Evaluating the environmental losses and benefits from flooding

Abstract
Flood events are natural disturbances with a multitude of environmental benefits. However, human influence has altered the interaction between floods and ecosystems, such that individual flood events may have long-term, negative impacts on the environment. Evaluating the effects of flooding on the environment is difficult due to the inherent complexity of ecological systems and the associated difficulty of defining ecological outcomes in terms of losses and benefits. The effects of flooding will vary depending on attributes of the ecosystem in question, past disturbance history and the timeframe over which assessment takes place. However, environmental evaluation is worthwhile, as it enables a more comprehensive picture of the effects of flooding with a view towards sustainability. Such an evaluation will alert us to the environmental, social and economic benefits of a more natural flood regime and the potential impacts of flood mitigation procedures.

This article presents a framework for conceptualising the environmental benefits and losses from flooding in the context of natural disturbance cycles and modified environmental systems. Using this as a basis, an approach is described for evaluating the effects of flooding on ecosystem condition using environmental indicators. This approach has potential to be incorporated into a broader social and economic assessment of the losses and benefits incurred by a flood event.
Introduction

Flooding is part of the natural cycle of many ecosystems and plays an important role in maintaining ecosystem function and biodiversity (Poff et al 1997). The multitude of environmental benefits from flooding also benefit society through the continuation of ecosystem services (Bayley 1995). However, major modification to natural processes and ecosystems through human activity, has created the potential for flood events to result in long-term, undesirable changes to the environment (eg Montz and Tobin 1997).

Historically, flood loss assessment has focussed on the direct economic costs of flooding, with accounting being undertaken for impacts that can be ascribed a value in conventional economic terms (Thompson and Handmer 1996). The environmental impacts of floods are rarely reported in flood loss assessments, although there is increasing recognition of the importance of losses that do not have a direct market value (Bureau of Transport Economics 2001). Also, assessments rarely consider the potential environmental benefits from events that are solely considered as a disaster from a human perspective. Accounting for the environmental effects of floods will enable a more realistic evaluation of the total costs and benefits of flooding; an evaluation that considers the environmental, social and economic benefits of a more natural flood regime and that alerts us to the potential costs of flood mitigation procedures.

Before an evaluation of the environmental effects of flooding can be made, it is critical to establish the impact of flooding on environmental losses and benefits. This is complex, because while the immediate impression is one of damage and destruction, flood events play an important role in the maintenance of biodiversity and ecosystem function of riverine systems in the long term (Poff et al 1997). Multiple factors such as previous disturbance history and ecosystem attributes will influence the scale and type of effect that a flood event has on the environment, and the direction of ecosystem recovery (US EPA 1999). Further, the criteria used for assessment and the timescale over which the assessment is undertaken will both influence the final evaluation of the extent of environmental losses and benefits.

By assessing the impact of flooding on ecosystem condition, a holist approach can be taken to the assessment of the environmental effects of flooding. Ecosystem condition is defined here as the health or condition of an ecosystem to maintain biodiversity and ecosystem function. Because of the complexity of ecological systems, the assessment of ecosystem condition requires
identification of sets of attributes that provide general indicators of a complex suite of ecological conditions (Lindenmayer 2001). Through measurement and monitoring of these indicators over time, it may be possible to provide an ecosystem scale assessment of whether the impact of a flood event has “driven” the ecosystem away from or towards the desired state of having a long-term capacity to maintain biodiversity and function. Although the scope of this document is the assessment of environmental effects of individual flood events and is not an examination of the consequences of altered flood regimes, it is critical that flood events are viewed in context of flood regimes, as they cannot be understood in isolation.

The purpose of this paper is to outline and conceptualise the broad environmental effects of flooding and to develop an approach to the assessment of environmental losses and benefits through evaluation of the effects of flooding on ecosystem condition. This paper is divided into three main sections. Firstly, a conceptual framework is outlined for understanding environmental losses and benefits in the context of natural disturbance cycles and modified environmental systems. Secondly, the effects of flooding on five broad ecological communities are described to outline how these effects vary between ecosystems. Thirdly, broad indicators are suggested for the assessment of changes in ecosystem condition to determine whether there have been environmental benefits and losses. By establishing a framework and methodology for assessing environmental flood losses and benefits, this approach has potential to directly contribute to an economic valuation of these costs and benefits, through an evaluation of the effect of flooding on the provision of ecosystem goods and services (eg Haeuber and Michener 1998, Wainger et al 2001). The focus here, is on ecological communities that are components of “riverine ecosystems;” defined by Arthington (1998) to be an all-inclusive concept of rivers that includes the source area, river channel, riparian zone, floodplain, groundwater, wetlands and estuary and features such as threatened species.

A conceptual framework of the environmental losses and benefits associated with flooding

It is important to ensure that environmental assessment and evaluation of flooding is embedded within a holistic framework that recognises the value of ecological integrity; i.e. the condition or "health" of an area. Native species and ecosystems have intrinsic value, as well as being of value to humans through the provision of ecosystem goods and services such as the purification of air and water; production of food and fibre; and fulfilment of peoples spiritual, cultural and intellectual needs (Daily 1999, CSIRO 2001, Salzman et al 2001). The framework developed here
(Figure 1), takes biodiversity and ecosystem function to be the overarching valued elements of the environment against which we can assess environmental losses and benefits. Flood events that cause changes in ecosystem condition that contribute to the long-term viability of the plants and animals living in flood prone communities and to ecosystem function have environmental benefits. Degradation in the long term of either diversity or function is counted as an environmental loss, and individual flood events are viewed in this context. Environmental losses and benefits are presented in the lower horizontal axis of the framework diagram (Figure 1).

**INSERT FIGURE 1**

Floods are characterised by five critical components: the magnitude of discharge, the velocity of the discharge, the duration of the flood, timing or seasonality of the event and the frequency of the disturbance. Together, these elements make-up what is known as the flood regime. Large flood flows maintain ecosystem productivity and diversity through processes such as transport and cycling of nutrients sediments and organisms between river channels and flood plains (Poff et al 1997, Baldwin and Mitchell 2000), and habitat creation and maintenance of channel structure through scouring fine sediments and washing organic matter out onto floodplains (Cullen et al 1996, Poff et al 1997). The organisms of flood prone systems are adapted to this disturbance, with many species of fish and macroinvertebrates requiring flood events to complete their life cycle (Junk et al 1989). In light of this multiplicity of environmental benefits from flooding, most research and policy has focussed on the environmental degradation resulting from flood mitigation and changes to environmental flows (eg Cullen et al 1996, LWRDDC 1997, Arthington 1998) rather than the potential negative impacts of individual flood events.

Individual flood events in combination with human activities such as vegetation clearance, river regulation and intensive agricultural production can result in long-term, negative effects on the environment. Increased levels of human activity in a region may increase the likelihood of the spread of pollutants (Montz and Tobin 1997) and invasive organisms (Howell and Benson 2000), transfer of nutrients and sediments (Moss et al 1992) and fish kills (McKinnon and Shephard 1995, McKinnon 1997). Changed flood regimes due to flood mitigation practices (Crabb 1997, Sparks et al 1998), urbanisation (Novotny et al 2001) and global warming in the future (Smith and Ward 1998) may also result in individual flood events that have negative impacts on native biota (eg Quinn et al 2000) and the chemical and physical structure of flooded ecosystems.
The top horizontal axis of the framework diagram (Figure 1) represents the degree of human activity in the flooded region in terms of modified landscapes and altered flood regimes. Increased activity drives the environmental effects of individual floods towards greater, long-term environmental losses.

The time-scale over which losses and benefits are assessed is also a critical component of this framework. In the short term an individual flood event may appear to be an ecological disaster, with unsightly deposition of sediments and debris, death and injury of plants and animals, and even local species extinctions. However, in the long term, flood events that are part of the natural flood regime will ensure the long-term viability of the plants and animals adapted to flood prone environments and the functioning of these ecosystems. It is essential that a time frame is established for the monitoring and evaluation of environmental losses that identifies a period deemed acceptable by society over which natural recovery can take place. If the system has not recovered within this period, a loss can be counted. Time is represented as the vertical axis on the framework diagram (Figure 1), with environmental losses or benefits changing over time through ecosystem recovery or further environmental degradation.

Because the effects of flooding on the environment will differ between different ecological communities, assessment of the impacts of flooding must be tailored for each system accordingly. The role of flooding in five broad ecological communities is outlined below to illustrate the diversity of ecological responses to flood events.

**The effects of flooding on different ecological communities**

The communities discussed in this document are the river channel, riparian zone, floodplain, wetland and estuary. Strictly speaking, the riparian zone and wetlands are included in the floodplain, however they have been treated separately in this document, due to the different ecologies of each. There are many other ecological communities affected by flooding that are beyond the scope of this paper for consideration. These include: embayments, inshore lagoons, littoral zones, outer reefs, inland lakes, coastal wetlands, saltmarshes, mangrove swamps and freshwater swamps. For each community discussed the environmental losses and benefits from flooding are described.
River channel communities

The river channel is a well-defined, high-energy ecosystem. Many ecological benefits stem from the lateral connections between rivers and floodplains that occur during flood events (Fairweather and Napier 1998). Overbank flows promote nutrient cycling (Baldwin and Mitchell 2000), inoculate rivers with carbon, algae and microorganisms and give riverine organisms access to floodplain resources, stimulating spawning and recruitment (e.g., Rowland 1989, Sparks et al. 1998). Flooding may also stimulate germination and re-establishment of aquatic macrophytes (Bendix and Hupp 2000). New habitat for aquatic organisms may be created through flood events through changes to stream cover and structural complexity due to the transfer of rocks, sediments and organic matter and the introduction of woody debris or snags (Wallace and Benke 1984). An increase in snags is also beneficial as they maintain friction in watercourses, helping to slow the system down and create a range of flow conditions (Gippel et al. 1996).

Flooding may also negatively impact on river channels. Erosion, which is exacerbated by flood flows, may occur at greater rates than would have occurred naturally because of altered flood regimes and land clearance (Abernethy and Rutherford 1999). Changes to surface water quality may also be profound during a flood event (Hart et al. 1987, 1988). Water quality is generally poorer in catchments where there has been extensive land clearance, as floodwaters flush increased sediment and nutrient loads into river systems (Moss et al. 1992, MDBC 2001a). Flood events can raise turbidity levels by as much as twenty-fold (Shafron et al. 1990) through erosion and algal growth in response to increased nutrients. This may in turn impact on aquatic organisms through increases in particulate matter that clog fish gills, and decreases in light levels, which results in decreased photosynthesis and water temperatures (Jolly et al. 1996). Another water quality issue is de-oxygenation, which may be exacerbated in land dominated by exotic plants that are intolerant of extended inundation (McKinnon and Shepheard 1995, McKinnon 1997). Run-off from pastures and urban areas may carry chemical pesticides and herbicides, nutrients from fertilisers and microbiological contamination (Montz and Tobin 1997). Poor water quality may result in fish kills (Gehrke 1991) and impact on other aquatic biota.

Environmental losses and benefits in terms of exotic species are complex in river ecosystems. Exotic species such as the floating weed Giant Salvinia (Salvinia molesta) can be flushed out of rivers in cyclonic floods and scouring may remove shallow rooted exotics such as Para Grass (Brachiaria mutica), however, if these plants disperse and become established further downstream, broader environmental benefits would be negated. Flood events may also play a role...
in the release of exotic fish species from outdoor ponds into river systems, but interestingly studies have shown that floods may disadvantage exotic fish, through aiding recruitment of indigenous species (Puckridge et al 2000) or through directly reducing populations of introduced fish species relative to indigenous species (Meffe 1984).

_Riparian zone_

The riparian zone is defined here as the vegetated area that grows immediately alongside rivers and streams. Riparian vegetation has a number of important ecological functions, including organic and nutrient inputs into the river system, stabilisation of riverbanks (Abernethy and Rutherford 1999), provision of instream habitat through fallen logs and root systems (Rutherford et al 2000) and habitat for fauna that exist in the riparian zone (O’Reilly et al 1999).

Flood events contribute to the erosion of river banks; a natural process that even occurs in areas that have good cover of native vegetation and is believed to be an important component of maintaining river health, as areas erode and are recolonised by vegetation (Poff et al 1997). Landscape change and altered hydrological regimes have accelerated these processes and flood events may exacerbate rates of erosion to the extent that the systems are unable to recover before the next large flow (O’Reilly et al 1999), particularly on unstable riverbanks where there has already been vegetation clearance (Abernathy and Rutherford 1999, LWRDDC 2000). A particular issue in cleared landscapes is that unimpeded floodwaters move much faster than in a floodplain with natural levees, and floodwaters may erode back through riverbanks, in a process known as avulsion. Destruction of riparian vegetation by floods is an issue in terms of reduction in size and connectivity of habitat, and decrease in structural complexity of riparian zones. These impacts will be of much greater importance in regions that have a narrow riparian zone such as dryland river systems where there is limited potential for re-colonisation by surrounding vegetation (E. Coleman, Queensland Department of Natural Resources, personal communication). Flooding may also contribute to the degradation of riparian vegetation condition through dispersal of propagules of exotic species and provision of nutrient rich conditions that enhance growth of invasive weeds (Howell and Benson 2000).

_Floodplain_

The floodplain occupies the land adjacent to the river channel, and may be defined in geomorphological terms as the alluvial surface constructed by a river under current environmental conditions (Dunn and Leopold 1978) or in hydrological terms as the area with a specified annual

Evaluating the environmental losses and benefits from flooding

7
probability of flooding, such as 1 in a 100 years. A gradient exists between the river and the outer edges of the floodplain, where species are adapted to varying degrees and frequencies of inundation (Junk et al 1989). Benefits to floodplains from flooding are largely a result of the lateral connections of floodplains to rivers (US EPA 1999, Baldwin and Mitchell 2000), as described in the previous section. Common biotic responses to flooding include breeding of waterbirds (MDBC 2001b), emergence and hatching of aquatic invertebrates and tadpoles (Boulton and Lloyd 1992, Nielsen 1998, MDBC 2001b) and establishment of vegetation (Bendix and Hupp 2000).

Although floodplain scour and sediment deposition are a natural phenomenon during floods, transportation and deposition of sediments during flood events will be increased in floodplains that have been extensively cleared. This will have negative impacts on the physical structure and biota of these systems. The increase in the magnitude of flows due to urbanization has resulted in the enlargement of floodplains (O’Reilly et al 1999), and as a consequence ecosystems that are not adapted to flooding may be inundated and severely impacted. Also, prolonged inundation during a flood event may result in mortality of floodplain plants (Chapman et al 1982).

A number of serious environmental weeds that become invasive in floodplain ecosystems in Australia are known to spread via floodwaters such as Olive Hymenachne (Hymenachne amplexicaulis), and the Giant Sensitive Weed (Mimosa pigra) (Calvert 1998) and post-flood conditions may also be ideal for the establishment of weedy species such as the Coffee Bush (Leucaena leucocephala), which germinates profusely after a flood event from seed lying dormant in the soil (Calvert 1998).

Wetlands

Wetlands are highly productive systems (Boon et al 1990) that contribute to floodplain ecosystems through their role in the export of organic matter and organisms back into the river channel, assimilation of nutrients, adsorption and filtration of pollutants, and flood attenuation (De Laney 1995). Wetlands also provide important nursery grounds for fish (Welcombe 1992). Floods are integral to the ecology of wetlands, with flooding being essential for the maintenance of wetlands and associated species (Quinn et al 2000). The depth, duration and timing of each flood event is critical for the dispersal, reproduction and establishment of the distinctive biota of wetlands. Even small changes in the rate of flooding, can impact on wetlands and alter species
composition and abundance (LWRDDC 1997). Flood events may also negatively impact on wetlands through scour, sediment deposition and oil and pollution contamination.

*Estuaries*

Estuaries have been defined as “semi-enclosed coastal bodies of water where salt water from the open sea mixes with freshwater draining from the land” (Audit, 2000). Major effects of flooding on estuaries include large plumes of suspended sediments, nutrients, phytoplankton and possible pollutants and a resulting increase in turbidity. There also maybe changes in phytoplankton community composition in response to nutrient pulses from the flood event (Grice *et al* 2000). Changes in water quality may affect seagrass communities, which are impacted by changes in light penetration through decreased water clarity. The large influx of freshwater into the estuarine environment may also have a serious effect. Because seagrass meadows provide critical habitat for numerous fauna, including fish and shellfish, and are the major food source of turtles and dugongs, flooding will affect the many species that utilise seagrass beds for food and habitat. Sediment levels of flood plumes will be greatly increased in catchments with substantial land clearance and erosion, particularly gully and streambank erosion (Caitcheon *et al* 2001).

*Summary*

Although the effects of flooding on ecosystem processes differ widely between ecological communities, there are broad classes of effect on key ecosystem processes that are common between a number of ecosystems. These are summarised in Table 1, and have been used as a basis for development of environmental indicators of ecosystem change due to flooding, which are outlined in the next section.

INSERT TABLE 1

**Evaluating the environmental losses and benefits from flood events**

The following is a brief outline of a range of environmental indicators that are appropriate for use in the assessment of the effects of flooding on ecosystem condition and the associated environmental losses or benefits. These indicators have been selected through the process of identifying how floods drive change in key ecosystem processes and hence ecosystem condition.
A critical issue for the assessment process is that in most cases there will be no baseline data available for an appraisal of flood effects. Ideally an assessment using a BACI (Before, After, Impact Assessment) would be undertaken, however such a design will not be possible unless comparative data is available from programs such as those undertaken for water quality monitoring. Comparison with control areas unaffected by the flood event may also be possible in some instances. However, in general the only means of assessing the impact of flooding on the environment will be through qualitative assessments by individuals familiar with the system under investigation. Potential experts that could contribute to an assessment include individuals on River Trusts and Catchment Management Authorities, university academics, council environment officers, land managers, and organisations such as state agencies, the Great Barrier Reef Marine Park Authority and the CRC for Freshwater Ecology. The emphasis in selection of these indicators has been on fairly coarse measures that could be used in a rapid appraisal, in a similar manner to the rapid appraisal method used in Victoria for the assessment of impacts of flood management activities (DNRE 2000). However, more complex indicators are also discussed.

The hydrological regime
The effects of recurrent disturbances are additive, with each disturbance modifying the effects of subsequent disturbances, and the ability of biological populations to survive and regenerate after a particular disturbance event, determining population response to the next disturbance (Bradstock 1999, Puckridge et al 2000, Rutherford et al 2000). Hence, the effect of an individual flood event can only be understood in the context of previous flood events, and the five components of the flood regime should be recorded during an assessment process and where possible compared to historical hydrological data, to determine deviation from a natural flood regime. This will enable an assessment of potential for the flood event to cause environmental losses and benefits and will be useful for future assessments. Arthington (1998) has reviewed holistic approaches to the assessment of environmental flows and these have potential application for the assessment of a changed flood regime. Also, the CRC for Freshwater Ecology is currently developing a hydrological index that will provide a useful tool in this regard.

Habitat loss and fragmentation
Extensive damage to habitat may occur through floods, however, ecological recovery can be rapid in unmodified ecosystems where flooding is a natural, dynamic attribute (Poff et al 1997). The process and degree of habitat loss and fragmentation through flooding will differ between ecosystems; and so assessments of habitat loss must vary, depending on the system under
investigation. A useful measure of changes in instream habitat would be to record changes in stream cover condition, using a simple rating system, such as that outlined in Shepherd and Siemon (1999). Instream cover is comprised of leaf litter, branches, rocks and vegetation. Riparian habitat loss and fragmentation through stripping of vegetation can be measured in terms of the change in width and continuity of vegetated stream length, relative to cover prior to the event. Assessment should be made for the canopy, middlestorey and the understorey. Similarly, changes in the cover of wetland and floodplain vegetation should also be recorded. Seagrass loss is a common measure of estuary health (Grice et al 2000) and the distribution and depth of seagrass cover may be an important indicator of the magnitude of flooding impacts on estuarine systems.

**Physical change**

Visual estimates of bank erosion and avulsion should be recorded and monitored after a flood event. Such estimates commonly form a component of Rapid Bioassessment Protocols for habitat assessment (Barbour et al 1999) and a similar approach could be used for assessment of flood impacts. Photographic records are an effective tool for this assessment. Re-establishment of vegetation and stabilisation of streambanks would be appropriate measures of ecosystem recovery. Sediment deposition is also a strong driver of physical change to flooded systems, particularly within river channel and floodplain environments. Although techniques are available to monitor the extent of deposition of new sediments (eg Phillips and Marion 2001), these are complex and time consuming.

Research suggests that natural disturbances maintain structural complexity of ecosystems and that this complexity promotes plant and animal diversity (Hansen et al 1991) through provision of a greater variety of niches. Flood events will influence the structural complexity of affected ecosystems, particularly in-channel environments, through erosion and transport of large woody material and sediments (US EPA 1999). A Rapid Bioassessment Protocol for physical habitat assessment in streams (Barbour et al 1999) could be undertaken after a flood event to describe change in the structural complexity of lotic systems. This system scores physical parameters such as in-stream cover, substrate quality, channel quality, riparian quality, and pool/riffle quality. The structure of physical microhabitats within streams, such as snags and rocks, will be profoundly affected by flood events. Visual assessment of changes in the density of snags can also be made following a flood event, during periods of low flow. Although important, measurement of...
changes in rocks would be time consuming and measurement of changes in biota that utilise these habitats would be a more simple assessment of associated losses and benefits of changes in physical habitat.

The Index of Stream Condition (ISC), uses indicators of bank stability, bed aggradation and degradation and the abundance of snags to develop a subindex of physical form (Ladson et al 1999). The ISC is used by Catchment Management Authorities in Victoria, to capture information about the physical condition and habitat of the stream channel and has potential for application to the assessment of flood impacts on ecosystem condition.

**Water Quality**

The core measures of water quality that should be considered after flooding are nutrient enrichment, turbidity and chemical and biological pollution. Because natural background water quality varies in response to factors such as climatic variation, geological development and soil composition, the assessment of changes in water quality would ideally be compared to paired reference sites or regional least-impacted reference sites (Bartošová 2000).

Nitrogen and phosphorous are two of the most significant nutrients limiting plant growth (Udy et al 2001), and hence are the most important to measure in an assessment of condition of aquatic environments. Measures of concentration should be given as nutrient loads (amount per unit time) to increase reliability (Fairweather and Napier 1998). Thresholds for various aquatic ecosystems will need to be developed to determine whether the changes will have a negative impact.

Turbidity is a measure of water clarity and reflects the presence of suspended matter or soluble compounds such as silt, clay, and algae (MDBC 2001a) with measurement commonly made in Nephelometric Turbidity Units (NTU). Because turbidity levels are highly variable within and between different water-bodies, it is difficult to define a limit that is reasonable for all aquatic systems (Jolly et al 1996). The *Australian Water Quality Guidelines for Fresh and Marine Waters* recommend that the seasonal mean NTU should not vary by more than 10% (Walker and Reuter 1996).

A basic assessment of the presence of pollutants can be made during a flood event through identification of water with an unpleasant odor of an oily sheen on the surface (Shepherd and Siemon 1999). More detailed measurement can be expensive and labour intensive, because there
are approximately 70,000 toxic substances that may affect water quality and impact on biota (Fairweather and Napier 1998). Further, such a large number of potentially polluting chemicals makes it prohibitive to set guidelines for their measurement (Fairweather and Napier 1998). It is recommended that potential sources of chemical pollution during a flood event be identified rather than undertaking ad hoc environmental sampling. Overflow from tailings dams used for storage of toxic heavy metal wastes is a particularly serious issue that should be monitored and assessed. Other potential sources of pollutants include: sewage, septic and industrial tanks, buried petroleum tanks, barrels, drums and containers, household hazardous waste and solid waste (Montz and Tobin 1997). Techniques are available to map the extent of sewage plumes (eg Grice et al 2000), however these require considerable time and resources and are not strongly recommended for use in post flood assessment.

The Sustainable Rivers Audit in Australia (Cullen et al 2000) aims to develop a water quality index that incorporates total phosphorous, electrical conductivity (salinity), turbidity and pH, and this may have potential in the future for the monitoring of the impacts of flooding on water quality.

**Nutrient flux**

A technique that uses microbial exo-enzymes can provide a measure of nutrient flux between river and floodplain systems. This technique can be adapted for use as an indicator of biofilm activity to determine rates of bacterial carbon processing and track responses of the microbial community to periods of connection between rivers and floodplains (Hillman et al 2001). However, this technique is complex and may be time-consuming.

**Introduction of exotic species**

Flood events influence the distribution and abundance of exotic species through processes of disturbance and dispersal. Changes in the number and abundance of plant and animal exotic species that are dispersed by floodwaters, or are affected by flooding in some way, should be measured for both terrestrial and aquatic ecosystems. Both increases and decreases in number and abundance of species are important to report, as they correspond to environmental losses and benefits respectively. Changes in abundance of ecologically significant exotic species could be assessed in terms of whether species populations had moved into a different abundance category,
such as: Abundant, Frequent, Occasional or Rare (eg Shepherd and Siemon 1999). Another simple but important measure of changes in exotic species would be an assessment of changes in exotic flora relative to indigenous flora, measured as change in cover of canopy, middlestorey and understorey plants (eg Shepherd and Siemon 1999) and fauna measured as change in approximate numbers or density of individuals relative to numbers for functionally similar indigenous taxa.

**Biological indicators of ecosystem condition**

Because the tolerances of biota to environmental conditions varies between taxa, the presence or absence of particular species or functional groups can be indicative of the condition of an aquatic system and provide a surrogate measure of system health (Cranston et al 1996, Karr and Chu 1999). In fact biological monitoring may in fact provide the most integrated measure of river condition (Karr 1999). Because aquatic taxa such as invertebrates, fish and aquatic plants, are the “end users” of water management they are routinely used in water quality monitoring (Fairweather et al 1998). Microbial indicators also have great potential for assessment of river health (Veal 1997). Aquatic systems that are stressed often show reductions in diversity as sensitive taxa disappear and pollution-tolerant taxa predominate (Rapport 1991). Taxa with narrow and specific tolerances make the most reliable indicators (Cranston et al 1996), with fish and macroinvertebrates being perhaps the most advanced biotic measures available (Cullen et al 2000).

Although it is not feasible to assess impacts of flooding on all species, it is particularly important that changes to populations of rare or threatened species is recorded to aid in their management and conservation. Assessment could simply be a record of whether species populations had moved into a different abundance category, such as that described above for weed species. Fish kills would be another appropriate measure of environmental impacts as kills may result from changes in water quality during flooding (McKinnon and Shepheard 1995, McKinnon 1997). The size of the kill (measured as number of fish per unit area or unit length of waterway) and approximate number of individuals and number of species (Fairweather and Napier 1998) would be key measures. Recording changes over time in fisheries production in marine regions affected by flooding, may also be a simple way of capturing information on environmental losses and benefits from flooding.

Macroinvertebrates are the taxonomic group with perhaps the most advantages for the assessment of the condition of riverine systems, in terms of their functional importance, their availability and...
wide distribution, and the ease of sampling (Cranston et al 1996). Data on macroinvertebrate community structure, combined with predictive modelling, is used in a system known as *AUSRIVAS* (Australian River Assessment System) to assess the biological health of Australian rivers (Barmuta et al 1998). This system has great potential for assessment of changes in ecosystem condition and ecosystem recovery from a flood event. The basic methodology of *AUSRIVAS* is to compare the aquatic macroinvertebrate fauna collected at a site, to model predictions of the fauna expected to occur at the site in the absence of environmental stress, such as pollution or habitat degradation. The AUSRIVAS program utilises a standard operating protocol and provides a standardised set of field sampling sheets, which could be incorporated into this approach to streamline assessments of flood losses and benefits. The composition and diversity of fish fauna is used as an indicator of estuary health (Blaber 2001) and for monitoring river health in an Index of Biotic Integrity (Harris and Silveira 1997). However, there are several difficulties in using fish to monitor water quality, including a lack of sampling protocols and knowledge about the water quality tolerances (Cranston et al 1996).

Caution must be applied when using biological indicators, because there are no universal indicators that can be applied at all geographic locations. Also, there is considerable argument as to whether indicator species can act as surrogates for determining the responses of other taxa to the same ecological conditions (Lindenmayer et al 2001). Problems will arise when there is a limited understanding of causal relationships between the species responses to changed ecological conditions and when there is a lack of knowledge about indicator sensitivity and the magnitude of the effect size that is detectable with the chosen indicator (Lindenmayer et al 2001).

*The evaluation process*

This broad list of environmental indicators described above are summarised in Table 2 and indicators that are too complex for use in a rapid appraisal are identified. This list is by no means definitive or prescriptive. Instead it outlines classes of environmental indicators that can be used in a post-flood assessment and that can be monitored over time, to assess the extent of ecosystem recovery from the flood event.

In an environmental assessment of the impacts of flooding, simple ratings could be given for each indicator selected and these could be weighted depending on their perceived importance. These will need to be qualitative, where no comparative data is available. Finally a score of the overall...
impact could be calculated to assess whether the flood event has driven the ecosystem toward benefits or losses in terms of changes to ecosystem condition. Depending on the indicators selected and the resources and expertise available for the assessment process, the summary of environmental effects of flooding will vary. Thresholds, standard protocols and methodologies could be developed through a more detailed analysis of the indicators outlined in this document and through discussion between experts in the field. An index could be developed for each ecological community that provides an integrated measure of changed environmental condition, following an approach similar to that of the Index of Stream Condition. Alternatively, a scorecard of ecosystem condition could be presented, such as that used to evaluate freshwater and estuary health in the Moreton Bay Ecosystem Health Monitoring Program (Grice et al 2000, 2001; Smith et al 2001).

Monitoring of indicators will be necessary to assess ecological recovery or further degradation, and hence environmental losses and benefits in the long term. It is recommended that an assessment be undertaken shortly after floodwaters subside, another at 6 months and a third assessment at least two years after the event. Scores for each assessment could be compared after the second and third assessment to determine whether there has been environmental recovery, increased degradation or no change; particularly in terms of instability and rates of erosion of soils, change in diversity of threatened species and invasion by exotic species.

Because the indicators outlined in this paper have been developed through identification of the major effects of flooding on key ecosystem processes, assessment of the effects of flooding on ecosystem services is a logical step and would in turn enable an economic evaluation of the environmental effects of flooding. An ongoing study on ecosystem services in the Goulburn-Broken Catchment, Australia (CSIRO 2001) has identified the maintenance of healthy waterways as a highly ranked ecosystem service for industries such as dairying, fruit and grapes, grazing, forestry, food processing, water production and recreation. Because floods have a broad influence on the health of waterways, there is great potential for evaluating the economic cost of flooding on these industries. Direct economic benefits of flood events could also be evaluated, such as the deposition of nutrient rich topsoil in floodplains (Bayley 1995) and maintenance of wetlands that mitigate the severity of flood events (Salzman et al 2001). Value should be based on each ecosystem’s capacity to provide goods and services, the quality and quantity of these goods and services and the demand for the services where they are produced (Wainger et al 2001). It is hoped that as more research is undertaken on how to measure ecosystem condition and to value
ecosystem services (eg Costanza and Folke 1997) that we may further our understanding of the economic value of more natural flood regimes and adjust our flood mitigation strategies accordingly.

**Conclusion**

The focus of this paper has been on building an understanding of the effects of individual flood events on ecosystem condition and discussing how this can be assessed. The approach outlined here will enable a standard methodology to be developed for environmental considerations to be incorporated into more traditional flood loss assessments. This is an excellent starting point for developing a methodology for the economic evaluation of environmental impacts of floods. By translating the ecological effects of flooding into effects on ecosystem services, an economic assessment of environmental losses and benefits could be undertaken. Consideration of the environment in flood loss assessments will better place land managers and policy makers to have a more sustainable approach to flood loss mitigation.
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Table 1: Summary of ecological processes that define ecosystem function and the effect of flooding on these processes. Attributes of a flood event that are the key drivers of ecological change include velocity, duration, timing, frequency, velocity, temperature, and transfer and dispersal of nutrients, biota and pollutants. Surrounding land-use and river management practices will also have an influence.

<table>
<thead>
<tr>
<th>Key Ecological Processes</th>
<th>Summary of broad effects of flooding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Environmental losses (-) and benefits (+)</td>
</tr>
</tbody>
</table>

| Critical Habitats         | “+” Re-establishment of aquatic, riparian and floodplain vegetation |
|                         | “-” Loss & fragmentation of vegetation (aquatic macrophytes, riparian, seagrasses) |
| Pattern and Connectivity of Habitat Patches | |

| Structural Complexity     | “+” Increase in snags |
|                          | “+/-” Erosion, stripping, sedimentation and avulsion |

| Nutrient Cycling          | “+” Transfer of nutrients & organic matter between floodplain & stream |

| Stabilising processes     | “+/-” Erosion & deposition of sediments |

| Purification Services     | “+” Recharge of ground aquifers |
|                          | “+/-” Increased turbidity, sedimentation & nutrients loads in freshwater systems |
|                          | “+/-” Flood plumes |
|                          | “-” Chemical & biological pollution |

| Biotic Interactions       | “+” Reproduction, dispersal & establishment of indigenous species |
| Population Dynamics       | “+” Exploitation of new food & habitat resources. |
| Genetic Diversity         | “-” Death, injury & local extinction of indigenous species through direct action of flood waters, decreased water quality, altered habitat & food resources |
|                          | “-” Dispersal of exotic species |

| Hydrological Patterns     | Because floods are a component of hydrological pattern and the natural disturbance regime, assessment of the effect of flooding on these processes is circuitous. Rather, assessment of the effects of modified hydrological patterns and natural flood regimes on other ecosystem processes described above, is important. |
| Natural Disturbance Regime | |

Evaluating the environmental losses and benefits from flooding
Table 2: Indicators for assessing changes in ecological condition, as defined by ecological processes. Complex indicators that may not be appropriate for a rapid appraisal are identified (*).

<table>
<thead>
<tr>
<th>Ecological Processes</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Critical Habitats</strong></td>
<td>- Change in width and continuity of riparian vegetation</td>
</tr>
<tr>
<td></td>
<td>- Change in stream cover condition</td>
</tr>
<tr>
<td><strong>Pattern and Connectivity of Habitat</strong></td>
<td>* Distribution and depth range of seagrass beds</td>
</tr>
<tr>
<td><strong>Patches</strong></td>
<td>- Re-establishment of vegetation (ecosystem recovery)</td>
</tr>
<tr>
<td><strong>Structural Complexity</strong></td>
<td>- Change to in-stream cover, channel quality, riparian quality, pool/riffle quality</td>
</tr>
<tr>
<td></td>
<td>- Visual estimate of change in snag density</td>
</tr>
<tr>
<td><strong>Nutrient Cycling</strong></td>
<td>* Microbial exo-enzyme technique</td>
</tr>
<tr>
<td><strong>Stabilising processes</strong></td>
<td>- Visual estimates of bank erosion and slumping, striping, landslides, gully incision</td>
</tr>
<tr>
<td></td>
<td>- Re-establishment of vegetation (ecosystem recovery)</td>
</tr>
<tr>
<td></td>
<td>- Extent of sediment deposition</td>
</tr>
<tr>
<td><strong>Purification Services</strong></td>
<td>- Increased nutrient loads (N and P)</td>
</tr>
<tr>
<td></td>
<td>- Increased turbidity (NTU)</td>
</tr>
<tr>
<td></td>
<td>- Chemical and biological pollutants – identified from potential sources</td>
</tr>
<tr>
<td></td>
<td>- Extent and duration of turbid flood plumes</td>
</tr>
<tr>
<td><strong>Biotic Interactions</strong></td>
<td>- Germination and establishment of indigenous plant species</td>
</tr>
<tr>
<td><strong>Population Dynamics</strong></td>
<td>- Change in numbers or abundance of significant species</td>
</tr>
<tr>
<td><strong>Genetic Diversity</strong></td>
<td>- Size of fish kills</td>
</tr>
<tr>
<td></td>
<td>- Change in fisheries production</td>
</tr>
<tr>
<td></td>
<td>- Change in number and abundance of exotic fish species</td>
</tr>
<tr>
<td></td>
<td>- Change in number and abundance of exotic weed species</td>
</tr>
<tr>
<td><strong>Broad indicators of ecosystem condition</strong></td>
<td>* Biological indicators including macroinvertebrates, fish and microbes</td>
</tr>
<tr>
<td><strong>Hydrological Patterns</strong></td>
<td>- 5 components of flood regime and comparison with hydrological record.</td>
</tr>
</tbody>
</table>
Figure 1: Conceptual framework for understanding environmental losses and benefits from flooding

- Short Term
  - Flood event
    - Spawning
    - Dispersal
    - Seed set
  - Environmental losses
    - Introduction of Exotics
    - Reduced water quality (pollutants & acidification)
  - Environmental benefits
    - Maintenance of ecosystem function
    - Recovery (through re-establishment, re-colonisation)

- Long Term
  - Extinction of species & ecological communities
  - Reduced ecosystem function
  - Long-term viability of ecosystems, species and populations
  - Maintenance of ecosystem function
  - Recovery

Degree of Human activity
- Low
- High

• River/floodplain management (e.g., dams, levee banks, channel modifications, floodplain modification, irrigation)
  • Land clearance/agriculture
  • Urbanisation

Evaluating the environmental losses and benefits from flooding