Department of Environment
and Heritage Protection

Natural assets for flood and cyclone resilience

Synthesis of scientific evidence on the role of natural assets to reduce the human impacts of floods and cyclones

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Disclaimer

August 2012

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Summary

Queensland's climate brings extremes of weather causing flooding and storm damage. As the climate continues to shift, it is likely that extreme weather events will occur with greater intensity. The evidence that human changes to the landscape impact flooding and cyclone damage is overwhelming. It is also clear that only building structural defences is not always cost-effective and can simply shift the problem. Around the world, interest is focusing on ecosystem-based approaches to natural hazard mitigation. We need to better understand how our landscapes function and what we need to do to absorb the energy of weather extremes.

There is no panacea to cure flooding or cyclones. As rainfall and cyclone events become more intense, flooding and storm damage will become more severe. It is clear that the most extreme events will overwhelm any mitigation approach—structural or natural. We have to live with floods as we already do with cyclones. The natural assets approach is important as it will still have benefit in reducing energy while structural approaches often offer little benefit once overwhelmed.

This synthesis paper draws together research into how natural assets can contribute to mitigation of floods and cyclones. Good scientific evidence is available but landscape processes are complex. Science is able to provide good advice that we can incorporate into landscape, natural resource management and environmental planning. The advice remains at a broad level because landscape complexity disguises the impact individual landscape components have on the system. It is essential to plan a whole of catchment approach based on a good understanding of that catchment's processes.

Careful design and planning of individual interventions can provide useful contributions to mitigation. The synthesis identifies factors that impact on the effectiveness of an intervention where they have been researched. Different species types, management and planting techniques have more effective properties. Further research is required into locally relevant characteristics and these are likely to be unique to each region or catchment. It is not suitable to reproduce an intervention that was successful elsewhere without assessing local conditions.

Restoring catchment vegetation reduces the amount of rainfall that forms runoff. This will have a flood reduction effect, particularly on smaller events. It is not always appropriate to recommend a return to natural state, however, most Queensland catchments are extensively modified and could not be effectively returned to natural function. Careful design of natural assets interventions can complement other practices including land-use planning or structural defences. The research covered indicates that the reduction provided by a natural assets approach is more cost-effective than only using a structural approach. The natural assets approach has other economic benefits including ecosystem services such as supporting biodiversity, fisheries, drinking water treatment and tourism.

The synthesis identifies a similar message for restoring floodplains. Floodplains provide natural flood storage and when allowed to flood, provide greater certainty around where flooding will occur and can reduce the impact of flooding on other areas. Floodplains can be constructed and augmented to provide maximum benefit in modified catchments. Interventions need to be carefully planned to balance potentially competing aims of flood management with other ecosystem goals.

Riparian areas delay the delivery of surface and groundwater to creeks and rivers which can reduce the downstream flood peak. Flood water velocity is the more hazardous aspect of flood damage. Catchment, riparian and in-stream vegetation slows down flood water reducing the hazard and reducing ecological damage to stream banks from erosion. Slowing and spreading the flood flow means increased localised flooding so land uses around riparian areas would need to be managed accordingly. Riparian vegetation offers numerous additional benefits for biodiversity and erosion, sediment and nutrient control for aquatic ecosystem health.

Land management practices are important to targeted restoration of catchment and riparian vegetation, and management of wetlands and floodplains. In addition, agricultural practices such as groundcover improvement, slope stabilisation and fire management can reduce the impact of heavy rainfall events.

Mangroves and coastal vegetation systems can provide a cost-effective storm barrier where they are viable ecosystems. The vegetation can attenuate storm surge energy and provide storage for coastal flooding. The vegetation systems need to be significantly large to act as a storm defence. They can provide a cost-effective supplement to structural storm defences providing significant reduction in construction and maintenance costs.

Vegetation can provide some protection from cyclonic wind damage, provided that the vegetation is appropriately managed. Well-established, strong trees and can trap debris and reduce cyclonic wind damage, but poor management such as lopping can weaken the tree and increase risk. Further research is required to understand vegetation and wind damage.

Overall, it is clear that there is a strong case for better understanding and harnessing the benefits of natural assets for flood and cyclonic damage reduction.

Introduction

The flooding and cyclones of the 2010–11 wet season saw most of Queensland declared a disaster area. Many Queensland communities also experienced significant flooding in the 2011–12 wet season. Globally, around three-quarters of disaster events between 1988 and 2007 were hydrological, meteorological or climatological in nature. Between 1974 and 2008, all natural hazards combined caused over 2.2 million deaths and economic losses of over US$1528 billion around the world (PEDRR 2010). The impacts vary between nations. Less developed countries tend to experience larger numbers of deaths while wealthy countries are facing increasing economic risk from natural hazards (UN ISDR 2011).

Australia's climate shows significant natural variability with major changes in rainfall patterns and cyclone tracking. Climate change is likely to increase the intensity of weather extremes. Uncertainties make changes in cyclone activity more difficult to predict but we are likely to experience more intense rainfall (IPCC 2007, 2012), and these trends are likely to apply to Queensland. A Queensland Government study proposed a five per cent increase in rainfall intensity per degree of global warming and expects the following temperature increases: 2 °C by 2050, 3 °C by 2070 and 4 °C by 2100 (DERM et al 2010).

Flooding and cyclones are natural processes. Organisations such as the United Nations International Strategy for Disaster Reduction (UNISDR) and the World Bank encourage the use of the term 'natural hazard' to describe them. Hazards have the potential to become disasters when they have a significant negative impact on human populations and infrastructure.

The way we adapt our built environment to these natural hazards can involve a variety of mechanisms including structural approaches such as dams, levee banks and storm walls. Evidence suggests however that overreliance on structural approaches can increase vulnerability, particularly when storm events exceed the levels for which the structural approach was designed. Land use planning can contribute by locating appropriate land uses in high-risk areas and locating residential and commercial development in areas of low or lower risk. Engineering advances can make structures located in flood prone areas more resilient. This synthesis focuses on the growing weight of evidence that natural assets such as forests, wetlands and floodplains can mitigate some of the impacts of flooding and cyclones.

Ecosystem-based approach

Interest in looking beyond structural approaches to flood and cyclone mitigation has been steadily increasing globally. Ecosystem based approaches recognise the role of natural assets in preventing flooding and mitigating negative impacts of natural hazards. Numerous international agencies have conducted reviews of the topic including:

- the World Bank (2010)
- the Partnership for Environment and Disaster Risk Reduction, a partnership of several United Nations (UN) agencies and international organisations (PEDDR 2010)
- the ProAct Network (UNISDR 2008)
- the International Union for Conservation of Nature (IUCN) (Sudmeier-Rieux et al 2006)
- the Food and Agriculture Organisation of the UN (FAO 2007)
- the Centre for International Forestry Research (FAO and CIFOR 2005)
- the UN Environmental Program World Conservation Monitoring Centre (UNEP–WCMC 2006)
- the UN International Strategy for Disaster Reduction (UNISDR 2004, 2008)
- the World Wide Fund for Nature (WWF) (Stolton et al 2008).

In 2008, a dozen UN agencies, international non-government organisations and specialist institutes formed the Partnership for Environment and Disaster Risk Reduction (PEDRR). The partnership aims to promote and scale-up implementation of ecosystem-based disaster risk reduction and encourage its incorporation in development planning at local, national and global levels. Findings from these organisations on the role of natural assets in disaster mitigation include:

Ecosystems, such as wetlands, forests and coastal systems, can reduce physical exposure to natural hazards by serving as natural protective barriers or buffers and thus mitigating hazard impacts. Well managed ecosystems can provide natural protection against common natural hazards, such as landslides, flooding, avalanches, storm surges, wildfires and drought. PEDRR 2010

Over the last decade, more and more Bank projects have been making explicit linkages between sustainable use of natural ecosystems, biodiversity conservation, carbon sequestration, and watershed values associated with erosion control, clean water supplies, and flood control. World Bank 2010

Natural barriers are cost-effective insurance against many types of natural disasters. Preventing loss is significantly less expensive than reconstituting livelihoods, and prevention measures need to be mainstreamed into disaster risk reduction. Such measures include investing in ecosystems such as sand dunes, mangrove belts, coral reefs, wetlands and use of forested slopes as barriers. Dudley et al 2006

In 2005 the Millennium Ecosystem Assessment noted that ‘changes to ecosystems have contributed to a significant rise in the number of floods and major wild fires on all continents since the 1940s’.

The World Conference on Disaster Reduction 2005 recognised the importance of the environment in disaster mitigation, adopting the Hyogo Framework for Action 2005–2015: Building the Resilience of Nations and Communities to Disasters (UN 2005). Key activities in the Hyogo Framework include:

- encouraging the sustainable use and management of ecosystems, including better land-use planning and development activities to reduce risk and vulnerabilities
- implementing integrated environmental and natural resource management approaches incorporating disaster risk reduction, including structural and non-structural measures such as integrated flood management and appropriate management of fragile ecosystems.

The AusAid (2009) Disaster Risk Reduction Policy supports the Hyogo Framework, and discusses strengthening capacities to protect ecosystems that can help reduce disaster risk (e.g. mangroves and coral reefs) and combating environmental degradation that enhances disaster risk (e.g. deforestation).

Natural assets provide a range of ecosystem services beyond disaster regulation including carbon sequestration, nutrient regulation and food provision. Ecosystem-based sediment control can reduce sediment loads and therefore costs for management of water infrastructure. Supporting biodiversity values can help support economic activity, particularly nature based recreation and tourism.

Purpose of this synthesis

The Queensland Government is undertaking a broad range of work to reduce vulnerability to natural hazards overseen by the Queensland Reconstruction Authority. The authority has undertaken a project entitled ‘Planning for stronger, more resilient floodplains’. This project is providing local government with interim floodplain mapping and guidelines on how to further develop their flood studies and incorporate them into planning schemes.

To complement this land-use planning approach, the departments of Environment and Heritage Protection (EHP), and State Development, Infrastructure and Planning (DSDIP) are developing a project entitled ‘Natural assets for flood and cyclone resilience’. This project is intended to provide guidance on how to manage natural assets in the landscape to increase community resilience to flooding and cyclones. It aims to develop a better understanding of landscape function in flooding and cyclone conditions to provide further guidance to planners moving beyond flood extent mapping.

This synthesis forms a component of the ‘Natural assets for flood and cyclone resilience’ project. It draws together the evidence from international and Australian scientific studies into the role of natural assets to identify what messages are supported and where further research is required.

There is high-level recognition internationally that healthy ecosystems can play an important role in disaster prevention and mitigation. There is strong scientific evidence to support this perception. Generalised understandings of how the landscape operates in flooding and cyclone conditions are presented below as hypotheses. The synthesis will draw together a range of evidence that supports or refutes such hypotheses. It is clear from the scientific evidence that exactly how individual assets operate in the landscape at a small scale is not well understood and cannot be readily generalised. Issues around natural resources have long been identified as 'wicked problems' due to the complex nature of landscape processes and interactions. Due to this, the synthesis is not likely to provide definitive advice. Instead, the evidence is reviewed and the best available advice is distilled and highlighted after each section.

Best available advice

The synthesis provides the best available advice that can be drawn from the evidence that natural assets can mitigate impacts from floods and cyclonic conditions.

The synthesis does not challenge the science of the fundamental processes that underpin the mitigation potential of natural assets, though these processes are briefly described at the start of each section. The synthesis focuses on papers that explicitly examine the relationship between a natural asset and functional aspects of riverine flooding, storm surges and strong winds.

Understanding flooding and cyclones

Flooding in simple terms is water that has inundated usually dry areas. This happens when:

- rainfall exceeds the infiltration capacity of the land leading to overland flows
- the amount of water in a watercourse exceeds the capacity of the watercourse to convey water leading to riverine flooding
- when storm surges, tsunamis or high tides exceeding normal levels inundate low lying coastal areas.

The definition of flooding is sometimes presented as 'water where it is not wanted' (Geoscience Australia 2011). However, flooding is a natural aspect of landscape function. Flooding processes have an important ecological role and are important to some ecosystems. Values of flooding include recharging groundwater aquifers, depositing nutrients, providing habitat for river and wetland species and supporting their recruitment, growth and productivity, and facilitating the dispersal of animals and plant propagules (Bravo de Guenni 2005, Poff et al 1997). Flooding only becomes a problem when human settlements and infrastructure are located in harm's way and when land uses are not compatible with the natural realities of hydrological processes in the landscape.

Communication with individual citizens in Queensland communities has shown a disparity in how people react to cyclones compared to flooding. There is acceptance that cyclones cannot be controlled and consequently communities must be managed accordingly. Conversely, flooding is seen as something that can be controlled by, for example, modifying rivers to drain more quickly or through structural approaches.

In fact, there are a range of measures and mitigation strategies to reduce the impact of flooding including:

- locating communities and infrastructure away from flood-prone areas
- using structural and non-structural approaches to:
  - improve landscape infiltration capacity to prevent small-scale flooding
  - retain water in the landscape or behind a dam to reduce downstream peak heights
  - slow down water flows to dissipate flood energy and prevent flood waters reaching damaging velocities
  - increase the flow capacity of rivers and creeks to more rapidly drain flood waters
  - alter the path of flood waters through dams and levees to protect vital infrastructure
- strengthening community and ecosystem resilience so that systems recover more quickly.

A natural assets approach to flood mitigation can contribute to almost all of the above measures and mitigation strategies. This synthesis reviews evidence for how different natural assets play a role in flood mitigation. Landscape function is complex and there may be many interactions that shape how floods behave. It is therefore expected that the evidence for how natural assets affect floods and cyclones will be similarly complex. However, looking at the performance of a natural asset in terms of flood behaviour rather than limiting this discussion to the end goal of reducing flood extent may offer opportunities to present some simple but powerful messages.

It is necessary to understand how our landscapes influence different flooding and cyclone behaviour to understand how natural assets can be used to change the processes that cause negative impacts.

Rainfall and runoff

Rainfall is intercepted by plants. Some rainfall collects on plant leaves and is taken up, or evaporates, never even touching the ground. Rainfall that reaches the ground is absorbed into the soil or runs off. The infiltration capacity of soil is governed by:

- soil type
- soil condition
- how dry the area is
- the underlying geology
- the slope of the land.

Orographic precipitation can cause significant variance in rainfall over small areas. This can cause a dramatic difference in the extent of runoff and flooding in steep slope areas over short distances.

When rainfall exceeds the plant interception and soil infiltration capacity, the water forms runoff by flowing over the land. Runoff follows the natural contours of the land and accumulates at the bottom of slopes and in natural depressions. These areas of water accumulation can form wetlands and riverine systems or can be usually dry, low-lying areas subject to frequent inundation. Stream channels are formed by natural erosion processes caused by water moving across the landscape. Runoff is generated more quickly on steeper slopes where soil cover tends to be thin and water holding capacity is low, and there are no significant areas where water can pool.

Flooding from runoff occurs from quick generation of runoff and will tend to affect localised areas. In urban and rural areas, the changes made to the landscape (impervious surfaces, changes to topography, soil condition, vegetation clearing) can make overland flows more likely to occur, whilst making it difficult to predict the flow paths it will take. Particularly extreme flash floods involve large quantities of fast moving water and are particularly hazardous to ecosystems and communities.

Natural assets hypotheses

- Improved rainfall interception and infiltration through increased vegetation cover, reforestation and landscape management practices for improved groundcover and soil infiltration would slow overland flows preventing or reducing flooding.
- Vegetation cover would slow overland flows reducing the potential for damaging velocities.
- Dry wetlands and floodplains can absorb runoff and slow the rate of delivery to a creek or river system. However, in periods with high antecedent rainfall these areas would already be saturated leading to increased runoff.

Creek flows

Water flows downhill at a speed determined by the water volume, channel size, landscape slope and roughness (rugosity). If the amount of water entering the channel system is higher than the conveyance capacity of the creek, the water-level rises. If the water level rises high enough it breaches the banks and causes floods.

The terrain and the speed at which water moves through the creek system will affect the points at which the creek will flood. Flooding will tend to occur in flatter areas of the landscape, where the fast moving water from steep upstream areas is slowed by changes in gradient.

Smaller creeks can be prone to flash flooding. High runoff from steep slopes or impermeable surfaces can lead to quick accumulation of water in streams and extremely quick rises in stream height. These floods affect the areas around the streams and can rise and fall in a matter of hours. The extent of flooded area amount and speed with which it is affected will be determined by the amount of rainfall and the volume and speed at which runoff is produced.

Natural assets hypotheses

- Reducing overland flow would reduce the rate and, to an extent, the quantity of delivery of water to creeks reducing the flood peak.
- Vegetation in creeks would slow water flow but increase the chance of localised flooding.
- Planning guidelines would need to respond to potential flood extent around creek areas.

River flows

As creek systems converge they form larger channels which can convey more water. The flow in a river system is determined by the amount of rain falling over the entire river catchment. This includes contributions from streams in upper parts of the catchment, and rainfall that runs off land and into the river directly. Not all river systems in Australia flow to the ocean—some inland systems flow into terminal lakes and wetlands, and groundwater aquifers.

Floods in river systems tend to be widespread and occur over longer time periods as the water accumulates in the river. A river flood may occur hours after the rain has ceased. The speed at which the floodwaters move will be affected by the character of the landscape, but fast moving river floods have the potential to do significant damage to both human and ecological systems.

Natural assets hypotheses

- Reducing overland flow would reduce and delay the amount of water entering rivers. Riparian vegetation would slow down water flows entering river systems both delaying and reducing flood peaks.
- Riparian vegetation and river channel rugosity would reduce flood velocities leading to less damaging flood waters.
- Reconnecting and reactivating floodplains would offer greater certainty around where flooding will be likely to occur.
- Restoring riparian forests, wetlands and floodplains would offer flood storage capacity.

Tidal interactions

As they reach the ocean, rivers are influenced by tides. Rising tides increase the pressure on flows coming downstream and will cause water levels to rise through coastal areas of the river system.

Interactions between freshwater flows and tidal systems can cause localised flooding along coastal areas. The impact and severity of these floods will be related to the amount of water coming from the inland systems and the tide level of the marine system. The highest spring tides that occur regularly through the year, known popularly as king tides, represent the highest risk. High spring tides are easily predictable, meaning early warning is possible, but difficult to mitigate.

Natural assets hypotheses

- Natural assets would reduce the rate of flood water reaching the coastal area.
- Riparian and coastal vegetation would reduce flood and wave velocities leading to less damaging flood waters.
- Reconnecting and reactivating coastal floodplains would offer greater certainty around where flooding will be likely to occur.
- Restoring coastal vegetation, riparian forests, wetlands and floodplains would offer flood storage capacity.

Cyclones

Damage from cyclones is caused by high wind velocities and through storm surges inundating coastal areas. The measures to reduce the impact of cyclones include:

- using structural and non-structural approaches to attenuate storm surges
- slowing down wind velocities
- ensuring building and infrastructure is designed to withstand high wind speeds
- strengthening community and ecosystem resilience so that systems recover more quickly
- providing a buffer zone between the coastline and infrastructure.

Natural assets hypotheses

- Coastal wetlands and mangroves can intercept and attenuate storm surges.
- Vegetation may slow down wind speeds.

Catchment vegetation and flooding

Flooding occurs when the quantity of water being supplied to the landscape exceeds the natural potential of the landscape to absorb and convey that water to the sea, inland lake, wetland or groundwater aquifer. This section reviews the impact that catchment vegetation can have on these processes. A relatively wide body of literature exists on the capacity of catchment vegetation to impact flooding. This literature is largely focused on the impact of deforestation and the potential benefits of reforestation. There is also research into the impact of other land uses after deforestation.

The common view is that forests help mitigate the likelihood and impacts of floods (e.g. FAO-CIFOR 2005, Calder and Aylward 2006, Tran et al 2010). This general understanding can be found in historical accounts dating back to the first century BC in the writings of Pliny who commented that 'often, disastrous torrents are formed after the felling of mountain woods, which used to hold back clouds and feed on them' (Andreassian 2004). Relating this belief to our understanding of flood behaviour, the hypothesis is that a naturally vegetated catchment would have a greater infiltration capacity than a deforested catchment. This would lead to less runoff reducing overland flow flood events and reducing the volume of water entering rivers and creeks. Vegetation, depending on types and density, would slow down moving water meaning less damage from high-velocity floods.

As with most environmental management issues, the processes and outcomes are complex. The hypotheses outlined in the introduction link catchment vegetation to certain aspects of flood behaviour. Producing a clear link between experimental or practical evidence and an overall effect on flood extent is much less clear because of the multiple complex interactions that occur in the landscape. This is represented in the lack of clear consensus in the literature on the role forests play in flood mitigation. For example, Bronstert & Kundzewicz (2006) comment that 'there are many publications devoted to forests and floods...but there is no such thing as a general theory. One can find inconclusive and conflicting evidence which can be summarised as follows: we know that we know little'.

Consequently, this synthesis focuses on drawing out messages about catchment vegetation that link to aspects of flood behaviour. Some of the literature identifies some of the factors that complicate the picture. In some cases, planning responses may be appropriate to mitigate shortcomings. The synthesis makes recommendations on where planning needs to respond and where further research is required.

Rainfall interception

The theory

Vegetation could have an impact on flooding through its capacity to intercept rainfall. An alteration to catchment vegetation can change interception of rainfall and subsequent loss through evapotranspiration, changed soil infiltration capacity and changed water storage in soils (Van Dijk et al 2009). Interception and evapotranspiration by vegetation occurs because trees generally have a higher aerodynamic roughness, greater leaf area and lower surface albedo than crops or pasture (Bruijnzeel 2004, Costa 2007). Crops and grasses absorb less water from the soil than trees (Bruijnzeel 2004). The capacity of forests to store rainfall is widely referred to as the 'sponge effect' (Bruijnzeel 2004, Van Dijk 2009, Nisbet et al 2011).

Synthesis of research evidence

The research covered in this synthesis clearly indicates that there is a link between vegetation clearing and an increase in rainfall runoff volumes. The details of these studies are presented in table 1.

Best available advice

Overall, there is a clear link between vegetation clearing and an increase in rainfall runoff.

Despite this evidence, it would not be appropriate to make a blanket recommendation for reintroducing vegetation as a flood mitigation measure. The evidence in Table 1 demonstrates the complexity of these processes. In general, the studies identify a clear link between vegetation and runoff at experimental sites or on very small catchments. Studies that attempt to look at larger areas tend to find less clarity in the relationship (Qian 1983, Thomas & Megahan 1998, Wilk et al 2001,Tran et al 2010).

The FAO & CIFOR (2005) report challenged ‘commonly held misperceptions’ about the role of forests in preventing floods. Some of the debate surrounds methodological issues (Oudin et al 2008, Alila et al 2009). Other challenges in developing a relationship in large catchments include:

- a lack of sufficiently sophisticated statistical modelling techniques to handle changes or cause and effect in large areas (Chappell 2006)
- natural climate variability can make it difficult to identify trends over time (Chappell 2006, O’Connell et al 2007, Van Dijk et al 2009, Wei & Zhang 2010, Peña-Arancibia et al 2012)
- land-use change is not uniform over large areas meaning multiple influences make it difficult to extract a single relationship (Thomas & Megahan 1998, Wilk et al 2001, Thornton et al 2007, Jackson et al 2008, Van Dijk et al 2009, Nisbet et al 2011)
- spatial variability of rainfall can mean changes in runoff are not detectable at the catchment level (Wilk et al 2001)
- limited data available for extreme events (Nisbet et al 2011).

The research covered clearly indicates that vegetation has the potential to affect local runoff and small-scale floods. The capacity for vegetation to mitigate extreme events is not clear and likely to be much more limited (Bruijnzeel 2004, FAO-CIFOR 2005, Robinson & Dupeyrat 2005, Tran et al 2010, Sriwongsitanon & Taesombat 2011, BMT-WBM 2011, Bathurst et al 2011). However, even apparently minor reduction in peak flows can lead to more significant reductions in flood probability (Bronstert & Kundzewicz 2006, Alila et al 2009). Bronstert &and Kundzewicz (2006) cite an example of a 10 per cent reduction in a flood peak equating to a change in flood probability from two per cent annual exceedence probability (AEP) to one per cent AEP. AEP represents the chance of experiencing a given sized flood in a year.

Best available advice

Vegetation is not likely to noticeably affect extreme flood events but has the potential to reduce local runoff and small-scale floods.

Some studies provide useful pointers to how further research could support an effective approach to harnessing the mitigation potential of catchment and riparian vegetation. It is clear that an evidence-based approach to integrated flood management is critical.

What is recognized, with some certainty, is that simplistic and populist land management solutions, such as oft-advocated solutions involving commercial afforestation programs, cannot ever represent a general solution and will, in most situations, have at best marginal benefit and at worst negative impacts [on flooding] (Calder and Aylward 2006).

Best available advice

An evidence-based approach to integrated flood management can harness effective catchment vegetation management to reduce the impacts of flooding.

An understanding of all the factors that can influence runoff should be considered. These include:

- rainfall variation spatially and temporally
- elevation
- slope
- geomorphology
- distance to the coast or other flow destination (e.g. inland lake or aquifer)
- soil depth
- soil compaction and disturbance
- soil fertility
- fire history
- backwater effects from confluence of two or more streams
- changes to river beds from sedimentation

- natural water table and soil water storage opportunities
- catchment saturation
- urbanisation and infrastructure development (Jones & Grant 1996, Yin & Li 2001, Bruijnzeel 2004, FAO & CIFOR 2005, Calder & Aylward 2006, Chappell 2006, Doerr et al 2006, Coe et al 2009).

Ilstedt et al (2007) found that runoff is reduced when agricultural land is reconverted to forest. The Jackson et al (2008) study conducted a field trial investigating the effect of planting small strips of trees on pasture hill slope land. This study found that the careful placement of interventions could reduce flood peaks by 40 per cent at the field scale. This is supported by other findings indicating that afforestation is more successful at reducing runoff in some locations rather than others (Nisbet & Thomas 2008, Hurkmans et al 2009). Some areas have a naturally high overland flow due to, for example a shallow impeding layer. Deforestation or afforestation is not likely to change conditions in this case (Bruijnzeel 2004). Reforestation may only be successful if it can overcome soil degradation, and the flood management approach can counteract changes to river bed morphology and the introduction of roads, drains and settlements (Van Dijk et al 2009). Ilstedt et al (2007) expressed that their research could not provide conclusions on appropriate species selection or planting techniques. It is evident that localised research would be required to investigate appropriate interventions in the catchment.

Best available advice

Local studies to understand the catchment context are essential to determining the best locations for vegetation interventions to mitigate flooding.

Table 1—Summary of studies relating to vegetation and runoff

Study/location	Scope of work	Conclusions	Further considerations/criticisms
Bartley et al (2006) Queensland	Analysis of Weany Creek sub-catchment of Burdekin.	Hill slopes with bare patches show 6–9 times greater runoff than vegetated slopes.	
BMT–WBM (2011) Queensland	Modelled peak flow changes from vegetation cover in SEQ 1970–2009.	If the whole catchment (including urban areas) was naturally vegetated, flows for 20 per cent or higher AEP events would decrease by 8 per cent on average.	Some sub-catchments showed more significant flood reduction, others would have experienced increased flood peaks due to water retention combined with subsequent heavy rainfall.
Bradshaw et al (2007) International—developing world	Statistical analysis of flood severity and frequency data from 56 countries 1990–2000.	10 per cent loss in forest would increase flood frequency by 4–28 per cent and flood duration by 4–8 per cent.	Criticised by Laurance (2007) and Van Dijk et al (2009) for excluding extreme events. Bradshaw et al produced a second paper (2009)—including extreme events leads to prediction that 10 per cent loss of native forest cover would still increase flood frequency by 3–25 per cent. Criticised by Van Dijk (2009) with argument that distilling a clear cause and effect between catchment vegetation is not possible due to large variations in climate, land use, population and hydrological condition.
Burch et al (1987) Victoria	Comparison of two experimental catchments, one with native vegetation, the other cleared and converted to grassland.	Total runoff and peak discharge significantly higher from the grassland site.	Antecedent soil moisture was an important factor in determining runoff content.
Coe et al (2011) Brazil	Study of Araguaia catchment (82 632 km^2) 1970s to 1990s.	Found a 55 per cent loss of native vegetation and 25 per cent increase in discharge.	Attributed two thirds of the increase to deforestation and the remaining third to changed climatic conditions.
Costa et al (2003) Brazil	Examined hydrological change in discharge volumes in the Tocantins basin (175 360 km^2) 1949–1998.	Decrease in natural vegetation and increase in agricultural land use (30–49 per cent). No significant change in precipitation but increase in annual mean discharge of 24 per cent and in peak season discharge of 28 per cent.	Criticised by Peña-Arancibia et al (2012) for not taking sufficient account of El Niño Southern Oscillation events.
Eldridge & Freudenberger (2005) New South Wales	Analysis of Riverina region for infiltration capacity.	Timbered strata on fine textured soils have higher infiltration capacity that grass or cultivated land.	

Study/location	Scope of work	Conclusions	Further considerations/criticisms
Fitzpatrick et al (1999) USA	Modelled impact of land use change in a Wisconsin catchment.	Under peak agricultural land use (66 per cent forest cover, 22 per cent cropland, seven per cent pasture/grass), flood peaks for a 50 per cent AEP event were three times higher than under natural 100 per cent forest cover. Current land use (58 per cent forest, 31 per cent pasture/grass, three per cent cropland) would have flood peaks double natural state.	
Howard (2010) Queensland	Paired catchment study in Wet Tropics region investigated storm flows between a naturally vegetated catchment and a pasture catchment.	Found no difference in storm flow.	
Ilstedt et al (2007) International—tropics	Meta analysis of impact of afforestation.	Infiltration capacity triples with afforestation on agricultural land.	Would need to investigate locally appropriate species selection, planting techniques and natural soil condition.
Jackson et al (2008) International	Field trial—effect of small strips of trees on pasture hill slope.	Careful placement of interventions can reduce flood peaks by 40 per cent at the field scale.	No conclusions on catchment level impacts.
Jones & Grant (1996) USA	Study of five Oregon river basins 1940s to 1990s for impact of deforestation.	Clearing produced detectable changes in peak flows.	Attributed to road construction which changed flow routing. This conclusion disputed by Thomas & Megahan (1998).
Komatsu et al (2011) Japan	Investigated impact of changing forestry practices on runoff.	No significant relationship with forestry practices such as thinning and pruning.	
Kramer et al (1997) Madagascar	Comparison of run off from secondary forest with swidden and agricultural land over nine year period.	Runoff 154 per cent higher from swidden land and 58 per cent higher from agricultural land.	Effect strongest for small and medium sized floods.
Locatelli & Vignola (2009) International	Meta analysis of 20 hydrological studies.	No significant difference found in storm flow between natural forest, planted reforestation and other land uses.	
Mahe et al (2005) Burkina Faso	Study of river flows in the Nakambe River 1970–1990.	Despite a fall in precipitation and the construction of water retention reservoirs, average and peak flows increased. Attributed to vegetation loss (13–43 per cent land area 1965–95).	

Study/location	Scope of work	Conclusions	Further considerations/criticisms
O'Donnell et al (2011) England	Modelled a 1967 extreme flood event.	Changes in land management had probably increased the flash flood effect at a small scale.	
Qian (1983) China	Investigation of runoff from 12 catchments in Hainan Island 1960s–1970s.	No detectable change in floods.	Humid tropical climate may limit deforestation impacts on atmospheric circulation and encourage rapid regrowth.
Robinson & Dupeyrat (2005) Wales	Investigated of impact of commercial forest harvesting in Plynlimon catchment.	Large scale harvesting had not detectable impact on peak storm flows.	Forests may be capable of suppressing runoff from smaller rainfall events but no extreme events. Forest cover could lead to increased runoff during extreme rainfall events, particularly for catchments with high antecedent soil moisture.
Siriwardena et al (2006) Queensland	Examined flow changes in the Comet catchment (16 440 km^2) during major vegetation clearing.	Runoff increased by 40 per cent.	Peña-Arancibia et al (2012) argued that most of the increase was due to climate change. Runoff still increased due to vegetation clearing.
Thomas & Megahan (1998) USA	Study of peak flows in Oregon basins.	Increase in peak flows for 20 years after clearing of small basins. Increase last for 10 years for selectively cut basins. Relationship significant in small basins (6–101 ha) but not detectable in large basins (60–600 ha).	
Thomas & Nisbet (2006) England	Modelled impact of afforestation in a catchment at four sites (40 ha total).	Planting woodland would delay progression of a 1% AEP flood by almost one hour. Desynchronisation of flows from a tributary catchment could lower flood peak by 1–2 per cent..	
Thornton et al (2007) Queensland	Paired catchment study in central Queensland comparing runoff from natural brigalow and pasture and cropland.	Proportion of rainfall becoming runoff doubled over the period from 5 per cent to 9–11 per cent.	Attributed to vegetation clearing, soil compaction, soil cover, soil structural decline and changes in surface roughness.
Tran et al (2010) Vietnam	Statistical analysis of rainfall and flood data 1989–2009.	Period of significant land use change but conclude that 71 per cent of flood level variance due to rainfall.	Forests have a only a minor impact on extreme flood levels.
Wei & Zhang (2010) Canada	Investigated impact of forest harvesting on a catchment area (2860 km^2)	Harvesting 32 per cent of the land linked to increase of 9.8 per cent in stream flow.	Counteracted by climate variability changes.

Study/location	Scope of work	Conclusions	Further considerations/criticisms
Wilk et al (2001) Thailand	Examination of runoff and rainfall 1957–95.	No significant change in water balance despite reduction in forest cover from 80 per cent to 27 per cent.	Suggest that shade trees in agricultural areas and abandonment leading to regrowth may have resulted in overestimation of vegetation loss. Land use change and rainfall not uniform spatially or temporally so difficult to draw clear cause and effect.

Wetlands and floodplains

If flooding in simple terms is water that has inundated usually dry areas, floodplains are the areas of the landscape most likely to flood. As discussed above, flooding is sometimes presented as 'water where it is not wanted' (Geoscience Australia 2011). Floodplains in many countries have been disconnected from their river systems as a result of human interventions designed to prevent water from going where it is not wanted. Most of Queensland's towns and cities are located on floodplains, both inland and coastal. There is a public perception that structural interventions can be used to prevent flooding. For example, during the 2012 flooding in Charleville, a local resident was quoted as saying, 'they [the government] could finish the job properly they were supposed to do, which was build a levee bank and divert the gully' (Courier Mail, 1 February 2012).

There are potentially negative consequences of the structural approach. If the flood event exceeds the design capacity of the levee and causes a breach, the consequences of flood water release could be more damaging for those behind the levee than if the levee had not been there. A levee may hold water at a damaging height for longer by constraining its escape. The presence of levees could cause communities to become complacent, assuming the levee will protect them. Diverting water with a levee can lead to more severe consequences elsewhere by flooding other areas to a greater extent or confining flow and increasing the energy of the flood as it finds release. The Queensland Floods Commission of Inquiry final report (2012) recommends that levee design, construction, placement and management should be regulated as a result of such concerns.

Disconnection of floodplains can have negative ecological consequences. Flooding processes are important to some ecosystems for recharging groundwater aquifers and depositing nutrients and supporting other ecosystem services such as increased habitat and food resources, enhanced recruitment and improved fisheries production (Bravo de Guenni 2005, Arthington and Balcombe 2011, Pittock and Xu 2011, WWF 2012).

The Queensland Government has released guidelines to support improvements to local government planning schemes, 'Planning for stronger, more resilient floodplains'. These provide advice on how to effectively map flood extent and incorporate this information into planning. A key recommendation is to go beyond the one per cent AEP defined flood event with a better understanding of flood risk as a multiple of likelihood and consequence. This leads to recommendations on how to plan for protection of flood-prone communities including relocation of housing and vulnerable infrastructure or adopting appropriate engineering solutions. Understanding the benefits of floodplains and wetlands as natural flood storage systems adds an additional dimension to floodplain planning. Designating an area as a floodplain can still allow appropriate low-risk activities such as grazing or some types of cropping with appropriate conditions relating to vital infrastructure, chemical storage and warning systems. Cropping and floodplain pastoral production benefit from flood sediment and nutrient deposition improving the land (Opperman et al 2009). The Floodplain Grazing Project provides advice to graziers on sustainable grazing in coastal floodplains in New South Wales (NSW DPI 2008).

This section looks at examples of floodplain reconnection for natural flood storage and studies into how to design and manage reactivated floodplains.

Natural flood storage

Floodplains create space for flood water to be stored safely. The European Commission (2006) describes several ways to use floodplains to help reduce flood risk:

- undertake controlled reconnection of rivers to their natural floodplains, such as through controlled levee breaches
- allow natural inundation of floodplains or constrain area with dykes
- relocate levees and impoundments further back from the river allowing land in between to flood when necessary
- construct flood bypass channels between a river and a floodplain
- protect existing riverine wetlands or construct new wetlands.

Analysis of floodplain wetlands and their contribution to flood mitigation has been extensively covered in the Bullock & Acreman (2003) literature review of 439 studies. The general conclusion of this review is that floodplain wetlands reduce or delay floods. Table 2 outlines further international studies of how floodplains help to reduce flood risk not covered by Bullock & Acreman (2003).

Table 2—Studies into floodplain storage

Study	Method	Impact
Acreman et al (2003) UK	Modelled impact of restoring the river Cherwell's channel to pre-engineered dimensions—reducing width and depth leading to earlier floodplain inundation.	Would reduce peak flows by 10–15 per cent. Engineering embankments have increased downstream peak flows by 50–150 per cent.
Gerrard (2004) Laos	That Luang marsh consists of 1500 km^2 of permanent and seasonal waterbodies, floodplains, swamps and marshes.	Flood reduction rate for Vientiane ranges from 100 per cent for a 50 per cent AEP flood to 25 per cent for two per cent AEP flood.
Hammersmark et al (2005) USA	Modelled impact of ecosystem rehabilitation in tidal marshes in the Sacramento–San Joaquin delta.	Removing levees would have a minimal impact of flood stages under a range of flood scenarios. Some reduction in upstream flooding expected, possible increase in downstream flooding under one scenario.
Hey et al (2009) USA	Modelled 'low tech' restoration of 18 210 km^2 (four per cent of the catchment) of the Mississippi river channel and floodplain.	During largest recent flood (1993), natural flood storage would have reduced peak discharge by 64 per cent. Estimate net social benefit value at US$500 million.
Opperman et al (2009) USA	Connection of a 9700 ha floodplain to the Sacramento River in the 1930s through construction of Yolo bypass.	Successfully conveyed floodwaters away from Sacramento.
Pitt Review (2008) UK	Poterric Carr nature reserve near Doncaster is a 200 ha wetland site that acts as flood storage.	In large scale flooding (2007) the site was estimated to hold 200 000 m^3 of flood water preventing flooding of thousands of homes.
Schwartz et al (2006) Eastern Europe	Examined flood prone areas of the lower Danube and identified almost 100 000 ha of potential floodplain restoration sites with 1.6 billion m^3 storage capacity.	If these areas, plus a further 500 million m^3, were restored, the 2006 flood level would have been 40 cm lower. Hulea et al (2009) estimated that the restored floodplains would provide €500/ha/year in ecosystem services.
US EPA (2006) USA	Acquisition of over 3200 ha of wetlands near the Charles River in Massachusetts in the 1970s by the US Army Corps of Engineers.	Seen as more cost effective than a sole reliance on a structural approach.
WWF (2012), Pittock and Xu (2011) China	Reconnection of over fifty floodplain lakes covering almost 3 000 km^2 to the Yangtze River.	Provides 13 billion m^3 of floodwater storage capacity and additional ecosystem services such as improved fisheries production.

Best available advice

Floodplains can provide a cost-effective alternative or supplement to structural mitigation approaches with additional ecosystem service and ecological benefits.

Design and management

The US Environmental Protection Agency (EPA) (2006) cites several factors that affect the function of a floodplain and its mitigation capacity including:

- floodplain size and character
- extent and type of vegetation present
- antecedent soil moisture
- location on the river/position within the catchment.

Using the US EPA (2006) estimated figures, one hectare of wetland can typically store 9370 m^3 of water. This is similar to the estimate of the storage capacity of the Poterric Carr nature reserve wetlands in Doncaster, UK (Pitt Review 2008). The European Commission (2006) estimates that a discharge of 1 m^3/second (m^3/s) over one day can inundate a one hectare (ha) area to a depth of almost nine metres. Peak flow from Wivenhoe Dam in the January 2011 flood in Brisbane was 7528 m^3/s. This rose to a peak flow of 10 000 m^3/s at Jindalee after joining other flood waters (Queensland Floods Commission of Inquiry 2011, Raymond 2011). These figures indicate that very large areas are required to mitigate large flood events.

Best available advice

Floodplains need to be appropriately sized in relation to local flooding expectations and limitations to flood storage capacity need to be understood.

Appropriate planning considerations are important to maximising flood storage effectiveness including:

- wetland flood mitigation capacity tends to be limited in catchment headwaters (Ogawa & Male 1986, Bullock & Acreman 2003) and could possibly have a negative impact through altering flood timing (Hooijer et al 2004)
- the relationship between wetland area and flood mitigation may not be linear—for example one study found that a 100 per cent wetland encroachment would lead to 100 per cent increase in peak flows but 25 per cent or less encroachment would have a minimal impact (Ogawa & Male 1986)
- catchments with less than 10 per cent of their natural wetlands remaining may experience significant increases in flood flows from small further wetland losses (Johnston et al 1990)
- constructed wetlands may have higher values for flood control than natural wetlands perhaps due to careful planning allowing for maximisation of opportunity (Ghermandi 2009 meta-analysis).

The fourth point relating to constructed wetlands being more effective is echoed in other studies that suggest that modified floodplains or a combination of floodplains and hydraulic structures may offer more flood mitigation than natural floodplains (Wang et al 2010, Castellarin et al 2011). For example, structuring a floodplain with minor dykes may offer better mitigation than a natural floodplain (Castellarin et al 2011).

Best available advice

Careful floodplain planning and design can offer opportunities to maximise flood storage potential beyond that of a natural floodplain especially in a highly modified catchment.

Cyclic floodplain reduction, a process to periodically reduce sediment or vegetation succession, may need to be carried out in modified floodplains and rivers. The natural processes that would usually carry out such rejuvenation do not occur in a modified system. Duel et al (2001) suggest that cyclic floodplain reduction should be carried out on river stretches over 25 kilometres (km) and floodplains over 250 ha. Baptist et al (2004) suggest that carrying out cyclic floodplain reduction on 15 per cent of the total floodplain at 25–35 year intervals would be enough to control long term flood levels. This strategy may not be effective in hydraulic bottlenecks.

There may be ecological and social benefits of floodplain restoration including supporting increased biodiversity, improved water quality and recreation opportunities. However, flood storage goals may conflict with biodiversity goals. Examples include disrupting bird nesting sites or community objectives such as hunting, grazing or nature conservation (Mauchamp et al 2002, RSPB 2010). Drained wetlands may in fact offer more flood storage than wetlands already storing water (Potter 1994). Large-scale ecosystem rehabilitation of floodplains including hydraulically rough forests, bushes and marsh vegetation may compromise flood mitigation potential, although cyclic floodplain rejuvenation may assist with this (Makaske et al 2011).

Best available advice

Plans for floodplain restoration must balance potentially competing goals of flood storage and ecosystem rehabilitation.

Another factor to consider is that pollutants accumulated in river sediment may contaminate floodplain wetlands when the floodplain is reconnected such as through a levee breach (Japenga & Salomons 1993, Sparks et al 1998).

Riparian vegetation

Water moving at high velocity will be more damaging than the same depth of water moving at low velocity. Moving flood water causes damage to buildings and infrastructure through hydrodynamic forces and through debris impact. Flood waters also cause environmental damage through stream bank and gully erosion, transporting sediments that may contain pesticides and nutrients to creeks, rivers, and estuarine and marine areas. Downstream flood peaks are likely to be lower if less flood water arrives at once. Therefore, slowing down flood water is likely to make it less damaging in both flood velocity and flood peak. Riparian vegetation reduces flood velocity and causes water to spread over localised areas and floodplains, and into wetland systems. This can remove some of the energy, sediments and nutrients from the system. Climate change is likely to lead to increased energy in storm systems leading to more intense rainfall (DERM et al 2010, IPCC 2007, 2012). Therefore methods to reduce flood energy will become increasingly important.

Flooding can damage crops when the water sits in the landscape for some time. For many years, Australian landholders were encouraged to clear riparian vegetation to speed up flood flow (Rutherford et al 2006). However, more recent evidence shows that riparian vegetation can help reduce the impacts of flooding at a catchment scale. Riparian vegetation also has other significant environmental and ecosystem benefits in stream bank stabilisation, sediment and erosion control, providing habitat structure and supporting biodiversity.

Reducing velocity

The studies reviewed in Table 3 show a clear link between riparian vegetation, reduced flood velocity, changed downstream flood peak and changed areas of inundation.

Table 3—Studies into impacts of riparian vegetation on water velocity and flow

Study	Method	Impact
BMT WBM (2011) Queensland	Modelled impact of planting 2 m riparian vegetation buffers along the tributaries of the upper Caboolture river.	Vegetation slowed water flow leading to reduced flood peak downstream by up to one metre and increased local flooding upstream by up to one metre.
Liu et al (2004) Luxembourg	Modelled impact of river rehabilitation in a small sub-catchment.	Increased channel roughness caused up to 14 per cent reduction in peak flow and delayed flood peak by two hours. Cannot extrapolate results to a large catchment. Increased flooding in headwaters.
Rutherford et al (2006) Australia	Modelling shows that dense vegetation could slow flood water from 8 km/h to 3 km/h.	Revegetation of the Murrumbidgee catchment riparian zone would reduce flood height at Wagga Wagga from 8 m to 6.1 m. Effect more pronounced for small to medium floods.
Thomas & Nisbet (2006) UK	Modelled impact of reforesting 2.2 km of a riverbank on a one per cent AEP flood.	Flood storage increased by 71 per cent and flood peak delayed by 140 minutes.

Best available advice

There is a clear link between riparian vegetation, reduced flood velocity, changed downstream flood peak and increased upstream flooding. The increased localised flooding spreads the flood flow, removing systemic energy and reducing flood-velocity damage.

Riparian intervention design

A variety of factors may influence the effectiveness of riparian vegetation in affecting flooding including:

- proportion of the network rehabilitated
- replanting location
- plant species type
- planting density (BCC 2003, Anderson 2005).

Rutherford et al (2006) present five rules of thumb:

1. Vegetation blocking less than 10 per cent of a cross sectional area will probably have little effect on flood stage. Therefore vegetation has more effect on small streams than large.
2. Vegetation is unlikely to have any effect on flooding on streams with a width to depth ratio of greater than 17:1.
3. Vegetation in the stream bed has more influence on flow than vegetation on the bank.
4. Vegetation that flattens down in a flood will probably have little effect on flooding.
5. Flooding will be most affected by riparian vegetation in catchment types that:
    a. are long and thin
    b. have a high drainage density
    c. have a short, steep headwaters section then a long low gradient section.

Simply returning riparian vegetation to modified streams will not necessarily return them to their natural state (Rutherford et al 2006). For example, a Victorian paired catchment study (Brooks et al found that clearing riparian vegetation had changed the geomorphology of the Cann River so significantly that the change would not be reversed simply through riparian revegetation.

In general, riparian vegetation will be more effective at reducing small floods. Floods occur naturally in completely unmodified catchments—riparian vegetation will not mitigate all flooding. Large dams and levees can provide significant flood protection in modified catchments. However, riparian vegetation can offer many other benefits, such as streambank stabilisation, erosion and sediment reduction, increased biodiversity and improved water quality (Anderson 2005, Rutherford et al 2006).

Best available advice

A whole-of-catchment approach is important to effective planning for riparian rehabilitation. In highly modified catchments, riparian vegetation is only part of a flood security approach.

Planning considerations

Riparian vegetation slows down flood waters, by reducing velocity and spreading the flow, to make them less damaging. It slows down the rate at which flood waters enter creeks leading to lower and later peaks downstream. This means that more water is held on land in the headwaters. In other words, reducing floods downstream increases floods upstream (Liu et al 2004, Anderson et al 2006, BMT WBM 2011). Modelling would need to be used to show where flood waters will back up if riparian vegetation is reintroduced. Some types of agriculture are destroyed by flood waters so careful consideration is required to balance the goals of reducing peak floods downstream and increasing or prolonging localised upstream flooding. Planners and agricultural extension workers would need to work with landholders to achieve an appropriate outcome.

This issue is more likely to be difficult to manage in urban areas where land uses are more varied (BCC 2003). In urban areas, the ecological benefits of riparian vegetation need to be weighed against flooding impacts. Management actions such as planting in the direction of current and trimming limbs below the likely flood level can help reduce resistance without extensively compromising ecological outcomes (Bott 2007). Brisbane City Council (2003) guidelines suggest that grasses and sedges better withstand high flow velocities than woody species. Trees close to the channel in deeper water will have a greater impact on flooding than trees further away from the channel.

Best available advice

Riparian vegetation can help reduce downstream flood peaks but may cause increased localised flooding upstream. Land use planning can ensure appropriate land uses occur in areas once again prone to flooding due to riparian vegetation.

Land management practices and flooding

The previous sections have considered the natural assets that can mitigate flooding to a certain extent. It is not practical to recommend a return to natural states in general as land-use requirements for agriculture and human habitation mean that many catchments cannot be restored to, or operate, in their natural condition. Therefore strategic interventions must be carefully designed to support a flood security approach. Landscape management practices such as fencing riparian areas to allow regeneration or planting strategic vegetation patches will support flood mitigation. There is further evidence that agricultural land management practices can impact flooding through their effects on rainfall infiltration and runoff.

Queensland agricultural land managers have been making significant improvements in reducing erosion and sediment runoff from their properties to improve water quality outcomes in rivers, creeks and coastal marine environments. Many of the land management practices to reduce flooding are similar to those for sediment and erosion control.

There is no definitive quantifiable link between land management practices and flooding, as with the previous sections on vegetation. However, the literature covers a variety of practices which do affect runoff. Using such practices, the UK government released a flood planning strategy entitled Making Space for Water. This strategy included recommendations on agricultural land management practices to reduce rainfall runoff as a flood-mitigation measure although the impacts at the catchment scale were not clear. The plan noted that it is likely that significant change across the catchment would be required (DEFRA 2004). Table 4 outlines some studies that link land management practices with flooding.

Table 4—Studies into land management impacts on flooding

Study	Conclusion
Brown (1972) NSW	Bushfire in 1965 affected catchment hydrology leading to higher than expected flood magnitudes in following years.
Doerr et al (2006) NSW	Burning of eucalypt forest caused widespread generation of soil water repellence leading to increased runoff, though this varied with burn severity and with rainfall intensity. The author noted that this counters the general assumption that fire creates soil water repellence.
Hess et al (2010) UK	Using modelling of land management practices (such as soil condition and measures to help reduce runoff) and runoff showed the potential to mitigate flooding. Only a few areas showed expected runoff reduction of over five per cent for the one per cent AEP flood. Drier regions had higher relative reductions in runoff. Greatest reductions achieved through the improvement of degraded permeable soils under permanent grassland in eastern England.
McIvor et al (1995) Queensland	Experiments on a range of pastures showed that ground cover can help increase condition of soil surface and impede overland flow to increase infiltration. For small storms and intensity (total rainfall <50 mm and intensity <15 mm/hour) only 40 per cent ground cover level was required to reduce runoff significantly. In large storms, cover had little effect on runoff.
Scanlan et al (1996) Queensland	Examined soil erosion and run-off from ten experimental rangeland sites. Cover was found to be a dominating influence on runoff, but the effect of cover was also influenced by other factors such as slope, event size and intensity and soil dryness.
United Utilities (2010) UK	The Sustainable Catchment Management Project (SCaMP) is testing the impact of restoring peat habitats through activities such as changing livestock management and drain blocking. An intensive monitoring program is testing for impacts on flooding, water quality (suspended solids, pathogens and nutrients) and water colour. The early indications are that the restoration has led to an improvement in rainfall retention and infiltration rates, which may have a favourable impact on downstream flooding.

Coastal vegetation systems and cyclones

Cyclones cause damage through high wind velocities and through creating storm surges. A storm surge is caused by low barometric pressure in the centre of the cyclone increasing the water level and a build up of water against the coast associated with the forward movement of the cyclone. Wave effects can increase the water level by the same elevation as the surge itself (Trollope et al 1972). In a tropical system a storm surge can be 300–700 km across, penetrate far inland and raise water levels for several hours (Feagin et al 2010). This causes damage in a similar way to rapid flood waters.

There is general acceptance globally that coastal ecosystems such as mangroves and saltmarsh absorb energy from waves and storm surges making them less damaging (UNEP-WCMC 2006; Stolton et al 2008). Such global acceptance is evident in, for example, the naming of a sacred coastal grove in Southern India which translates as ‘the forest that controls the waves’ (UNEP-WCMC 2006). Around 90 per cent of fishers interviewed by Walton et al (2006) in the Philippines believed mangroves provided protection from storms and typhoons.

Interest in tsunami mitigation led to the development of some of the literature on the benefits of coastal vegetation. Some of the findings of the tsunami literature are likely to be relevant to cyclone mitigation. However, tsunamis are inherently different to storm surges. A storm surge has a shorter wavelength, more of its energy near the water surface and is sustained by cyclonic winds. A tsunami is created by an earthquake and is a large, fast travelling wave. Findings from studies based on tsunamis may not always be useful (Das & Vincent 2009). There is greater controversy around tsunamis (see for example Kerr & Baird 2007, Feagin et al 2010) but this synthesis focuses only on storm surges caused by cyclones.

Other literature deals with the mitigation potential of vegetation for short-period waves. Some of these findings may be relevant to cyclone mitigation. However, storm surges are different as they are more likely to lead to a longer period of base water level rise with greater net force and greater spatial extent. The science on short-period wave attenuation may not necessarily be extrapolated to the conclusion that vegetation can reduce the effects of storm surges or tsunamis (Feagin et al 2010).

The literature reviewed supports the premise that coastal ecosystems can mitigate storm surges. The literature is not able to clearly quantify the mitigation potential.

Coastal ecosystems mitigate storm surges through attenuating waves as they pass over or through wetlands, marshes and mangroves. Wave energy is lost through frictional drag as the wave passes mangrove or saltmarsh vegetation and through bottom friction in shallow water areas (Shepard et al 2011). Increased bed roughness as a result of vegetation trunks, branches and roots reduces currents and dissipates wave energy (Quartel et al 2007). This reduces the strength of a storm surge, and can reduce its peak or delay its arrival inland (Wamsley et al 2010). Additional benefits of vegetation include trapping floating objects such as broken branches.

Wave attenuation

Table 5 summarises studies that have examined the link between coastal ecosystems and wave attenuation.

Table 5—Studies into coastal ecosystems and wave attenuation

Study	Conclusion
Gedan et al (2011)	Meta-analysis of wave attenuation over unvegetated wetlands. Found that vegetation is critical to wave attenuation.
Massel et al (1999) Townsville & Japan	Field observations in mangrove forests showed significant attenuation of wave energy over a relatively short distance. Townsville: 50 per cent of wave energy transmitted through 230 m of mangroves, less than 20 per ecnt of energy transmitted through 310 m.
Mazda et al (1997) Vietnam	5–6 year old mangrove trees reduced waves by 20 per cent due to drag force on the trees. This effect persisted even when water depth increased.
Quartel et al (2007) Vietnam	Compared wave attenuation over bare mudflats, mangrove forest fringe and dense mangrove forest. Dense mangroves reduced wave height 5–7.5 times more than bare mudflats.
Shepard et al (2011)	Meta analysis found that salt marsh vegetation had a significant effect on wave attenuation and shoreline stabilization. The presence of wetlands reduces wave heights, property damage and human deaths.

Best available advice

There is a clear link between coastal vegetation systems such as mangroves and saltmarsh and wave attenuation but making an extrapolation for storm surge mitigation is difficult.

Storm surge attenuation

Table 6 summarises studies that have examined the link between coastal ecosystems and storm surge attenuation.

Table 6—Studies into coastal ecosystems and storm surge attenuation

Study	Conclusion
Agrawala et al (2003) Bangladesh	Expected that the Coastal Embankment Rehabilitation Project would result in 50 per cent less deaths from cyclone storm surges with an average return interval (ARI) of 10 years.
Brody et al (2006) USA	Found that altering natural wetlands in Florida and Texas exacerbated coastal flooding.
Costanza et al (2006) USA	Extrapolated historic observations to estimate that 80 km of existing coastal marshes could reduce a southerly storm surge by 3.66 m at New Orleans.
Das & Vincent (2009) India	Found that villages in Orissa with intact mangrove systems were better protected during a 1999 super cyclone. Mangroves significantly reduced the number of cyclone caused deaths.
Day et al (2007) USA	Observations suggest each kilometre of unchannelised wetland landscape mitigated hurricane Rita's surge by 4.7 cm/km. Intact Louisiana wetlands reduced hurricane Andrew's surge by 7.9 cm/km. Degradation of the Mississippi Deltaic Plain increased community vulnerability to hurricanes Katrina and Rita. They recommended maintaining and where possible increasing the wetland systems on the plain to complement protective levees.
Fritz & Blount (2006) Bangladesh	Modelled impact of planting mangroves on Hatia Island. The best case scenario found that a 600 m tree buffer would reduce the peak storm surge by seven per cent.
Granek & Ruttenberg (2007) Belize	Found that monitoring equipment survived better in storms at a protected wetland site than at a cleared site.
Kemp (2008) USA	Estimated that marshlands attenuated hurricane Rita's surge by 13 cm/km. Modelling estimated that the loss of baldcypress– water tupelo forests and marshlands caused by construction of the Mississippi River Gulf Outlet led to 70–80 per cent more overtopping of New Orleans levees.
Krauss et al (2009) USA	Found that mangrove wetlands in Florida reduced storm surge water level height by 9.4 cm/km over intact, relatively unchannelised expanses and by 4.2 cm/km along a river corridor.
Shaffer et al (2009) USA	The wetlands lost to construction of the Mississippi River Gulf Outlet navigation canal would have attenuated the storm surge at New Orleans by at least 1.35 m.
Wamsley et al (2010) USA	Modelling estimates 2 cm/km to 17 cm/km storm surge attenuation by coastal marshes. Data from hurricane Rita suggested that surge attenuation rates ranged from 4 cm/km to 25 cm/km.

Best available advice

There is clear evidence that coastal vegetation systems such as mangroves and saltmarsh can attenuate storm surges.

The studies in Table 6 demonstrate that there is a clear link between coastal ecosystems and storm surge attenuation but providing a definite quantification is difficult. The US Army Corps of Engineers tried to provide a standard estimate in 1963—that 14.5 km of marsh would attenuate storm surge by 1 m. This was later shown to be inaccurate (Resio and Westerlink 2008, Wamsley et al 2010). The Shepard et al (2011) literature review identified a critical research gap in quantifying coastal ecosystem storm-surge attenuation. The UNEP WCMC (2006) report identifies a lack of scientific data to quantify the impact of mangroves on coastal protection.

Best available advice

There is a critical need for further research to quantify the storm surge attenuation capacity of coastal vegetation systems.

Coastal ecosystem characteristics

Part of the reason for the lack of clear quantification is that there are various site characteristics that affect coastal ecosystem attenuation capacity.

Site characteristics found to impact attenuation capacity include:

- local wetland and mangrove vegetation species, density, structure, biomass, size and height
- surrounding local bathymetry, topography and shore slope
- offshore profile which affects the effectiveness of coastal vegetation systems to establish an effective barrier (Massel et al 1999, Alongi 2008, Lacambra et al 2008, Krauss et al 2009, Wamsley et al 2010, Shepard et al 2011, Shulmeister, pers. comm. 6 July 2012).

The literature gives a clear indication that a significant system breadth is required:

- Stolton et al (2008) cite a Thai report that recommends a minimum mangrove barrier of 150 m
- Alongi (2008) suggests at least 100 m is required to see a reduction in wave flow pressure
- Fritz & Blount's (2006) modelling of mangrove planting in Bangladesh led to the conclusion that narrow strips of coastal forest offer little flood mitigation benefit and that several kilometres of forest are required to significantly reduce the impact of storm surges
- Gedan et al's (2011) literature review found evidence for small wetland strips providing some wave attenuation
- Barbier et al (2008a) found nonlinear relationships between system size and attenuation suggesting that small changes in mangrove extent will not result in a significant change in storm mitigation potential.

Best available advice

Wetland and mangrove systems need to be significantly broad to attenuate storm surge, potentially at least 100 m.

Some studies have been conducted into the species of vegetation that best attenuate waves and storm surges:

- Hadi et al (2003) found that Rhizophora mangrove forest provides more attenuation than Ceriops forests
- Tanaka et al (2007, Sri Lanka and Thailand) found that Rhizophora apiculata and Rhizophora mucronata mangroves, and Pandanus odoratissimus were most effective
- Mazda et al (1997) found that Kandelia candel is less effective than other mangrove species that have pneumatophores such as Bruguiera and Rhizophora species.

Best available advice

Certain species of mangrove such as Rhizophora are more effective due to their large system of air roots.

Storm characteristics

The characteristics of the storm causing the surge affect the mitigation potential of coastal ecosystems. Storm characteristics cannot be controlled, hence it is important to be aware of the potential limitations of coastal vegetation mitigation. This was demonstrated in the variation of response to hurricane Katrina in different areas of Louisiana. Western Louisiana experienced a fast moving hurricane and inland attenuation rates ranged from 1 m per 11 km to 1 m per 19 km. Eastern Louisiana experienced steady wind and the maximum surge occurred at a levee situated behind almost 40 km of marsh.

The wetlands may have changed the speed of the water reaching the levee but did not greatly affect the surge level as the wind was so strong and steady that it overwhelmed frictional resistance (Resio and Westerlink 2008). Day et al (2007) noted that Louisiana's barrier islands and wetlands did not stop a 10-metre surge during Hurricane Katrina.

Storm characteristics that affect coastal ecosystem mitigation capacity include:

- size
- speed
- track
- wave characteristics
- intensity
- tidal stage upon impact (surge arriving at high tide means higher water levels leading to less drag) (Massel et al 1999, Alongi 2008, Lacambra et al 2008, Krauss et al 2009, Wamsley et al 2010).

It is clear from the literature that coastal ecosystems will provide proportionally greater mitigation for smaller events such as tropical storms rather than cyclones (UNEP WCMC 2006, FAO 2007, Barbier et al 2008b, Gedan et al 2011). However, as Barbier et al (2008b) point out smaller storm events are more frequent so mitigation against them is likely to reduce economic damage significantly. The Gedan et al (2011) small meta-analysis found that wave attenuation was lower during storm surges than other wave events. However, although storm surges and tsunamis can overwhelm the vegetation attenuation capacity, small wetlands can offer substantial protection from waves due to high attenuation over the initial distance.

Best available advice

Coastal ecosystems will provide proportionally more mitigation of smaller events.

Economic value

If coastal ecosystems provide some mitigation of storm surges and waves then there is less need to construct other defences such as storm walls. In modified systems where return to a natural state is not possible, coastal ecosystems can complement structural defences (Defra 2004). Table 7 summarises studies that have identified economic aspects. Managed realignment schemes that move structural coastal defences inland to allow the coastal area to develop intertidal habitats can often lead to reduced ongoing maintenance costs. The intertidal habitat in front of the structural defence reduces erosion from the waves (Tinch & Ledoux 2006).

Table 7—Studies analysing the economic contribution of coastal ecosystems

Study	Conclusion
Costanza et al (2008) USA	Statistical analysis on hurricane damage in the US since 1980 found wetland area and wind speed explained 60 per cent of the variance in damage. Estimated that a hectare of coastal wetlands provided an average damage cost reduction of $8240/ha/year (with a large range of $250–$51 000).
Empson et al (1997) UK	The UK Environment Agency estimate that the cost of building a sea wall behind 30 m of saltmarsh would cost £800 per metre as opposed to £5000 per metre without saltmarsh.
IFRC World Disasters Report 2002 Vietnam	The Red Cross planted 12 000 ha of mangroves. Planning and protection for this area cost US$1.1 million. The estimated reduction in maintenance costs for structural defences was estimated at US$7.3 million per year.
Sathirathai & Barbier (2001) Thailand	Replacing mangroves with equivalent protection would cost US$12 263/ha/year for 20 years. Demand estimated at US$3 679/ha/year. Barbier (2007) later re-evaluated with a different methodology concluding that the previous estimates overvalued mangrove protection. However, expected storm damages for loss of 1 km^2 of mangroves was still estimated to be US$585 000.
Sudmeier-Rieux et al (2006) Malaysia	Estimated that structural measures would cost as much as the lost value of mangroves for storm protection. Mangroves provide further ecosystem services which cannot be replaced so mangrove retention would be economically beneficial.

Best available advice

Coastal ecosystems can provide a cost-effective alternative or addition to structural defences where their establishment is ecologically viable.

Unintended consequences

Some literature (Table 8) identifies potential side effects or unintended negative outcomes that can occur from ineffective implementation of a natural assets approach.

Table 8—Studies covering unintended consequences

Study	Conclusion
Fritz & Blount (2006)	Showed that in one site in Bangladesh, surge level would have increased due to forests trapping the flow coming from other parts of the island. Coastal forests can sometimes funnel flows along creeks increasing surge along the creek corridor.
Kerr & Baird (2007)	Afforestation schemes can cause social injustice through the eviction and poor compensation of inhabitants, particularly in developing countries.
Latief & Hadi (2006)	Narrow belts of trees may be ineffective in the face of an extreme event. Trees can be uprooted and carried inland increasing debris damage.
Wamsley et al (2010)	Slowing a storm surge in one area may redirect water towards another, causing a local storm surge increase.

These studies show that it is important to take into account a bigger picture of the coastline when planning for coastal ecosystem rehabilitation.

Best available advice

It is important to adopt a holistic planning approach to take into account potential negative consequences if all factors are not given sufficient consideration.

Vegetation as cyclone wind protection

High-velocity cyclone winds cause infrastructure damage through wind pressure and through mobilising debris. Building standards have progressed to make homes and infrastructure more resilient to high wind speeds. This contributed to reduced damage from Cyclone Yasi in 2011 than experienced with previous cyclones. Trees can cause damage during cyclones as vegetation debris is picked up by the wind. Understanding this is important to planning urban development and providing advice to residents on how to prepare their gardens to reduce the impact of cyclonic winds on existing vegetation. This section will look at the potential for trees in an urban area to be used to mitigate cyclone wind speeds. There is some literature available but the subject does not appear to have been researched extensively.

There is evidence that vegetation absorbs and resists wind energy reducing wind turbulence and momentum (Van der Sommen 2002). The damaging force of wind is proportional to the cube of wind velocity so the destructive capacity of wind should be reduced significantly with small reductions in wind speed (Greening Australia & Calvert 2011).

Trees can also mitigate damage by acting as a debris barrier. This was observed after Cyclone Tracy in Darwin (Cameron et al 1983), Cyclone Winifred in Innisfail (Oliver & Wilson 1986) and Cyclone Yasi in Townsville (Greening Australia & Calvert 2011). Even fallen trees have been observed to be effective at catching and trapping wind-blown debris (Cameron et al 1983). Counter intuitively, a tree that falls on a house may also play a role in holding the roof on and so keeping the belongings inside and potentially salvageable (Van der Sommen 2002, Jackes 2011).

Wind and debris damage

Table 9 summarises the key studies that have linked vegetation and wind protection. Research in this area seems to be limited.

Table 9—Studies into vegetation as wind protection

Study	Conclusions
Boughton et al (2011) Cyclone Yasi, Townsville	Post-1980s houses suffered less damage. Post-1980s houses that did suffer damage caused more significant debris damage than houses in older suburbs. Attributed to smaller blocks and less vegetation in newer suburbs.
Cameron et al (1983) Cyclone Tracy, Darwin	Damage caused by trees quite insignificant compared to damage from building debris. Newer suburbs suffered more damage—attributed to protection by mature vegetation in older suburbs. Comparison of caravan park sites—damage significant at site with no trees; much less damage at site with young, strong trees; some damage at site with ‘over mature’ trees due to debris.
Mason & Haynes (2010) Cyclone Tracy, Darwin	Vegetation could not provide significant shielding for properties. Widespread defoliation meant less capacity for wind resistance.
Van der Sommen (2002) Cyclone Tracy, Darwin	Anecdotal evidence suggested direct damage from trees was minimal and that trees played a protective role. Upland areas with low tree cover suffered more damage than areas without tree cover. Less vulnerable houses have less benefit or even potential costs from tree cover. Poorly designed or otherwise vulnerable houses likely to benefit from the presence of carefully planned, selected and managed trees.

Best available advice

Trees, especially younger but well established, strong and well-managed trees, can trap debris and reduce wind energy to limit cyclone damage.

Design characteristics

Some studies provide some useful indication on design and planning characteristics that can help to maximise the potential for vegetation to provide protection from cyclonic winds.

Van der Sommen's (2002) study provided the following observations:

- Canopy spacing, height and vegetation density must be considered in relation to the dimensions of the building being shielded.
- Single row, high-density windbreaks planted four tree heights away from the building reduced air infiltration by around 60 per cent.
- Measured height did not seem to make a significant difference in susceptibility to stem failure for many species but mixed evidence for other species with some showing increased instability with size and others showing the opposite.
- More significant relationship between wind, tree height and root failure.

Tree species affect protective capacity. Greening Australia & Calvert's (2011) survey of Townsville after Cyclone Yasi found a small proportion of species constituted most of the 150 trees damaged. Species and trees vary in wind resistance, trunk flexibility, wood density, crown symmetry and the presence of hollows. Some recommendations for more cyclone resilient plants have been made (Cameron et al 1983, Greening Australia & Calvert 2011, Jackes 2011). Studies have shown no significant difference between the protective capacity of native and exotic trees in cultivation situations (Van der Sommen 2002; Greening Australia & Calvert 2011).

Management actions and environmental factors influence tree resilience including:

- watering regime (shallow and frequent watering encourages shallow roots)
- clustering with other vegetation
- size at planting (with larger-sized initial plantings suffering from poor root development)
- pre-cyclone lopping which may weaken subsequent branch growth and actually increase cyclone risk from branch failure (Greening Australia & Calvert 2011, Townsville City Council 2011).

Best available advice

The limited research on vegetation and wind mitigation suggests that carefully designed and managed interventions with appropriate tree species may support mitigation.

Greening Australia & Calvert (2011) identified a lack of public knowledge around wind mitigation by trees. There is little official government advice on the protective value of vegetation or on which species are better to plant. For example, the Queensland Government's disaster preparation website, Harden Up, has a picture of a prepared tree with 'trimmed branches'. There could be a problem if this advice is misinterpreted, encouraging lopping which can lead to weakened branches and increased danger.

Best available advice

There is a need for improved public awareness on the links between vegetation, mitigation of cyclonic winds and damage.

Concluding message

The research covered in this synthesis shows that there is a clear case for using natural assets in a holistic flood and cyclone hazard management approach. Further research needs to be undertaken to provide some more targeted advice on specific interventions. Better understanding of individual catchments is also required to ensure local characteristics, and how they affect natural hazards, are understood.

It is evident that natural assets will have the most impact on reducing or preventing flood and cyclone damage from events with a lower average return interval. The more extreme events will overwhelm any approach. This is true of structural approaches as well. The research shows however that natural assets interventions are likely to be more cost-effective in many cases than structural approaches. They also provide other economic benefits through supporting ecosystem services. Furthermore, an overwhelmed structural defence can lead to increased damage such as when a levee is breached or a dam fails. Well established natural assets are resilient to continue to reduce systemic energy even in extreme events.

There is no panacea to flooding or cyclones. A holistic approach should include land-use planning, natural assets interventions and structural defences balancing the needs of the catchment, ecology and community. In this way, Queensland can live with its environment understanding that floods and cyclones are natural processes with their own benefits to the systems that support our lifestyles and livelihoods.

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