involves repetitive calculations to describe the temporal and or spatial patterns in vegetation response. This section identifies four different categories of modelling, based loosely on the complexity of the modelling approaches, and describes them using examples from Australia and North America.

Section 1: Introducing Floodplain Wetlands

Understanding floodplain geomorphology and hydrology is the key to understanding ecological diversity of floodplain wetlands, and for understanding the vegetation. In this section, the key features of geomorphology and hydrology are introduced, to show the diversity within and between floodplains. Floodplain water balance, which is an important topic of this guide, is also introduced, and its link to water regime outlined.

What are floodplains?

Floodplains are fluvial depositional environments formed over long periods from sediments transported by rivers in flood. In terms of river flow velocity, floodplains are low energy environments, a result of their very low slopes and low relief (Note 1).

The rate of floodplain formation depends on the prevailing flow regime in the river and on the nature of sediment delivery from the upper catchment. Most floodplains are *polyphasic* ie. they have been formed under variable flow, climate and deposition conditions, whereas a *monophasic* floodplain is one formed under just one set of conditions. Old floodplains are unlikely to be monophasic, but young ones might be. The age of floodplains varies. The Willandra Lakes on the Lachlan River distributary are at least 55,000 years old, whereas coastal floodplains of the Northern Territory are 3–6,000 years old. An appreciation of the age of a floodplain and its forms is useful for understanding its ecological diversity. Floodplains on large rivers are large, covering 100,000–200,000 hectares.

Fluvial forms on floodplain wetlands are mainly relict channel features, such as *billabongs* and *anabranches* (eg. Figure 1). Billabongs, which include ox-bows, cut-off meanders and small lentic features, can be numerous and quite diverse. If billabongs originate from a period of higher discharge, their dimensions will exceed those of the contemporary river, and they will have different sediment characteristics. Floodplain age and formation can be a short guide to billabong diversity. Anabranches are channels that leave then re-join the present river. Typically, these flow at times of high discharge. Often, but not always, an anabranch is a paleochannel and its dimensions are different from the present river. Anabranches are a notable feature of the major rivers in the Murray–Darling system.

Note 1
Floodplain classification

Lack of scientific and ecological studies of floodplains have hindered understanding of floodplain ecology.

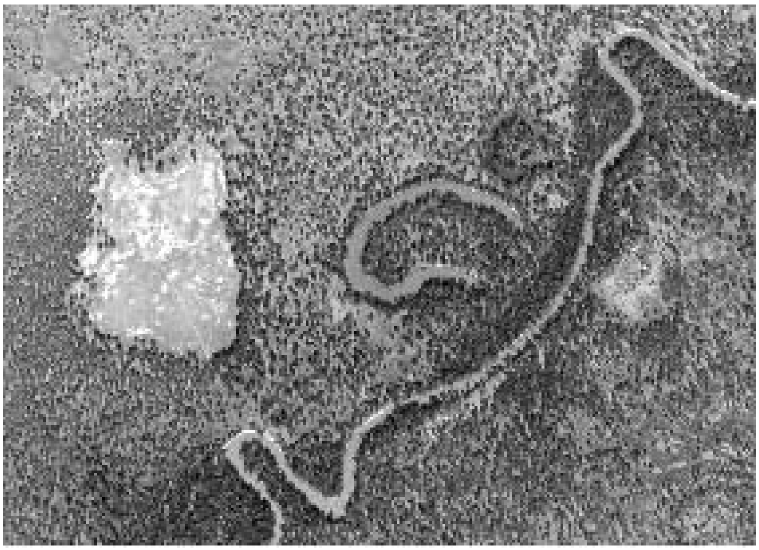
An example of this is that as yet there is no Australia-wide system of floodplain classification.

In general, the most effective classification systems are those that are based on their formative processes, also known as functional or genetic classifications. For floodplains, this means a classification system based on stream power, discharge and sediment characteristics.

A genetic floodplain classification system has been developed by Nanson and Croke (1992). Their Class C, low-energy cohesive floodplains, covers terminal wetlands and most of the floodplains in the Murray–Darling Basin.

Figure 1. Floodplain features

The floodplain of a lowland alluvial river in the southern Murray–Darling Basin. Both fluvial and non-fluvial features are evident: see the relict channels and the dune. Non-fluvial features typically have distinctive soils or lithology: if elevated, as shown here, these features serve as ecological islands, increasing regional diversity and acting as a refuge in major floods.



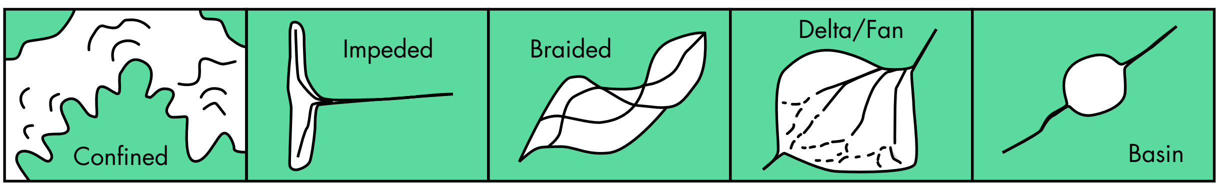
Non-fluvial forms on inland floodplains include aeolian features such as dunes and shallow deflation basins with their distinctive quasi-circular shape and accompanying lunette on the downwind side.

The width of the floodplain generally increases in the downstream direction as the river valley widens. In the middle reaches of most alluvial rivers, the floodplain is bounded by valley walls that constrain floods, so most floodwater returns to the main river channel. The lowest reaches of alluvial rivers are usually beyond the lateral constraints of valley walls, so floodwaters spread out. Consequently, there is very little return to the main river channel, except in major floods. In this very low energy environment, the river virtually ceases. Such floodplains are described in this guide as *terminal*. These terminal floodplains may take different forms, such as an alluvial fan or delta, with a slightly concave cross-section and a divergent distributary channel network, or may be basin-like (Figure 2). (Understanding floodplain form and whether it is confined or not helps to understand floodplain hydrology, surface topography and its variability, the distribution of floodwaters, and ecological complexity.) *Confined* floodplains, then, are where a flood exiting the upper river reaches slows down and spreads out, but is bounded by valley walls; the lower *unconfined* floodplain can be considered as where the flood dissipates.

On long rivers, confined floodplains are steeper on the upper plains where the rivers exit from the uplands; and flatter further downstream. The upper and lower confined floodplains are therefore differentiated by valley slope.

Figure 2. Forms of floodplain wetlands

Schematic diagram showing some types of floodplain wetlands. From left to right, two types of confined floodplains, and three unconfined and terminal floodplains, with little through-flow. Floodplains with braided channels are more fragmented and more complex than basin-like ones. All these are found in the Murray–Darling Basin.



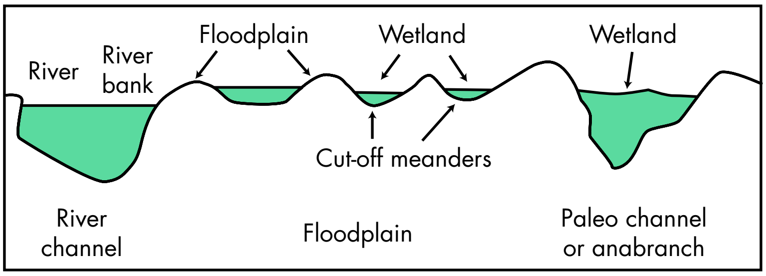
Understanding floodplain form and whether it is confined or not helps to understand floodplain hydrology, surface topography and its variability, the distribution of floodwaters, and ecological complexity.

What are floodplain wetlands?

In this guide, a floodplain wetland refers to the whole floodplain surface, so includes fluvial and non-fluvial features (Figure 1); 'wetland' (Note 2) refers to those areas that retain water, and 'floodplain' refers to those areas that drain readily (Figure 3). This is an ecological perspective: geomorphologists would refer to these areas as a floodplain.

Figure 3. A floodplain wetland

A cross-section through one side of a confined floodplain, showing how floodplain wetland refers to a mosaic of floodplain and wetland habitats.



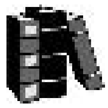
The different-aged fluvial forms described above provide a range of water-holding areas on the floodplain, and hence a diversity of wetlands. A floodplain wetland is therefore a complex or a mosaic of wetlands and floodplains, and of water regimes, and hence habitat types for vegetation.

Introducing the hydrology

The hydrology of a floodplain wetland (large or small) is described by its water balance. Over any period, the change in water stored in the wetland is equal to the sum of the water inputs, less the water outputs.

The water inputs to be considered are surface inflows, direct rainfall, and groundwater inflows. Because floodplain wetlands are mostly riverine systems, surface inflow is usually dominated by river-sourced floodwater. In areas of high intensity and localised rain events, local run-off from rain falling on the immediate floodplain area and draining into a wetland on the floodplain can be significant. For floodplain wetlands far from the river channel, and/or poorly connected to the river, local run-off is often the dominant input. The relative importance of river floodwater and local run-off will usually vary through time, with small inputs from local run-off occurring much more frequently than the larger inputs of river-derived floodwater.

The water outputs to be considered are surface outflows, evapotranspiration and groundwater outflows. Surface outflows include the losses of water through distributary channels away from the river, especially on unconfined floodplains, and the return of flood water to the main channel as river water levels subside.



Note 2
Defining wetlands

Numerous definitions of 'wetland' can be found in Australia, as elsewhere. In part this is due to gradually rejecting, over the last 20–30 years, European and Northern Hemisphere cool–temperate views and vocabulary, and replacing these with words and ideas that suit most of Australia's arid and semi-arid inland areas.

The most comprehensive definition of wetland is the internationally-used Ramsar definition (see Web Listing Section).

Because of its wide acceptance overseas and because of Australian treaty obligations, the Ramsar definition is used, totally or in part, by Federal and State governments, and is the basis for much policy and regulations.

Although the Ramsar definition does recognise types of wetlands, it is not a wetland classification system.

Note 3
Wetland classification

The most effective type of classification is one that facilitates the transfer of scientific knowledge and management understanding from one wetland to another.

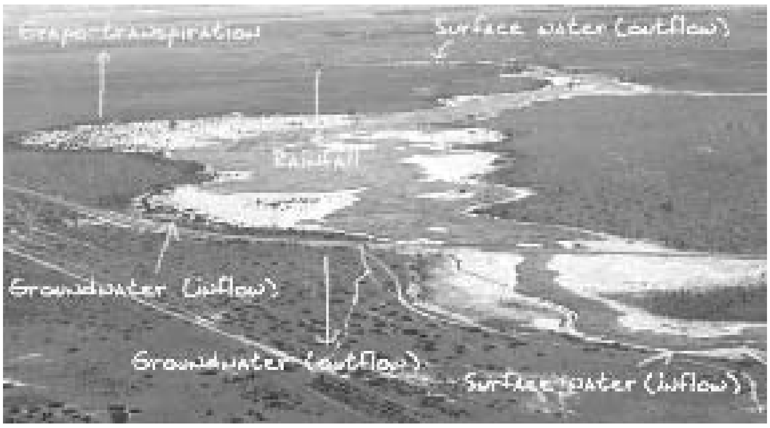
As with floodplain wetlands (Note 1) this requires a functional classification, as done for wetlands in the Darling system of Western Australia (Semeniuk and Semeniuk 1995).

Most of the wetland classifications currently in use in Australia are descriptive only. Some rely on vegetation presence and abundance to define wetland types. Unfortunately, this makes it difficult to accommodate change without producing a further classification.

Useful discussions of classifications, wetlands and wetland classification in Australia are given in Pressey and Adam (1995), and in Sainty and Jacobs (1994).

Figure 4. Wanganella Swamps, southern New South Wales, July 1992

Aerial photographs, even oblique low-level colour photographs such as this was originally, are valuable in determining flowpaths during floods, and in revealing impediments. Floodwaters are slightly ponded upstream of the Cobb Highway. The dominant vegetation is cumbungi, *Typha* spp., in the original image looking pink–grey because it is senescent.



Evapotranspiration is usually a major component in the water balance of a floodplain wetland, especially in arid or semi-arid regions. Evapotranspiration depends not only on the local climate — that is, on the prevailing temperature, humidity and wind speed — but also on the vegetation. Vegetation has a critical role, with species differing in transpiration rates, rooting depth, leaf area, and *albedo*, a measure of radiation reflectance. Leaf area also affects direct rainfall interception and direct evaporation. The aerodynamic roughness of the vegetation affects advective interactions with the air above, and this then influences transpiration and evaporation. Because of these complex interacting factors, the accurate determination of evapotranspiration losses is difficult.

On many floodplains, infiltration is directly determined by the duration of flooding, and this determines shallow groundwater recharge. In soils of low permeability, for example, prolonged flooding is required to achieve significant recharge. Unlike many coastal wetlands or wetlands on sandy soils, groundwater exchange is rarely dominant on floodplains and it is surface flows, as well as losses via evaporation and plant water use, that dominate the water balance.

Groundwater losses are difficult to estimate, and although in some cases significant, they are less often a major component of the water balance of floodplain wetlands. The importance of groundwater depends on the nature of the soils and the underlying aquifers. Coarse alluvial deposits below the contemporary floodplain — that is, the sands and gravels laid down in an earlier phase of floodplain development — provide aquifers with high water-holding capacity. Such aquifers may be overlaid by fine silts and clays, preventing a direct connection to the surface. These underlying aquifers are an alternative water source for deep-rooted species such as most floodplain trees and some shrubs (Section 5, Special studies).

When constructing a wetland water balance, a time step must be chosen. The appropriate time step depends on the rate at which wetland water levels vary, and the required accuracy of water level assessment. For small wetlands, or wetlands with frequent or rapid inflows, where fringing vegetation has been identified to be of critical importance, levels will vary rapidly and a daily water balance will probably be required. For larger wetlands, or those with infrequent and slower inflows, a monthly water balance may be sufficient. At each time step, the water balance calculations will determine the change in water storage volume. The time-varying storage volume describes the water regime of the wetland.

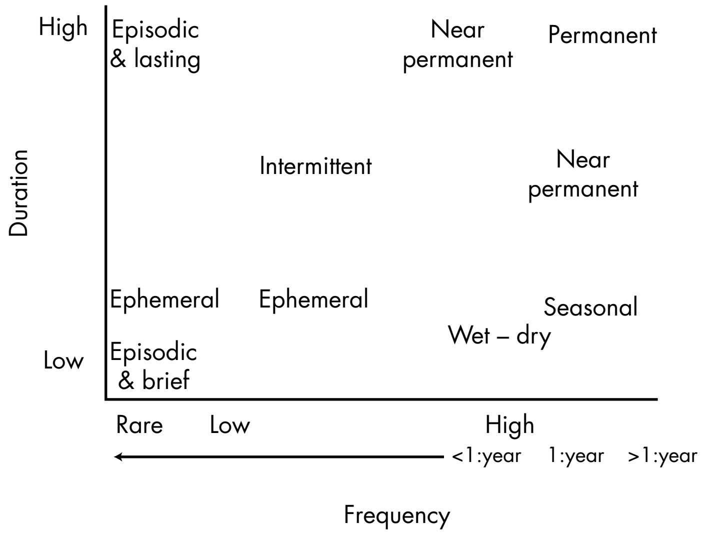
Water regime

Water regime is the pattern of water, principally water depth (and the lack of water) through time, so includes duration, seasonality and predictability. These are considered measures of 'wetness' but similar measures of 'dryness' are equally important for floodplain wetlands in dry and hot climates. Dryness can be described, or estimated, by measures of soil moisture. The term *water regime* is used in Australia in preference to the North American term *hydroperiod* which is too restrictive a description with its emphasis on duration and presence of water.

The water regime of a whole floodplain wetland can be quantitatively described, based on its water balance, as changes in storage volume. Changes in storage can be converted (using a volume-to-area relationship) to changes in depth. Depth is emphasised here as it is the hydrologic variable of most relevance to most plants. If a whole floodplain wetland is considered as a single unit, then only an average description of water regime is obtained.

Figure 5. Wetland water regimes

Types of wetland water regime are shown here as an interplay of two gradients of increasing 'wetness': flood frequency and duration. For clarity, flood frequency is shown as a continuous, qualitative variable, ranging from rare to annual flooding, and flood duration as high or low. Floodplain features with high duration are typically cut-off meanders and deflation lakes, all of which are isolated waterbodies, but include also small features such as gilgais and wallows. Areas with low flooding duration are those with imperceptible slopes, such as terraces, higher landforms, banks and relict non-fluvial features.



Note 4
Wetland water regime

This is a list of the preferred words and definitions for types of water regime for Australian wetlands.

Williams (1998) recognised three types: permanent, intermittent and episodic, with intermittent and episodic being separated on the predictability of flooding. He rejected temporary and ephemeral.

Paijmans et al. (1985) recognised four types: permanent and near-permanent; seasonal, being alternately wet and dry; intermittent, meaning alternately but irregularly, wet and dry; and episodic, being dry most of the time.

Boulton and Brock (1999) added ephemeral to the list of Paijmans et al. (1985), specifically to include those wetlands which are flooded very briefly, perhaps only for days, and unpredictably.

Note 5
Water balance for the Gwydir Watercourse

The volume of the Gwydir Watercourse (part of the fan-like lower Gwydir River, northern New South Wales) was estimated by Bennett and McCosker (1994). Rainfall input was based on average monthly rainfall with two states, summer and winter, set at 60 and 35 mm per month; evapotranspiration was based on actual pan records and assumed to be three times as high in summer as in winter, 300 mm and 100 mm per month; a target depth of 30 cm surface water was chosen as representative of the floodplain wetland area; and water required to fill soil storage was estimated as 30 cm under average dry conditions, but 50 cm under prolonged dry conditions.

A total of 3 ML/ha will be needed if antecedent conditions are wet, and 6 ML/ha if antecedent conditions are dry, with 0.7–2.4 ML/ha per month to maintain inundation.

Floodplain wetlands, being a mosaic of forms (Figures 2 and 3) are also a mosaic of water regimes. Flood frequency and duration provide a useful way of describing the range and diversity of water regimes in wetlands, and hence on floodplain wetlands (Figure 5).

The interaction of flood frequency and duration accommodates most of the terms in common usage.There has been no standard terminology to describe the different types of wetland water regime (Note 4), although this is beginning to be addressed.

Determining the water regime for wetlands and for wetland plants by quantifying wetland water balance is the approach favoured in this guide. An example, for the Gwydir wetlands, is presented (Note 5).

Pathways. A wetland water balance recognises three pathways for water movement: surface water, sub-surface water and atmospheric water. Each pathway can move in two directions: inflow and outflow for surface water; infiltration or re-charge and discharge for sub-surface water; and rainfall and evapotranspiration for atmospheric water.

Storage volume. At long time scales, the sum of the inputs equals the sum of the outputs, and there is no long-term change in the storage volume. At shorter time scales, the sum of the inputs does not equal the sum of the outputs, and the storage volume varies considerably.

This storage term is the one of most interest here, as it is this term that describes the wetland water regime in terms that link to the floodplain vegetation. The storage volume includes *surface* water (water above the ground surface) and *sub-surface* water (water stored in the soil column). Sub-surface flow reflects exchanges between the soil storage and deeper aquifers.

For large or complex floodplain wetlands, the storage volume can be estimated directly, and approximately, based on inundated area. For small, discrete wetlands where the wetland morphometry is known, or can be easily established, the storage volume can be determined by monitoring changes in water levels. Morphometric information is used to provide a depth–volume relationship. For all wetlands, changes in the storage can also be calculated from inflow and outflow data. For those floodplain wetlands where river flow dominates surface inflow, inputs as run-off and rainfall may be ignored. However, in a few floodplain wetlands, notably riverine lakes and floodplains remote from the river, direct inputs — whether as rainfall or run-off from the local catchment — can be significant and may even dominate inflows. Groundwater inflows are typically small on floodplain wetlands, although there may be localised effects on floodplains with lenses of coarse material close to the surface. This is not always true for groundwater outflows.

Storage volume hydrographs. Storage volume hydrographs show a record of the changes in storage volume through time. The shape of a storage volume hydrograph can give a rough idea of which pathway is dominating.

Thus, the *rising limb* (Figure 6) can often be considered as representing only surface inflows. Groundwater inflows can be ignored during periods of surface inflow, but may be significant at other times. The effect of groundwater inflows is evident either as a slowing of the falling limb or as minor rising limbs in their own right, particularly when storage volumes are very low. Such inflows will be slow and have a subdued hydrograph peak.

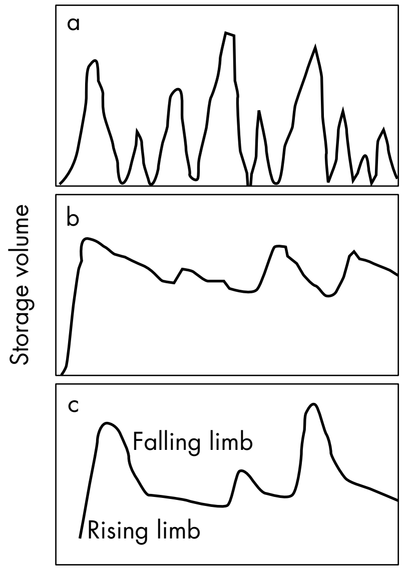
The shape of the *falling limb* (Figure 6) is a combination of surface outflows, evapotranspiration, and groundwater outflow. Because evapotranspiration and groundwater outflows are usually slow compared with surface outflows, the slope of the falling limb indicates which outflow pathway is dominant.

A **steep falling limb** (Figure 6a) indicates surface-dominated outflows. This can be expected on unconfined floodplains with a surface cross-section that is slightly convex, or on higher ground on confined floodplains where water returns to the river from the floodplain as river levels drop. Terminal wetlands, although often on a floodplain that is convex overall, usually have depressed areas that retain water and offer near-permanent wet habitat.

Slow-falling limbs (Figure 6b) indicate little or no surface outflow, so losses are due to evapotranspiration and groundwater outflow. This can be expected in billabongs, riverine lakes, and other wetlands on confined floodplains where surface topography does not allow free surface drainage.

Rapid surface drainage (Figure 6c) occurs after flooding until the minimum level of the outlet channel(s) is reached; further reductions in water level occur slowly as a result of evapotranspiration and seepage.

Figure 6. Storage volume hydrographs



Section 2: Introducing the Vegetation

This section gives an ecological background to floodplain vegetation, by looking at some of the ways that water, and water regime, affect plants. Water is first considered as part of the plant environment and described as environmental gradients across the floodplain, then as a resource, and finally as a resource and as an environment that affects other resources. Vegetation attributes that are routinely used to describe terrestrial vegetation are presented, in the context of Australian floodplains. Descriptive approaches such as growth-forms and plant functional types are outlined in relation to the floodplain environment. Plant water regime and its seven main components are presented, and the value of focusing on depth is emphasised.

Water as a part of the environment

The purpose of this section is to introduce floodplain vegetation, first by describing the spatial character of floodplain as a habitat for plants, and then by giving some background about floodplain plants. The background is necessary because there is no single text on floodplain ecology (Notes 6 and 7). Please note that this is not a comprehensive guide to either plant ecology or floodplains.

Wet–dry gradients and patchiness

Floodplain wetlands are characterised by having a range of growing conditions: from wet to dry, shallow to deep, favourable to stressful. Which conditions are favourable and which are stressful depends on the species. This range can be seen as an environmental gradient, from 'wetness' to 'dryness'. It is useful to recognise these gradients, not just because they determine vegetation patterns but because this understanding can streamline floodplain investigations, especially in relation to vegetation sampling and water regime.

Environmental gradients may be gradients in resources, such as nutrients, or in physical conditions, such as temperature; the gradients can be described as changes across space, or through time. An environmental gradient need not be water-related, but as this guide focuses on water management, it is water and water-related gradients that are discussed here. On most floodplain wetlands, these are likely to be the strongest, ie. have the most influence.

Examples of spatial gradients occurring on floodplains are:

- **longitudinal gradient,** down the long axis of a river — on confined floodplains, this is evident as gradual change in flow regime because of progressive flattening and attenuation of the

Note 6
Floodplain vegetation

General descriptions of wetland and floodplain plant communities can be found in "The vegetation of Australia" (Beadle 1981), in selected chapters in "Australian vegetation" (Groves 1981, 1994), and there is a brief guide in "Waterplants in Australia" (Sainty and Jacobs 1994). There is no text dedicated to floodplain vegetation or its ecology in Australia but information is included in "An ecology-flows handbook…." (Young, in press)

Note 7
Research on floodplain plant ecology

The ecology of floodplains is described in "Living on the floodplains" (Mussared 1997). Scientific studies have focused on individual plant species (usually structural dominants) and their abiotic (usually water, sometimes soil) environment, with only a few studies on regeneration and dynamics. "Ecology of fresh waters" (Moss 1998) and "Vegetation processes in swamps and flooded plains" (Breen et al. 1988) are among the few texts that consider floodplain vegetation.

flood hydrograph. This corresponds to a gradient in flood frequency and duration;

- **lateral gradient**, away from the main river channel — on confined and unconfined floodplains, this corresponds to flood frequency; this gradient can be broken up by intermediate conditions represented by channels on highly dissected floodplains. This corresponds to a gradient in flood frequency and duration;
- **vertical gradient**, for floodplain wetlands with simple forms and especially around the margins of individual wetlands. This corresponds to a gradient in water depth and duration.

These gradients intersect across floodplains (Figure 5). Such gradients are particularly obvious on infrequently inundated floodplains, where the transition from more frequently flooded areas to less frequently flooded ones is quite marked. Vertical gradients result in vegetation banding or zonation around wetlands (Figure 7).

Figure 7. Vegetation zonation

Vegetation zonation showing spatial changes in dominance and structure at Lake Cowal, a floodplain lake in western New South Wales, as it was in the mid-1970s. The gentle slope at the edge of this shallow lake corresponds to a flood duration gradient. From the left: The river red gum *Eucalyptus camaldulensis* woodland with scattered river coobah *Acacia stenophylla* has a well-defined shrub–tussock grass layer, of lignum *Muehlenbeckia florulenta* and canegrass *Eragrostis australasica*. The understorey becomes progressively more aquatic, initially with a ground cover of aquatic herbs, mainly nardoo *Marsilea drummondi* and milfoil *Myriophyllum verrucosum*, and these are then replaced with beds of the submerged herb, *Vallisneria* sp. Over the same area, as the river red gum trees become less frequent and lose vigour, they are replaced by lignum shrubland, which also eventually becomes sparse. The uneven nature of the slope was the result of the construction of farm tanks, dams and channels. Based on Vestjens (1977).

On many floodplain wetlands, the pattern of growing conditions is made more complex by fluvial forms and subtle changes in surface topography. For example, on confined or braided floodplains (Figure 3) intersecting channels break the floodplain into patches that may flood at different frequencies, depending on their elevation; and intersecting and diverging channels create flow-paths of variable and changeable velocity. Floodplains with geomorphic features that retain water, such as billabongs, depressions, wallows or gilgais, thus have several patches where surface flooding is prolonged.

A question of resources

The size and vigour of a plant is set by the quantity and availability of the resources needed for growth. Even when these resources are abundant, size and vigour rarely reach their maximum potential because of the effects of other species, through competition, parasitism and herbivory.

In all ecosystems, the quantity, quality and availability of the four principal resources needed by plants — oxygen (O_2), carbon dioxide (CO_2), light and nutrients — vary. Species have a range of adaptations to exploit resources when these are available, and strategies to conserve or survive when resources are low or unavailable. Water is essential for plants, as for all living organisms, as it is the medium in which biochemical processes take place. For plants, water is needed for photosynthesis, the process that converts CO_2 into organic compounds needed for plant structure, storage and reproduction.

More than a resource

Considering water only as a resource for plants ignores that, for many wetland plants, water has other functions: reservoir, support and dispersal. For submerged plants, or plants with submerged leaves, water is an additional source of nutrients. For many emergent, and most floating-leaved species, it offers some support (Figure 8): these plants lack strong supportive tissues so tend to flop when water levels recede. Flood waters help to disperse seeds and other propagules. Species that are dependent on flooding for dispersal tend to have very buoyant seeds (or fruits); for these plants, the presence of structures such as gates and regulators can adversely affect ecological connectivity. Examples of species with buoyant fruits, but which are not dependent on floodwaters for dispersal, are the introduced burrs, *Xanthium* spp.

The paradox of flooding

Flooding creates a paradoxical situation whereby the abundance of one resource, namely water, alters or reduces the availability of other resources needed for photosynthesis and growth. This balancing act is illustrated here by focusing on just two of the four main resources — oxygen and carbon dioxide. The fundamental difference between dryland and wetland plants is that aquatic and amphibious species have a range of physiological and ecological adaptations to compensate for their watery environment.

Oxygen

Oxygen is freely available in the atmosphere and so to the leaves of terrestrial plants and to emergent aquatic macrophytes. Oxygen is not freely available if leaves are submerged.

It is a similar story with roots. Roots can respire freely while the soil is aerobic but if the soil is flooded, then soil oxygen is rapidly depleted (by bacterial and plant root respiration) because it is not replenished from the atmosphere. Plant roots become starved of oxygen, and *phytotoxins* can enter them.

Some aquatic plants with aerial leaves have developed ways to pressurise oxygen in the leaf and so drive it internally down the plant to the roots. The capacity to do this is limited to a few growth-forms, mainly emergent and floating-leafed macrophytes. Species with these growth-forms differ in their capacity to pressurise oxygen and to ventilate their rhizome and roots, and such differences help explain why species differ in their tolerance of different depths of water. Trees apparently do not pressurise oxygen but have developed other adaptations. In estuaries, trees such as mangroves have special root structures called *pneumatophores* that project into the air and help to aerate the root system. Some trees such as paperbark and river red gum can develop adventitious roots in response to flooding. Other trees and shrubs of inland floodplains have few specific adaptations for oxygenating their roots, so their roots are likely to suffer oxygen starvation under flooding.

The time between flooding and when soil oxygen is depleted, and the time for this to become evident as canopy stress (often yellowing then leaf senescence), can only ever be an approximate estimate. This is because of the influence of sub-surface factors that are difficult to assess, such as how extensive a root system is, presence of air-pockets and macropores, and soil physical characteristics. Observations for individual sites are informative and a useful rule-of-thumb but should not be treated as precise and accurate estimates of flooding tolerance.

Carbon dioxide

The availability of inorganic carbon changes after flooding. Carbon dioxide is taken up mainly by leaves, through specialised openings called stomates. For plants with leaves in the air, CO_2 is freely available and becomes limiting inside the leaf only if the stomates close, for example to minimise water loss. The plant must therefore balance taking up carbon and preventing water loss. Because of this, plants in certain environments have developed different carbon acquisition strategies, known as C-3, C-4 and CAM (Note 8). The significance of these for understanding water requirements of floodplain wetlands, is that C-4 plants have a greater water-use efficiency (carbon fixed relative to water lost) than C-3, but CAM has greater water-use efficiency than C-4. (Section 5, Evapotranspiration).

For aquatic plants with submerged leaves, carbon acquisition under water is a different problem. First, there is the rate of supply. Free CO_2 is available to submerged leaves, because CO_2 is very soluble in water, but it diffuses much more slowly than in air, so this can limit plant growth. To compensate for this, some submerged species obtain some of their CO_2 from the sediment. Second, there is the question of the forms of carbon. In water, inorganic carbon is also present in forms other than CO_2, and one of these, HCO_3, can be used by some species. The relative quantities of the forms of inorganic carbon are strongly influenced by pH. Free CO_2 is available only up to pH 7: between pH 7 and pH 10, inorganic carbon is in the form HCO_3. Thus, long-term or sustained increases in pH will disadvantage those species which are obligate CO_2 users (Note 8).

The capacity of Australian submerged plants to use HCO_3 is poorly known, although it has been established that Australian material of *Ceratophyllum demersum*, *Potamogeton crispus*, *Vallisneria americana*, as well as the introduced *Elodea canadensis*, can use HCO_3.

Resources without flooding

The dry period between floods creates the opposite resource situation — inadequate water. In warm, dry climates, floodplain plants that continue to grow, albeit slowly between floods, must adapt in some way to conserve water and to protect against desiccation. Thus, many trees and shrubs from inland floodplains and from episodically flooded

Note 8
Carbon acquisition strategies

C-3 is shorthand for plants that fix carbon dioxide into a three-carbon product, and C-4 into a four-carbon product. In plants with CAM, 'crassulacean acid metabolism', carbon dioxide is temporarily fixed as a four-carbon product by night then photosynthesis continues during the day. C-3 is the most common carbon fixing strategy; C-4 is more prevalent in tropical and subtropical grasslands, and in hot, saline conditions, both areas where high water-use efficiency is an advantage. C-4 plants include some species of *Cyperus*, *Eleocharis*, and *Paspalum*, and some weeds, notably *Echinochloa crus-galli*. CAM is the least common strategy: although usually associated with succulent plants, it occurs also in submerged plants from nutrient-poor waters.

Information about C-3, C-4 and CAM can be found in academic texts on plant physiology. The carbonate – bicarbonate – carbon dioxide equilibrium is described in most aquatic ecology texts, eg. Boulton and Brock (1999); photosynthesis of submerged plants is in Moss (1998).

floodplains survive there because they have evolved strategies for low water use.

In contrast, aquatic and wetland plants rarely have water-conserving strategies. Submerged plants, for example, have leaves rarely more than a few cells thick and virtually no protective outer cuticle, so they dehydrate rapidly in the sun. Wetland plants with aerial leaves, such as emergent and floating-leafed macrophytes, have a thick or waxy cuticle on their leaves but transpire readily.

Most aquatic plants 'ride out' the dry inter-flood periods by strategies other than physiological adaptations. One strategy that is typical of annuals is avoidance, exemplified by short life-span and setting seeds, hence reliance on the seed-bank. Another strategy, typical of perennials, is to enter a low-activity or no-growth phase. In this, water loss is restricted by leaf-shedding, or by complete canopy senescence and die-back. The plant survives with its sensitive generative tissues buried in the sediment, or as hard-coated seeds or some other propagules. Aquatic plants have a wider range of propagules than do terrestrial species, with rhizomes, corms, tubers, turions, spores and nodal fragments as well as seeds.

The long-term survival of these propagules depends on being buried in protective sediments and on the sediments being protected from disintegration by trampling or machinery. In general, water-conserving strategies are better developed in shrub and tree species occurring on the infrequently-flooded parts of floodplains.

Adaptations, tolerance and stress

Differences in adaptation to resource availability means species are found in particular sequences, ie. at different positions on the environmental gradient from 'flooded' to 'dry'. This is evident in zonation (Figure 7), the concentric patterns of species in the littoral zone around a billabong or up a riverbank. On a larger scale, a similar distribution can be seen across a floodplain.

The degree of adaptation can be described as obligate or facultative; and adapted or tolerant. In the floodplain wetland context, species dependent on aquatic conditions to provide resources, support and opportunity for regeneration are *obligate* species, whereas those that can survive on wet muds (at least temporarily) after flood recession and still flower and set seed, are *facultative*. Thus, submerged plants such as *Vallisneria* which die of desiccation on flood recession are obligate for inundation, whereas many species of milfoil, *Myriophyllum* spp., that can grow on wet muds, especially during cooler conditions, are facultative. Similarly, species may be *flood-adapted*, meaning they have specific adaptations that allow growth under flooded conditions, whereas species that survive but are not adapted to grow are *flood-tolerant*. An equivalent situation occurs in relation to dry conditions on the higher parts of a floodplain, where plants may be *drought-adapted* or *drought-tolerant*.

The tolerance range of a species to a particular component of the water regime, such as depth, can be inferred in various ways, including specific investigations. Descriptive generalisations such as growth-form can be helpful (Figure 8).

Floodplain vegetation

Ecological range

The array of plants on floodplains includes species that are adapted to dry, almost terrestrial, conditions, to aquatic conditions, and to the various intermediate conditions. Words used in this guide to refer to these plants are given below:

Aquatic plants usually refers to those plants that are adapted to growing in, on or under water. Definitions vary, and while it is easy to agree that submerged species are aquatics, it is not always accepted that medium–tall sedges such as *Eleocharis acuta* and *E. dulcis* from intermittent or seasonal wetlands are aquatics. Aquatic plants may also be known as **water plants**, or **hydrophytes**.

Amphibious plants are those plants that grow or survive on wet exposed mud flats. These may be aquatic plants such as *Ludwigia peploides*, stranded by falling water levels, or a completely different type of plant, the semi-terrestrial ones that germinate and grow rapidly in these conditions (Figure 9).

Wetland plants are those found growing in a wetland. In wet–dry floodplains, they include amphibious and terrestrial and, arguably, also exotic species. The definition of wetland plants is probably the least precise of the definitions listed here.

Macrophyte means literally 'large plant', a name coined originally to distinguish these from microphytes such as phytoplankton. It is now used almost interchangeably with aquatic plants, and includes the stoneworts *Chara* and *Nitella* in the family Characeae because, even though these are algae, they have a herb-like form.

These terms, being difficult to define satisfactorily for all conditions and all plants, are flexible. When buying or using books to identify wetland and floodplain or aquatic plants, it is advisable to check the definitions being used. Only State or national floras are fully comprehensive.

The plants may be short- or long-lived perennials, biennials or short-lived annuals; they may be small or simple forms, such as duckweeds and charophytes, or large woody species, such as trees.

Temporal changes

On wet–dry floodplains, the changes that result from flooding and later from flood recession, provide a brief but distinct growing opportunity. Short-lived and dormant herbs and *forbs*, that is herbaceous plants other than grasses, grow quickly; rapid growth alters the appearance of a perennial community.

A lignum shrubland may have an understorey of short sedges, aquatic herbs or terrestrial grasses, depending on time since flooding, but is still a lignum shrubland. If, however, the lignum is removed, then what was the understorey now appears as a dynamic, constantly changing wetland plant community.

It would be a mistake to interpret all herb–forb wetland plant communities as the result of disturbance. The aquatic herbs that germinate or regrow on lagoon floors after flooding are a transient plant community; as the wetland dries out, the plants in this community die.

The lagoon floor is then colonised by opportunistic, amphibious then terrestrial species, and the previous community persists as propagules and seeds.

Structural diversity

The structure of a plant community is its three-dimensional organisation. Terms to describe vegetation structure come from both terrestrial and aquatic plant ecology, and both are necessary to describe the vegetation of floodplain wetlands. Simplistically, structure means the height, density and species composition for each vegetation layer.

Typical terrestrial growth-forms are trees, shrubs and tussock grasses. These give rise to vegetation types such as forests and woodlands, shrublands and perennial grasslands. Their vertical structure is very evident, being at the scale of the human observer.

Typical aquatic growth-forms are emergent macrophytes, which comprise mainly grasses, sedges and rushes; submerged macrophytes; floating-leafed plants and free-floating plants. These form distinctive grasslands, sedgelands and herblands. Their structure may be partly underwater, and is generally much less obvious to the human observer.

The range of structural vegetation types on a given floodplain is determined by its ecological diversity and by its location, whether tropical or temperate, coastal or inland. Vegetation structure is significant because it determines habitat for floodplain fauna, both above and below the water. Fauna respond to different vegetation attributes, depending on animal size and need (Note 9). Some species can be quite narrow in their requirements, which need to be carefully included. Structural diversity is high across floodplains because of the diversity of the plant communities, but is lower within each plant community.

Distribution of floodplain species

Many floodplain species have a fairly wide geographic range and so occur on more than one floodplain, but within a climatic range. Examples of species with a wide geographic range are river red gum *Eucalyptus camaldulensis*, and lignum *Muehlenbeckia florulenta*. Species composition of a floodplain is therefore not unique. Instead, there is considerable overlap between floodplains, especially those which are close or have similar soils and climate, or are in same ecoregion, or ecological region. An Australia-wide system of biogeographic regions has been developed. It is known as the Interim Biogeographic Regionalisation of Australia (see Web Listings section) and is the best guide presently available.

Some species have a restricted range or are confined to just one floodplain or catchment. An example of a floodplain tree with limited distribution is yapunyah *Eucalyptus ochrophloia*, which is found in north-western New South Wales and south-western Queensland (Note 10).

Wide geographic range is characteristic of many aquatic and wetland plants. Some occur across ecoregions, showing a temperature tolerance. Some are found across the Australian continent, such as *Typha domingensis*, which is naturally widespread, and *Typha orientalis*, which has a distribution that has been extended westwards across the continent since European settlement. A few native aquatic and wetland

Note 9
Vegetation structure as habitat

Plants are habitat that is exploited by different species, for different lengths of time, and for different reasons. The undersides of floating leaves may be grazed daily by molluscs; beds of submerged plants may become nursery areas for weeks; dense riparian shrubs may periodically become a velocity shelter for fish during floods; emergent macrophytes or lignum may be nesting sites in most years. The value of plants as habitat is contingent on the environment. For example, a study of darters, cormorants, herons and egrets on the Murrumbidgee River found that although these all nested in river red gums *Eucalyptus camaldulensis*, species differed in the type of tree chosen, and in how many species 'shared' a tree. Unlike other waterbirds, great cormorants nested in dead trees, probably because these were associated with a near-permanent water regime (Briggs et al. 1993). Consideration of vegetation as habitat needs to include not just living plants, but dead ones such as debris dams and snags.

species have an even wider geographic range. Species such as *Phragmites australis*, *Azolla filiculoides*, *Potamogeton crispus* and *Paspalum distichum* are found in both Northern and Southern Hemispheres: plants such as these with very wide distributions are called *cosmopolitan*. Many Australian aquatic and wetland species belong to genera that are widespread across Australia, and across the world. They include *Potamogeton*, *Eleocharis*, *Cyperus*, and *Myriophyllum*.

Species richness — the number of species per hectare of floodplain — is not particularly high on inland warm-temperate floodplains, especially when compared with wet heathlands or some terrestrial plant communities in Australia. Inland floodplains typically record 100–200 plant species overall. Species richness is apparently much higher in other floodplains, such as coastal floodplains of northern New South Wales where 70–100 aquatic macrophyte species alone have been recorded, and tropical floodplains where 200–300 species have been recorded. Species richness is much higher in disturbed and developed catchments, where it is boosted by non-native species, mostly agricultural weeds or escapees: these may be as much as 20–30% of the total species count.

Description

The formal description of plant communities should include some detail on floristics, structure, abundance and even comments on vigour. To date it has been a common practice to refer to floodplain communities in a short-hand form, by their dominant species and its growth-form; for example, lignum shrublands, black box woodlands, red gum forests, cane grass grasslands.

These 'species + growth-form' descriptions are useful but limited: 'species + growth-form' is an incomplete description of a plant community, as it gives no information on species other than the dominant one and little information on structure.

Note 10
Biogeography of water plants

For water plants, the greatest floristic differences across Australia are between temperate and tropical regions. This is true at the level of species, genus and family. In a given region, there are nearly twice as many monocot species as dicot species, 50–70% compared with 24–41%; ferns are usually poorly represented with only about 5% of all waterplant species. Endemism, that is the number of species restricted to a region, is generally low in south-eastern and temperate Australia (1–5% of waterplant species), is marginally higher in tropical regions (approximately 8%). Endemism is quite significant in the south-west of Western Australia and in New Zealand (38–44%). For more, see original scientific paper by Jacobs and Wilson (1995).

Ecological groups

Ecological groups are a means of reducing bulky amounts of information about species. Such groups, even if they are only approximate and are based on incomplete science, can still serve, to a limited extent, as a rough 'model' (a guide to) of species behaviour or response. Ecological groups can be based on observations, assumptions, or measurements, and are typically a mixture of all three. Two types of ecological groups relevant to water management and to understanding wetland plants are growth-forms and plant functional types, or PFTs.

Aquatic growth-forms

Some understanding of how well plants are adapted to aquatic conditions can be inferred from their growth-form.

Plants with comparable *morphology*, or shape, are said to have the same growth-form. For aquatic and wetland plants, growth-form indicates, very roughly, the position of roots and leaves relative to water level, and to sediment. Growth-form is therefore a useful first approximation of adaptation to the aquatic environment and, being based on visual information, is easy to apply (Note 11).

Note 11
Growth-forms

Field guides to wetland plants emphasise visual cues, so tend to use growth-form as part of the identifying characteristics. Growth-form is usually combined with other characteristics, often expressed in plain English; for example, growth-form and leaf shape "submerged, not feathery" is used by Sainty and Jacobs (1994). See Hutchinson (1975) for an introduction to historical terminology and the source of technical words such as hydrophytes and macrophytes.

For a description of terrestrial growth-forms current in Australia, see Walker and Hopkins (1990).

However, growth-form does not make perfect predictions about how a group of species responds to water regime. This is because growth-form is not a complete summary of all adaptations, nor do all species with the same growth-form have the same adaptations. Growth-form refers to only one phase in the life cycle, the established adult, and to just one part of a plant's environment, namely water level. Conventional descriptions of growth-form do not cover amphibious or mudflat species very well.

Figure 8. Structural diversity

In wet seasons, floodwaters spread into rarely-flooded areas where the species of macrophytes that develop are influenced by the season of flooding. Autumn flooding on the Murrumbidgee floodplain has produced a sparse cover of *Marsilea drummondii*, *Triglochin dubium*, *Rumex* and unidentified grasses. Nearby (not shown) was dense continuous growth of *Eleocharis acuta* in shallow ponded water; in deeper water, dense beds of Characeae and *Damasonium minus* with abundant shield shrimps, *Notostraca*. Delta Creek, May 1990.

Although widely used in scientific and general literature, there is no standard set of names for growth-forms. This is not as frustrating as it sounds, because modern practice is to use descriptions such as free-floating or floating-leafed plant, rather than classical terminology (Note 11). In the past, scientists struggled to develop an all-encompassing set of names to describe all aquatic and some amphibious growth-forms. This resulted in a plethora of quasi-technical terms in the scientific literature of up to about 25 years ago. A few, such as *hydrophyte* and *macrophyte*, remain current. A limited number of conventional aquatic growth-forms is used in this guide (Figure 9).

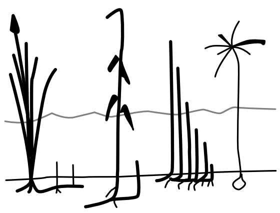
Plant functional types

Plant functional types (PFT) are groups of plants with a similar response or responses to one or a range of specific environmental conditions, such as resource availability or disturbance. Responses are a set of traits. The traits may be measurements, such as biomass, seed size or specific leaf area, or may be based on published knowledge, such as whether a plant is a C-3 or a C-4 species. The choice of these traits assumes they are representative of, or correlate with, ecological characteristics such as competitiveness, seedbank longevity or relative growth rate. Alternatively, traits may be empirically defined through experiments; for example, by germinating or growing a number of species under

Figure 9. Aquatic growth-forms

Text gives a general description, with notes on adaptations and some examples. Diagrams are drawn to different scales, (*) indicates an introduced species.

EMERGENT MACROPHYTES – erect forms



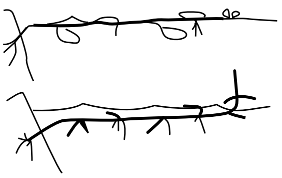
Rooted in sediment, leaves growing through water, into air. Size ranges from tall >1 m, medium to small. C-3 and C-4 species. Forms with leaf blades have high surface area, often very productive. Tall forms often dominant.

Can grow in permanent water, but tolerant of periodic temporary dry conditions or deeper water. Rhizome and rhizosphere oxygenated from leaves.

Tall and medium forms are mainly perennials. Most perennials have substantial underground carbohydrate storage, usually rhizomes but sometimes as corms or tubers.

Monocots, mostly from Cyperaceae or Poaceae. Examples of species are *Typha*, *Phragmites*, *Eleocharis*, *Cyperus*, *Baumea*, *Bolboschoenus*, *Juncus*.

EMERGENT MACROPHYTES – trailing forms



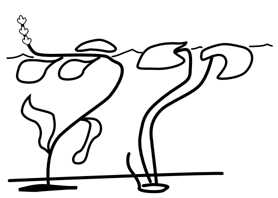
Rooted at channel edge or bank. Leaves on water or slightly rising above surface, from floating stems or stolons. Trail downstream in low-velocity current.

Buoyancy mechanisms for stems not always evident but can include inflated hollow stems, spongy tissues. Stems flexible, not rigid, so move easily with small changes in water level or waves.

Many species have rootlets at nodes, some species can establish from fragments with these.

Examples: *Ludwigia peploides*, *Rumex bidens* (*), *Nymphoides* spp., also several grasses with prostrate-ascending stems, eg. *Pseudoraphis spinescens*.

FLOATING-LEAFED MACROPHYTES – trailing forms



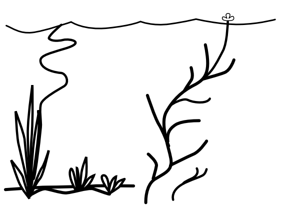
Rooted in sediment, leaves floating on water surface. Floating leaf typically rounded or oval, glossy above, and may become more erect when leaves are crowded. Some species have, initially, submerged leaves.

Grow in or near permanent water, to 2 m sometimes 3 m, depth range defined by length of stem or petiole. Stems have lacunae, and/or aerenchyma, to facilitate internal movement of gases.

Mainly perennials. Rhizome may be compact at stem base, or bulky and extensive.

Species in the family Nymphaceae, also *Ottelia ovalifolia*, *Brasenia schreberi*, *Potamogeton tricarinatus*, *Marsilea* spp., *Villarsia reniformis*, *Nelumbo nucifera*.

SUBMERGED MACROPHYTE



Rooted in sediment, and grow submerged in water, <0.5 to several metres deep. Leaves variable, being strap-like, linear or dissected, usually thin, near-transparent. Root systems often shallow, flowering stems delicate. Stems with lacunae, aid gas movement, give buoyancy.

Depth range depends on water clarity. Use either CO_2, or CO_2 and HCO_3.

Perennials and annuals. Rhizomes and stolons typically slender. Pollination is at surface, so depth limits distribution of flowering plants. Extends to deeper water by vegetative expansion.

Characeae and Najadaceae. Species include *Vallisneria* spp., *Hydrilla verticillata*, submerged *Myriophyllum* spp., submerged *Potamogeton* spp., and carnivorous *Utricularia* spp.

FREE-FLOATING MACROPHYTE

Plants floating on water surface, leaves in air, root or rootlets dangling in water.

Fast growth rate and large populations can build up rapidly. Plants easily moved and concentrations can build up down-wind or be carried by current.

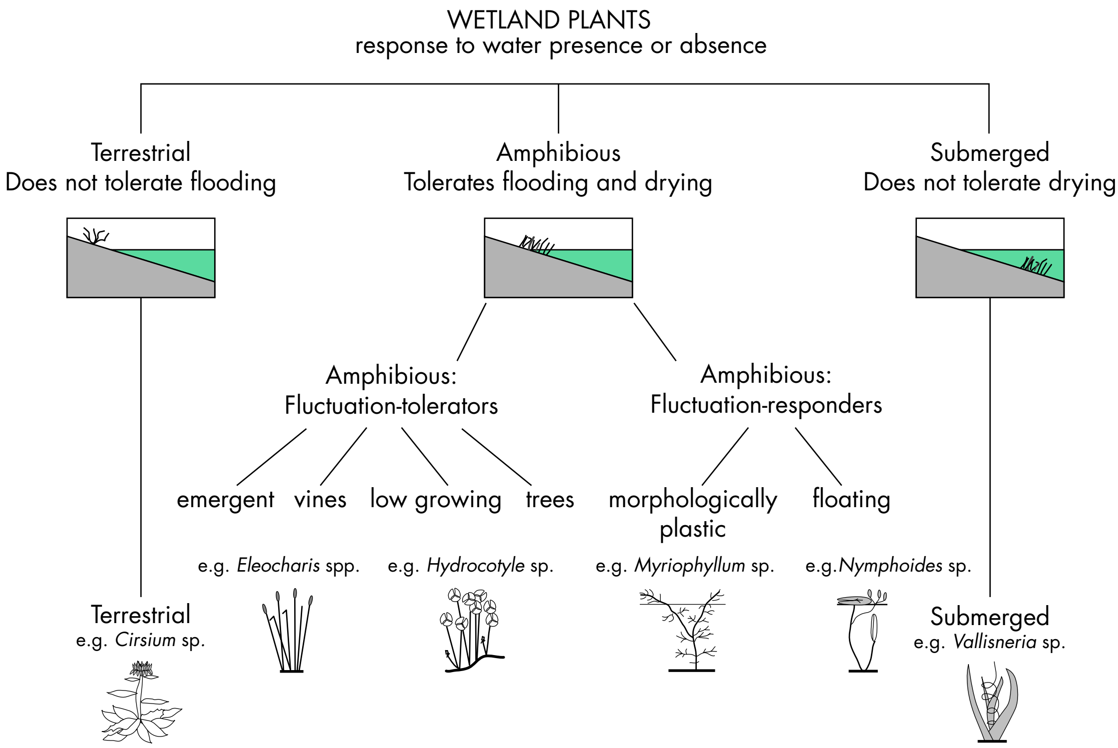
Includes ferns and some economically significant weed species such as *Eichhornia crassipes* (*), *Salvina molesta* (*). Native species are *Azolla*, spp., duckweeds in Lemnaceae, *Pistia stratiotes*.

identical conditions. PFTs differ from growth-form in that they focus on assumed or observed responses.

PFTs can be used in models of vegetation change. This is an attractive approach because it is a way of reducing the enormous complexity of modelling species individually to a few recurrent patterns. PFTs have yet to be used in modelling dynamics of floodplain vegetation. This will require putting species into functional groups based on their responses to flooding and drying, and to changes in water regime. The system of PFTs developed for wetland plants (Figure 10 and Note 12) is relevant, at least to part of floodplain wetlands; no PFTs have yet been worked out that include both floodplain and wetland species.

Figure 10. Wetland plant functional types

Seven plant functional types identified from 60 wetland plant species, on lagoons on the New England Tablelands (diagram supplied by M. Brock, 1999).



Plant water regime

The water regime of a floodplain wetland is its characteristic pattern of flooding, drying or water-level changes. These changes can be described in terms of when water level changes occur, how much, how fast and for how long (Figure 5). For plants, water regime is also the pattern of flooding, drying or water-level changes but it refers to the specific patterns needed to ensure species *maintenance* and *regeneration*.

- **A maintenance water regime**, as used here, is the water regime needed by an established mature plant to survive in the long-term; that is to grow and to periodically flower, and also to set seed at intervals that ensure the population seedbank or propagule bank is maintained.

- **A regeneration water regime** is one that ensures periodic establishment or re-establishment of plants, whether from seed or from other propagules. If from seed, then the regeneration water regime must satisfy conditions for seed germination followed by successful seedling establishment; if from propagules, then there are similar requirements for initial or follow-on conditions, although these may be subtly different.

Maintenance and regeneration requirements are usually quite different. The environmental conditions required for germination, or for survival of a seedling, are not the same as those required by the adult plant. For example, many emergent macrophytes germinate on wet muds, comparable to drawdown conditions; only some have seedlings that can tolerate submergence. Shallow water is likely to be detrimental, at least until the plant reaches a critical stage: in contrast, adult plants can tolerate water depths ranging from 0 to about 1.5 metres.

Components of plant water regime

Water regime refers to the hydrograph shape and size, and the pattern of hydrographs through time. Size and shape characteristics are correlated under natural conditions, but this can change once a river is regulated or its flow regime modified. Describing a hydrograph shape and the pattern of hydrographs through time in terms of its components is useful, in terms of clarifying plant responses. Seven components can be recognised (see below): of these, the most frequently studied are depth and frequency.

Depth:The importance of depth and the effects of changing depth are very much dependent on species growth-form and size. Plants with rigid or erect aerial leaves, such as emergent macrophytes, seedlings and tussock grasses, can grow in water to a certain depth, depending on their height or size. Equally, they can tolerate an increase in water depth, provided a reasonable proportion of the canopy or stem is not submerged, otherwise they become stressed or may even die (Note 13). Thus, although depth is measured in absolute terms, in millimetres or metres, the ecological effect on these plants depends on the size of the species in question. Floating-leafed plants with flexible petioles can grow in water up to two metres deep, depending on how effectively the rhizome is ventilated from the leaf, and can tolerate fluctuations in water level, roughly of 10–20 cm, such as caused by wind-induced waves. Free-floating and submerged forms are not greatly affected by increases in depth, unless this causes a reduction in light.

Duration of inundation: Duration refers to the time that *surface water* is present, measured in weeks or months. Duration is important for obligate aquatics as it defines the potential growing period for adults, including flowering and seed-set or storage, or the time frame for germination and seed-set if an annual. For facultative aquatics or those tolerant of mud-flats, conditions may be favourable for growth even after there is no more surface water, for as long as the soils remain waterlogged or moist. For floodplain species, duration of flooding defines the period when soil water is recharged by infiltration.

Season of flooding: Season, or timing, here refers to when flooding begins. Season is significant because it is a short-hand way to refer to a combination of climatic factors that affects plants: temperature, day-length, and whether day-length is increasing or decreasing.Temperature determines the rate of physiological processes, evident as growth;

Note 12
PFTs on Tableland lagoons

The first Australian study of wetland PFTs was done on isolated lagoons on the New England Tablelands. Seven PFTs were defined in terms of their response to water regime (Brock and Casanova 1997).

These seven PFTs were empirically determined by a combination of experiment and observation of 60 wetland plants. The lagoons have variable water levels and an intermittent water regime, and the littoral zone, being periodically exposed and submerged, means these lagoons are a variable and unpredictable environment in which to grow and the complete plant life cycle.

Several of the 60 species used in this study are also found on inland floodplains, but dominant floodplain species are not included.

An alternative system of wetland PFTs has been developed in North America but not yet applied in Australia. This recognises three main plant types: ruderal, matrix, and interstitial: it is useful for disturbance rather than water regime (Boutin and Keddy 1993).

Note 13
Changes in depth

Some herbaceous non-woody species with aerial leaves show a surprisingly quick response to increases in water depth. The stem carrying the leaf, or the leaf itself, grows rapidly to the surface. For example, the rhizomatous fern, *Marsilea mutica*, can grow through 10 cm water to reach the air overnight, and through 100 cm in about 6 days (Yen and Myerscough 1989).

Response to increased depth tends to be slower in emergent macrophytes such as *Baumea arthrophylla*, *Bolboschoenus medianus*, and *Typha orientalis*, and for these, increases in depth typically result in a change in resource allocation, indicated by how much of plant biomass is root, rhizome and canopy. This represents a shift in the importance of nutrient uptake, storage and photosynthesis, and hence a shift in growth strategy (eg. Rae and Ganf 1994, Froend and McComb 1994, Blanch et al. 1999).

Amphibious plants, such as the milfoil *Myriophyllum variifolium*, have developed morphological plasticity for the wet–dry littoral zone (Brock 1991, Casanova and Brock 1991).

temperature can limit germination, as some species have germination temperature thresholds. Day-length determines the energy available for photosynthesis. Some species have specific day-length and/or temperature requirements or tolerances, and may be winter-growers or summer-growers. For long-lived woody species, such as riparian trees (eg. black box *Eucalyptus largiflorens*) season of flooding may be more important for flowering than for leaf growth. Responses to climate is a species-specific response, and is not linked to growth-form, as the example for two emergent macrophytes shows (Note 14).

Rate of rise: Rapid increases in water-level may submerge emergent and floating-leafed aquatic plants unless they can grow or extend fast enough to keep the leaf or the photosynthetic stem, known as a *culm*, in the aerial environment (Note 13).

Frequency: Frequency is the number of times flooding occurs. Annual and short-lived aquatic plants (ie. those living for less than one year) are generally flooded only once in a life-span; perennial aquatic and woody floodplain species may be flooded several times, ranging from once or even twice per year to once every five to seven years, or even less often. For these, frequency is a long-term average (which does not account for variability). Flooding can be the stimulus or opportunity to flower and set seed; thus flooding at a critical frequency is essential for species dependent on the seedbank to maintain their presence. In the absence of flooding, a seedbank ages and propagules lose viability. For perennials, flooding is typically the time when resource constraints are lifted: plants can replenish their reserves, flower and so recharge the seedbank. Frequency thus influences population long-term vigour and hence survival.

Inter-flood interval: The inter-flood interval is the period without flooding. The length and recurrence of this is most relevant to those plants that maintain a low level of growth in the absence of flooding, such as perennials on the higher and drier parts of floodplains. Here, the inter-flood interval can be a period of water stress, so its duration and recurrence and timing will affect long-term vigour. Perennial species survive this period through water-conserving mechanisms. On inland floodplains, trees (and possibly shrubs, though this has not been determined) are opportunistic water-users, and can utilise other water sources, such as heavy rainstorms and groundwater, if and when these are available.

Variability: Variability refers to the regularity or range of values for any of the components of water regime, although is more usually reserved for flood frequency.

Important components

The relative importance of these seven components for a particular plant species or group of species has not been determined, and would require a complex experiment to disentangle. As a rule of thumb, it is suggested that depth, duration, and season are most important at an annual time scale, but that frequency, inter-flood interval and variability (or its converse, regularity) are most important over longer time-scales.

Unlike in rivers, velocity is not an important component of the water regime for plants of floodplain wetlands. This is because velocity on floodplains, consistent with their being depositional areas, is generally much slower than in the main river channel, even during floods. In-channel habitat does occur on some floodplains, and these flowpaths may have a fringe of emergent and trailing plants on their banks. High velocity channels may acquire characteristics and species more typical of river channels.

Although it is not an important component of water regime for plants, velocity is nonetheless significant on the floodplain, especially those floodplains that have been cleared or where channel bed has *degraded*, ie. become cut down, as the result of channel erosion. For these, the relationship between flow and inundated area (Section 6 and Figure 23) has changed. Flowpaths are generally only a small fraction of a floodplain wetland, usually too small to be recognised within a whole floodplain management plan, except by hydraulic modelling.

The effects of changing water regime

The effect on the vegetation of changing one or more components in a water regime depends on which components are altered, and what species are present.

If water regime changes from intermittent to near permanent (Figure 5), the increase in flood frequency or flood duration means soils may not return to their earlier aerobic condition, resulting in soil waterlogging and deoxygenation. This is an opportunity for invasive plants tolerant of wetter conditions, or for plants requiring a wet sequence to germinate and establish. However, these conditions cause stress or even death for perennial species reliant on soil oxygen.

If an area is flooded less often and/or for shorter periods, ie. the water regime changes from seasonal to intermittent (Figure 5), then soils will tend to dry out. This will result in widespread water stress or localised death of perennial floodplain plants that are intolerant of drought or not adapted to dry conditions, and the expansion of terrestrial annuals and other opportunistic species.

If season of flooding changes from winter to summer, as on many regulated rivers, then a species shift to summer-growers can be expected.

The consequences of increasing or decreasing one or two components can be anticipated from the frequency–duration grouping of water regimes (Figure 5). Shifting from near permanent to permanent is less of an ecological change than shifting from episodic brief to near permanent, although a change nonetheless. Changing the season of flooding or of draw-down is not covered in the frequency–duration diagram, but can be expected to lead to a major change on plant species.

Changes which cause a loss of vigour in one species may favour another. Such a change can be an opportunity for exotic species to establish. If exotic species are the focus of a water management plan, it will be necessary to establish that water regime is the sole factor contributing to its establishment and persistence. Establishment may be encouraged by repeated disturbance, such as cattle trampling, or by preferential grazing, and persistence may be the result of a long-lived seedbank.

Restoring an original water regime is not a guarantee that the exotic plant species will disappear.

Note 14
Seasonality

The ecological consequences of changing seasonal patterns in flow regime have not received as much attention as, for example, flooding frequency.

Not only can changes in seasonality lead to changes in species composition, but to structural changes. For example, native aquatic grasslands are being invaded by the dominant tree species in the Barmah Forest (Bren 1992) as a result of seasonal changes.

Species seasonal responses, whether for maintenance or regeneration, cannot be anticipated from ecological types such as growth-forms or PFTs, so must be determined from the literature or through special studies. For example, contemporary studies of two emergent macrophytes done in the same locality found that, for *Typha orientalis*, the main period of canopy development was August to December with biomass peaking in December–January, whereas for *Phragmites australis*, it was spring–summer, August to March with biomass peaking in March–April, (Hocking 1989, Roberts and Ganf 1986).

For an experimental study of the importance of season of flooding, see Nielsen and Chick (1997) and Britton and Brock (1994) on seedbanks.

Focusing on depth

Water regime analysis needs to consider all components of plant water regime. A limitation of most field investigations is their emphasis on just one, sometimes two, components, with the assumption that other components have not changed. Flood frequency is often chosen, probably because it is easily quantified by inundation mapping and hydrologic modelling, but it is only one of seven components.

With floodplain wetlands, the sheer size and diversity of the floodplain area presents particular challenges. Unlike small, isolated waterbodies where frequency, magnitude and duration of flooding are relatively uniform or tightly correlated, water regime is not uniform across the floodplain; thus, statistics based on spatial averages may not be meaningful. Ideally, flood frequency and duration, and other components of plant water regime, should be estimated for hydrologically homogeneous sub-units of the floodplain wetland. However, this could result in working with numerous, very small management sub-units, making modelling an impossibility. Typically, these sub-units are aggregated and larger spatial units such as plant communities are considered.

An alternative is to reinterpret plant water regime as spatial and temporal variations of just one component — depth — by working with three states:

- inundated and submerged;
- inundated, but not submerged; and
- not inundated.

In this way, plant water regime can be modelled as a time series of these three states. For each state, key statistics are the mean duration and the variability of the duration. Other useful statistics are the mean and variability of the period between the occurrence of a given state, and the seasonal occurrence of the three different states.

Focusing on depth represents an ideal, targeted at developing models. Even if modelling is not the aim, focusing on depth is one way to reduce complexity and make it easier to work with water regime.

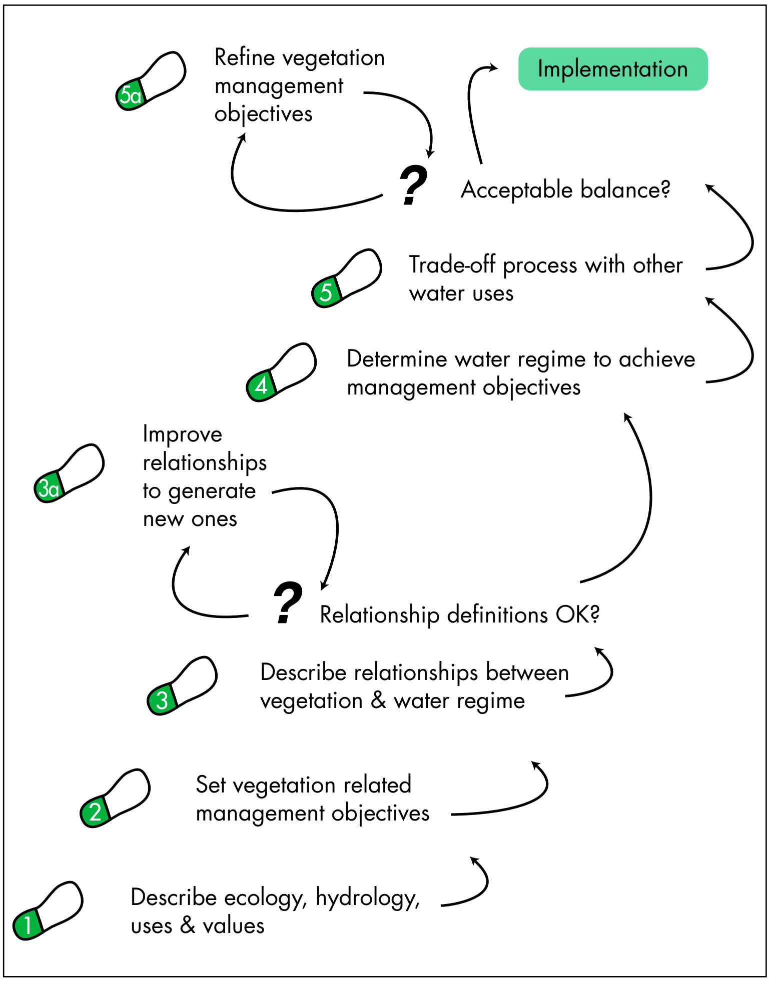
Section 3: A Step-wise Procedure

The process for determining the water requirements for plants of floodplain wetlands can appear complicated and even circular to those involved in the process, but in fact it follows a series of well-defined steps. These steps are similar regardless of political process or which floodplain wetland is being considered. This section describes the five steps in this general procedure. Only Steps 3 and 4, both purely biophysical, are treated in detail here.

Outline

The general procedure comprises five steps (Figure 11) which should be followed in every investigation.

Figure 11. Flow chart showing five steps for determining the water requirements of floodplain wetlands plants



Note 15
Internet data

Environmental data are available from Internet sites such as Long Paddock and Bureau of Meteorology for weather records, Bureau of Rural Science for soil maps — particularly in the Murray–Darling Basin, and AUSLIG for satellite imagery. Full details are given in the Web Listings.

Note 16
Historical data

Historical information can have a special role. It is an opportunity for interested individuals or groups to contribute. However, historical information is generally sparse, difficult to find, rarely quantitative and sometimes of doubtful technical quality. Because of this, historical projects may need different management and clear goals.

Historical studies may contribute in three ways.

One: as data, contributing information and helping to fill gaps in the scientific record. This can extend understanding beyond what is known by the investigators. An example is compiling past flood histories, as done on the Darling Anabranch (Withers 1994).

Two: an understanding of what has happened, especially in terms of past land uses, can help explain some environmental and vegetation patchiness and anomalies. This will affect sampling design, improving it and interpretation.

Three: in highly modified floodplain wetlands, knowing the past condition can help clarify management goals, as happened at the Moira Lakes and on parts of the Lachlan River (Roberts and Sainty, in press).

The data, tools and techniques used in each step will vary from one floodplain plan to another, depending on circumstances such as opportunities and constraints. For example, time and resource constraints will vary between investigations, as will the extent and usefulness of existing data.

This general procedure makes only two assumptions: one, that the management objectives relate in some way to the vegetation, whether it is abundance, character or condition; and two, that these measures of vegetation (abundance, character and condition) are dependent to some degree on the water regime of the floodplain wetland.The degree to which this dependency — or relationship — is describable will vary.

Thus, the main variations in the general procedure are in the tools and techniques used in acquiring and analysing vegetation and water regime data (Step 3), and in the tools and techniques used in predicting vegetation response to water regime changes (Step 4).It is these two steps that this guide addresses.

Step 1: Describing the floodplain wetland

The first step is to describe the floodplain wetland using only available data and information.

'Description' here means the floodplain wetland's water balance, its ecology, especially as this relates to floodplain vegetation, and its uses and values.These data will be in a range of formats — as reports, as electronic data, as maps and on the Web (Note 15). Collection of new data may be required later in the process, once management objectives are made clear, and once gaps in knowledge gaps have been identified.

Information on the most important component of plant–water regime, the spatial and temporal variation in water depth, is rarely available or is quite limited.At this stage, description is likely to focus on the water balance of the floodplain wetland. Information useful for describing all six components of the water balance is described above (Section 1): local climate, surface and groundwater flow, and plant water-use or evapotranspiration data. In addition, information on wetland soils can be of use in quantifying the water regime.Typically, however, the hydrology data that are directly available will be limited to, for example, relatively short records for one or two components, or to particular flood events.

Information useful for describing floodplain wetland vegetation includes vegetation or land-use maps, aerial photographs and satellite images. Historical information has a particular role (Note 16) and may be useful in describing species response and changes in plant communities.The value of historical information depends on knowing its context, ie. its date and location, so that the contemporary weather and/or flooding conditions can be established, and its locality. Detailed information, such as vegetation transects, ground cover and understorey species in forest and woodland areas, may be available from agency or station records; although this can be extremely useful, it is seldom available at the start of an investigation.Vegetation data are usually patchy, and maps are scarce, and may be out of date. Despite these drawbacks, what is available may be adequate to set management goals, as in Step 2. Most of what is needed in Steps 3 will have to be specifically collected.

All the uses and values that relate in some way to the vegetation of the floodplain wetland must be identified: conservation, environmental protection, grazing, recreation, and tourism. These uses and values may be linked to specific types of land tenure, whether private or public. Conservation values may be associated with the protection of endangered or threatened species, or with certain features of the vegetation for habitat. Recreation may be water-based (for example, canoeing) or nature-based, such as bird watching. Grazing may be associated with one particular plant community or even species. Collating such information will provide an understanding of the character, function and values of the floodplain wetland under consideration.

Step 2: Setting management objectives

The second step is to set the management objectives specific to floodplain vegetation.

Early in an investigation a statement of the vegetation-related management objectives must be attempted. These will be a sub-set of the complete set of management objectives. They are not limited to the environmental objectives, but include objectives relating to any productive or economic uses that depend on the vegetation or its condition, eg. floodplain grazing and honey or timber production (Note 17).

These objectives should be stated as quantitatively as possible. This can be done by identifying appropriate vegetation measures, and setting target values for these measures. Abundance, character, and condition of vegetation must be related to wetland water regime (Step 3). Examples of such measures are the area of each plant community, specific mix of plant community types (eg. grassland, shrubland, and woodland), species diversity in different plant communities, balance of native and introduced species, and the condition of a particular community or species. Surrogate measures may also be useful: these are measures which provide an indirect indication of the attribute of interest. An example of a surrogate measure is using the condition of a species to indicate the condition of an entire plant community. To be useful in an ongoing management sense, all measures need to be amenable to monitoring, so it is possible to assess how well management objectives are being met.

As overlaps between competing objectives become apparent, it will be necessary to make trade-offs between objectives. Where possible these conflicts should be resolved as early as possible. The conflicts may emerge only once vegetation–hydrology relationships are considered.

It is likely that management objectives will be refined later in the process, either as the appropriate measures relating to water are changed (Step 3), or if a trade-off process shows the target values of these measures to be unrealistic (Step 5). Management objectives may evolve following implementation and review of a changed water management regime, as a part of an adaptive approach to resource management.

Note 17
Setting targets

Water regime targets can be set quite simply, as in a restoration program: return the water regime to its original condition, or as close as possible. Other vegetation targets can be set, through a community consultative process, and the water regime needed to reach these can be identified by simulation modelling. This path assumes that species response to water regime is well enough understood. In both cases, it is necessary to ensure that water regime is the main factor affecting vegetation of the floodplain wetland. Examples of other factors that might come into play are: a depleted seedbank; when poor tree condition is the result of pathogens rather than water regime; if groundwater conditions have changed.

Step 3: Vegetation–hydrology relationships

The third step, and one which is central to this guide, is building a vegetation–hydrology relationship.

The basis for estimating the water requirements of floodplain wetland vegetation must always be some degree of understanding of the relationships between the condition of each of the plant communities and its water regime. The better the understanding, the greater the ability to predict, with confidence, the likely vegetation outcomes of water regime manipulation. The understanding needed to define these relationships may come from prior investigations and existing data for the floodplain wetland under consideration, or from investigations of other floodplain wetlands with similar climate, hydrology and vegetation (Note 18 and Section 4: The evaluation process). In most such investigations, extra effort will be needed to improve the understanding of these relationships (Step 3a). Just how much effort will be expended depends on resources available, economic values in question, and the quality of the relationship. Vegetation–hydrology relationships are the basis for modelling the changing status of the vegetation as a result of a water regime change (Step 4).

The type of information available on vegetation–hydrology relationships will help to determine which measures to use for management objectives. This is because these objectives are best couched in terms of measures that can, in some way, be predicted.

Vegetation–hydrology relationships may start — and often do — with descriptions of the 'natural' (ie. pre-European) or 'pre-disturbance' vegetation and hydrology, and descriptions of the current vegetation and hydrology. These data usually provide only an empirical relationship. Interpretation of this may be confused by concurrent changes in land use, such as grazing, recreation, or forestry operations; all these can affect species composition, vegetation structure and density. There are seven components of water regime from a plant perspective (Section 2). Determining which of these is dominating the vegetation response, or is the most influential at a particular locality, can be difficult when only limited data are available.

Measures of health or condition have not been well-linked to specific environmental stressors, such as altered components of the water regime, and some are difficult and resource-intensive to monitor. There is a danger that relying on simple measures could lead to a minimalist approach. An example might be using presence–absence as the only measure of vegetation response, either at the level of species or plant community. Although presence–absence data can be integrated at a higher level as frequency data, this approximates abundance, and does not address character or condition. More detailed spatial measures are needed where there is a mosaic of species or communities. These may establish tolerance ranges (Note 18) of different species or plant communities to individual components of plant water regime, and help define curvilinear functions describing species response. Such responses can be used to develop statistical models of species distribution, and contribute to modelling.

A reasonable amount is known about the water regime tolerated by several common or widespread plant species in some regions (Note

18), but 'tolerance' can be interpreted in a variety of ways, and does not imply a specific plant response. Using this type of information in a predictive way is therefore difficult.

If no quantitative data are available, and no relevant scientific or technical information on a species or a community can be found, and it is not possible to conduct experiments, then expert opinion (usually based on experiences from other wetlands or on broad general ecological knowledge) and anecdotal information will be used.

Typically, existing knowledge of vegetation–hydrology relationships will be inadequate for the study area, and new, or refined, relationships will be needed: this is Step 3a (Figure 11). These new hydrological data will describe the spatial and temporal variations in water regime, at an appropriate scale, and new vegetation data will describe the spatial and temporal variations in the vegetation, also at an appropriate scale. There will also be a role for more intensive studies, including focused experiments to link cause and effect, or to establish interactive effects (Section 4: Options for new information, Section 5: Special studies).

Note 18
Species information

A reasonable amount is known about tolerance ranges for some species in some regions, although this has rarely been collated. Tolerance ranges, if that is the only information available, should be used with caution: tolerance refers to a range of conditions, which may include conditions which are marginal for a species rather than optimal. A summary of current knowledge of the water regime requirements for selected plant species in the Murray–Darling Basin has been compiled from literature and other sources (Roberts and Marston 1999).

Step 4: Determining the required water regime

4 In this step, the water regime required to meet the pre-determined management targets is established. This involves using the vegetation–hydrology relationships to predict likely vegetation condition, across the floodplain wetland if possible, given a changed water regime.

Predictions may be simple or complex. An example of a simple prediction is 'moving closer to the natural water regime will move the vegetation closer to the desired state (with all the inherent assumptions of a restoration program). An example of a complex prediction is a set of numerical simulations using climate-driven hydrology models, or even floodplain hydraulics models (Section 7), and dynamic vegetation response models. It is more likely, however, that the approach to predictions will lie somewhere between these two extremes, such as in hydrology simulations. These can drive static models of vegetation response, thus capturing the inherent variability in the hydrologic regime, but without modelling the population dynamics or other stochastic processes inherent in plant community responses. Clearly, predictions should be made in terms of the adopted vegetation measures, thus ensuring the links to the stated management objectives and to ongoing monitoring.

Where the predictions are based on numerical calculations, unless an optimising model is developed, the determination of the required water regime to meet target values usually involves some trial and error. Given the limited understanding of vegetation–hydrology relationships, and hence their usually simplistic empirical form, optimising modelling is seldom appropriate, and simulation modelling is usually relied upon.

Simulation modelling takes account of the temporal variations in hydrology and vegetation response, and may also consider aspects of spatial variability. To adequately capture temporal variability, the choice of simulation time-step is important (Note 19). What is appropriate depends on the time scales at which responses (in terms of the selected

Note 19
Modelling and time-steps

In some situations the only flow data available may be aggregated weekly or monthly discharge. This is unlikely to be adequate for those hydrological simulations which require accurate predictions of flow volumes entering floodplain wetlands, such as commence-to-flow levels (CTFs) (Note 32 Determining CTFs). While it can be very difficult and time-consuming to calibrate daily flow models on lowland rivers, the improved accuracy allows greater confidence and involvement from those affected by changing river flow patterns. Consequently, the task of identifying and exploring possible trade-offs becomes much easier.

vegetation measures) are expected to occur and upon data availability. For those floodplain wetlands with water regimes which are sensitive to daily changes in river flow levels (such as on confined floodplains), simulations of river hydrology at daily intervals will be required to accurately predict surface inflows. Because limited knowledge determines that assumed vegetation–hydrology relationships are typically simple, simulation of wetland vegetation responses will usually be done at monthly, seasonal, or even annual intervals, particularly for terminal floodplain wetlands.

Floodplain wetlands that are particularly dissected (Figure 2: braided) may require special efforts because wetland water regime is spatially variable, and the vegetation appears patchy. Descriptions of these spatial variations will be needed to predict specific vegetation measures. Similarly, simulations of these spatial variations in water regime and vegetation response will be required. All this will be difficult without a *geographical information system* (GIS). Spatial representations may be based on a regular or irregular grid, or on polygons defined on hydrologic or vegetation attributes. In the case of a grid, the resolution should relate to the resolution of spatial data to be represented, and the resolution required in predicted measures.

Spatial simulation of the water regime may be limited to water balance calculations, for a number of hydrologically homogeneous elements. If accurate predictions of water depth are required, a topographic representation of the floodplain will be required. The most appropriate is a *digital elevation model* (DEM). If surface flow velocities differ greatly from one flood event to the next, or from one part of the floodplain to another, then a full hydraulic representation will be required. Hydraulic simulations are data intensive and numerically complex. In addition to representations of the surface topography, values of surface roughness, for example Manning's *n* (Section 6 and Note 33), will be required. Surface roughness is usually highly variable, spatially and temporally.

Step 5: The trade-off process

5

The fifth step is resolving trade-offs with elements outside the floodplain wetland, ie. with other water users. This step is contingent upon achieving a quantitative description of which water regimes will be needed in the river and on the floodplain wetland to achieve the management objectives specific to the vegetation.

Trade-offs are needed when there are competing interests for the water upon which the condition of the floodplain wetland depends. Usually, floodplain wetlands are dependent on riverine flooding. River regulation and/or upstream water extraction, for whatever purpose, will alter the water regime in floodplain wetlands. This external trade-off is distinct from, and occurs well after, internal trade-offs between competing uses: eg. the ideal water regime for grazing of floodplain wetlands may differ substantially from the ideal water regime for wetland conservation. The internal trade-offs that were determined in Step 2 of the procedure, where management objectives were specified, should have been resolved by this stage. The management objectives should, as far as possible, reflect the agreed balance of wetland uses. Some conflicts may become apparent only after vegetation–hydrology relationships are investigated in detail, and so iterations through Steps 2 and 3 may be necessary.

External trade-offs should consider the costs and benefits associated with the floodplain wetland and with other water uses in the same water management system, which is typically a catchment. As there will always be implications, it can be difficult to express all the costs and benefits in equivalent terms — such as monetary units, so the trade-off process is unlikely to be a simple economic analysis. Resolving trade-offs is usually time-consuming, involving community and industry groups, and local and State government representatives. A description of these activities is beyond the scope of this guide.

Section 4: Old and New Data

One of the first decisions is whether to use existing vegetation–hydrology relationships, or to develop new ones. An assumption of this guide is that existing hydrological data are likely to be adequate, so the question is how to use and improve the water regime available. However, it is likely that there will be few useful vegetation data so these will have to be collected. This section discusses evaluating existing knowledge, then outlines options for developing new relationships, based on field studies. Special studies and experimental research have a definite role, which tends to be overlooked.

The evaluation process

Deciding on the value and quality of existing information about plants and about vegetation–hydrology relationships can be frustrating. It is likely that what was thought to be irrelevant may later prove valuable; conversely, what was thought to be useful may turn out not to be so. It is mainly by working with information that its value and quality become apparent. Some advisory pointers are given below.

Even if robust quantitative information can be located for all key plant species, which experience suggests is highly unlikely, site-specific investigations will still be needed on floodplain hydrology. It is only by establishing actual spatial and temporal distributions of plant water regimes across the study wetland that management will be able to estimate volumes needed, and address catchment questions of delivery, such as timing.

Evaluating existing information

Knowledge transfer is the short-cut phrase used in this guide to refer to the application of species or plant community information from one floodplain wetland to another. In doing this, it is useful to distinguish between types of information. Two types are suggested here, as a rule of thumb: qualitative and quantitative. Both are relevant to maintenance regime and regeneration regime.

Qualitative. Certain types of ecological responses and strategies refer to states, options, strategies, and conditions. These can be described as qualitative knowledge. Examples are: whether a species is a summer or a winter grower; whether its seeds are water-dispersed or bird-dispersed; whether its seedlings are tolerant or intolerant of submergence; whether it is a C-3 or a C-4 species (Section 2 and Note 8), whether it is a HCO_3 user; whether it is an annual or a perennial. This type of knowledge is essential for understanding species behaviour, for designing experiments, for defining trade-off questions, and for assessing priorities.

Species information of this sort is stable; meaning it is unlikely to change, and is not site or context-specific. Thus, in terms of knowledge transfer, it can be used in a range of environments.

Sources of information include written material, such as scientific literature for species that have been well-studied, field guides, and State and regional floras and plant books. For less well-researched species, anecdotal information, observation and expert opinion can make valuable contributions.

Quantitative. Quantitative information defines or measures the responses of a plant, species or community. Quantitative information is used extensively in monitoring, in assessment, in research, for making formal and statistical comparisons, for modelling and for defining species response shapes. Examples of quantitative information are plant biomass, percentage flowering, density, and species richness. All these are influenced by ambient conditions and, in particular, by factors that control growth and growth rate, such as temperature, resources such as light or nutrients, stress such as prolonged drought, and by interactions with other species such as herbivores and competitors. Sources of quantitative information are usually scientific papers and reports, including overseas studies, at least for cosmopolitan species.

Several plant species of floodplain wetlands occur in other types of wetlands, such as coastal lagoons and groundwater wetlands; this extends the relevant literature beyond floodplain studies.

When consulting this literature, it is essential to develop an understanding of the study sites or conditions where the research was originally done, even if in the same ecoregion (Section 2: Distribution of floodplain species). There may be site-specific factors influencing the plant or community of interest, factors which may not be evident immediately or be well-reported in that particular paper. Examples of such factors are plant vigour, plant age, soil type or condition, and weather or climate. Quantitative information should be transferred from one floodplain wetland to another with caution, particularly if the two floodplains differ in certain ecological respects. The following examples emphasise this point.

Unseen factors. One-off field observations, for example of tree response to flooding or drought, are interesting, but are not a definitive guide to species tolerances.

Tolerance, whether to drought or flooding, is affected by factors that may not be noticed by the observer, particularly if such factors are transient or not obvious. For example, drought tolerance will be determined, not just by drought but by the condition of the tree, the size of its root system, the position of the watertable and the quality of the groundwater. Similarly, flooding tolerance, or time until permanent water kills a tree, is greatly affected by depth and extent of the root system, variability in soil texture, and the presence of air-pockets in the soil matrix. None of these can be readily ascertained from the surface.

Site-specific conditions. Studies on one floodplain may have limited applicability to another.

Black box *Eucalyptus largiflorens*, a riparian tree of the semiarid and arid areas of the Murray–Darling Basin, survives in good health on certain parts of the Chowilla floodplain, South Australia (not all parts:

see Figure 15), despite a three-fold reduction in flood frequency on the lower River Murray. Black box, as befits a long-lived riparian tree in the semiarid zone, is conservative in its water use and can use either groundwater or soil water (ie. following rain) or a mix of the two, depending on groundwater salinity. The Chowilla floodplain has some distinctive hydrogeological features. It is a regional discharge point for groundwater in the Murray Basin, and this groundwater can be very saline; and construction of Lock 6 has resulted in raising this groundwater by about 2–3 metres under most of the floodplain, to well within the tree root zone (Walker et al. 1996).

This combination of shallow, saline groundwater and reduced flood frequency is unlikely to be repeated on other floodplains in the Murray–Darling Basin so findings about black box need to be applied with care. Qualitative findings, that black box tolerates saline groundwater by being a salt excluder, or that it has low transpiration rate and is a conservative water user, can be transferred. More problematic, however, are its tolerance levels; the ability to survive a three-fold reduction in flood frequency may be linked to its use of shallow groundwater with a certain salinity range, a situation not necessarily present on other floodplains.

Other site-specific factors. This example uses a special case, an unexpected characteristic in the weather pattern.

The cosmopolitan grass *Cynodon dactylon* on the Pongolo floodplain in subtropical southern Africa regrows after flood levels recede. Growth is initially rapid, as measured by its *relative growth rate* (RGR, a standard growth response used in experiments) for the first 50 days, then declines; herbivores graze the fresh pick as water levels recede. Soil moisture slowly declines after exposure, reaching the permanent wilting point about 63 days after water levels have receded. However, stress was not detected in the grass until about 35 days later, or 98 days after recession. Onset of water stress was apparently postponed, because of local mists and fogs, which initially supplemented soil moisture but then virtually disappeared about 100 days after flood recession (Furness and Breen 1986). The importance of mist and fog in the water balance for this plant was not obvious. Thus, it would be easy to overestimate the capacity of the grass to survive winter exposure by about 30 days.

In terms of transferring information between floodplains there are no simple rules, but considering the species, its size and its growth-form may help to determine what types of information are important.

- Riparian trees and shrubs are known to be deep-rooted, thus these species grow in an environment which is difficult to characterise from the surface.
- Submerged species can be expected to be more sensitive to changes in water quality and light than other floodplain wetland species.
- Emergent macrophytes are mainly clonal perennials, often rhizomatous, and have underground meristems protected from desiccation.

Modelling is a special case where it is routine to use data and knowledge from outside the site, but where validation is also routine.

Options for new information

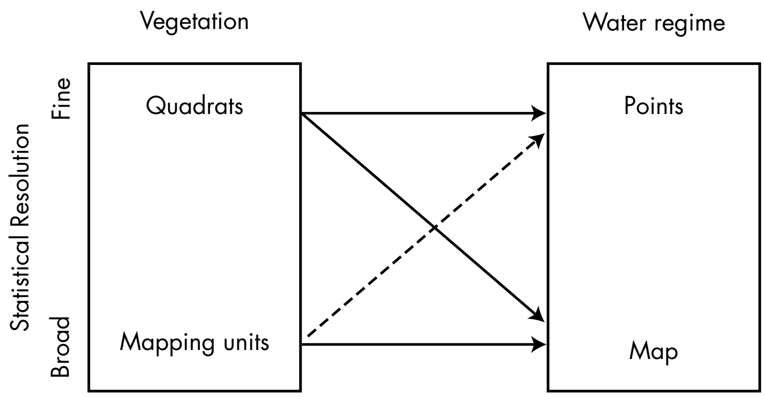
If existing knowledge is lacking or inadequate in some way, then it will be necessary to build a new set of vegetation–hydrology relationships that will provide the information needed. There are only two options for this: empirical studies, based on field work; and manipulative experiments.

Empirical studies

Field-based studies interpret existing or previous distribution of a species or a community in terms of its present or previous water regime. Typically, this is done by linking spatially-defined information about the vegetation to its environment, where environment is wetland water regime. The linkage can be done using information at a fine or broad (coarse) resolution level (Figure 12).

Figure 12. Vegetation–hydrology relationships

Vegetation–hydrology relationships can be built using fine-scale or broad-scale information. While all combinations are theoretically possible, in practice, one is rarely used: broad-scale vegetation information with fine-scale hydrological information (indicated by dotted line). The fine-scale information should be a representative sub-set of the broad-scale, such as a structured sub-sample.



For vegetation, fine scale usually means sampling using a *quadrat*, which is a defined sampling unit of known area; broad scale usually means a vegetation mapping unit. A quadrat may be any shape, but it is easier and advisable to use a square. Its size is determined by the size of the plant(s) being sampled. If too large, then it could involve collecting unnecessary data. Several quadrats will be needed per site (a site being a value of water regime component) in order to sample the natural variability in plant response.

Vegetation data are linked to water regime, usually as *inundation maps* (Section 6 and Appendix 1). The analytical techniques for doing this include correlation, regression, pattern analysis, descriptive statistics and graphical analysis. Relationships based on graphical analysis, correlation or descriptive statistics lack predictive power so are generally limited in application to restoration projects, or projects where the intent is to change conditions to be more like restoration.

Current practice is to analyse inundation maps, which show flooded areas in terms of flow size, and reinterpret the information as flood frequency. This is rather limiting, and the ecological value of inundation maps would be greatly increased by including other components of plant water regime (Section 2) in a combined system to show spatial variations across the floodplain wetland. In both large and small wetlands, linkage can be done at the broad-scale using a GIS, backed by descriptive or regression analysis. Vegetation information can be represented at this broad scale, using mapped vegetation units (usually a mixture of structure and floristics) or by community composition and condition. Current practice of using 'species + growth-form' constrains understanding (Section 2). The inclusion of measures of abundance, character or condition as separate GIS layers is rarely done and would greatly increase the value of linkages at this broad scale.

Studies on the Barmah Forest

Several studies using grid-cell analysis, a GIS-like approach, were made by Bren and colleagues to determine the maintenance water regime of river red gums *Eucalyptus camaldulensis* in the Barmah Forest; the regeneration water regime was also considered.

These were among the first of such studies in Australia, and are notable for the extensive research and reporting on field techniques and data analyses. The published descriptions contain details about methods and offer insights. The focus was on river red gum as a forest resource but the issues are directly relevant to any vegetation question on a floodplain wetland.

Components of water regime investigated were flood frequency (Bren and Gibbs 1986), flood duration (Bren 1987) and timing. Other topics were: inundation mapping (Bren and Gibbs 1986); changes resulting from river regulation (Bren et al. 1987); links between river red gum condition, understorey and flood frequency (Bren and Gibbs 1986); using elevation (AHD) as a surrogate for flood frequency on floodplain wetlands with an overall elevation range of 10 metres, but a local range less than that (Bren and Gibbs 1987); consequences of seasonal shifts for forest ecology (Bren 1992); and past and probable future changes as a consequence of changing water regime (Bren 1988, Bren 1993).

Experiments and special studies

An experiment is distinguished from other detailed studies because it is a structured design, with replication, based on manipulating experimental conditions to make statistical comparisons.

In an experiment, the experimenter has control, and changes one or more of the independent variables being investigated. This may be at the laboratory level — eg. in the laboratory, glasshouse or experimental ponds — or in the field. In general terms, laboratory experiments are easier to manage, so are sometimes preferred because the greater control of experimental conditions makes the results clearer. Field experiments can be harder to do effectively. It is not so easy to achieve the desired range of experimental conditions or treatments (eg. flood size or timing), and there is a possibility of damage by animals or vandals. It is harder to maintain an experiment and to correct problems at a distance of a few hundred kilometres. Nevertheless, the benefits of a field experiment are substantial: greater realism, and the possibility of testing more than one species at once. Laboratory experiments have greater treatment control and less risk, but are less applicable to natural conditions. The two approaches are complementary.

The term 'natural experiment' is used to refer to opportunities for investigation which utilise spatial or temporal change to make comparisons.The change represents a 'treatment', but unlike an experiment the treatment is not applied in a controlled or replicated way. Examples of such treatments are events such as a flood or drought, giving a before–after comparison, or between areas with different management, such as different sides of a fenceline. Such sites or patches or events are a great opportunity when the 'treatment' is far beyond any field experiment. Floods are a classic example (Note 20).These so-called 'natural experiments' are not experiments in the correct scientific sense, as they lack experimental controls and replication.

Roles for experiments

The value of experiments and detailed studies is that they build on empirical studies, as set out below.Australian examples are given in Section 5 (Special studies).

Information gap. Empirical studies based on linking current vegetation distribution with water regime, for example via an inundation map, cannot resolve questions regarding regeneration, although they may suggest possibilities.The water regime needed for regeneration may be a brief or atypical condition, different from that for the adult plant (Section 2), especially in the case of clonal, rhizomatous and stoloniferous species.

Define species response to water regime.The growth response of an adult plant or seedling to a specific component of water regime can be measured.This is valuable when that component cannot be easily determined by empirical studies on the floodplain. Examples are the effect of spring versus summer flooding, or survival time without flooding.

Exotic species. Exotic species are common in floodplains in eastern Australia, comprising up to 30% of all species, but only some such as lippia (Figure 13) cause widespread concern. Exotic species are a major concern in northern floodplains where species such as *Mimosa pigra* have covered areas so large that floodplain ecology must be affected. In eastern Australia, where river regulation and altered flow regime are thought to be factors contributing to the success of some exotics, it is sometimes assumed that water regime restoration will lead to their elimination (Section 2). Such assumptions can be easily tested; for example, using cut turfs in experimental ponds.

Species interactions. Changing floodplain water regime will improve conditions for some species but not for others.A shift in resources, and hence in species vigour will alter species interactions and could result in changing species composition, and in altered community boundaries. Competition experiments can indicate the likely outcome of a proposed change in water regime.

Checking restoration assumptions. Restoring water regime will not achieve the aim of restoring vegetation if key species have been lost, if seed is not viable, if the seed/propagule bank is depleted (Note 21), or if exotic species germinate first and out-compete native seedlings. Assumptions regarding viability of the seed/propagule bank, and its responsiveness to a new or altered water regime can be readily established in pond trials, using samples collected from across the floodplain wetland, and subjected to flooding treatments, mimicking seasonal or depth effects.

Note 20
Flooding at Chowilla

A considerable quantity of salt moves from the Chowilla floodplain into the River Murray. Various theories to explain this have been proposed, but understanding has been hampered by lack of information about interactions between groundwater and floodwater. In 1990, a large flood inundated 77% of the floodplain wetland, providing in a 'natural experiment' the opportunity to determine the effects of river flooding on groundwater. Having previously established a network of piezometers and monitored groundwater levels, it was straightforward to sample the network for water quality before and after the flood. Using logged piezometer data and before–after water quality, a modelling approach was used to determine reasons for watertable fluctuations and to explore dilution of the saline groundwater. This established clearly that there was very little vertical recharge across the floodplain, no hydraulic connection between floodwater and watertable, no salt leaching from the profile and little freshening of groundwater (Jolly et al. 1996).

Note 21
Seedbank studies

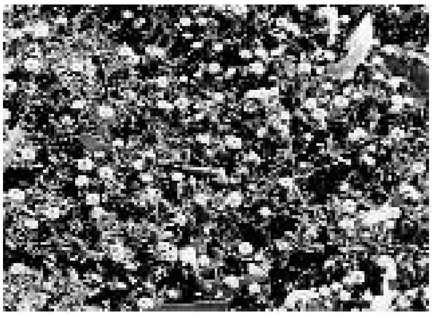
Seedbank studies have been done in only a few Australian wetlands, though these cover a range of wetlands and climates: grassland seedbanks on a coastal tropical floodplain (Finlayson et al. 1990); aquatic and wetland weed species in a rice-field in southern inland New South Wales (McIntyre 1985); and a series of studies on lagoons on the New England Tablelands.

The New England studies cover specific taxa such as charophytes (Casanova and Brock 1990, 1996), seasonal patterns (Britton and Brock 1994) and methods. Knowledge from these studies has contributed to the development of plant functional types (PFTs) (Note 12, Figure 9).

The longevity and dynamics of all propagules, such as rhizomes, corms, tubers, spores and seeds, are almost completely unknown, making testing seedbank viability an important part of a restoration program.

Figure 13. Lippia, a floodplain weed

Lippia *Phyla canescens* an attractive stoloniferous floodplain weed, common in the Murray–Darling Basin, where it occurs on most westward-flowing tributaries. It is intolerant of wet conditions and is killed by submergence of 4–8 weeks.



Data analysis

Exploratory

Exploratory data analysis is an important preliminary step when embarking on building a relationship between water regime (hydrology) and vegetation. In this, hydrology and vegetation data are analysed to determine which water regime attribute(s) appears to be linked to a particular characteristic of the vegetation.

After checking the data for errors, there is a choice of techniques that can be used to explore vegetation response to a single water regime attribute: graphical analysis; summary statistics to a single attribute of water regime; plotting vegetation attribute as a response of a water regime component; box-and-whisker plots; and gradient analysis. Complicated relationships (more than two components) based on plant community descriptions can be explored using ordination, a type of multivariate analysis such as multidimensional scaling. In the absence of specific information about vegetation behaviour, the preferred techniques are those that do not assume a linear response to an environmental variable. Several software packages are available and it is advisable to consult with a person experienced in design and analysis of this kind of data, such as a biometrician.

Determining empirical relationships

The most common and, for large areas such as floodplain wetlands, usually the most practicable approach to determining vegetation–hydrology relationships is the analysis of existing vegetation and hydrology data to establish empirical relationships. Empirical relationships can be determined either from spatial data analysis or from temporal data analysis or a combination of both.

Spatial data analysis relates the spatial variability in vegetation to the spatial variability in the water regime for a single point in time. Two issues arise from this: the first is that, where temporal variability is high, this will not give comprehensive understanding; the second is that the vegetation at a point in time should be considered as a function or ‘outcome’ not only of water regime through time, but also of previous vegetation condition and composition. Thus, the current vegetation retains a ‘memory’ of past hydrology and past vegetation, and is not simply a consequence of the most recent flood or drought but of the entire water regime, and of prior vegetation states. It is therefore inappropriate to relate vegetation type or condition simply to a single 'time slice' of hydrology, such as flood extent. Because of these strong temporal influences, spatial analysis alone will not produce close relationships. However, spatial analyses using maps of the flood frequencies or other statistics that encapsulate a water regime history may be usefully related to the vegetation type or condition.

Related to the concept of a memory in the system, is the concept of an equilibrium in the water regime and in the vegetation. If a shift occurs in the water regime, for example because of an increased level of abstraction, then the vegetation may take many years to reach a new equilibrium with the changed regime: what is seen might be a mix of residual and new elements (Note 23).

Where a change in the hydrologic regime has occurred and temporal vegetation data suggest that an equilibrium has not yet been reached, modelling techniques can be used to predict the likely equilibrium condition (Section 7 and Note 39). Typically, the hydrologic regime itself is not in equilibrium, but is changing through time, for example, because of increasing demands and abstraction levels. Temporal analyses are needed to relate the patterns in the hydrologic time series to the patterns in the vegetation time series. If the water regime is not in equilibrium, but contains a significant trend, the vegetation may never completely reach an equilibrium with the hydrologic regime, because of the time required to adjust to a new stable state; that is, the vegetation is continually adjusting to an ever-moving equilibrium condition that it never actually attains.

It becomes extremely difficult to establish any sound hydrology–vegetation relationships if all the vegetation data available represent non-equilibrium conditions.

It should be noted that the equilibrium conditions described here refer to *dynamic equilibria*; that is, oscillating around a long-term mean rather than being constant, because there may still be cyclic variations, such as seasonal or other periodic patterns.

Temporal analyses can be undertaken using individual hydrologic time series. If no modelling of the internal hydrology of the wetland has been done, then the vegetation state or condition of the entire floodplain wetland can be related only to the hydrologic time series available, that is for the entire wetland. This hydrologic time series can take different forms: it may be a time series of total storage volumes, or flow data from a nearby river gauge that ignore all other aspects of the water balance. The spatial resolution at which the water regime can be represented therefore limits the resolution to that which is useful for describing the variability in vegetation. Typically, large floodplain wetlands will be represented as a number of hydrologic sub-units; in these cases, the vegetation in each sub-unit is described separately. If detailed topographic information is available, this may be used to describe the spatial distribution of hydrologic variables such as inundation frequency or duration within a hydrologic sub-unit. This may enable finer resolution vegetation information to be used in the analyses.

Techniques useful for analysis of vegetation and hydrology data begin with simple linear regressions relating a single measure of the vegetation to a single measure of the hydrology. Multiple linear regressions enable a single measure of the vegetation to be expressed as a linear function of a number of hydrologic variables. Where linear relationships do not fit the data well, exponential relationships ($y = ae^{bx}$) or power functions ($y = ax^b$) may be used. Higher order polynomials are not recommended, as few relationships in nature are well-described by equations of this form, which constrain a relationship to specific parameters. Instead, splines maybe used to develop general curvilinear functions that match the data well. Splines are functions that are defined on sub-intervals, and so a well-matching spline function is composed of pieces of simple functions defined on these sub-intervals, joined at their endpoints with a suitable degree of smoothness.

Analyses that explore the full range of spatial and temporal patterns in the data can be employed, but because of the higher dimensionality of these approaches they are very complex, computationally intensive, and require the involvement of a statistician with expertise in this area. *Spatio-temporal modelling* is an active research area, and one which is likely to provide powerful new techniques for the analysis of wetland vegetation and hydrology data.

Applications

There are two applications for vegetation data relevant to management of floodplain wetland vegetation. One is building a useful vegetation–hydrology relationship, in order to make a water allocation/management decision. The other is setting up a monitoring program to measure the success of that decision. These overlap, but are not the same.

Building vegetation–hydrology relationships

Vegetation data required for building predictive vegetation–hydrology relationships will depend on the spatial level of resolution achieved in hydrological modelling (Section 6).

There is a degree of judgment entailed in selecting the parameters and in matching the vegetation data to the environmental data. On one hand, it is important not to start with a data set that is too small: part of the building process is to identify which water regime attributes and which vegetation variables can be statistically linked, a process that ultimately identifies which are redundant. On the other hand, a minimum data set of only three parameters (groundwater salinity, flooding frequency, and groundwater depth) was enough to describe riparian tree health (Overton et al. 1994).

Ongoing monitoring

An effective monitoring program requires a clear sense of what is being monitored and why; and how often observations are to be made. The choice of what measures are to be used for monitoring will depend on what other measures are being monitored, at what time interval, what resources are required to do the monitoring and any subsequent analysis and interpretation. Associated with this are two relevant but sometimes overlooked questions:

- who is going to do the ongoing monitoring: will it be done in-house or by contracting out?
- how is quality-control to be assured — by training and documentation or by hope?

The primary decision is whether to rely on remote sensing, or field work, or a combination of both.

The design of a monitoring program is not part of this guide. Monitoring the effects of environmental water allocations is the subject of a recently completed project (Reid and Brooks n.d.) that includes a discussion of 'change indicators' (eg. Reid and Brooks, in press).

Section 5: Obtaining Vegetation Data

When there is little or no previous information about water regime for relevant species, then vegetation–hydrology relationships must be established from scratch. This section describes what sort of vegetation data to obtain, and whether to do this at the level of species or community; if at species level, ways of choosing species are outlined. Different measures of vegetation are described — abundance, character and vigour — and examples given for species, community and different growth-forms. Techniques for measuring abundance, character, and health are outlined, rather than given in detail. Examples are given of Australian studies and experiments to show how these complement a field-based vegetation–hydrology relationship.

Field methods and protocols

Field methods, and sampling and analysis protocols, are readily available for terrestrial vegetation. These are an appropriate starting point, but some methods and procedures will need to be adapted for floodplain wetlands. There are no texts specially written for macrophytes, or for wetland or floodplain vegetation. When designing a sampling program, it is worth consulting with plant ecologists who have direct experience of the types of plants, or expertise in areas such as sampling design, mapping, remote sensing, physiology, ecology, use of stable isotopes, and analysis. If prediction and modelling are the eventual goals, then it is important to have skilled advice from the outset, to ensure that appropriate data are collected and to avoid the possibility of collecting data which do not conform with planned expectations.

The purpose of this section is to provide a perspective on obtaining vegetation data for building vegetation–hydrology relationships for large floodplain wetlands. The value of specific studies or experiments is explained and Australian case histories are included.

What to use?

A vegetation–hydrology relationship can be established at the level of species, community or the whole floodplain. The choice of which to use should be determined by the vegetation-related management objectives defined at Step 2; but it may also be influenced by the resources available, including time, and the type and quality of the hydrological data. In practical terms, the choice is between species and communities. Ways of choosing an appropriate species, or a set of species, are described below. Given the current state of knowledge, it is at present easier to work with species than with communities, though the goal should be to work with plant communities.

Using species

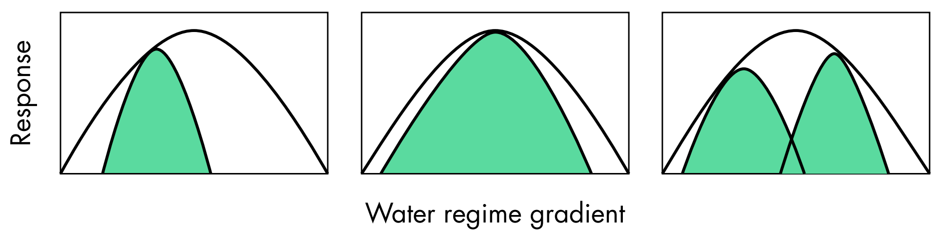
Individual species have been the centre of management programs, particularly in the area of conservation and agriculture. Because of this, a species approach seems normal. However, a management program based on single species is likely to be too narrow.This can be avoided by choosing a species carefully or, preferably, by working with a suite of species.Ways of choosing a species are outlined below.

There are several circumstances when a single-species approach may be useful or valid: when it has been specifically cited in a management objective; when it is accepted as a surrogate or an indicator for a whole plant community; when a plant community is mono-specific or has very low species richness (eg. 1–2 species), as in grasslands and sedgelands and, to a lesser extent, in some riparian forests and woodlands; when a species has a special significance, either for its economic importance (such as for forage or honey), or for its conservation significance (such as rarity or habitat value), or for its management significance (such as its economic, nuisance or weed value).

On floodplains that are wholly or partly managed for production, it may be valid to choose just one species, that is the production species, for that part of the floodplain wetland. In nearly all other cases, one species is highly unlikely to be an adequate way to represent a plant community. For example, if the chosen species has an environmental tolerance (water regime preference) that is much narrower than the community (Figure 14) it is representing, then prescribing a water regime based on this species will mean that the unrepresented part of the community receives an inappropriate water regime; in the long-term, this will lead to change.

Figure 14. Species versus community responses

A species is a member of a plant community, therefore species response (shaded) can only be a subset of a community response (unshaded) to a water regime gradient. Left: if species response is a small subset, then the species under-represents the plant community. Centre: if the species response is close to the whole community, then the species is a reasonable representation of the plant community; but the water regime gradient is then very broad and cannot be defined by a single value. Right: using two or more species can represent the plant community: size and condition states in a broadly-tolerant dominant may be used instead of species. Response may be any measure of abundance or condition; response shapes vary and are unlikely to be as simple or as symmetric as shown. Water regime gradient may be any single component, such as depth or duration, or components in combination. (See also Shape of species response, page 62.)



However, if the chosen species has an environmental tolerance that is wide relative to the community, as happens with some structurally dominant species, then it may prove difficult to establish a plant–water regime relationship that is clear, because of the range in the data.

Alternatives to the single-species approach are to use more than one species or equivalent per community, in order to represent the water regime range, or to select representative, indicator or focal species.

Note 22
Types of species

Suggested reading for background on different types of species: for keystone species, see Power et al. (1996); for rare species, see Kunin and Gaston (1993); for focal species, see Lambeck (1997); for use of surrogate species, see Caro and O'Doherty (1999).

Selecting species

Individual species should be chosen with care. Broadly speaking, species can be selected using either ecological or non-ecological criteria. Examples of ecological criteria are species that are dominant, invasive, or rare (dominant and keystone species are discussed further below); because these are not necessarily representative of the plant communities where they are found, supplementary species will be needed (Note 22).

Dominant species define and characterise a vegetation type or plant community. In common and ecological usage, 'dominant' refers to structural dominants, as in species + growth-form. Dominance in a technical sense refers to abundance (the most numerous species). The first sense is the only one that has so far been used for selecting species in floodplain studies.

Species + growth-form has been used for mapping floodplain wetland vegetation and then linking it to water regime on the Macquarie Marshes and on the Chowilla floodplain. However, as with vegetation description (Section 2), a vegetation–hydrology relationship based on this is likely to be an over-simplification that fails to capture ecologically-important spatial variability in either the dominant species or its understorey.

Spatial variability in the condition, size or even morphology of dominant species, or in understorey species composition, is particularly noticeable when the dominant species grows across a relatively wide range of water regime conditions (Table 1 and Figure 15). In Australia this seems to be more typical of floodplain vegetation in inland south-eastern Australia where tree species richness is low, such as with river red gum *Eucalyptus camaldulensis* and black box *Eucalyptus largiflorens*. These two tree species have a similar response to the increasingly unfavourable conditions across a water regime gradient. As flood frequency decreases, tree height and canopy size become progressively smaller, tree density decreases, and the understorey changes from species tolerant of or requiring flooding to species tolerant of drier conditions or intolerant of prolonged flooding (Table 1). Such changes in the dominant species are obvious and have been used as measures of tree health in the Barmah Forest studies and on the Chowilla floodplain. The understorey also changes across the floodplain, but whether its changes in species composition and structure perfectly correlate with changes in the dominance has not been firmly established.

A **keystone species** is one that has a greater influence on ecosystem processes than might be expected relative to its abundance (as biomass). The influence of keystone species is exerted by consumption and through interactions such as competition, mutualism, dispersal, pollination, disease, or by modifying habitats; in this last case, they can be known as ecosystem engineers.

Keystone species are obvious candidates for a species-based study. Identifying a keystone species among floodplain wetland plants is not easy: the concept is relatively new and there is as yet no precise or easy-to-use protocol. The lack of a formal protocol need not hinder selection of a plant as a keystone species, providing this can be scientifically defended; there must be valid grounds for suspecting that the species has a disproportionate effect on ecosystem functioning. For example, in some ecosystems, submerged macrophytes have been recognised as being keystone species.

Table 1. Spatial variability in dominant species and understorey

Flood frequency	Number of times flooded in 22 years	Tree height	Understorey composition
High	15–18	33	Moira grass
Moderate	12–16	28	Terete culm sedge + swamp wallaby grass and warrego summer grass
Moderate	12–16	28	Terete culm sedge
Moderate	12–16	28	Common spike rush + swamp wallaby grass and warrego summer grass
Moderate	12–16	28	Warrego summer grass
Low	6–10	31	Disturbed wallaby grass, introduced species
Low	6–10	25	Wallaby grass
Low	6–10	22	Swamp wallaby and brown-backed wallaby grasses + common spike rush

Mature river red gum *Eucalyptus camaldulensis* in the Barmah Forest ranges in height from an average of 33 metres where flooding frequency is 'high' to 22 metres where it is 'low'. Species composition of the understorey also changes with decreasing flood frequency. These estimates of flood frequency are based on 22 inundation maps, from 1963 to 1984 but excluding 1967. Flood frequency was linked to differences in river red gum by mapping flood frequency and overlaying an existing map of river red gum called 'site quality' (I and II and III), prepared for forestry assessment. The links between understorey and overstorey were established separately. Based on data in Bren and Gibbs (1986).

Non-ecological criteria may be less rigorously defined, as these are not intended to be indicative of a whole community or process. Species may be important for social, historical, economic or traditional reasons. An example is a **flagship** species, which is one that attracts and involves the public.

Using plant communities

A plant community is a group of species tending to occur together, and which has a definable structure and floristic composition. A vegetation–hydrology relationship can be established by treating a plant community as an entity, and linking it to water regime. The analytical tools are as for species, ranging from correlation to regression but, in addition, ordination (Section 4) can be used to interpret which environmental variables (ie. aspects of water regime) are influencing the plant community. Plant communities occurring on floodplain wetlands can be identified as part of vegetation mapping (Note 27), by floristic analysis, or by both.

Using plant community to define vegetation–hydrology relationships has certain advantages. The number of communities is much fewer

Figure 15. Range of tree condition within a species

Range of tree condition, using black box *Eucalyptus largiflorens* as an example, and two examples from the Chowilla floodplain and two from the River Murray floodplain. Examples of good and poor condition can be found within a single floodplain on most developed and regulated rivers.

[1] Black box on an infrequently-flooded part of the Chowilla floodplain, and close to the area which has not flooded since 1956. Most of the trees (90%) are coppice re-growth, the ones in the foreground are dead, but further back the trees have a small but vigorous canopy. In March 1994, mean tree height was 4.7 m, mean crown diameter 3.33 m, and Grimes index for this site was 11/20. The salinised character of the soil surface is evident with dense ground cover of *Disphyma crassifolium* subsp. *clavellatum*. Photo taken in September 1993.

[2] An isolated tree on the Chowilla floodplain. The vigorous part of the canopy is smaller than the dead branches indicating at least one cycle of growth, dieback and recovery. Although this part of the Chowilla floodplain is flooded when River Murray flow reaches 101,900 ML day^{-1}, trees are quite similar to Photo [1]. In March 1994, trees near here had a mean tree height of 5.8 m and a mean crown diameter of 4.2 m. The mean Grimes index for the area was 10/20. Photo taken in March 1993.

[3] Tall (15 m) erect form of black box tree from near a drainage line, high on the River Murray floodplain near Mildura. This tree had almost no dead branches, and carried abundant buds. The hanging leaves are distinctive, and this pendulous habit occurs in some individuals. Photo taken in September 1993.

[4] Tall (17 m) black box with spreading open canopy; in mature and old trees, the spreading habit is even more exaggerated, and the branches may reach down to ground level, creating a semi-circular canopy. This black box, also from near Mildura, carried abundant buds when photographed in September 1993.

than the number of species, so selection is not an issue. Community level information is a better integration of ecosystem processes, as well as of spatial variations and temporal differences. The measures used to describe plant communities may appear abstract compared with species descriptions. Disadvantages are that a plant community is not really an entity, and certainly not a fixed entity and 'new' communities may appear (Note 23). A plant community changes through time, with seasonal responses, as plants grow and age, and as environmental conditions change. Communities are particularly dynamic on wet–dry floodplain wetlands. In shrublands, the herbaceous understorey may change from aquatic to amphibious to terrestrial through a flood–recession–dry sequence; and in aquatic grasslands and herblands the dominant species may change. Rather than considering wet and dry communities as separate entities, it is more useful to recognise them as temporal phases, replacing each other through time. The importance of co-varying spatial and temporal variability and gradients on floodplains (Section 4) make this a challenging and developing form of analysis.

Only a few spatio-temporal sequences in floodplain plant communities have been documented (Figure 16). Working with species + growth-form avoids dealing with temporal change in the understorey.

Note 23
'New' communities

The process of environmental change and biotic adjustment means that vegetation may be composed of two elements: a suite of original (ie. pre-modification) species, and a suite of newer species, including both native and non-native species, but usually characterised by having rapid dispersal mechanisms. In riverine and floodplain systems, there are 'new' communities associated with water regime changes. Some are quite characteristic for a region. Examples of new assemblages are: the littoral fringe of willows *Salix* spp. and cumbungi *Typha* spp. on weir pools, where the stabilised water levels favour these species; dead black box trees with cumbungi as understorey, on floodplain depressions where increased flooding has caused tree death and conditions suitable for emergent macrophytes.

Describing the vegetation

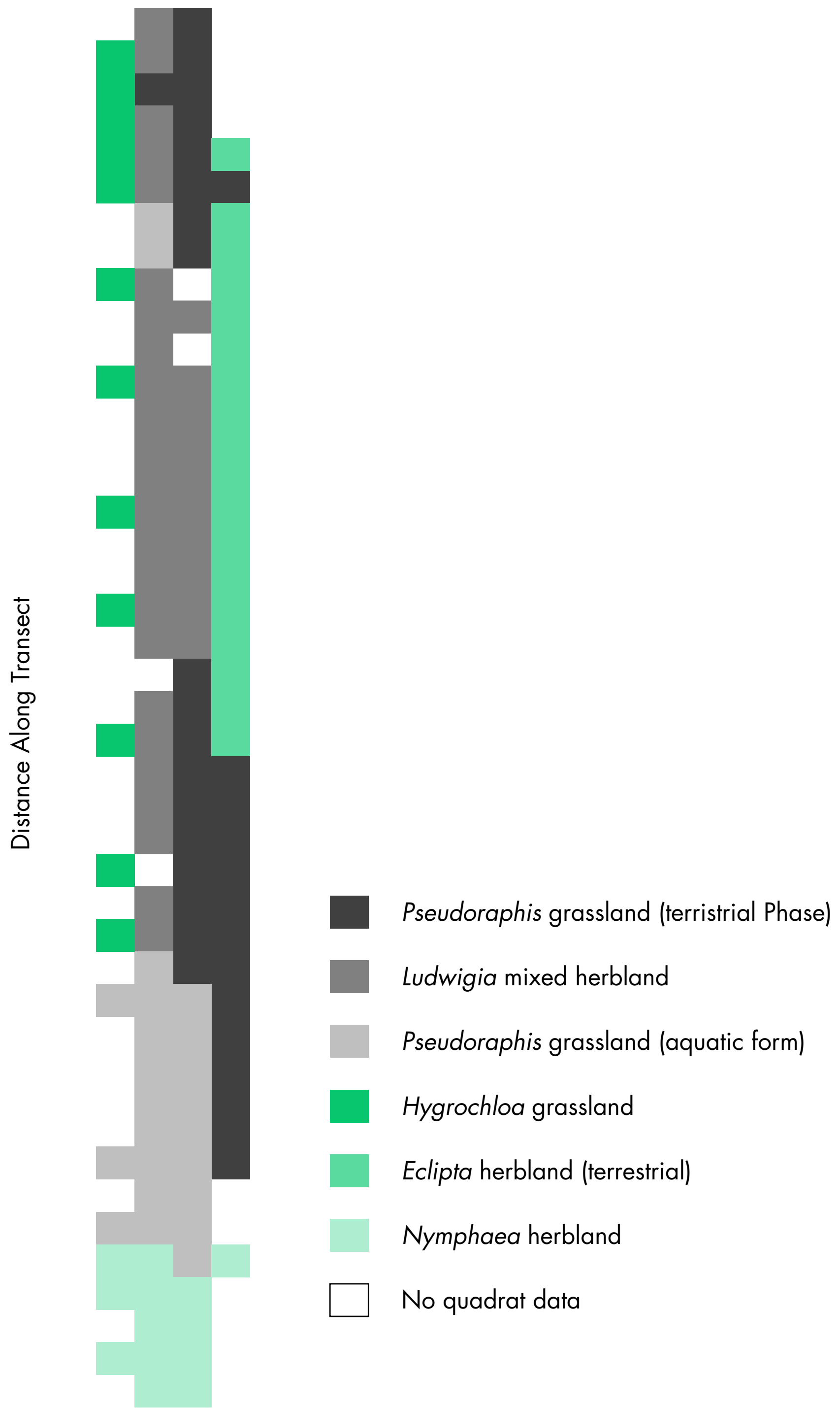
For building a vegetation–hydrology relationship, vegetation needs to be described as a response to water regime. In doing this, water regime can be considered as one or a series of separate components (Section 2), such as depth or frequency in a univariate analysis; or as two or more components in combination; or as a multivariate analysis. Combining different components to form an index is not recommended, as such indices can limit interpretation. The choice of which components to use is governed by what growth-form is being considered, whether maintenance or regeneration is the critical question, or whether any of the components are inappropriate for the species or the floodplain wetland, or even redundant for the management questions being raised. There is also a pragmatic element, ie. to use what historical or simulated hydrologic data are available. The choice between univariate and multivariate analysis may depend on what analytical skills and expertise are available or can be commissioned.

Plants differ in how well they are adapted to a particular water regime. Assuming no other environmental factor is limiting, then under favourable conditions, a given species will be present, be vigorous, and will flower; if conditions are not favourable, then plant condition will be poor, flowering is unlikely or it may be absent.

Plant responses can be described and measured, in terms of abundance, character, and condition ('character' is a non-standard term used in this guide). Each of these can be described in more than one way, depending on the ecological level of interest (whether species, community or floodplain) so can be quantified using more than one type of measure. Resolving which type of vegetation data and what level to choose is very much influenced by intended use of the vegetation–hydrology relationship: is it to describe, quantify, or to be used predictively? These are the only applications considered here. Other applications, such as ongoing monitoring (Section 4), have specific

Figure 16. Spatial–temporal sequence

Spatial–temporal sequence in plant communities on a fixed 400 metre transect from floodplain (at top) to billabong (lower) on the Magela Creek floodplain, showing a seasonal change from late wet (March) through to late dry (October). There is little change at the wetter end of the transect, where *Nymphaea* herbland persists in the permanent water of the billabong. Strong zonation patterns are evident, as in March with *Hygrochloa* and *Pseudoraphis*. However, these zonation patterns are not fixed. At each successive sampling, the zones are redefined as the species change and the boundaries between the species also change. Re-drawn from Finlayson et al. (1989).



requirements. Examples of abundance, character and condition for each level are given below.

Abundance refers to quantity, and is measured by number, size or extent, and can be applied to species or communities. When applied to a species, it includes density, cover, and frequency as well as measures of size, such as biomass, height or diameter. When applied to a community, it usually means area, but may include biomass. When applied to a floodplain wetland, it refers to its area.

Character refers to distinctive features. When applied to a species, it includes life history attributes such as annual or perennial, details of its origin, eg. whether native or non-native, and any characteristic describing reproduction and dispersal strategy. When applied to a community, it includes species composition, species richness and structural diversity. When applied to a floodplain wetland, it includes the number of the plant communities, and their structural and habitat diversity.

Condition is species vigour, so may refer to physiological processes, leaf condition or whether a population is self-maintaining. When applied to a species, condition can describe vigour directly, for example photosynthetic rate, water relations, leaf area including leaf area index or LAI (leaf area, one surface only, relative to area of the plant), number of leaves, or the presence of turgid rather than wilting leaves. Plant condition can also be described negatively, for example as stress or presumed stress, or as poor canopy condition due to lack of flowering, low seed viability, leaf senescence or presence of dead material. Population measures used to assess vigour include incidence of juvenile, mature, reproductive and senescent individuals flowering; measures of stress include incidence of mortality, as well as abnormal foliage or other descriptors of leaf stress in the canopy. Disease, parasitism and herbivory, although measures of canopy condition, are not direct responses to water regime: however, levels of all these can increase if plants are stressed for other reasons.

When applied to a community, condition refers to species abundance or character, or structural character such as height and number of strata; for example, poor condition reports on species composition showing what percentage are annual, alien, exotic or invasive. Community and species vigour can also refer to regeneration potential, so can include an assessment of seedbank viability (Note 24) and other propagules. When applied to a whole floodplain, condition includes the number, abundance and type of communities, and could include aggregated community response measures such as area of dead trees. Stress can also be detected remotely, using remote sensing techniques sensitive to chlorophyll-*a* (Note 25).

It is wise to use more than just one measure, because plant response is complex.

Measures of condition

Measures of condition, as they relate to water regime, are emphasised here. This is because these are less well-established than measures of abundance or character for floodplain wetland plants, so harder to find guidance on in standard texts. Changes in water regime, depending on what the changes are, may produce two types of stress (Section 2): one is water-stress, resulting in desiccation, leaf loss, and stunted growth;

Note 24
Seedbank viability

The viability of a seedbank, can be readily assessed. Procedures for doing this are described in simple visual terms in advisory leaflet "Are there seeds in your wetland ?" (Brock and Casanova 1997).

Note 25
NDVI: Remote sensing and foliage vigour

NDVI is a vegetation index determined by remote sensing (satellite) which is commonly used to monitor the vigour of vegetation foliage; it is suitable for a range of plant growth-forms, from extensive grasslands and woodlands, to individual canopies. NDVI means normalised difference vegetation index, and is based on ratios and differences in reflectance and absorbance in near-infra-red (NIR) and red range of the spectrum. NDVI has been correlated with leaf area index, with percentage vegetation cover and green leaf area. NDVI was used on the Great Cumbung Swamp (Brady et al. 1998).

Note 26
Canopy condition index

A visual assessment of tree canopy condition initially developed in south-eastern Queensland for assessing health of eucalypt forests, has been used on floodplain trees, in particular on black box *Eucalyptus largiflorens*.

The original index (Grimes 1987) was in four parts: crown size, crown density, dead branches and epicormic growth. Modifications by different users to make this more suitable for ecological purposes make it difficult to compare floodplains. Nonetheless, the index has proven useful so continues to be used.

In modified form, this index has been used for *E. largiflorens* on the Mirrool Creek floodplain (Roberts and Wylks 1992) and on the Chowilla floodplain (Jolly et al. 1996).

Estimates of tree health have been used to assess and monitor non-eucalypt species around wetlands in Western Australia (Froend et al. 1987).

the other is oxygen deprivation in the root zone, resulting in reduced photosynthesis, possibly phytotoxin trauma in the roots and even culms, stunted roots, and reduced nutrient uptake. Symptoms for established plants include leaf-burning, leaf-shedding, premature canopy senescence, stunted growth, reduced reserves and dieback of branches. All these can be detected at the species level.

Sustained stress, such as altered water regime, affects plant vigour. This can alter competitive interactions between species, or even alter dominance and so create an opportunity for other species. At the community level, this can be detected as a change in area, by shifts in community boundaries, and by increased incidence of opportunistic species or of species more closely associated with the 'new' conditions, whether they be drier or wetter. Thus, measures of community condition can include presence and abundance or area of invasive species. An indicator species may point to wetter conditions, or drier conditions, or seasonal shifts. Useful examples of indicator species from eastern Australia are cumbungi *Typha* spp. for wet conditions, and lippia *Phyla canescens* for drier conditions (Figure 13). Indicator species need to be clearly associated with the change, and not with another environmental condition, such as stock grazing: some unpalatable *Juncus* species increase under grazing pressure.

For species and community, lack of regeneration is a serious long-term loss of vigour. In choosing lack of regeneration as a measure (eg. lack of seedlings, no juveniles or saplings, only ageing and senescent trees present), it will be necessary to establish that this is an outcome of water regime alone or in combination with something else, and not the result of other factors such as rabbits.

Condition and growth-form

Leaves are the basic unit of growth for most plants so are also a good starting point to assess plant vigour and condition. Some aspects of leaf vigour are common across growth-forms. For example, it is a useful but simplistic assumption that a plant with larger leaves, or greater photosynthetic area (more leaves, higher LAI) will be in better health than a plant with smaller photosynthetic area or which has some leaf area that is not fully photosynthetic (yellowing, brown spots, dead leaves) or that is damaged or incomplete (insect damage, leaves being shed, burnt). Condition of leaves can be assessed remotely, using NDVI (Note 25) or assessed from the ground using indices of canopy vigour (Note 26), or its physiological condition measured in the field.

Many of the methods for measuring vigour have been developed for agricultural or forestry species. Consequently, the techniques and equipment for estimating health and vigour are better developed for floodplain trees than for other growth-forms, especially aquatic species. There are few means for measuring the health and vigour of leafless species (see below).

Trees

Canopy condition index. A visual assessment of canopy condition is compared with reference material, then scored. When using such indices, it is important to use printed reference material in the field throughout the investigation in order to standardise observations. It is also essential to identify examples of the full condition range, from dead or very poor to vigorous (Figure 15). Canopy indices are ordinal data, and this can affect how summary statistics such as mean are calculated and used, especially in multivariate analyses.The index in common use (Grimes index; Note 26) is specific to eucalypts, and assumes epicormic regrowth.This index would need to be modified for use with other species, such as *Casuarina* and *Melaleuca*. Even within eucalypts, species differ in form and shape.A new reference set covering the full condition range will be needed when applying a condition index to a species not previously assessed in this way. Modifications made by individual workers mean that inter-species comparisons are not valid, and possibly even intra-species, if from different sites.

Standard physiological techniques for measuring water stress, such as xylem pressure potential, are more useful as a research or monitoring tool when undertaking a time series in relation to soil water.

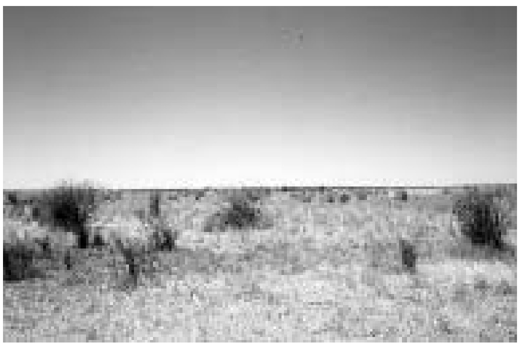
Other than trees

For many emergent macrophytes, the perennial part of the plant (the rhizome, the tubers etc.) is underground and the canopy is the only part of the plant that is visible. In these cases, there is an overlap with abundance measures; condition can be size and colour of the canopy, estimated directly as biomass, leaf number, LAI or recorded indirectly using height or shoot density.

Condition options are very limited for leafless plants such as many emergent macrophytes (eg. *Eleocharis*,*Juncus*, *Schoenoplectus* etc.) which have a photosynthetic culm, and for leafless twiggy shrubs such as lignum *Muehlenbeckia florulenta*, and grasses such as canegrass *Eragrostis australasica*. Suitable measures are estimates of size, such as height, diameter, cover or (select species only) stem density (Figure 17). With lignum, as with other leafy shrubs, size can be estimated from aerial photography.

Figure 17. Vigour in leafless species

Lignum *Muehlenbeckia florulenta* under dry conditions but showing the difference in height, twig density and overall habit between well-watered (left) and infrequently-flooded areas (right).



Spatial issues

Broad-scale and fine-scale

The basic approach to building an empirical vegetation–hydrology relationship (Section 4) is to link spatially-defined vegetation data with spatially-defined hydrology data.

Note 27
Mapping floodplain wetland vegetation

Aerial photographs, both colour and black/white and including photomosaics, have been extensively used for mapping floodplain vegetation, for example the River Murray floodplain (Margules et al. 1990), the Murrumbidgee–Lachlan confluence (Pressey et al. 1984), the Macquarie Marshes (Brereton et al. 1996), and the lower Darling (Green et al. 1998). Visual interpretation of satellite imagery has been used on the Murrumbidgee–Lachlan confluence (Johnston and Barson 1993) and on the lower Gwydir (McCosker 1999).

Current spatial and spectral resolution of satellite data make it difficult to map botanical classes of floodplain wetland vegetation using satellite data alone, ie. without supervision, or field work. Fine-scale resolution of vegetation classes on the ground is best addressed by combining satellite data with aerial orthophotography, as done on Chowilla floodplain (Overton et al. 1994).

Broad-scale. At the broad-scale, maps of hydrology and vegetation have used a limited range of material. Hydrology maps have been generally limited to a single water regime component, usually inundation; by linking inundation with river flow data, inundation can be re-expressed as magnitude or frequency, although rarely mapped like this. Once the link between inundation and river flow is established, other components of water regime can be interpreted, such as duration or timing, yet these are rarely mapped. The availability of GIS means such mapping could easily be routine.

Vegetation maps are also constrained, being representative of plant communities in terms of structure and/or floristics. The type of map, whether structural or floristics or combined, is dependent on what methods are used for mapping.

Fine-scale or point information for hydrology is rarely recorded so is rarely used for building vegetation–hydrology relationships. The advantage of fine-scale hydrological information would be better correlation with vegetation, through more accurate records of depth, duration and timing. Fine-scale information for vegetation is usually quadrat based, with detail about vegetation structure, abundance, character and condition.

Quadrats may be placed within a community randomly, in a stratified way or by stratified random sampling. It is more efficient, in terms of time and resources, to structure sampling. One way to do this is by sampling along an environmental gradient: this could involve using a transect or a 'gradsect'.

A transect is a line along which vegetation is sampled, using point information, indirect methods, or quadrats. Transects are basic to vegetation description as they reveal species changes along a gradient, and define community boundaries and zonation. Belt transects, that is transects of contiguous quadrats, are most useful for determining spatial patterns. This approach is likely to generate too many data if used to define species response to a water regime gradient: for that purpose, it is better to use a gradsect. A gradsect is a transect orientated along the steepest environmental gradient; that is, the gradient exercising greatest influence within the study area, such as flood frequency or depth. A gradsect can be several kilometres long, and can be sampled at intervals. At each sampling site, the natural variability in species response should be sampled using random quadrats. The sampling sites may be well separated, but need not be in a perfectly straight line, provided they follow the environmental gradient.

Vegetation mapping

A vegetation map is prepared using remote imagery, aerial photography or satellite imagery, with field work to confirm interpretation and to provide the necessary floristic and structural detail. Similar techniques are used as for inundation mapping: visual interpretation of images, whether aerial photography or hard copy of satellite imagery. If satellite imagery is used, then a number of techniques such as histogram slicing, and supervised and unsupervised classification are employed (Note 27). Overall, satellite images are more useful for defining woody and non-woody vegetation. Mapping techniques used by herbarium staff in each State are useful examples to follow for vegetation mapping.

In visual interpretation, homogeneous photopatterns are delineated based on colour, texture, tone and shadow. Tree height, crown characteristics and canopy shape can be included, eg. from stereoscopic aerial photo interpretation, if woody vegetation is a significant part of the floodplain wetland or appears to be diverse in this way. Field work is done to confirm boundaries between mapping units, and to describe each photopattern, either qualitatively or quantitatively, using quadrats. Boundaries can be quite attenuated on some floodplains, and where this occurs, transition zones have sometimes been mapped as separate vegetation types. Vegetation data recorded in the field should include: floristics, for species composition and richness; canopy conditions for health; and population age structure of dominant or key species.

Species-based relationships

Statistical models

A statistical model of a species' distribution predicts a response or dependent variable from a number of predictor or independent variables; this means predicting the presence of a plant species from a set of environmental variables, such as components of water regime. These are called *statistical models* because they are based on statistical distributions and hence can estimate an error term. An advantage of generalised linear modelling is that, unlike simple linear models (Section 4), it can accommodate a range of statistical responses (such as Poisson, ordinal, binomial) and use different types of data (such as continuous or categorical variables).

Statistical models are an effective way to predict the likely response of an individual species to environmental change, such as water regime. The model is constructed using presence–absence data with physical descriptors of the environment from a number of sites. If the physical environment can be geo-referenced, for example by using a GIS, then it is possible to predict the probable distribution of the species across the landscape. Although several kinds of statistical procedures can be used to build a statistical model, only two are used in practice: GLM (generalised linear models) and GAM (generalised additive models).

GLMs have been more commonly used, but GAMs have the advantage of being data driven, thus they make no a priori assumptions about response shape. GLMs can be used with GIS systems but GAMs are more difficult to integrate. Because they do not produce a conventional regression model, GIS layers cannot be combined as variables in an equation.

Neither GLM nor GAM has been much used for predicting the distribution of riparian and wetland plants; such an approach, although data hungry, could be useful for evaluating the consequences of management changes for key species with some precision. Lehmann (1998) reports the results of studies on the distribution of three submerged species of *Potamogeton* in a lake in Switzerland. GLM has been much used in terrestrial ecology to predict species distribution, eg. from herbarium records and climate data (Note 28); see also *Eucalyptus* species (Austin 1998).

Note 28
Modelling species distribution

An example of how species records can be used to generate maps of potential distribution can be found on the Environment Australia web page (Web Listing). Only a selection of all Australian plant species is available on this database of herbarium specimens. Potential distribution maps of each species are generated by an experimental modelling tool called GARP (Genetic algorith for Rule-set Production). GARP uses internally generated surfaces of climate, soils and geology across Australia. A central assumption in GARP is that species distribution is primarily controlled by climate: if this is not true, then maps will be unreliable or wrong. Thus, this tool is of value for terrestrial species only. In the case of wetland and riparian plants, the primary controlling factor is water regime.

Shape of species response

The shape of species response is often presented as a near symmetric curve (Figure 14). This is a convenience for explanatory purposes. In fact, response shapes vary, and are rarely symmetric and are rarely linear. For this reason, graphical analysis is an essential first step in a vegetation–hydrology relationship to determine if it is appropriate to use linear analysis. If it is not linear, it is inappropriate to use statistical descriptions and mathematical functions that assume linearity, such as linear regression, multiple linear regression, and PCA (principal components analysis).

Special studies

Experiments and specific studies have been under-utilised in floodplain studies yet can greatly improve understanding of vegetation hydrology relationships beyond what can be learned from field data (Section 4).

Manipulative replicated experiments can be done in the field using transplant experiments, constructing water exclosures or enclosures, or even flooding different parts of the floodplain. The number of factors investigated and the number of replicates are likely to be fewer in the field than in a laboratory experiments. Examples of experiments and investigations into specific components of water regime are described below. This is not a comprehensive guide to experimental approaches, but a selection of recent experiments on Australian species.

Single-species studies

Single-species studies document the response of a species to a range of water regime components, singly, in sequence or interactively. Often the experimental conditions have been derived from actual descriptions of water regime from the study site. The experimental approach described here could be applied to seedbanks, following the testing procedures described by Brock and Casanova (Note 24).

Sedge + depth: Growing *Bolboschoenus medianus*, a 1.5 to 2 metre high sedge, in pots in an outdoor experimental pond at fixed depths from 20 cm above to 60 cm below water for 81 days, and recording biomass and carbon assimilation rates, clearly indicated that this species grows best at 0 to –20 cm. The plant can tolerate deeper water but does so by drawing on reserves in the tubers (Blanch et al. 1995). Thus, water deeper than 20 cm is likely to be detrimental for this species in the long-term.

Tree + season and frequency: The effect of timing of short floods and of flood frequency on mature river red gums was investigated in the Millewa forest (Bacon et al. 1993). Twelve 0.8 ha exclosures were aligned parallel to flood-runners in the forest, and were set up to sample the spatial gradient away from the flowpath. This gave an extra layer of information to the experiment, showing that the beneficial effect of short-term flooding was localised to the flood-runner and areas immediately adjacent, except for trees overlying shallow aquifers.

Seedlings + relative depth and duration: Seedlings of a lagoon tree aged 4 months, 1 year and 2 years were grown in pots in an outdoor pond at depths ranging from none, half or all of their height (ie. depth relative to height of young tree) for 3 to 14 weeks. Depth and duration, and their interaction, were chosen as experimental factors because of observations that submergence was likely to be limiting recruitment. Recording survival and growth, not just immediately after submergence but also at the end of a post-submergence recovery period, showed the importance of including delayed responses when making assessments (Denton and Ganf 1994).

Tree seedlings + depth and duration: 'Mesocosms' (similar to large pots, with drain-holes to manipulate water levels) and smaller pots were used in an outdoor experiment to test the effects of water depth and flood duration on saplings and seedlings of *Melaleuca quinquernervia*. This tree is a pest in Florida but is a native and valued species on floodplains in tropical Australia.

Comparative studies

Comparative studies extend the single-species approach by subjecting two or more species to the same experimental treatments. From the results of such studies it is possible to make an informed guess as to which species would be favoured by a particular water regime.

Examples of multi-species studies done in the field are: the effect of changing water levels and depth on *Baumea arthrophylla* and *Triglochin procerum* (Rea and Ganf 1994); and water regime (mainly depth and duration) and eutrophication effects on *Baumea articulata* and *Typha orientalis* (Froend and McComb 1994).

Regeneration and maintenance: Three macrophyte species were compared in a series of experiments investigating their regeneration from fragments, seasonal growth patterns, and survival and growth in water depths ranging from 10 to 100 cm. The species, *Marsilea mutica*, *Ludwigia peploides* and *Myriophyllum aquaticum*, all occurred at Bushell's Lagoon, west of Sydney. The study concluded that the two native species were better adapted to fluctuating water levels, while stable water levels suited the introduced milfoil (Yen and Myerscough 1989).

Comparative studies need not be limited to species, but could include seedbanks. For example, the viability of different parts of a floodplain wetland could be tested to determine which areas might need supplementary planting.

Competition studies

Competition experiments are important because it is very difficult to accurately predict interactions between species based on current knowledge. Water may be a resource or a stress, or both: thus, changing water regime will affect the vigour of species differently. If their competitive interactions change, then species composition will change, boundaries may alter and the abundance of target species, whether nuisance or exotic or rare plants, may be affected. Competition studies explore how two species affect each other's growth under specified conditions.

A standard design is to grow each species separately (a 'monoculture' as a control) and together, in varying densities, and under a range of conditions. Competition experiments done in the laboratory tend to be large, and involve very many pots; they require strengths in experimental design, planning, and analysis.

Note 29
Remote sensing: the future

Research is currently underway to determine spectral characteristics associated with leaf senescence and leaf water stress, using a test site with a number of young trees, planted in a replicated experimental lay-out, on well-fertilised and nutrient stressed sites crossed with varying degrees of water stress. The target species is *Eucalyptus camaldulensis*. Spectral reflectance differences have been already detected for other eucalypt species (Laurie Chisholm, pers. comm., 1999).

Figure 18. Heat pulse sensor

Heat pulse sensor and logger being checked on the bole of a black box tree *Eucalyptus largiflorens*. Heat is used as a tracer. The unit comprises a heater and two sensors, inserted into tree sapwood, at fixed distances above and below the heat. Estimates of sapwood area are needed to scale from sap velocity to tree flux per day.

Native and exotic species: Australian sweetgrass *Glyceria australis* and the introduced rush *Juncus articulatus* co-dominate Mother of Ducks Lagoon, New England. *J. articulatus* was concentrated in the lower part of the lagoon, though it was not clear whether this was because of wetter conditions or repeated disturbance from stock and waterbirds. Growing the species, separately and together, for two growing seasons and under three water regimes (damp, flooded to 10 cm, and fluctuating between these) showed greater growth in the introduced rush under fluctuating conditions and under sustained high water levels (Smith and Brock 1996).

Other specialised studies

Water sources + stable isotopes: Naturally occurring stable isotopes of water, ^{2}H (deuterium) and ^{18}O, can be used as tracers to identify what water source a plant is using: whether from deep within the soil profile, from recent rain, or from floodwater. Comparing the isotopic signatures of water in the plant with all its possible sources at a given point in time gives an instantaneous 'snapshot'. Using a series of such snapshots, covering a range of environmental conditions, and relating this to plant water status, allows a picture of plant water-use strategy to be built up. In this way, it is possible to determine whether a plant is dependent on a particular water source or is more flexible. This has proved a powerful technique for riparian plants. Nearly all studies to date have been on trees, and the technique is just beginning to be applied to riparian and floodplain herbs and forbs. For descriptions of this technique, its application on riparian trees in Australia, see numerous studies on black box and river red gum on the Chowilla floodplain by Walker, Jolly and collaborators (eg. Walker et al. 1996).

Groundwater discharge through plants: The roots of certain plants, notably trees and shrubs, may take up groundwater which is then transpired. The use of stable isotopes can demonstrate that this is occurring; accurate estimates of transpiration are needed in order to quantify the transpiration flux. Heat-pulse technology (Figure 18) can be used to estimate transpiration by measuring sap velocity, then these transpiration estimates can be scaled up to estimate tree flux per day, or to homogeneous areas of a floodplain (eg. Thorburn et al. 1996).

Section 6: Using Water Regime Data

The hydrologic variable of most relevance to plants is water depth. However, water depth data are rarely available for large wetlands. Depth can be obtained directly, or indirectly by water balance calculations from existing data. This section focuses on the indirect ways for obtaining depth, but recognises that water regime can be defined in other ways. Options for estimating the different components of a floodplain wetland water balance are described, with emphasis on spatial and temporal variations across the floodplain wetland. The application of water regime data for hydrological modelling is described, with current Australian examples, although these are rarely based on depth.

Estimating water depth

Water depth is the hydrological variable that most clearly summarises plant water regime, if expressed as a spatially and temporally variable measurement (Section 2: Focusing on depth). Water depth can be measured directly, but good sets of direct measurements are rarely available for characterising the spatial variability of depth in large floodplain wetlands, and are hard to obtain. This is in contrast to small individual wetlands where the spatial variability of depth is low, and so changes in depth can be recorded at a single location. On large floodplain wetlands, water depth can be estimated indirectly using water balance calculations (Section 1). Changes in water inputs and outputs can be used to estimate changes in the volume of water in the floodplain wetland, and volume can be expressed as depth using inundation area, as this is a function of surface topography.

Although depth is an effective way of summarising plant water regime, it has not been central to Australian studies of floodplain wetlands, which have tended to focus on flood frequency. The aim of this section is to present the ideal hydrological variable, ie. water depth, and at the same time present other aspects of plant water regime that have been the backbone of floodplain research.

Direct estimates. Changes in depth can be measured directly using water level recorders of various types. In large floodplain wetlands, the spatial variations in depth will vary through a flood and will be different from one flood to the next. Many water level recorders are needed to capture this spatial variability of depth. Knowing how many recorders are needed and where to site them is process of trial and error. Maximum flood height recorders, as used in the Macquarie Marshes, record maximum depth at a location, but must be modified if they are to record time.

Indirect estimates. Indirect estimates can be made using measurements of the inundation area, the changes in storage volume, and descriptions of the floodplain topography. These are outlined in this section, using storage volume and inundation area, including how to use topographic data to determine the spatial variations in depth. Techniques available for determining inundation areas are presented, followed by a description of the hydrological techniques for determining the different components of a water balance.

Using storage volume and inundation area

An average water depth (in metres) for a floodplain wetland can be calculated by dividing storage volume (in cubic metres) by inundated area (in square metres). For this, inundation area and storage volume for a large flood are needed.

This average water depth ignores the proportion of the storage volume held in the soil. An improved estimate can be obtained by determining the soil storage volume. The spatial variability in water depth can be estimated using descriptions of the surface topography of the floodplain.

Soil storage volume

Storage volume includes both surface water and water held in the soil, also known as the *soil moisture store*, and this can account for a significant fraction of the total storage volume. Subtracting the soil moisture store from the total storage volume will leave surface water, giving a more accurate estimate of average water depth.

The soil moisture store, as a volume, is the depth of water that infiltrates the soil profile, integrated across the inundated area. Infiltration is mainly a function of *soil hydraulic conductivity,* the rate at which water moves through the soil; soil cracking and flood duration also contribute. For example, in soils with low hydraulic conductivity, the depth to which flood water infiltrates is defined by the length of time the surface is inundated. Surface drainage and evapotranspiration may deplete the storage volume before the soil is fully saturated.

Estimating the soil moisture store for a floodplain wetland is not simple, partly because the process of infiltration varies greatly between soil types. For soils other than cracking clays, infiltration occurs by the downward advance of water through the soil profile. For these soils, the moisture store, when saturated, can be estimated as a function of soil depth and soil porosity (the proportion of the soil volume represented by pore spaces). When the soil moisture store is not full, for example, if infiltration has been limited by flood duration, infiltration rates and flooding duration need to be estimated. Hydraulic conductivities have been established for many soils, but the application of these values in field situations is usually constrained by a lack of data describing the spatial variability in soil types. Furthermore, soil cracking and macro-pores can increase initial infiltration rates to orders of magnitude higher than laboratory derived values.

In the Murray–Darling Basin, the lowland river floodplains on the Murray and Darling Riverine Plains are characterised by cracking clays. These soils behave very differently from lighter soils, and the infiltration process is very different. As these soils dry, deep cracks form in the soil, sometimes forming discrete columns of soil (Figure 19). Infiltration occurs as a rapid filling of these cracks, and water subsequently moves laterally through the soil away from the cracks. As the soils wet up, they begin to swell, closing off the cracks. Once the cracks are filled, very little water enters the soil profile. The volume of water that infiltrates is determined by the volume of the cracks.

Figure 19. Cracks after winter rains

Germination in shallow cracks on cracking soil on the Hay Plains, July 1990. On some floodplain wetlands, notably riverine lakes in semiarid areas, deep holes and cracks are important as habitat for native fauna (Briggs and Jenkis 1997).

Estimating crack volume

The volume represented by the cracks and holes depends on soil type and on how long the soil has been drying out. For most cracking clays, the soil moisture content at saturation is about 40% by volume, but when air-dry, it is about 9% by volume. This means approximately 31% (and as much as 35%) of the total soil volume may be available to absorb water.

If the soil is dry, and assuming a typical cracking depth of around 1 m, then this is equivalent to an infiltration depth of 300 mm, which corresponds to a volume of 3 ML/ha. In very dry conditions, cracks may extend to 2 m, which is equivalent to an infiltration depth of 600 mm or 6 ML/ha.

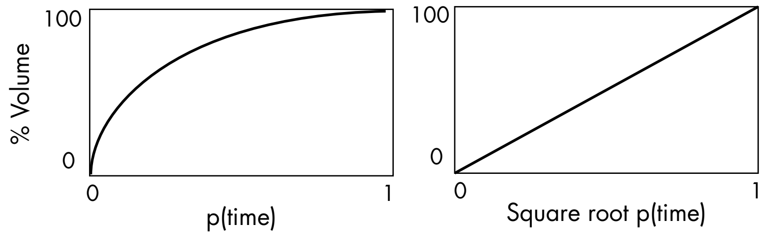
If the soil is not fully dry, then crack volume can be estimated as a function of the drying period. For this, crack volume, expressed as a percentage of the fully dry volume, is a linear function of the square root of the drying period expressed as a proportion of the time required to dry fully (Figure 20). For example, for a floodplain where complete drying takes 400 days and leads to a crack volume equivalent to 600 mm infiltration depth, then the crack volume after 200 days would be equivalent to around 425 mm.

Spatial variations

Using just the surface water component of the wetland storage volume allows calculation of only a spatially averaged depth value. For floodplain wetlands that are topographically complex, water depth will vary considerably from place to place across the floodplain.

Figure 20. Crack volume and drying time

Volume is expressed as a percentage of the fully dry volume, and time is expressed as a proportion of the time required to dry fully. Left: the relationship between volume and time; right, the same relationship re-expressed in linear form, as volume and the square root of time. Time is expressed here as a proportion, with maximum time being 1. The time required to dry fully is site-specific.



To describe such spatial variations in water depth requires, as a minimum, a topographic description of the floodplain wetland. If it is assumed that the depth of water stored in the soil profile is uniform across the wetland, and that the absolute elevation of the water surface is also uniform, then a topographic description of the wetland and an estimate of surface storage volume are all that are needed to prepare a map of the spatial patterns of water depth. How to obtain and use topographic information is described below.

However, these two assumptions are not always realistic. The soil water store is not uniform because infiltration, and hence the depth of water in the soil store, will vary markedly between different soils. Neither is the water surface completely flat. The large size of most complex wetlands, their low gradients and high flow resistance (due to vegetation), mean that water levels can take a long time to stabilise, so water elevation will usually vary across the floodplain wetland. Natural variations in surface topography may be complicated by structures, levees, roads or bridges that, until they are over-topped, prevent low-lying areas from being inundated. Thus, complex sequences of inundation may result from even a single inflow event.

Coping with such complexities requires far more than a topographic description of the wetland; one possibility is detailed modelling of water movement within a floodplain wetland. Modelling is discussed at the end of this section.

Describing the topography

For small, individual wetlands, the topography can be described using conventional surveying when dry. For large floodplain wetlands this is not feasible. Topography of larger floodplains can be determined using stereoscopic aerial photographs, which are the basis of most traditional topographic mapping. However, the variations in water depth that are significant for plants (Section 2) are usually the result of topographic variations of less than a metre. This fine level of vertical resolution is not represented on standard topographic maps, and so special purpose maps may need to be prepared. An alternative to aerial photography is laser altimetry (Note 30) which, while expensive, is a rapid means of getting high-resolution topographic information.

As well as in conventional maps, topographic information can be stored in digital form as a digital elevation model (DEM). DEMs can be created from any topographic information, their vertical resolution depending on the accuracy of the source data. The great value of a DEM is that it can be coupled a with a GIS and inundation areas to produce maps of water depth for different storage volumes. These are an important layer of information, for example in GIS models.

Estimating inundation areas

To obtain an indirect estimate of water depth is just one reason for estimating inundation area. Inundation maps have proven useful in building vegetation–hydrology relationships, as they also provide a spatial description of some components of plant water regime that would be difficult to otherwise obtain. Inundation mapping thus serves several purposes, and is considered a very worthwhile investment.

Using data from remote sensing

Inundation area can be mapped using images of flooded area, from either airborne or satellite-borne instruments. The data collected are either from a passive signal (reflected natural radiation of different wavelengths), or from an active signal (reflection of a generated signal). Sensors for passive signals are most widely used. Many sensors for passive signals detect a wide range of wavelengths including visible light and infra-red. The two most common active signals used are radar (generated radio signals) and laser (generated light radiation). These have been used overseas, especially in tropical areas such as the Amazon, where cloud penetration is needed. In Australia, most inundation mapping has been done using conventional satellite imagery for large floodplain wetlands (Note 31), and aerial photography, preferably colour, for small wetlands.

Aspects of remote sensing, and technical information on the different sensors, their sensitivity, range, and relative cost are given in the Appendix 1 (Tables A1 – 4 and A1 – 5), for a range of commercially available airborne sensors.

Linking volume and area

Linking volume and area over a range of flood events of different sizes is the basis for building a volume–area relationship for the floodplain wetland. This is a powerful tool that has been used in eastern Australia. Building and using such a series is the basis of this section. Volume is presented in two ways: as storage volume, and as flood volume. Indirect estimates of depth can be established using the same data, or just one or two data sets.

To construct a volume–area relationship requires a number of data points, in order to cover a realistic range. The images for this need to be selected with care (Appendix 1) in order to minimise 'noise'. On floodplain wetlands that are infrequently flooded, or which are in a dry cycle with no recent flood events, it will be difficult to obtain sufficient number of inundation images.

Building a relationship between volume and inundation area allows *interpolation* and *extrapolation* to give estimates of the inundation area for storage volumes for which remotely sensed images are not available. Interpolation refers to estimating values between two data points. Extrapolation refers to estimating values beyond the largest flood for which remotely sensed data are available, and is typically inaccurate.

Note 30
High-resolution topographic mapping

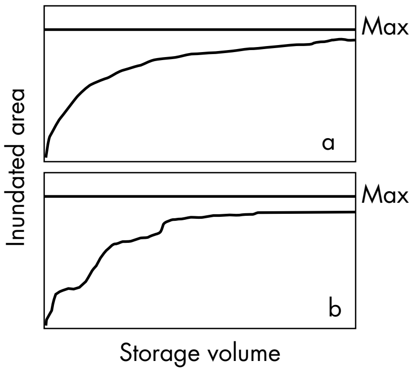
Airborne lasers, such as laser induced direction and ranging, LIDAR, can collect floodplain topography data with a horizontal resolution of 3 metres, and a vertical resolution of 10–15 cm.

Note 31
Inundation mapping in Australia

A range of techniques has been used for inundation mapping in Australia: visual interpretation of satellite imagery on the Barwon–Darling (Cooney 1994) and the Lower Gwydir (McCosker 1999); histogram slicing on the Chowilla floodplain (Noyce and Nicolson 1993), the Macquarie Marshes (Brereton et al. 1996) and the Lower Darling (Green et al. 1998); and classification on the Great Cumbung Swamp (Sims 1996).

Synthetic aperture radar (SAR) is being increasingly utilised for flood mapping, eg. in the Northern Territory (Milne 1998). Its great advantage is that plant foliage can be completely transparent to radar so it can be used to map floodwaters under dense vegetation. Data sets are complex, and require experienced practitioners. Airborne hyperspectral scanners such as CASI and HYMAP can provide 3–5 metre resolution maps of inundated areas, plus water data such as turbidity and chlorophyll-*a*.

Figure 21. The relationship between inundated area and storage volume



Storage volume.The relationship between inundated area and storage volume is best considered as a curve asymptotic to a line representing the maximum area of the floodplain (Figure 21a).

Departure from a simple curve may occur as a result of errors in the data, or, if there are sufficient and accurate data points, may reflect floodplain topography. For example, in some floodplain wetlands large increases in area will occur as new 'bench' or terrace levels are inundated (Figure 21b). Restricted data sets which sample only part of the total range will look linear (Appendix 2).

Flood volume. River flow can be used as a surrogate for wetland storage volume.This assumes that river flooding is the dominant input and that the volume in storage before flood inflow is small relative to inflow volume.These assumptions are reasonable in arid and semiarid regions, and it is here that a relationship between river flow (total flood volume) and inundated area can be useful.A second assumption, which can be checked by overlaying inundation maps, preferably in a GIS (Appendix 1) is that the capacity of the inflow channel has not changed within the time frame of the study.

Although the relationship between inundated area and total flood volume is sometimes assumed to be linear — as, for example, on the Gwydir Watercourse (Pathways.A wetland water balance recognises three pathways for water movement: surface water, sub-surface water and atmospheric water. Each pathway can move in two directions: inflow and outflow for surface water; infiltration or re-charge and discharge for sub-surface water; and rainfall and evapotranspiration for atmospheric water.) and the Macquarie Marshes (Kingsford and Thomas 1995) — this relationship (like storage volume and inundation area) is best considered as a curve, asymptotic to a line representing the maximum area of the floodplain (Appendix 1).

Once again, departure from this curve may be due to technical or interpretation errors, to variations in floodplain topography, or to factors affecting the distribution of floodwater, such as floodplain roughness, and antecedent conditions, such as soil wetness or dryness. Antecedent conditions can differ markedly between floods, and for this reason, river flood volumes are less likely to be well related to inundation area than are storage volumes.

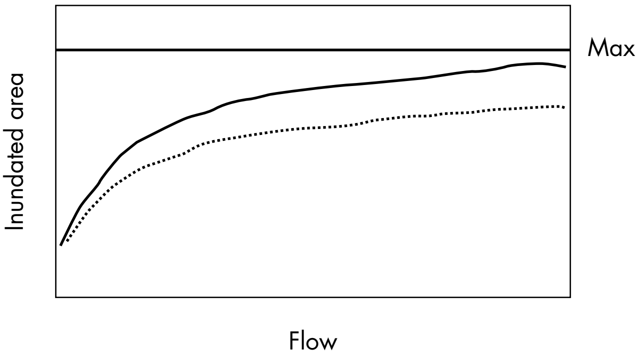
Antecedent conditions.Antecedent conditions can alter the area inundated by a given river flood volume. Important antecedent conditions include: soil wetness or dryness (whether through rainfall or previous recent flooding), vegetation condition, which affects surface roughness; and the season, which determines the rates of evapotranspiration.

Because of the very strong influence of soil conditions on surface water distribution, separate curves for antecedent conditions, wet and dry (Figure 21), are recommended.This will increase the resources required but should return better predictions and will be useful in modelling, if that is planned.Alternatively, one curve representing just one set of conditions — the most typical or the most easily obtained — could be constructed.

Antecedent conditions have not been well accounted for in inundation mapping to date, appearing as 'noise' rather than as a layer of potentially useful information. For this reason, the examples given are hypothetical (Figure 22).

Figure 22. Antecedent conditions

The solid curve refers to a wet floodplain or a winter flood with low evapotranspiration, and the dotted curve to a dry floodplain or a summer flood with high evapotranspiration.



Estimating storage volumes

Storage volume is the second unknown, after inundated area, needed to estimate floodplain wetland water depth. As described in Section 1, water balance calculations, ie. an assessment of all inflows and outflows, are required to determine the changes in storage volume of a wetland. Here, the techniques for estimating the different inflows and outflows are described. For floodplain wetlands, surface inflows from river flooding and evapotranspiration are usually the dominant input and output, respectively, so are dealt with in greater detail.

Estimating inflows

If surface inflows are predominantly a result of river flooding, then surface inflows to a floodplain wetland can be directly estimated using river flow data and *commence-to-flow* (CTF) levels (Note 32). If significant inflows come from local floodplain run-off, then rainfall–run-off calculations are used to estimate inflows.

For large and complex wetlands, estimating inflows directly may be difficult because of multiple and interconnected flowpaths, and hence it may not be possible to construct a water balance.

For small discrete wetlands, a time series of water depths can usually be obtained by direct monitoring using a water-level recorder. However, even for small discrete wetlands, the available record of water levels is often short, and simple modelling of inflows (using river flow or rainfall data) and outflows (mainly evapotranspiration) is used to extend the time series.

Using river flow data

Inflows can be estimated using river height or flow data together with CTF levels (Note 32). Flows may travel down relict channel features, also known as floodrunners, or down anabranches, or by general over-bank flow. CTF is the stage height at the nearest gauge at which river water begins to flow into the floodplain wetland. This reading (in metres) is converted to discharge using the rating curve for that gauge. The gauge may be either upstream or downstream, but must be representative of the CTF at the location of interest. For a gauge to be

Note 32
Determining CTFs

Commence-to-flow (CTF) levels can be determined by consulting with landholders, by surveying or by linking inundation area to river height or discharge.

Surveying is labour-intensive, and is more suited to individual wetlands than to wetland complexes. The lowest point in the sill between wetland and river must be identified, and its height above river level estimated, taking care to choose constant flow conditions, then relating these to the closest (usually upstream) gauge.

Likely sources of errors are locating the lowest point, and relating this to the gauge.

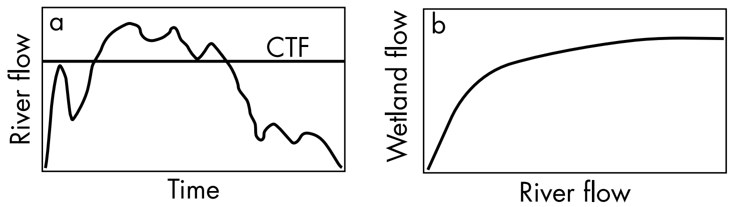
CTF for whole river reaches can be determined from inundation patterns. Remotely sensed images can define when flooding begins, and can be linked to river discharge. Timing of the image relative to flow is critical, ie. on rising limb and before flood peak. If several wetlands are processed simultaneously, this will give a statistical distribution for a river reach, thus facilitating trade-off decisions. A historical series can be compiled and be linked to other hydrological analyses, such as frequency and timing.

Imagery was used to define CTFs on the Barwon–Darling (Cooney 1994), on the lower Darling (Green et al. 1998) and is being used on the mid-Murrumbidgee floodplain (Frazier 1999).

representative, there should be no major inflows (for example, tributaries) or other outflows (for example, anabranches) between the gauge and the CTF location. The gauging station must have a reliable rating curve for higher flows and all or most of the floodwaters should pass the gauge in-channel. This is because direct gauging of out-of-channel flows to establish the high end of rating curves is extremely difficult.

Figure 23. Commence-to-flow and inflow

Left: a river hydrograph with a fixed commence-to-flow (CTF level); a proportion of the river flow above this level will flow into the wetland. Right: the relationship between river flow and wetland inflow for river flows above the CTF level; this defines what proportion of river flow enters the wetland.

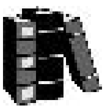


Determining CTF is relatively easy for a discrete wetland. It is much more difficult for floodplain wetlands, as these can be connected to the river by multiple surface flow paths, each with a different CTF level. Furthermore, the relationship between river flow and surface inflow for each surface flowpath is non-linear, reflecting the capacity of the distributary channel, the local gradients, and the surface and form roughness which provide resistance to surface flow. These factors mean that, for flows above CTF level (Figure 23a), the relationship between river flow and inflow to the floodplain wetland through a flood-runner is typically non-linear (Figure 23b).

CTF level must be accurately determined, as inflow volumes are very sensitive to value. To obtain accurate estimates of inflow volumes from historical or simulated river flow data, daily rather than monthly flow data must be used. Converting a CTF level based on daily flow data to a monthly total introduces large errors, because of the typically high level of sub-monthly flow variability.

A flow gauge close to the floodplain wetland is needed if historical river flow data are to be used and there must be reasonably long records from this. The high variability of river flow means a historical record of more than 50 years is desirable. If the historical record is only short, then it may be extended using catchment modelling based on a longer rainfall record. If the only flow data available are from a site remote from the study area, river hydrology modelling can be used to route flows through the system, and to provide flow estimates for the nearby river.

If the river is ungauged and river flows are estimated using a catchment rainfall–run-off model, then the CTF level can be estimated using an empirical, uniform-flow-resistance equation. The most common is the Manning's equation which expresses flow as a function of channel cross-sectional area, hydraulic radius (the cross-section area divided by the wetted perimeter), water surface slope, and a roughness coefficient, 'Manning's *n*' (Note 33).



Note 33
Manning's *n*

Manning's *n* can be estimated from tables of empirically derived values such as those in Chow (1959) or Pilgrim (1987). Channel dimensions can be measured in the field, and the water surface slope estimated from the floodplain surface (Gippel 1996).

Manning's equation

$$Q = 1/n\, A\, R^{2/3}\, S^{1/2}$$

where Q is discharge, A is cross-sectional area, R is the hydraulic radius, S is the water surface slopes, and n is a roughness coefficient.

Estimating local run-off inflows

Floodplain wetlands which receive significant inflows as run-off from their direct catchment are likely to be distant from the river channel and/or not well-connected to the river by flood-runners: for example, Lake Wyara (Note 34).

Commonly, floodplain wetlands with significant local run-off inflow also occur in arid or semiarid regions characterised by periodic high-intensity rainfall events. Examples are shallow riverine lakes, especially those partly formed by aeolian processes, since these typically occur in floodplains with few or inactive relict alluvial channels linking the wetland to the main river. Local run-off is seldom monitored and indeed such flows would be difficult to monitor directly. Instead, run-off must be estimated directly using run-off coefficients or more complex rainfall–run-off models; or indirectly as the residual from rainfall inputs and evapotranspiration loss calculations.

Both direct and indirect approaches require at least rainfall and land cover data.

Direct estimates

Run-off and rainfall. The simplest method to estimate surface run-off is using *run-off coefficients* and rainfall data.

A run-off coefficient is simply an estimate of the proportion of the rainfall which becomes run-off. Thus multiplying the run-off coefficient by the rainfall depth (or volume) gives an estimate of the run-off depth (or volume). Run-off coefficients may be used at annual, monthly, or daily intervals. However, as the time interval gets shorter, this method is more prone to error, since the time-varying soil moisture status of the catchment becomes an increasingly important determinant of actual run-off. Seasonal variations in evapotranspiration from the catchment are also averaged out by 'annual' run-off coefficients. The main drawback with using run-off coefficients is obtaining accurate values (Note 35).

USDA. Another simple method that is slightly more realistic is that for agricultural lands devised by the United States Department of Agriculture (USDA) Soil Conservation Service.

This takes into account the fact that 'losses' (that fraction of rainfall which does not become run-off) vary according to the amount of water the soil can absorb (USDA 1972, Williams and LaSeur 1976). This is, in turn, a function of soil type and antecedent soil moisture. The latter is related to the period since the last run-off event. The method uses sets of curves which relate event run-off to event rainfall; each different curve has a curve number which reflects the soil type and condition. Selection of a curve number from tables of empirically derived values allows run-off depth values to be read from a graph as a function of event rainfall depth.

Note 34
Lake Wyara

Lake Wyara on the Paroo River floodplain in south-western Queensland, is an example of a wetland system where local run-off is more important than river flooding.

In the last 108 years, Lake Wyara is estimated to have had only four inflows from river flooding, although the lake has probably filled at least 16 times (Timms 1998).

Note 35
Run-off coefficients

Run-off coefficients vary between regions, and within a region will vary systematically with catchment size. Because run-off coefficients are widely used, local authorities may be able to advise on appropriate values. Alternatively, published values of annual run-off coefficients for small catchments can be found in Nelson (1985) as a function of rainfall, evaporation, soil type and vegetation cover. Hudson (1981) provides simple tables to estimate annual run-off from small agricultural catchments, but the applicability of these to Australian conditions is unknown.

All of the curves are described by the equation:

$Q = [I - 0.2S]^2/[I + 0.8S]$

where Q is the run-off depth in millimetres, I is the rainfall depth in millimetres and S is the catchment storage value in millimetres.

S is related to the curve number, CN, by the following equation:

$S = 1000/\mathrm{CN} - 10$

This method of run-off estimation is used in a number of different hydrology models including the PERFECT model developed in Australia and validated using data from north-eastern Australia (Littleboy et al. 1992), and the Soil and Water Assessment Tool (SWAT) developed by the USDA. Curve numbers for different soil and vegetation types are determined from measured run-off volumes using the above equations.

Examples of some curve numbers based on Queensland data can be found in Freebairn and Boughton (1981). Tables of curve numbers from North American data can be found together with SWAT documentation (Web Listing).

Complex rainfall–run-off models. More complex rainfall–run-off models can also be used to estimate surface run-off inflow volumes. These require rainfall data, estimates of catchment evapotranspiration, and estimates of various catchment parameters to enable estimation of infiltration to the soil water store, and deep drainage from the soil moisture soil. Modelling rainfall–run-off modelling is seldom simple, and specialist expertise is usually required. A discussion of available catchment models and modelling is beyond the scope of this guide.

Indirect estimates

An alternative to estimating the run-off component directly is to assume that the rainfall on the local catchment of the floodplain wetland is transformed into either run-off or evapotranspiration.

As a residual. In this simple water balance approach, run-off can be estimated as the residual from rainfall inputs and evapotranspiration outputs. This assumes that any change in the soil moisture store is minor. This is a reasonable assumption only for longer time periods (months or seasons): accurate run-off estimates for single events are unlikely to be obtained using this method.

Rainfall and catchment. Rainfall inputs can be estimated simply from monthly rainfall depth data and catchment area: methods for estimating evapotranspiration are described (below). These are equally applicable (or more so) to the catchment area of floodplain wetlands, as to the wetland itself. An example of the use of this approach is the work of Crapper et al. (1996) who modelled the water levels in Lake Goran in the Namoi River catchment, New South Wales using rainfall data and estimates of evapotranspiration.

Rainfall and evapotranspiration. Another indirect method of estimating run-off from rainfall is the use of empirical relationships between rainfall and evapotranspiration; once again run-off is estimated as the residual. An example is the Holmes and Sinclair (1986) relationship based on long-term annual rainfall–run-off relationships for 19 large catchments across Victoria with mean annual rainfalls between

500 mm and 2500 mm. Because of the other variables affecting a catchment water balance, this approach can be expected to be useful only at annual time scales or coarser. The high rainfall data sets used in the Holmes and Sinclair relationship make it of little use for floodplain wetlands in arid or semiarid regions, although it may apply to those in temperate regions. It is not considered appropriate for tropical regions.

Estimating outflows

Determination of storage volumes requires estimates for outflows, or losses, from the wetland as well estimates of inflows. Evapotranspiration is usually the most important outflow on terminal floodplain wetlands, it is also one of the most difficult to estimate.

Evapotranspiration

Evapotranspiration is the total evaporative water loss from natural surfaces. On floodplain wetlands, it combines *evaporation*, which is water loss from open water surfaces, damp soil, and surfaces of living or dead plant material, with *transpiration* which is the diffusion of water as vapour from within living plants into the external airstream. The rate of this outward diffusion is mostly under active plant control (less so for aquatic plants) through controlled openings termed stomates, with control being related to carbon dioxide concentration, the rate of photosynthesis, and plant water stress levels. Transpiration occurs mostly while the plant is actively photosynthesising, that is in daylight hours (Section 2 and Note 8). In contrast, evaporation is continuous. For data sources relevant to evapotranspiration, see Note 36.

Evapotranspiration requires energy to supply the *latent heat of evaporation* to transform the liquid water into the gaseous state. Most of this comes from *solar radiation* but some also comes from the air, or thermal mass of water, soil and even vegetation as *sensible heat*, particularly in arid conditions or where vegetation surfaces are very well ventilated. Maximum evapotranspiration rates can be limited by the amount of available energy, but actual rates are more commonly limited by the amount of water in the root zone and the stress condition of the vegetation. Transpiration rates change through the year, influenced by seasonal conditions and canopy age.

There are three types of methods: direct measurement, indirect measurement and indirect estimate. All three are used, but only the third is recommended here for floodplain wetland water balance studies.

Direct measurement of evapotranspiration uses a water budget approach. This can be made only by growing plants in a sealed container and measuring all the water that enters, departs or is stored. This is called a *lysimeter* and, to be accurate, they should be continuously weighed (Note 37). The requirements for accuracy are strict: location and design are critical. Lysimeters must have as large an area as possible in order to be representative of the wetland vegetation, and they should be completely surrounded by a large expanse of identical vegetation to ensure that all energy exchange mechanisms are absolutely identical with the surrounding vegetation. Despite the apparent simplicity of this approach, errors are easily incurred and avoiding these requires a degree of technical expertise and experience.

Direct measurements using lysimeters can generate gross over–estimates of transpiration, by as much as 2–5 times, through inappropriate size,

Note 36
Evapotranspiration

A review of the available literature shows there are few wetland evaporation data for Australia. Suggested values for K_c and K_s are provided (Appendix 2) and linked to descriptions of Australian wetland vegetation. Long-term mean monthly data on areal potential evapotranspiration (APE) is satisfactory, and APE can be used as mean monthly values of ET_0.

Original and calculated data are being prepared for public release via the Bureau of Meteorology, either from maps or on CD-ROM; these will eventually include navigation and interpolation algorithms to allow estimation of values at any geographic location in Australia.

Limited climatic data sets are available from the Bureau of Meteorology web site (Web Listings), other meteorological variables are available, as computerised surfaces from certain universities, or from a commercial archives.

Note 37
Lysimeters

Much of the research using lysimeters or estimates of latent and sensible heat fluxes to estimate evapotranspiration has been for irrigated crops, although some includes field crops and natural surfaces. These data sets allow the development of methods of estimation based only on climatic data (see text). The best descriptions of this method and its application to irrigated cropping can be found in Allen et al. (1998) and Jensen et al. (1990): these also contain some information about natural surfaces including wetlands.

For problems with using lysimeters, see Allen et al. (1997).

monitoring, precision levels, scaling factors, and lysimeter location. For this reason, literature estimates of transpiration, especially those that are reported relative to an open water surface, should be viewed with caution. In many studies, the transpiration measured is not representative of the main stand of vegetation but indicative only of the abnormal conditions at its margins. Before using transpiration data from the literature, it is suggested that their reference condition be noted and compared with the recommended independent standard, such as 'well-watered grass surface' (Table A2 – 2). For these reasons, data based on lysimeters are unlikely to represent natural systems very well.

Indirect measurements of total evapotranspiration can be made by taking detailed aerodynamic and climatological measurements in the airstream above an evaporating surface. Such studies need to be done over time to determine how evapotranspiration changes through the seasons, or changes as the plant canopy matures then ages.

Measurements are made of the vertical gradients in temperature and water vapour concentration, from which the relative magnitudes and directions of the fluxes of latent and sensible heat can be deduced. Their ratio is termed the *Bowen ratio*, and one such technique is termed the *Bowen ratio method*. Temperature measurements can indicate energy storage rates in water, soil and plant mass per unit area and, together with measurements of radiant energy over the surface, can be used in the energy balance equation to deduce the latent heat flux rate and so the evapotranspiration rate.

Such studies are effectively site-specific research, requiring a greater level of technical experience than lysimeter studies.

Indirect estimates of evapotranspiration can be made using climate data. This is recommended as it does not require a major research project. Daily climatic observations can be used, but weekly or monthly averaged data or monthly climatic averages are more usual. In contrast to irrigated crops which are homogeneous, floodplain wetlands are a mosaic of evapotranspiration units, such as open water, exposed soil and different plant communities (Table A2 – 1). This heterogeneity makes the definition of type and areal extent less accurate than for large areas of irrigated cropping, so calculations using daily or weekly data are probably not worthwhile. In most cases mean climatic data are probably adequate.

- First, calculate evapotranspiration for a *reference crop* or *reference surface*, ET_o using a minimum data set of *incoming solar radiation*, R_s, *mean air temperature*, T_a, *mean water vapour content*, e_a, and *windspeed*, U, and the characteristics of the reference surface. These calculations are described in Allen et al. 1998, including the preferred method based on the *Penman–Montieth equation*. As the literature contains a variety of reference surfaces, such as shallow open water, lakes, well-watered grass, well-watered alfalfa / lucerne, it is important that the actual reference surface be clearly stated.
- Second, derive *crop coefficients* for optimal conditions, K_c and use these to estimate evapotranspiration under optimal conditions, ET_c as the product of ET_o and K_c. Evapotranspiration under optimal conditions is sometimes termed *potential crop evapotranspiration*.

- Third, estimate *actual evapotranspiration ETc adj:* this is usually different from ET_C for reasons such as the stress condition of the vegetation, the environmental difference from the theoretical well-watered surface of very large extent specified in ET_0 and ET_C. This final estimate of evapotranspiration, *ETc adj* is the product of a *stress coefficient*, K_S multiplied by ET_C; it is sometimes called *actual evapotranspiration* ET_a. This will be used here.

$$ET_C = ET_0 \times K_C$$

$$ET_C \text{ adj} = ET_C \times K_S$$

CAUTION: Values of ET_o, K_c and K_s depend on the reference surface, so if using values reported in the literature, it is essential to establish how they are calculated and expressed. Factors for converting from other reference surfaces to a well-watered grass surface, the reference surface recommended by Allen et al. (1998), are given in the Appendix 2 (Table A2 – 2).

Surface outflows

Surface outflows are a significant component of the water balance of most floodplain wetlands, especially during and immediately following a flood inflow event. Some terminal wetlands, despite their name, have water passing through, and in large flood events, this volume can be large. These surface losses may be via a single main channel, or more commonly, via many separate distributary or braided channels across the surface of an alluvial fan. Confined floodplains lose water through surface flows by transfer from one area to another, and ultimately back to the main river channel. These return flows occur as water levels in the river fall, typically via anabranches. Channels that carry floodwater away from the river may be different from those that return it. In contrast, for floodplain wetlands that are close to the main channel, the pathways for incoming surface inflows and for returning them to the river will frequently be the same.

Surface outflows typically occur quickly once river flood levels fall, at least down to the level where the surface topography retains water on the landscape (Figure 3). Because of the extremely low relief on lowland floodplains, the pattern or quantity of surface outflows can be easily altered, deliberately or accidentally, by obstructing or closing flood runners or by building levees across the floodplain. As with surface inflows, regulating structures are used to control both the amounts and timing of surface inflows and surface outflows. For example, the Menindee Lakes in New South Wales used to fill and drain naturally by surface flow from the Darling River. Both inflows and outflows are now managed, and the lakes are used for water storage.

Direct estimation of the surface outflow component of a floodplain wetland is difficult. Distributary channels are almost never routinely gauged, so hydraulic calculations are required. This requires application of a hydraulic resistance formula, such as the *Manning's equation* described earlier, using estimates of water levels, channel dimensions, slope, and roughness.

Groundwater interactions

Interactions between a wetland and underlying groundwater systems may be as inflows or outflows. Most floodplain wetlands have relatively insignificant (in terms of water budget) outflows to groundwater. Areas in the landscape which hold water are not free-draining and so are not usually areas of groundwater recharge. Some floodplains, however, are sites of significant recharge and deep percolation to groundwater, and in these cases groundwater losses must be considered. Techniques based on chemical properties, such as ionic concentrations and naturally occurring, stable isotopes can be used to quantify fluxes.

Many wetland systems have significant groundwater inflows and may be surface expressions of the groundwater system. Overall, groundwater inflows are usually volumetrically small. Hence, where the investigation is focusing on the impacts of changing river flows, rather than changing groundwater levels, groundwater inflows can be ignored in water balance studies. Records from the piezometer network should indicate whether major changes in groundwater levels have occurred, for example in relation to irrigation practices or, as often happens, in conjunction with river regulation. In these cases a more careful consideration of groundwater aspects is required.

Although not important in water balances, groundwater may be important for the vegetation, with groundwater inflows maintaining the floodplain wetland vegetation during dry periods. Determining the importance of groundwater for floodplain species is suggested as a specific activity (Section 5: Special studies; Note 20).

Factors affecting interpretation

Factors affecting understanding and interpretation of water regime, the components of the water balance, and effects on vegetation, include climate variability, water extraction and storage from the wetland, modifications to floodplain topography and roughness, and effects of water quality.

Climate variability

The high inter-annual variability of rainfall, and hence river flows, on the Australian continent have been clearly demonstrated (eg. Finlayson and McMahon 1988, Puckridge et al. 1998, Riley 1988). For example, Riley (1988) demonstrated significant *decadal* (10-year) variations in streamflow for a number of inland rivers in New South Wales, in particular, highlighting the drier than average period from 1900 to 1946 for these rivers. The magnitude of the differences in annual run-off volumes between these drier periods and the wetter periods is, in some cases, similar to the current annual levels of water abstraction from the rivers. This makes interpreting the impact of water resource development and determining environmentally appropriate water regimes, all the more difficult.

Climate variability should always be considered in hydrological investigations, especially when trying to describe 'natural' flow regimes, when designing environmental flow regimes, and when seeking to predict the outcomes for wetland vegetation of an environmental flow regime.

Water extraction and storage

Factors other than river flow which can dramatically change the floodplain wetland water balance are the construction of levees, the use of the wetland as an irrigation supply storage, and the use of the wetland as a sink for irrigation drainage water.

Water extraction from the wetland, by reducing the volume of water present, may have similar impacts as reduced flooding from the river. Conversely, using the wetland as a sink, that is increasing water, will have very different impacts.

Changes in groundwater levels in the vicinity of a wetland can also have significant impacts on the wetland water regime and hence on vegetation communities.The most common change in Australia is the raising of groundwater levels due to broad-scale irrigation, but groundwater extraction which lowers the watertable also has the potential to significantly alter wetland water regimes.

Modifications to floodplains

Because of the flat topography of floodplains, small changes in ground level have a disproportionately large impact on water movement and flood inundation patterns. Examples of this are levee construction to modify flood patterns; road and rail construction; aggradation and degradation of flow paths (Figure 24); and regulatory weirs in levee banks to controlled flooding. Roads and railways are frequently the flood boundaries by virtue of their slight elevation above the floodplain. These modifications to the floodplain affect relationships between inundated area and flood volume, as well as other river–floodplain linkages, including movement of juvenile fish and plant propagules, and the two-way exchange of organic debris and dissolved nutrients.

Certain floodplain land uses and land-management activities can significantly modify the hydraulic character of the floodplain.The use of floodplains for cropping, including dry lake beds, may alter soil properties and change the infiltration behaviour during the next flood. The type and condition of crops, the type and intensity of grazing, and the use of fire in forest management all have the potential to alter the roughness of the floodplain surface, and hence change the patterns of flood advance.

Water quality

The quality of the water within and entering a floodplain wetland can be a key component of plant habitat description, and is strongly related to catchment lithology, and land management of the catchment and floodplain. Even under natural conditions, there is a great variety of water quality conditions between different floodplain wetlands and through time, particularly in salinity and turbidity.The land use and management of the catchment is important in determining river water quality and hence floodwater quality, and changes in salinity, turbidity and nutrient levels are common. Irrigation drainage may carry elevated nutrient levels and loads of agricultural chemicals.Agriculture may also alter shallow groundwater quality, with subsequent impacts on groundwater-linked wetlands.

Finally, the way floodwater is managed on the floodplain may alter water quality. Small structures can pond water for long periods, where natural surface movement would otherwise occur, and may lead to interactions with organic forest litter, lowering the dissolved oxygen levels, and causing a build-up of various organic compounds such as polyphenols. The natural incidence of these *blackwater* events is poorly known.

Figure 24. Degraded channel

Part of the lower Gwydir floodplain showing a flood runner which has cut down; the banks and the floodplain are mainly covered with lippia. This type of erosion limits the spread of floodwater and can invalidate volume–inundation area relationships. Photo taken in dry conditions, in 1993.

Modelling wetland water balance

Once a time series for each inflow and outflow (or at least the dominant inflows and outflows) has been established for a matching period, prediction of changes in storage volume of the wetland through time is possible. This constitutes a model of the wetland water balance. Because each time series is likely to contain some degree of error, it is desirable to *validate* the model using independent estimates of storage volumes. In cases where the inflow and outflows have all been estimated directly from hydrologic, climatic and vegetation data (for instance river inflows and evapotranspiration outflows), images of inundation areas for different floods will provide an independent means to validate the water balance model.

A water-balance model can be used not only to explain past hydrologic behaviour but also to predict future hydrologic behaviour under altered conditions. For example, a model may be used to determine the impacts on storage volumes of an altered river flood regime. A model may also be used to predict the impacts of imposed changes in the vegetation, such as the changes in storage volume that would result from the removal of large trees from a floodplain. A discussion of catchment and river hydrology modelling techniques is beyond the scope of this guide (Note 38).

Spatial variability. Floodplain wetlands that have variable topography and soils will also have variable water regime and vegetation. This spatial variability must be recognised. Little can usefully be said about the expected vegetation response if the wetland is considered as an entity, represented by a spatially averaged water regime. Instead, water balance calculations should be undertaken on sub-components of the floodplain wetland. These sub-components should be areas that have nearly uniform hydrologic behaviour; examples are surface depressions with similar flooding and retention characteristics; or floodplain terraces with similar flood frequency and duration characteristics and similar vegetation roughness.

If aiming to restore the 'natural' water regime, it is less important to understand spatial variability than in the case of rehabilitation, where a prediction of the vegetation response is required.

Water movements. In low relief environments, such as lowland river floodplains, water moves relatively slowly and is strongly influenced by surface roughness. Water-balance calculations do not consider flow resistance, so may give a poor indication of how water moves and is distributed across the floodplain. For accurate predictions of this over short time steps, modelling water movement will be required. For example, if the topography and roughness of the floodplain are such that surface water flows at speeds of a few centimetres per second (equivalent to hundreds of metres per day), then to predict the daily distribution of water across a floodplain many kilometres in extent will require consideration of flow velocities and hence surface roughness. However, if it is only necessary to predict the monthly distribution of water, water-balance calculations and a consideration of the topography will be sufficient.

Modelling flow velocity requires a *hydraulic*, rather than a hydrological, perspective. Modelling the hydraulics of a floodplain wetland accounts for the energy involved in the surface flows, not just the volumes of

Note 38
Catchment modelling

To understand the mathematical techniques used in modelling rainfall–run-off process, overland flow and channel flow, see a general introductory hydrology text; for example, "Physical hydrology" (Dingman 1994). For more about the available models of catchment hydrology see "Computer models in watershed hydrology" (Singh 1995) and for floodplain hydrology and hydraulics see "Computer-assisted floodplain hydrology and hydraulics" (Hoggan 1996).

water. This requires representing the ground surface slopes (floodplain topography) and the surface roughnesses. Surface roughness can change dramatically with vegetation type and condition, or with changing soil surface condition.

Topographic and roughness data can give a two-dimensional representation of the movement of water across the floodplain, based on complicated hydraulic calculations. The data needs and complexity of the calculations depend on the level of spatial representation that is used. The level of detail should be determined by the level of spatial resolution required to provide information to enable the required predictions of vegetation response. Hydraulic modelling of floodplains is a major undertaking, usually based on complex computer modelling using large data sets. Accurate calibration or even validation of such models is often constrained by the lack of appropriate data to describe floodplain water movement.

Australian examples

Five Australian examples of wetland or floodplain hydrology modelling are described below, all from the Murray–Darling Basin. The first is a simple water balance approach. The second is an empirical model based on relating river levels to inundation imagery. The third and fourth examples are of hydraulic floodplain modelling: one of the lower Macintyre River floodplain by Connell Wagner (Qld) Pty Ltd, the other of Condamine–Balonne River floodplain by the Snowy Mountains Engineering Corporation (SMEC) (Marr 1999). The last example describes the range of different wetland and floodplain modelling approaches used in the IQQM river hydrology model developed by the NSW Department Land and Water Conservation.

EFDSS and the Murray–Darling Basin

One of the simplest approaches to representing water movement through a wetland complex was taken in the development of a floodplain water balance model by Whigham and Young (1999), for use in an environmental flows decision support system (EFDSS) (Young et al. 1999).

The EFDSS imports daily river flow data from an external river hydrology model, and uses this to run a simple water balance model for linked storages or elements (Whigham and Young 1999). The water balance model is conceptualised as a series of connected pipes and storages. Pipes have a minimum level at which flow begins, and a maximum capacity. Storages have a constant area, a maximum capacity and an exponential decay on storage volumes. These parameters can be used to 'calibrate' the behaviour of the floodplain model to the observed pattern of storage volumes or water levels. It is not intended that the model be used to represent groundwater inflows or direct rainfall inputs, although these could be represented using pipes. Pipes are used to represent surface inflows: while outflows are represented using pipes and/or the decay function on storage volumes. Typically, surface outflows are represented using pipes, and the decay function is used to represent the cumulative effects of evapotranspiration and groundwater outflows.

The two main limitations of the model in its present form are that storages have a constant area (rather than a volume–area relationship) and so depth estimates are inaccurate and the storage volume decay function is not seasonally variable.This means that the strongly seasonal patterns in evapotranspiration cannot be represented.

The lower River Murray, South Australia

For the floodplain of the lower River Murray in South Australia, an inundation prediction model has been developed based on satellite imagery.

The model predicts the area of the floodplain inundated solely on the basis of river flow level. River and weir-pool water levels are simulated using the River Murray Flow Model. Satellite images taken at known river levels were used to develop a relationship between area inundated and river water levels.

The floodplain is represented as a series of 'flood inundation response units' each of which floods in response to a given water level at a given 'trigger point' (Sykora 1999).The model predicts whether an area of the floodplain will be wet or dry at any given time, but does not predict water depth. Because there are several locks to regulate water levels on the lower river, there is a considerable degree of control over what areas will be flooded. Furthermore, the low river gradients mean the flood hydrograph travels slowly, and so with advance warning, locks can be manipulated either to minimise flooding (opening locks), or to inundate certain areas for environmental purposes.

The Macintyre and RUBICON

The model developed for the lower Macintyre River floodplain used the RUBICON unsteady flow hydraulic model.The RUBICON model was developed by the Wallingford Institute of Hydrology (UK) and the Danish Hydraulics Institute. It was applied to the Macintyre River floodplain to investigate the impacts of proposed levee constructions, but could also be used for environmental investigations. RUBICON represents floodplains as a network of nodes and linking branches.

Hydraulic model for the Condamine–Balonne

For the Condamine–Balonne River floodplain, SMEC used an 'in-house' hydraulic model which employs an implicit finite difference algorithm to solve the equations for conservation of water mass and momentum and thus route flows through a multi-channel network. Importantly, even during the rising limb of the flood hydrograph, the direct rainfall inputs to the water surface and the evaporation and infiltration losses were large, and had to be computed at every time step (Marr 1999).

IQQM in New South Wales

The Integrated Quantity and Quality Model (IQQM) of river hydrology developed by the New South Wales Department of Land and Water Conservation has used several different representations of floodplains and wetlands (Podger, pers. comm. 1999).

- In the model of the Border Rivers system, several floodplain storages are linked to the river channel.Variable flows into these storages are calculated as a function of the water level difference between the river and the storage, and of the crest level between the river and the storage. Flows back from the storage to the river occur at a constant rate below a given level difference threshold.

- In the model for the lower Darling River, the Menindee Lakes are represented as interconnected storages. Flows in both directions are determined as a function of water level differences.
- For the Lowbidgee section of the Murrumbidgee River, the IQQM model determines the outflows down the various distributary channels from a series of look-up tables that record the relationship between river flow rate and distributary channel flow rate.
- IQQM development work is in progress to represent the complex Macquarie Marshes on the Macquarie River. These developments are most likely to be based on a one-dimensional network representation, as used in the RUBICON hydraulic model. The move to hydraulic modelling for IQQM will impose the additional complexities of ensuring conservation of momentum of water movement (velocity of water movement), as well as simply the conservation of water volumes. Slow travel times, which are a feature of very flat topography such as the lower Macquarie (and other inland rivers), mean that hydraulic modelling can realistically be attempted on a 12-hour or even one-day time step. The development of hydraulic components to IQQM for floodplain wetlands will greatly enhance its usefulness in floodplain wetland investigations and management.

Section 7: Predicting Vegetation Responses

The general procedure advocated in this guide is to use vegetation–hydrology relationships to predict the likely future state of floodplain wetland vegetation as a result of proposed changes to water regime. The process of making these predictions is referred to as modelling. While modelling may be as simple as expert predictions based on a conceptual model, in general it involves repetitive calculations to describe the temporal and/or spatial patterns in vegetation response. This section identifies four different categories of modelling, based loosely on the complexity of the modelling approaches, and describes them using examples from Australia and North America.

Simulation modelling

Wetland vegetation management, as advocated in this guide, is based on couching management objectives in terms of vegetation target conditions, and determining the water regime required to achieve these. Rehabilitation is philosophically different from restoration, which seeks to return to some prior condition.

With restoration, there is an assumption that, in the absence of other significantly modified conditions (for example, grazing), restoring the prior water regime will be sufficient to effect a change back to the prior vegetation condition. Thus, for restoration, it is not necessary to determine vegetation-hydrology relationships; it is enough just to determine what the prior hydrology was.

With rehabilitation, however, the vegetation targets are different from a known prior condition, and vegetation-hydrology relationships must be defined to enable specification of the necessary water regime to achieve the vegetation targets. However, it is seldom possible to use these relationships to say "We want the vegetation to be like ***this***, therefore the water regime must be ***that***". There are several reasons for this. First, the relationships between water regime and vegetation are not simple, either in terms of the number of variables or their form. Even simple measures of vegetation depend on several components of the water regime; responses are likely to be non-linear and include critical thresholds. Second, high spatial and temporal variability are typical of both the water regime and the vegetation in most Australian floodplain wetlands. Characterising this variability in descriptions of the target condition is difficult. Finally, because our knowledge of these relationships is so imperfect, it is unlikely that a single water regime description will relate to a single vegetation condition description. Rather, it is likely that several different water regimes (expressed as tolerance ranges) will, to the best of our predictive ability, result in the same vegetation condition.

Instead of using relationships in an *optimising* manner (what water regime is needed to achieve a specific vegetation condition) it is more realistic to use them in a *simulation* manner. Simulation, or scenario-testing, asks: "If *this* is the water regime, then what is the vegetation likely to be?" Or even "If no plan it put in place, then will the vegetation be the same?" (Note 39). Determining the water regime to achieve a vegetation target by simulation necessarily requires iteration. The modelling described in this section is all simulation.

Note 39
The 'do-nothing' option

The 'do-nothing' option is just as important a scenario in decision-making as all the other flow management options, and should have equal treatment.

The do-nothing option describes what the vegetation is likely to be, based on current trends.

It can be explored using hydrologic simulations, trend analysis or just vegetation data transition probabilities, such as Markov chains. This is a specialised area of data analysis.

The results of a simulation describe the expected vegetation patterns (spatial and or temporal) under a particular water regime. Simulations may be undertaken for the historical climate conditions with changed water management *scenarios*, or for *stochastic* climate conditions under a range of water management scenarios. Stochastic climate conditions are generated based on the statistical properties of the historic record, and therefore represent 'typical' climatic sequences. These are neither forecasts nor projections. As well as water-management scenarios, climate-change scenarios may be of interest. These may include changes in rainfall amounts, rainfall variability, or temperature, and humidity changes that will alter evapotranspiration. Climate change scenarios are investigated by modifying the climate input data, either the historic climate data, or the stochastically generated climate data. Climate- and water-management change scenarios may of course be combined to investigate the likely range of wetland vegetation outcomes for different possible futures.

The approaches to modelling vegetation response can be categorised according to how the water regime is modelled and the nature of the vegetation–hydrology relationships. Depending on the nature of the relationships, predictions may include the pattern of temporal changes in vegetation at a 'point' under given water regimes, the static spatial pattern of vegetation at some future 'equilibrium' condition, or a more complex combination of the spatial and temporal dynamics of the wetland vegetation under different water regimes. Four categories are used below to describe the major differences in modelling.

Category 1: hydrologic/expert opinion

Approaches in this category rely on hydrologic modelling (water balance) of the water regime, and vegetation–hydrology relationships derived from expert opinion. Relationships of this type may be qualitative and stated as logic rules, as in expert systems, may use quantitative but non-dimensional representations such as index values, or may use quantitative empirical relationships or 'rules of thumb' based on experience.

Although approaches in this category are the simplest, there is a considerable range in their complexity because of the different levels of spatial detail used in hydrology modelling, and to the range in complexity of expert-derived relationships.

AEAM and the Macquarie Marshes. An example of a very simple approach is that taken by Norris and Jamieson (1990) in their development of an 'adaptive environmental assessment and management' (AEAM) computer model for the Macquarie Marshes in New South Wales. The AEAM method for assessing environmental impacts was developed in Canada in the early 1970s by Holling (1978). In AEAM, the interactive process involving scientists, managers and community to develop the computer model is considered more important than the model predictions themselves. It provides a means of reaching a shared understanding of the system under investigation, and a framework for communication between stakeholders. The AEAM model of the Macquarie Marshes includes a monthly water-balance model, a vegetation model and an agriculture model. The water-balance model calculates the storage volume in each of 12 water-management areas at each time step, based only on the initial storage volume, maximum storage volume, river inflow, and evaporation. This is a very simplified water balance, assuming no groundwater interactions, no direct rainfall input, no transpiration and no surface outflow. The vegetation model is based on five 'vegetation' categories (including permanent open water) and a set of rules which describe the hydrologic pre-conditions for a grid cell to change from one type to another. The rules are based on expert opinion, with no validation of the model.

EFDSS and lowland rivers. Another simple approach is that taken by Young et al. (1999) in their development of an 'environmental flows decision support system' (EFDSS) for lowland rivers in the Murray–Darling Basin.

The EFDSS includes a floodplain hydrology model (Section 6: Australian examples) to provide a wetland storage volume. It then uses these storage volumes to drive the model of vegetation response. For modelling vegetation response, the EFDSS provides a simple framework that allows users to define vegetation 'classes', which may be individual species, associations, or communities. For these vegetation classes, the user describes the habitat preferences for different hydrologic variables. The habitat preferences are represented by dimensionless index values ranging from zero to one. The overall habitat condition is determined by a simple arithmetic combination of the index value preferences for each hydrologic variable. The modelling framework considers both 'adult habitat' and 'regeneration habitat'. The hydrologic variables for which preference curves must be defined are fixed, and include inundation duration, inundation timing (season), inundation frequency, pre-inundation dry period duration, and inundation depth.

IQQM and Macquarie Marshes. A third example in this category is the modelling of the Macquarie Marshes in New South Wales by Brereton et al. (1996). In this work, a relationship between the river flows upstream of the Marshes was developed from comparisons of river flow data and flood extent maps. Using the IQQM hydrology model (Section 6: Australian examples) for the Macquarie River, the flood sequences for different flow-management options were simulated. From mapping of the Marshes vegetation together with the flood extent maps, three vegetation classes were defined. The different vegetation classes were based on identifying the areas flooded by different size floods, and identifying the dominant species in these different flood regions. For each of these vegetation classes, four different health categories were defined in terms of the previous year's flood regime.These categories were based on visual inspection and expert interpretation of the flood regime for the 'natural' scenario from IQQM.The natural scenario uses the historic rainfall series to generate flows in the river system with no regulation and no diversions. One-hundred-year simulations using IQQM therefore allowed time series of the health status of each vegetation class to be generated.

Category 2: hydrologic/empirical

Approaches in this category again rely on hydrologic modelling (water balance) of the water regime, but use empirical vegetation–hydrology relationships derived from analysis of relevant data.The empirical relationships may have been derived for the location being investigated, or may have been derived from prior investigations in similar locations. The empirical relationships may be based primarily on analysis of spatial data, or on analysis of time series data, or on complete analysis of spatio-temporal patterns.The nature of the available relationships will dictate the nature of the possible predictions. Relationships may take various forms, including regression models (linear or higher order relationships), and probabilistic models based on definition of joint probability distributions; for example, the probability of vegetation measure 'A' occurring in water regime class 'B' (Section 4).

Prairie wetlands, ND.An example is the modelling work of Poiani and Johnson (1993) for two semi-permanent prairie wetlands in North Dakota.The modelling included a simple daily water balance model for individual wetlands.The water balance included direct rainfall inputs, local run-off, and evapotranspiration. Groundwater exchanges were not directly considered.The water elevations determined by the water balance model were used together with ground elevation data to calculate water depths for each cell in a grid representation of the wetland. Six vegetation types (of species with similar life-histories) and an open water category were used in the vegetation response model. The vegetation response model is a series of rules that describes the seasonal water regime conditions necessary to effect a change from one vegetation category to another.These rules were based on data, observations and analysis from a significant amount of prior field research by various investigators in these prairie wetlands. Both models were developed and calibrated using data from one wetland, and then run and evaluated for a second wetland.

Riparian wetlands, Ontario.A second example is the logistic regression vegetation–hydrology model of Toner and Keddy (1997) for riparian wetlands in Ontario, Canada. In this investigation, models were developed to simply predict the presence or absence of woody cover, as determined by locating the woody–herbaceous boundary within a wetland.A set of seven hydrologic variables was selected to reflect the depth, duration and time of flooding. Relationships between vegetation (woody or herbaceous) and the hydrologic variables were established by logistic regressions. Relationships were developed using first, each hydrology variable and four other site variables, and second, all possible combinations of the seven hydrologic variables. Statistical criteria were used to select the best model generated.The model was not independently validated by the authors, nor was it linked to a hydrology model for use in scenario simulations.

Category 3: hydraulic/empirical

Approaches in this category are similar to those in Category 2, except that here the water regime is modelled in greater detail, using hydraulic modelling. This puts a considerable extra level of complexity on the water regime modelling, and associated extra data demands. The prediction of water depth and flow velocities increases the range of water regime parameters on which vegetation–hydrology relationships can be based. The range of types of empirical relationships is the same as for Category 2.

Riparian vegetation and inundation. An example is the work of Auble et al. (1994) who investigated the relationships between riparian vegetation type and the percentage of time inundated. The model is based on gradient analysis along a gradient of percentage of time inundated. Three vegetation types and an open water category were defined and, by sampling randomly located plots, the probabilities of each vegetation type occurring in each of 12 inundation duration classes were determined. The HEC-2 (Hydrologic Engineering Centre 1990) hydraulic model was used to predict water levels at different river cross-sections under different water management scenarios. These water levels were translated into predictions of the proportion of plots in the different inundation duration classes. These, coupled with the probabilities of vegetation types occurring in each class, enabled calculation of the proportion of the total area that would be in each cover type. A probabilistic model of this type could easily be implemented in many wetland situations using hydrologic rather than hydraulic modelling.

Category 4: hydraulic/process

Approaches in this category are the most complex, involving both hydraulic modelling of the water regime, and process-based modelling of the vegetation response. By 'process-based' is meant that at least some aspects of physiological vegetation response to the water regime are modelled. Modelling the physiological responses of the vegetation to the water regime requires detailed information of soil, vegetation, water quality and climate parameters. Because of the large data demands and the computational complexities, this sort of modelling is often conducted only at single sites. Modelling the spatial patterns in vegetation at larger scales based on this detailed level of soil–vegetation–atmosphere dynamics is very complex and because of the data demands and computation costs is normally only attempted for areas of a few square kilometres at most.

Chowilla floodplain, SA. An example of modelling the physiological responses of vegetation at a site is the work of Slavich et al. (1999) for black box trees (*Eucalyptus largiflorens*) on the Chowilla floodplain in South Australia. The model used (WAVES) was a one-dimensional daily time step model describing water and carbon transfer through the soil–plant–atmosphere system. Simulations investigated the changes in vegetation growth and salt accumulation in the soil in response to changes in watertable depth and flooding. Changes in watertable depth were imposed to simulate the effects of groundwater pumping. The changes in flooding that would result from changed operation of upstream regulating storages were determined empirically using regression equations relating river discharge to flood heights. In this sense, the water regime was represented in very simple hydrologic terms.

However, this and similar studies are reasonably placed in this category, because the soil water regime must be modelled in considerable hydraulic detail, including solving Richard's equation for unsaturated flow through the soil profile.The hydraulic modelling of the water regime in this case is for vertical water movement in this soil, rather than for horizontal surface flows.A process-based equation is included to estimate transpiration.The model is used to predict the changes in canopy leaf mass, by estimating the carbon assimilation rates. It assumes that soil water availability, determined by daily soil matric and osmotic potential, modifies canopy gas phase conductance and hence carbon assimilation rate, and the proportion of assimilated carbon allocated for canopy growth (Slavich et al. 1999).

Slavich et al. (1999) acknowledge that while water availability is probably the major control on leaf canopy area, many other factors also play a role.The predictions therefore represent potential vegetation responses.The model has not been validated, but sensitivity analyses have shown that predictions of LAI are sensitive to relatively small changes in the parameter that represents the proportion of carbon allocated to leaves.This parameter cannot be measured at the canopy scale over any significant period, and so must be calibrated.

Plantations, northern Victoria.An example of process-based vegetation response modelling in spatial simulations is the work of Silberstein et al. (1999) in modelling plantation growth in northern Victoria. In this work, spatial representations of soil profiles, vegetation type and climate are used in 'TOPOG_Dynamic', a three-dimensional version of the WAVES model described earlier.The water regime is modelled hydrologically above the soil surface, with rainfall, run-off, evaporation, and transpiration estimated for each catchment element. The vertical and lateral movement of water infiltrating into the soil profile is modelled hydraulically. In the application reported by Silberstein et al. (1999) predictions were compared with field observations.These showed reasonable to good agreements in the time series outputs of watertable depth and different vegetation responses within calculated error bounds.

Although TOPOG_Dynamic has not been applied in wetland vegetation modelling, its representations of water regime and of plant response are equally appropriate for modelling the growth of woody wetland species. Because of the data demands and computational complexity of the model, it is not suitable for application to areas more than a few square kilometres at most.Although in the implementation described above, surface water movement was adequately represented hydrologically, versions of the TOPOG model have employed solutions to the kinematic wave equations for determination of surface flow hydraulics (eg.Vertessy and Elsenbeer 1999).These algorithms could be implemented in hydraulic simulations of surface flows in wetlands, together with the spatially explicit predictions of tree responses.

Everglades.A third example is the work undertaken in the Florida Everglades and reported by Fitz et al. (1996).This work involved the development of a general ecosystem model (GEM) that captures the feedbacks among abiotic and biotic components of the wetland system.

For example, changes in surface and sub-surface water and nutrient availability are explicit controls on algae and macrophyte growth, while macrophytes influence surface water availability via transpiration, and surface water movement by their contribution to surface roughness.

The GEM is run as a unit model embedded in the cells of a spatial model. Modelling the water regime includes water-balance calculations that partition water into three separate stores (above surface, the unsaturated soil zone, and the saturated soil zone) and hydraulic calculations of surface water movement. The macrophyte growth model predicts changes in photosynthetic carbon biomass by a production model limited by a multiplicative environmental control function that includes light, nutrients, temperature and water. The macrophyte model is a small part of the large and complex GEM, which is designed for exploration of large ecosystem dynamics rather than the specific and accurate prediction of a single component such as vegetation. Fitz et al. (1996) do not report on any attempts to validate the models described.

Finally, it should be pointed out that many complex, spatially distributed models have been developed: of catchment and river hydrology; of surface and sub-surface hydraulics; and of vegetation response. The development, refinement and even use of such models are major undertakings that require considerable resources, especially appropriate modelling expertise. The coupling of hydrologic/hydraulic models adds an extra level of complexity, and while examples have been quoted, there are few examples for major wetland systems, no examples for floodplain wetlands in Australia, and all examples are better viewed as research investigations than wetland management applications.

Concluding Remarks

The decision on what modelling approach to take is usually determined by resource constraints: how much time and money are to hand, and what data are already available? If these are in relatively short supply, approaches such as AEAM and the EFDSS provide useful frameworks for capturing and integrating expert opinion and using it in simulation modelling. These approaches are also suited for use in interactive workshops that facilitate stakeholder participation and education.

Where more time and money are available, more detailed investigations will be possible, but note that the development of such models is a major research undertaking, and a major investment. Detailed modelling of large, heterogeneous floodplain wetlands will always present a major challenge, at least in terms of data requirements. It is unwise to embark upon complex modelling studies of a floodplain wetland system without a clear understanding of the reasons for doing so, and without a realistic assessment of the time, money and skills needed for the task.

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Web Listings

The Internet listing and addresses given in this section are a sample only of what is available, provided as starters. Surfing and following related links will reveal numerous others (Note 40). Details were correct at time of publication but internet addresses and server locations frequently change so no guarantee can be made regarding links and connections.

Note 40
Data on the Web

More and more information is being stored on the Web or available through it. At the start of an investigation, it will be worthwhile determining: what types of data are available through the Web; what is relevant to the study site; whether it is free or has costs; and whether it is easy to download and is in a compatible format. As this is likely to date quickly, it will also be worth considering whether to access Web information once, or on a continuing basis; if the latter, then to ensure resources are adequate. As an introduction to Web information, some relevant sites are given in this Web Listing.

Soils data

Geotechnical maps for the Murray–Darling Basin, by EN Bui, CJ Moran and DAP Simon
http://www.clw.csiro.au/publications/technical98/tr42-98.pdf

Murray Darling Basin Soil Information, Bureau of Rural Science
http://www.brs.gov.au/mdbsis/maps/index.html

Australian Geological Survey Organisation (AGSO)
http://www.agso.gov.au/

SWAT, a Soil and Water Assessment Tool developed by USDA using a run-off estimation method
http://www.brc.tamus.edu/swat/index.html

Climate and weather data

Bureau of Meteorology
http://www.bom.gov.au/

SILO, meteorological data for agriculture
http://www.bom.gov.au/silo/

The Long Paddock, climate data for agriculture and the environment
http://www.dnr.qld.gov.au/longpdk/index.html

Biological data

Interim Biogeographic Regionalisation of Australia (IBRA)
http://www.environment.gov.au/epcg/erin/guidelines/technical/dsdl/natmis/examples/ibra.html

River Rehabilitation Manual for Australian Streams by Ian Rutherfurd, Kathryn Jerie and Nicholas Marsh
http://www.rivers.aus.net/publicat.htm

Directory of Important Wetlands. It explains how to find this kind of information, and information about the wetlands listed in the Directory
http://www.environment.gov.au/wetlands

Environment Australia. At this site species records can be used to generate maps of potential distribution
http://www.environment.gov.au/search/mapperf.htm

Remotely sensed and digital imagery

ACRES (Australian Centre for Remote Sensing)
http://www.auslig.gov.au/acres/index.htm

AUSLIG (Australian Surveying and Land Information Group)
http://www.auslig.gov.au/

Appendix 1: Remote Sensing

Choice of application

Remote sensing has several potential applications when estimating the water requirements of floodplain wetlands. Examples are: to compile an inundation map for a depth measurements; to compile a time series or an event-series of inundation; to map vegetation; to monitor vegetation. Applications using radar still under development and not fully ready for routine use include: to define the phreatic surface; to characterise the sub-surface sediments; to recognise individual species.

A summary of costs, technical specifications regarding space-borne and aerial sensors, coverage dates, overpass frequency (satellite imagery) and scene size are given in Tables A1 – 1 and A1 – 2. For a comprehensive review, and pointers to future applications, consult:

> "Evaluation of the feasibility of remote sensing for monitoring national state of the environment indicators" by J. Wallace and N. Campbell 1999. Australia: State of the Environment Technical Paper Series (Environmental Indicators), Department of the Environment, Canberra.

Choice of application is usually determined by size of study area, resources available, intended use and availability. As a general guide, final choice depends on size and scale: applications most suitable for small wetlands or individual billabongs are generally inappropriate, cumbersome or even too expensive for large floodplain wetlands: and vice versa. Therefore while it is valid to copy what has been done elsewhere, this should be done with caution, making sure it suits the study area.

Inundation mapping

Both aerial photography and satellite imagery have been used for inundation mapping in Australia; the use of radar is just beginning. For large areas it is more cost-effective to use historical satellite imagery than to obtain historical colour photographs (if available). The reverse is true for small wetland areas, where aerial photography, preferably colour if available, is most suitable as it gives better resolution.

Current practice regarding inundation mapping in Australia has been to use historical satellite images to build up an incremental sequence. Availability of historical material (Table A1 – 2) and the high variability of most Australian rivers means the source material is effectively constrained to Landsat TM and/or Landsat MSS; sometimes to Spot imagery if lucky with an appropriate flood sequence in the last 13+ years. Examples of this approach are given in Note 31.

An alternative to using historical imagery is to commission airborne hyperspectral or radar imagery, and build a sequence by following one flood. This has not been attempted, but the technical advantages are enticing: radar can penetrate through cloud and through overhanging vegetation; hyperspectral imagery has fine spatial resolution; and following a single flood would remove much of the 'noise' associated with obtaining images from different points in time.

Table A1 – 1. Sensor, cost, and suitability for floodplain wetland management

Sensor	Cost	Potential use in floodplain wetland management
Spaceborne	*Cost per scene*[a]	
Landsat MSS	$700	Vegetation condition monitoring, inundation mapping
Landsat TM	$5,250	Vegetation condition monitoring, broad classification, inundation mapping
SPOT MS	$1,700	Vegetation condition monitoring, broad classification, inundation mapping
SPOT Xs	$1,900	Inundation mapping
NOAA AVHRR		Secondary image selection, NOAA-greenness index to track vegetation response
RADARSAT	$6,150	Inundation mapping, canopy moisture content, weather and sun independent
ERS-1 SAR	$2,200	Inundation mapping, weather and sun independent
Airborne	*Cost per hectare*[b]	
AVIRIS	Not commercially available	Medium resolution vegetation mapping, inundation mapping
CASI	$1.50	High accuracy vegetation mapping, inundation mapping
HYMAP	Not commercially available	High accuracy vegetation mapping, inundation mapping
LIDAR	Not commercially available	Floodplain DEM construction
AIRSAR	Not commercially available	Vegetation mapping based on structural information, inundation mapping weather and sun independent
Video	$1.60	
Aerial photography		
CIR Aerial photography		

a Scene size varies between sensors (see Table A1 – 2: Specifications for sensors suitable for floodplain wetland management). Costs are based on the best available resolution, and minimal pre-processing. For a more comprehensive guide to costs visit the ACRES web page at http://www.auslig.gov.au/acres/index.htm

b Cost per hectare varies according to the area and location flown. These prices are based on a quote for 50,000 hectares at 1 m × 1 m resolution somewhere in the Murray–Darling Basin.

Note: prices are subject to change and these data should be used as a guide. Dollars were correct as of mid-1999.

Image selection

This section relates to use of satellite imagery for inundation mapping, especially where it is intended to build a time series using historical images.

Prior to ordering images, it is advisable to become familiar with history of river flows within the proposed time frame (hydrograph return times, hydrograph shapes), with rainfall records, and whether there have been substantial changes in the catchment or river. Graphical preparation, ie. placing symbols of when imagery is available onto hard copy hydrographs, and marking inappropriate times such as when cloud cover is high based on weather records or when there are gaps in flow records, has not been done but would be useful. Image selection can then proceed by a process of elimination, resulting in a short list of appropriate dates. The selection should span a range of flows, target specific conditions, be free of cloud, be recent, and be standardised for antecedent conditions; most importantly, there should be river flow or wetland inflow data available (ie. no gaps in records).

Table A1 – 2. Specifications for sensors suitable for floodplain wetland management

Spaceborne sensors	Coverage dates	Spatial resolution	Spectral resolution	Overpass frequency	Scene size
Landsat MSS	1972–present	80 m × 80 m	4 × 10–20 nm bands vis–nir	16 (currently, less frequent in past)	184 km × 172 km
Landsat TM	1982–present	30 m × 30 m	7 × 10–20 nm bands vis–nir–swir	16	184 km × 172 km
SPOT MS	1986–present	20 m × 20 m	3 × 10–20 nm bands vis–nir	26 days (less for off nadir view angles)	60 km × 60 km
SPOT Xs	1986–present	10 m × 10 m	1 × 25 nm band vis	27 days (less for off nadir view angles)	60 km × 60 km
NOAA AVHRR	1979–present	4000 m × 4000 m	4 × 10–20 nm bands vis–nir	7 days (nominal)	global NDVI product available as CD-Rom
RADARSAT	1995–present	10 m × 10 m	radar	Flexible	50 km × 50 km
ERS–1 SAR	???	30 m × 30 m	synthetic aperture radar	35 days	100 km × 100 km

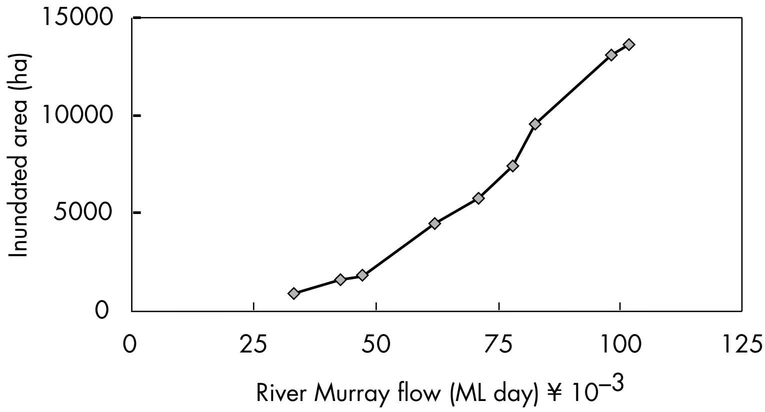
Airborne sensor	Sensor type	Spatial resolution	Spectral resolution	Spectral range	
AVIRIS	Hyperspectral	20 m × 20 m	10 nm, 224 bands	400–2500 nm	as acquired
CASI	Hyperspectral	0.8–5 m^2	2.2 nm min., 10 – 72 bands	400–1000 nm	as acquired
HYMAP	Hyperspectral	2–10 m^2	16 nm, 128 bands	400–2500 nm	as acquired
LIDAR	Profiling laser	3 m intervals horizontally	minimum vertical accuracy 10–15 cm		as acquired
AIRSAR	Synthetic aperture radar	10 m × 10 m	3 microwave bands		as acquired
Video	visible	1 m × 1 m	filtered panchromatic		as acquired
Aerial photography	visible	1 m × 1 m	panchromatic		as acquired
CIR Aerial photography	multispectral	1 m × 1 m	3 × 10–20 nm bands		as acquired

Seven points over the flow range is barely enough to define the shape of an incremental inundation map, and ten points is suggested as a target. Nine points for the Chowilla floodplain (Figure A1 – 1) were enough to define the linear part of the inundation-area curve (Figure 20).

The type of floodplain, whether confined or unconfined, can influence how inundated area is presented, and what hydrologic variable to use. On confined floodplains, such as Chowilla, where the total floodplain area can be defined, then inundated area can be expressed as a percentage of the floodplain, which can be a more effective communication tool than absolute area. The data shown (Figure A1 – 1) range from 5.2% at 33,110 ML/ day to 77.2% at 101,100 ML/day.

Figure A1 – 1. Inundation-area curve

Inundation-area curve for a confined floodplain wetland, the Chowilla floodplain, South Australia. The nine images cover a range of flows from within a relatively narrow time frame, from 1984 to 1990, for a rising limb (from Noyce and Nicolson 1993).

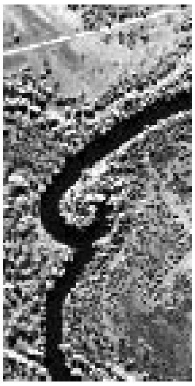


Inundation area can be related to hydrologic variables using linear and non-linear regression analysis. If the regression is statistically significant, it can be used predictively, but should not be applied beyond the range of the data used in the defining the linear part of this curve. Numerical analysis is relatively new and has been tried in relation to the Great Cumbung Swamp by Sims (1996) and by Brady et al. (1998). Multiple regression is one way to accommodate antecedent conditions, and was tried on the Lachlan River. The mixed success of this first attempt (Table A1 – 3) does not invalidate this approach, which could have great value if predictive ability could be improved. In this case, the combined rainfall/evaporation factor contributed most to the discrepancy.

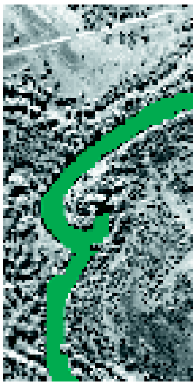
Standardisation Standardisation is as important as other factors in limiting interpretation, and in achieving cost-efficiency. Nearly all investigation on floodplain wetlands in the Murray–Darling Basin have found that, for a number of reasons, the number of images used in analysis was considerably less than the number purchased.

This is a clear message that image selection needs to consider two antecedent conditions: soil moisture, whether wet or dry (time since last flood, time since major rainfall); and timing of image relevant to flood hydrograph (rising limb, flood peak, falling limb). These can be

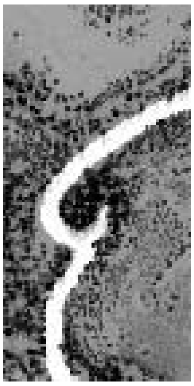
Figure A1 – 2. A visual expression of the information range and quality obtainable from remote sensing

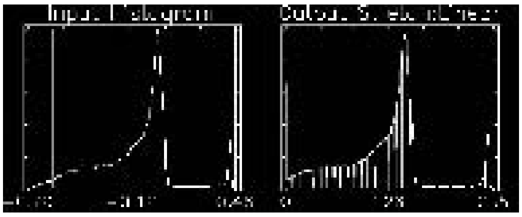


a. Grey-scale



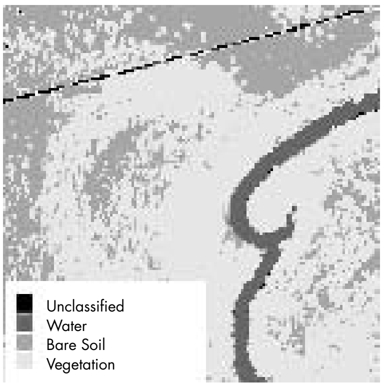
b. Grey-scale with water in colour (usually red)





c. These images show the result of using band ratios to increase discrimination between water pixels, which here have a value between 0 and 1 whereas non-water pixels have a value between —1 and 0.

d. This is a multispectral image with three basic classes: water, bare soil and vegetation.



used as exclusions; or can be quantified, and the values incorporated as a co-variate in a numerical analysis.

The falling limb may be useful in defining areas of greater flood duration but their value for defining flood extent is likely to be compromised: by the tail of a flood, vegetation will have had time to respond, obscuring the inundation area. The problem of vegetation overhang or growing through water means the rising limb is preferred for inundation mapping, by satellite imagery.

Table A1 – 3. Measured and predicted inundated area

Comparison of measured and predicted inundation area for eight dates for the Great Cumbung Swamp. Observed inundated area was based on satellite imagery. Predictions were made using an empirically-derived multiple linear regression based on previous inundation area and changes to wetland storage volume, over the same time-frame. Changes in storage volume were based on measured in-flows from three gauging stations, adjusted for direct inputs and losses with a rainfall and evaporation factor (from Brady et al. 1998).

M-area (ha)	3,560	6,320	4,240	13,100	4,400	2,800	3,790	4,160
P-area (ha)	3,950	4,030	3,810	12,990	4,540	3,710	4,970	4,390
% difference	10.8	–36.3	–10.1	–0.9	3.2	32.2	31.2	5.4

In addition, if it is known that changes have occurred on the floodplain which might affect the passage or flood waters, such as vegetation clearance, erosion of channels, concrete structures, channel blockages or clearing, then it would be advisable to select images representing just only the most recent situation.

Commissioning new imagery. Current practice in terms of establishing a volume or flood inundation area relationship is to use historical data. The use of historical data can be restrictive, because of the difficulty of standardisations, as described above, and because a complete range may not be available. Commissioning a special set of images, using hyperspectral imagery or radar, has not been implemented yet in Australia. With falling costs, and greater need for precision, this is likely to become a real option in the future.

An in-house cost–benefit analysis is suggested before making a decision whether to proceed with historical satellite or specially-commissioned imagery. This should consider not just technical issues such as data quality, but additional benefits.

Interpretation

In inundation mapping, the initial step is to interpret the images and determine areas that are water, and which are dryland. This can be done by visual interpretation, or by computerised analysis. A visual representation of this for a river–billabong–floodplain is shown in Figure A1 – 2.

Visual interpretation. Visual interpretation is open to criticisms of subjectivity, observer bias, and problems of inter-observer consistency: these can be important if a time series is being prepared, or if maps are being overlaid. Visual interpretation requires hard copy, either of air photos or satellite imagery, or a single-band (grey scale) satellite image and the user visually discriminates and delineates inundated areas. It relies on the user to visually discriminate and delineate inundated areas. Despite the obvious subjectivity of this, some skilled practitioners find visual interpretation of satellite images to be more effective than relying on computerised analysis.The human eye can successfully integrate and interpret complicated information such as flow lines in shallow water over submerged vegetation, and can account for and understand changes in water quality across a flood front.

The main difficulties are in defining boundaries when water is overhung with vegetation, and in comparing RGB combinations with grey-scale imagery.

Computerised analysis. Computerised analytical techniques for processing satellite imagery are histogram slicing, band ratios or classification.

Histogram slicing uses single band grey-scale digital data images, and clusters pixels according to their brightness. Its advantages are only that very little data processing is required. Its disadvantages include subjectivity in slicing images, difficulties in maintaining consistency between images, and potential to underestimate water area if obscured by overhanging leaf canopy. Band ratios improve the detection of water pixels.

Classification refers to a range of numerical techniques, generally these are based on two or more bands of digital data, ie. cannot be done on a hard copy. Classification, if properly done, requires field back-up or reference areas to 'train' the image which can also be limiting and requires a degree of familiarity with remote sensing data or packages.

Checking interpretation

In inundation mapping, where water boundaries can be hard to define (see above), a simple check on mapping can be implemented by overlaying maps.

Overlay check

The assumption behind this procedure is that successively larger floods will inundate the same area as a smaller flood plus some 'new' area. Overlays done with hard copy only (eg. on light table) give a qualitative indication of error. Overlays done using a GIS indicate magnitude of error.

Sources of discrepancy between successive flood maps are: errors in estimating hydrologic variables (storage volume, wetland inflow); errors in estimating inundation area, such as ambiguous data, subjective interpretation, poor quality imagery, incorrect rectification; natural changes to flood patterns, such as fallen trees, minor channel avulsions; anthropogenic changes on the floodplain, such as flowpath aggradation or degradation; flowpaths completely or partly obstructed, for example by structures such as levees or bridges, or simply fences or fallen trees; and vegetation clearance affecting roughness and water distribution.

A process of elimination is needed to determine which of these are the sources, in particular which are operator and technical errors, and which are site-specific factors.

Overlaying can also be used to compare different methods (Table A1 – 5).Agreement within 5% looks robust but larger discrepancies merit attention.

Table A1 – 4. A flooding overlay check

Inundation area for three flood events on the Gwydir River, 1975 to 1983. Agreement between flood events, indicated by the area of overlap and non-overlap, was low, and was not dependent on flood size. Reasons for this were not determined at the time the analysis was done, but this was a period of floodplain development (Roberts, unpublished data).

Event size	Area of overlap	Area of non-overlap
150 GL[a] month and 130 GL month	11,033 ha	6,0001 (35.2%) of smaller flood not flooded by larger flood
150 GL month and 303 GL month	29,801 ha	7,935 ha (21.0%) of smaller flood not flooded by larger flood
130 GL month and 303 GL month	13,580 ha	3,474 ha (20.4%) of smaller flood not flooded by larger flood

[a] GL = gigalitre = 1,000,000,000 litres

Table A1 – 5. Comparison of two methods

Inundated area estimated for three floods using two methods of interpretation: Method 1, visual interpretation of flooded area on hard copy, measured by planimetry; Method 2, micro-BRIAN estimated flooded areas after rectifying grey-scale images, using scanned and digitised hard copy (Roberts, unpublished data).

Date of image	Method 1	Method 2	Change as %, as area (ha)
1 November 1975	37,500	37,736	<1% (236 ha)
19 September 1978	96,800	113,284	14.6% (16,484 ha)
24 October 1983	16,300	17,034	4.5% (734 ha)

Appendix 2: Evapotranspiration

Evapotranspiration data

This Appendix gives 'best guess' estimates of K_C and K_S (Table A2 – 1) for use in indirect estimates of evapotranspiration, as outlined in the third method in Section 6.

Table A2 – 1. K_c and K_s for plant communities typical of south-eastern Australia

Plant community (Structure + Dominant)	K_c	K_s
TREE-dominated plant communities		
Riparian forest – mainly eucalypts eg. river red gum (*Eucalyptus camaldulensis*)	0.8 To be confirmed	Oasis and saline water effects unlikely
Open woodland eg. blackbox, coolibah eg. river coobah (*Acacia stenophylla*)	0.4 for blackbox types	0.1–0.5 (saline groundwater, blackbox types)
SHRUB-dominated plant communities		
Shrublands – contrasting forms		
• Twiggy and deciduous eg. lignum (twiggy)	0.3 – 0.6	
• Succulent and salt-tolerant eg. chenopods eg. *Atriplex*, *Chenopodium*	0.3 –0.6 (Values for dry to wet conditions)	
GRASS-dominated plant communities		
Grasslands – dryish water regime, rapid responses on flooding, tussock perennials eg. Warrego summer grass and Canegrass	0.8–1.0 when flooded and actively growing	0.1–0.2 when droughted
Grasslands – trailing or mat forming, aquatic types eg. Moira grass (*Pseudoraphis spinescens*) and water couch (*Paspalum distichum*)	1.3–1.4	Not applicable
Grasslands – tall erect, including other grass-like emergents growing in water 0.5–1.5 m deep. eg. *Phragmites australis* and cumbungi (*Typha* spp.)	1.3–1.4 when flooded	0.4–0.6 when senescent
SEDGE-dominated plant communities		
Sedgelands – medium-tall erect culms with no lamina, and low LAI: cover wide ecological range from near permanent to intermittent eg. *Eleocharis*		
Sedgelands – medium–tall, erect culms with bracts acting as leaves eg. *Bolboschoenus*, *Cyperus*	1.3–1.4 when flooded	0.4–0.6 when senescent
AQUATIC HERB-dominated plant communities		
Aquatic herblands – dissected leaves, emerging through the water, and under water: milfoils	1.3	Not applicable
Aquatic herblands – broad or large flat blade leaves on or just above the water surface eg. pondweeds (*Potamogeton* spp.) and water ribbons (*Triglochin* spp.)	1.1–1.3	Not applicable

Continued on next page

Table A2 – 1. (cont'd) K_c and K_s for plant communities typical of south-eastern Australia

Plant community (Structure + Dominant)	K_c	K_s
AQUATIC HERB-dominated plant communities — cont'd		
Submerged plants – with either blade or dissected leaves eg. ribbon weed (*Vallisneria*) and sago weed (*Potamogeton*)	1.15	Not applicable
Free floating vegetation • Small forms (LAI approx 1.0 and flat on surface) mainly *Azolla* and duckweeds • Larger forms (LAI 2.0+ and over 25 cm high) unusual in temperate Australia, eg. outbreak of water hyacinth limited to Gwydir	1.2	Not applicable
LINEAR features & PATCHES		
Open water – in channels flanked by wet swamp vegetation	1.2	
Channels with tall riparian woodland	1.4–1.5	
Channels with open water patches and emergent grass-like macrophytes	1.3	
Paleostreams or **dry channels** which are vegetated by trees	0.4–0.6	
Bare areas, salt encrusted areas of low infiltration and low water storage capacity	0.05, rarely 0.2	

Estimates of K_C and K_S values are expected to be applicable to different plant communities on floodplain wetlands. Plant communities are described by structural attributes, and assume large areas unless otherwise stated, for example linear strips of woodland. These estimates are based on experience in evapotranspiration estimates, work done on different plant communities in the Okavango Delta, Botswana, and Australia, where relevant data are applicable. Published values in scientific literature are generally not available for Australian floodplain communities (P.M. Fleming, pers. comm. 1999). When using published evapotranspiration data for wetland plants, not only is it necessary to be aware of whether evapotranspiration was measured directly or indirectly (Section 6) but to know what 'reference' value was used as these differ. The magnitude of differences in reference values is best appreciated by relating them (Table A2 – 2) to the standard reference surface recommended here, the well-watered grass surface (Section 6).

Table A2 – 2. Range of reference values, relative to well-watered grass

Standard grass surface	1.0
Open shallow water	1.2
Alfalfa or lucerne surface	1.3
Standard US Class A pan evaporimeter	1.4–1.5
US Class A pan with bird screen	1.3–1.4
Australian sunken tank	1.2