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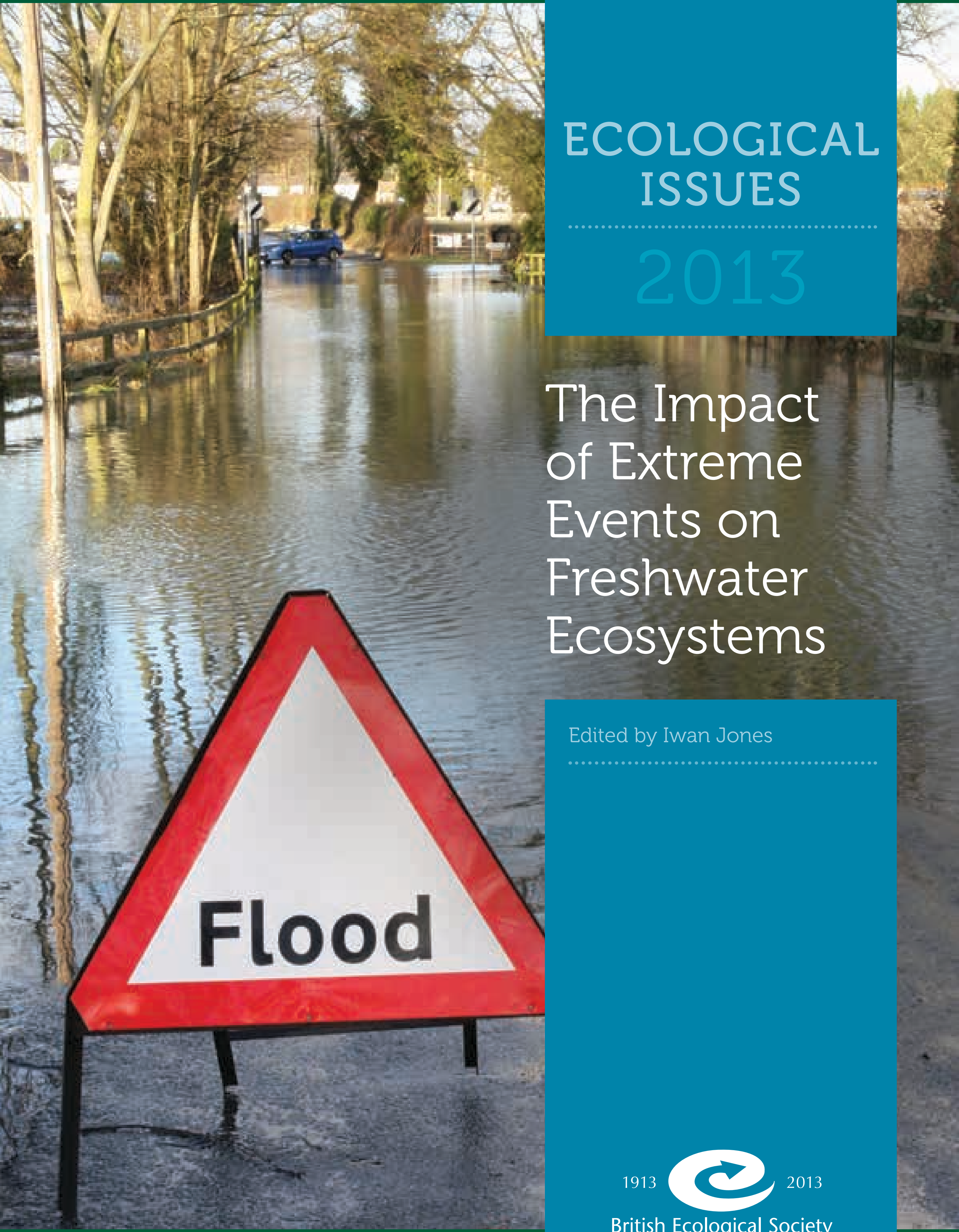
The Impact of Extreme Events on Freshwater Ecosystems

Edited by Iwan Jones



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1 Introduction

Extreme events include floods, droughts and heatwaves

Our climate is changing. Average global temperatures have increased since 1950 and are predicted to increase further. Together with this global warming, weather patterns are changing too.

Extreme weather events, such as torrential rainfall, droughts and heat waves, are now occurring with greater frequency and intensity in some areas (Box 1.1). Other extreme weather events may also have increased, although the occurrence of such inherently rare events limits how confident we can be of significant change. These changes to weather patterns are consistent with climate change models, which predict that rainstorms will become more torrential and heatwaves more severe in the future. Both average conditions and variability are predicted to increase in coming decades. This means that extreme weather events will become much more common (Figure 1.1). Whilst model predictions are uncertain, a changing climate is expected to lead to changes in the frequency, intensity, spatial extent, duration and timing of extreme events (Box 1.2). In the future, we are likely to experience extreme weather and climate events that are historically unprecedented.

Whilst changing weather patterns present human society with immediate difficulties, such as flooding of property and infrastructure, they are likely to have long-term effects on society through changes in the wider environment. Society is reliant on a range of benefits from the environment, obtained both as tangible goods (e.g. food from fisheries, reeds for thatching) and more subtle services (e.g. purification of water, health benefits of recreation). Extremes of climate and weather may affect many levels of the ecological hierarchy from individual organisms to entire ecosystems, with potentially profound impacts on the supply of the ecological goods and services valued by society. The balance of priorities between immediate, often localised impacts (e.g. flood damage to property) and longer-term, more widespread impacts on the delivery of ecosystem goods and services presents an obvious challenge: "What is the best way to manage the impact of extreme weather events?" To answer this question there is a pressing need to understand both the immediate and future consequences of extreme events for ecological systems.

It is possible to define extreme climate and weather events in a historical context (e.g. worst drought since 1976), by percentiles (e.g. the highest and lowest 1% of occurrences), or return values (e.g. a 1 in a 100 year flood). Each of these definitions must be set against a baseline from a given reference period. In reality this baseline appears to be shifting. In future, it is likely that we will experience conditions that we now consider extreme more frequently (Figure 1.1).

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Box 1.1

Assessment of changes in extreme events

Assessment of changes in weather and climate are hampered by the amount and quality of historic data available. This is particularly true of extreme events, which are inherently rare, further restricting the data available. Strong regional variations are apparent, both in the availability of data and in the pattern of change. Nevertheless, according to the Intergovernmental Panel on Climate Change (IPCC, see http://www.ipcc.ch) past data indicate that worldwide since 1950:

- It is very likely that there has been an overall decrease in the number of cold days and nights.
- It is very likely that there has been an overall increase in the number of warm days and nights.
- It is likely that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures at the global scale.
- There is medium confidence that some regions of the world have experienced more intense and longer droughts.
- It is likely that more regions have experienced increases in the number of heavy precipitation events than decreases.
- There is medium confidence that anthropogenic influences have contributed to intensification of extreme precipitation at the global scale.

Assessments of climate-driven changes in the magnitude and frequency of floods are limited by the lack of precise measurements of flood parameters and the confounding effects of changes in land use and water engineering works. The available evidence does not show consistent agreement.

The IPCC suggest that by the end of the 21st century:

- Substantial warming in temperature extremes is expected.
- It is virtually certain that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur.
- It is very likely that the length, frequency, and/or intensity of warm spells or heatwaves will increase over most land areas.
- It is likely that the frequency of heavy precipitation events or the proportion of total rainfall from heavy falls will increase over many areas of the globe.
- Heavy rainfalls and average maximum windspeeds associated with tropical cyclones are likely to increase with continued warming, although possibly not in every ocean basin.
- There is medium confidence that droughts will intensify in some seasons and areas.
- Projected precipitation and temperature changes imply possible changes in floods.
- There is medium confidence (based on physical reasoning) that projected increases in heavy rainfall will contribute to increases in local flooding in some catchments or regions.

Source: IPCC

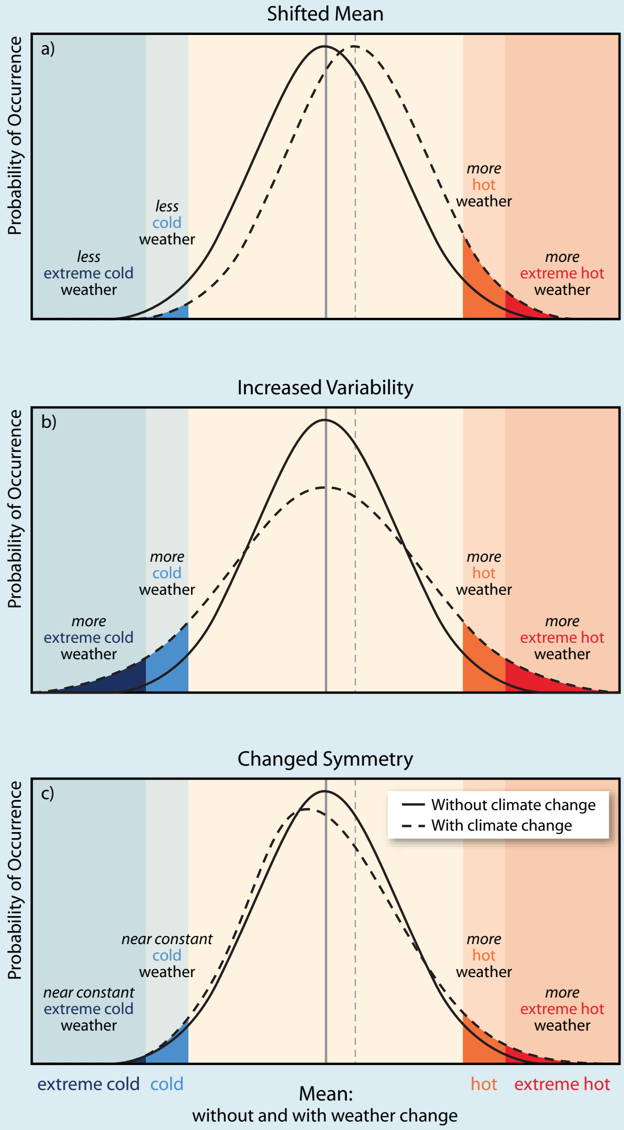
Figure 1.1
The effect of changing climate on the occurrence of extreme events

As the climate changes, the range of conditions experienced will change. The effect on the occurrence of extreme events will depend on how distributions differ between present and future climate:

(a) effects of a simple shift of the entire distribution toward a warmer climate;
(b) effects of an increase in temperature variability with no shift in the mean;
(c) effects of a change in the shape of the distribution, in this example a change in asymmetry toward the hotter part of the distribution.

Similar changes are likely to occur in other weather parameters, e.g. precipitation, wind speed.

Redrawn from IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, Figure SPM.5



As we are considering ecological systems, here we are concerned about those rare or unusual weather and climate (hereafter climatic) events that have the potential to push ecosystem structure and/or functioning well outside what is considered normal (current baseline) variability. Such extreme climatic events are likely to have ecological impacts that last far longer than the actual physical event itself. Such events will have a low frequency of occurrence and are likely to be outside thresholds at the upper and lower ends of the range of observed climatic conditions. From this definition, it can be seen that climatic extremes are defined quantitatively in two ways:

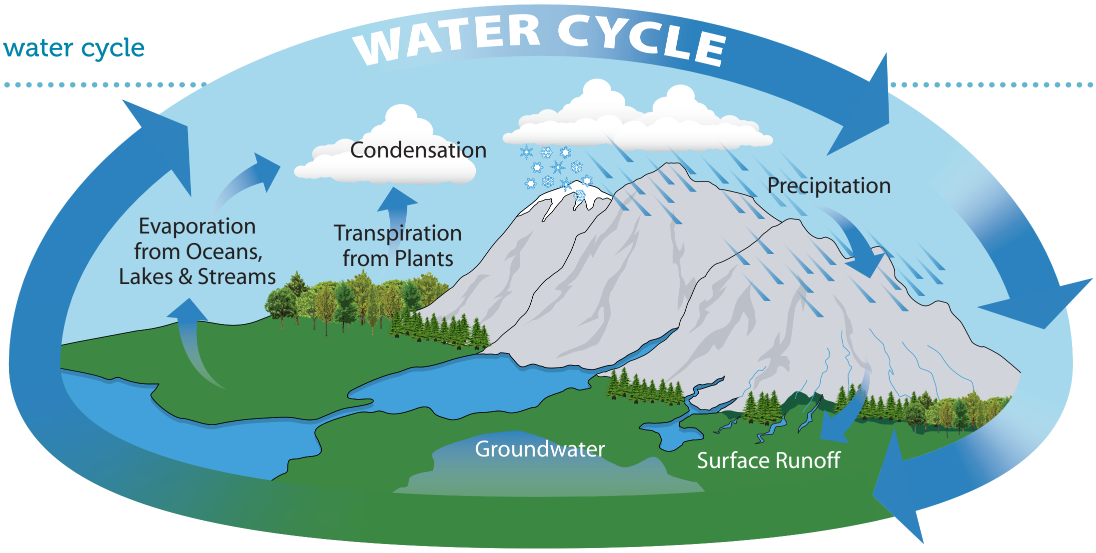
1) Related to their probability of occurrence,
2) Related to a specific climatic threshold.

However, it should be pointed out that climatic events from the extreme tails of probability distributions are not necessarily extreme in terms of their impact, and extreme impacts can result from combinations of climatic events that, in themselves, are not extreme. Impact results from a combination of the occurrence of extreme climatic events, the extent of exposure to the effects of the event and the vulnerability of the system. Hence, the ecological impacts of extreme climatic events will vary naturally both in time and space. Furthermore, human activities can and will influence these impacts by altering the extent to which ecosystems are exposed to the effects of extreme events and by affecting their vulnerability to them. For example, rivers will be more exposed to the impact of drought where flows have already been reduced by abstraction. To best manage impacts, we must first identify where ecosystems are vulnerable and exposed.

Freshwater Ecosystems and the Water Cycle

What we perceive as weather is just a small part of the water cycle. Water falls from the atmosphere as precipitation, flows as surface or ground water through the landscape towards the sea, and returns to the atmosphere through evaporation (Figure 1.2). Regional changes to these processes are expected with climate change. As the water cycle is a crucial driver of many processes (e.g. erosion and deposition, nutrient cycles), these changes will affect all ecosystems wherever they occur. Fresh waters are particularly vulnerable to such changes because these relatively isolated ecosystems are entirely dependent on the quantity and quality of water available.

Figure 1.2
Schematic of the water cycle



Freshwater ecosystems are a distinctive feature of the landscape. We typically distinguish flowing ('lotic') waters, such as rivers and streams, from apparently still ('lentic') waters, such as lakes. The water in rivers is moving, the flow interacting with substrate in the channel and the land along the riverside. This movement tends to create a range of distinct habitats, such as shallower riffles, deeper pools and exposed islands. The water in most lakes is moving less obviously, flowing slowly from inflow to outflow and circulating within the lake due to wind-induced mixing. Sometimes, lake water divides into vertically stratified masses that are not distinct to the naked eye but are defined by differences in temperature; these create warmer and better-illuminated areas in the upper waters and darker, cooler habitats in the deeper waters. Both rivers and lakes are vulnerable to extreme events that substantially alter the natural water movement, water volumes and rates of change.

An extreme event can be strikingly visible, such as a high-flow event in a river where the water becomes thick with suspended sediment and uprooted aquatic plants, erodes the river banks and overflows into the surrounding floodplain. In contrast, the impacts of extreme events on other freshwater ecosystems may be largely imperceptible to the untrained eye. For example, a lake whose water column has stratified in summer to create a warm surface layer overlying deep, cooler water can be mixed by a violent storm. This mixing can result in a flush of nutrients that may encourage algal blooms. Although this superficially static volume of water may appear to be unaffected, a key driver of lake ecology, i.e. nutrient availability, is being altered by such events. In shallow wetlands even small changes in water depth can cause substantial changes in wetted area and chemical processes in the soil. In both rivers and lakes, the event may disrupt the natural disturbance regime of the system, causing significant changes that degrade habitats, alter biota or switch the whole ecosystem to an alternative state. If the capacity of the ecosystem to endure such changes (i.e. its resilience) is exceeded, these changes will be permanent or ones from which the wildlife will only recover very slowly.

Disturbance within normal bounds

Disturbance in an ecological sense can be defined as any relatively discrete event that disrupts the biological structure and dynamics of the system. The challenge occurs when systems are affected by extreme events that exert novel impacts beyond previous natural ranges that may significantly, and perhaps permanently, change them. Disturbances that are within the previous range of experience play a central role in natural ecosystems, creating and regenerating habitats. Extreme events, by definition, have occurred rarely in the past. Hence, any changes to the frequency and intensity of extreme events represent a significant change to an existing disturbance regime. Impacts are most likely where changes result in novel events never before witnessed within a particular ecosystem.

Variability in the hydrological regime defines many characteristics of freshwater ecosystems. For example, the highly predictable seasonal variation in the flows of chalk streams in response to changes in groundwater levels produces communities that are markedly different to those of rivers draining impermeable geologies, where rainfall causes sudden, marked changes in flow (Box 1.3). Such variability in flows defines the physical structure of the river and its surrounding landscape (e.g. the floodplain and associated wetlands) and determines the connectivity between the two. Change in this sense is natural, and indeed often essential, for these systems to function normally. Variations in flow are required to create new habitats and maintain or reset succession in existing ones. The range and predictability of variation also dictates what organisms can persist. Whilst variation may be the norm, changes outside the normal range can have profound long-term effects. Alterations to hydrological regimes, particularly the number and severity of extreme events, may be the cause of the most pronounced effects of climate change on freshwater ecosystems.

Lakes, ponds, rivers and wetlands are defined by their hydrological regimes, so the same broad characteristics that define the impact of disturbance can be applied to all fresh waters. Disturbance varies with frequency (how often the event occurs), amplitude (size of the event), duration (how long the event lasts), timing (when the event occurs and how predictable it is), rate of change (how the event manifests) and spatial extent (area affected by the event) but, in general, follows one of three patterns:

- Pulses that are relatively short lived and with a distinct, and usually rapid, start and end; they are usually an intensification of existing processes, such as a flood pulse in a river or a severe, storm-related mixing event in a lake.
- Press disturbances, are long-term changes that start sharply and are sustained for a long time, perhaps forever: the creation of a dam, which alters flows both downstream and upstream, is an example of a press disturbance.
- Ramp disturbances, are long-term changes where change is slower, steadier, and may occur in distinct steps: droughts are often ramp disturbances, steadily worsening rather than starting suddenly.

Source: Lake (2000)

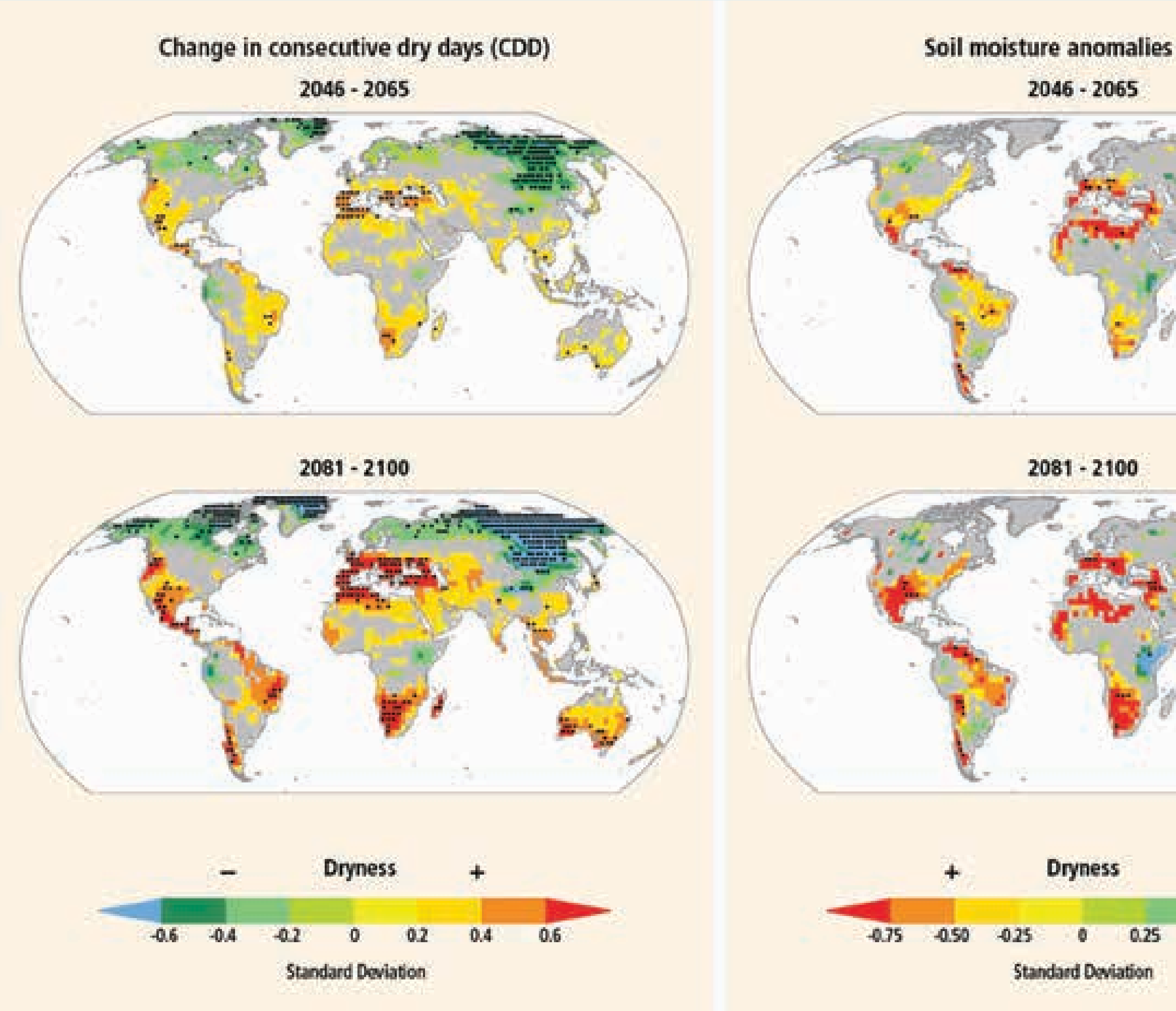
Note that all of these three types of disturbance are defined by time. The most important measure of time, in terms of the ecology of the system, is the length of the disturbance relative to the life history of the wildlife affected, especially generation time (i.e. how long it takes an organism to go from birth to reproduction, which may be hours for micro-organisms or several years for some fish and other vertebrates). In the short-term disturbance affects which species can persist in the ecosystem, and in the long-term influences how species evolve resilience to disturbance, for example through adaptations to their morphology (e.g. streamlined body structures to enable benthic organisms to resist high flow velocities) or behaviour (e.g. breeding during periods that avoid high-flow events).

Extreme disturbances

Physical disturbances such as floods and droughts are important events that shape freshwater assemblages, by removing organisms and opening resources to those species able to resist or recover from these events. For any given system, disturbances occur with a regime defined by a characteristic frequency, amplitude, duration, timing, rate of change and spatial extent. Climate change models predict that extreme climatic events will occur more frequently in the future (Box 1.1). Such extreme events will push disturbance regimes beyond their previous natural ranges, such that organisms will experience environmental conditions that are surprising or historically unprecedented. Profound changes to freshwater ecosystems will occur where the capacity of the ecosystem to resist and/or recover from the impact of these extreme events is exceeded. Although we define extreme events in terms of climatic parameters, in ecological terms their impacts are extreme once the ability of the system to endure the event (i.e. community resilience) is exceeded. Such events will cause profound, long-term and potentially permanent changes to freshwater ecosystems.

Figure 1.3

Projected changes in dryness using two indices

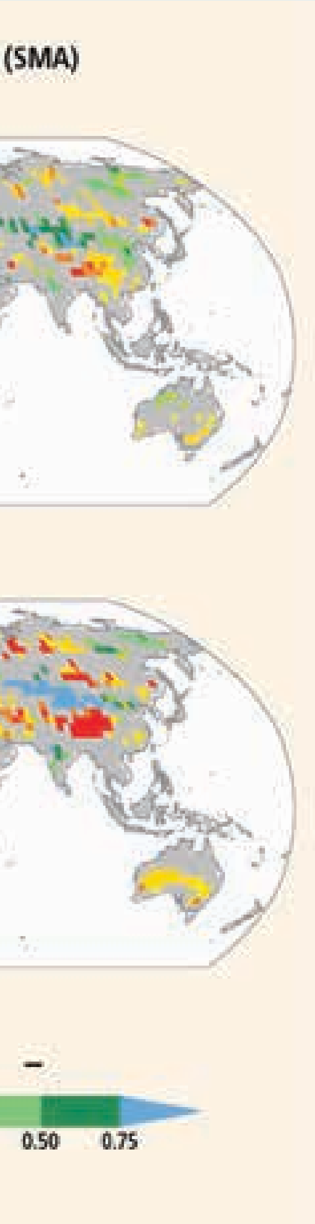


BOX 1.2

Changing weather patterns

The confidence in the predicted changes in the direction and magnitude of climatic extremes depends on many factors. These include the type of event; the region and season covered by the prediction; the amount and quality of historic data available to assess the current status and to base future predictions; the extent to which we understand the processes involved in determining the event; the reliability of the simulation models; and confidence in the predictions of future greenhouse gas emissions.

In order to deal with this uncertainty, predictions are made using multiple models and common patterns are highlighted. Using this approach, regional variations are apparent in the extent, direction and confidence of predicted changes.



Left
Change in annual maximum number of consecutive dry days (CDD: days with precipitation <1 mm).

Right
Changes in soil moisture (SMA: soil moisture anomalies).
Increased dryness is indicated with yellow to red colours; decreased dryness with green to blue. Projected changes are expressed in units of standard deviation of the inter-annual variability in the three 20-year periods 1980–1999, 2046–2065 and 2081–2100. The figures show changes for two time horizons, 2046–2065 and 2081–2100, as compared to late 20th-century values (1980–1999), based on global climate model simulations under emissions scenario SRES A2 relative to corresponding simulations for the late 20th century. Results are based on 17 (CDD) and 15 (SMA) global climate models contributing to the CMIP3. Coloured shading is applied for areas where at least 66% (12 out of 17 for CDD, 10 out of 15 for SMA) of the models agree on the sign of the change; stippling is added for regions where at least 90% (16 out of 17 for CDD, 14 out of 15 for SMA) of all models agree on the sign of the change. Grey shading indicates where there is insufficient model agreement (<66%).

Source: IPCC

Box 1.3
Time and space: the continuum of hydrological variation

Freshwater ecosystems are defined by their hydrology. Lake water residence times describe the mean time that water remains within a lake basin (the inverse measure is flushing rate). This is determined by the local climate, the catchment (e.g. topography, geology, land use), and the size and shape of the lake basin. Residence times vary greatly among lakes, ranging, for instance, from an average of nearly seven years in the very deep Loch Morar in Scotland to just nineteen days in the relatively shallow Bassenthwaite Lake in the English Lake District. In ponds, such variation is reflected in the pond's longevity, and the duration and timing of any drying phase. Similarly, the discharge in rivers (the volume of water passing per unit time) reflects both the size of the river and the speed of water movement, and is affected by the catchment and the land use within it, and the local climate.

Within a hydrological system, the flow of water (discharge/residence time) varies both within and between years (Figure 1.4-1.8). Predictability of water movement is a key determinant of the biota. Whilst variation in flow with season can be large (e.g. in rivers fed by snowmelt), the organisms present will be adapted to such seasonal variation where it occurs regularly. A different suite of organisms will persist in systems where irregular variations in flow occur both within and between years.

The extent to which an extreme event will have an ecological impact will depend on the previous disturbance history: systems with a naturally high disturbance regime are likely to be more resilient.

Figure 1.4
Sydling Water

A highly predictable groundwater-fed chalk stream in Dorset.

Figure 1.5
River Ogmore

An unpredictable surface-fed river rising in the hills of South Wales.

Figure 1.6
Daily river flow in Sydling Water

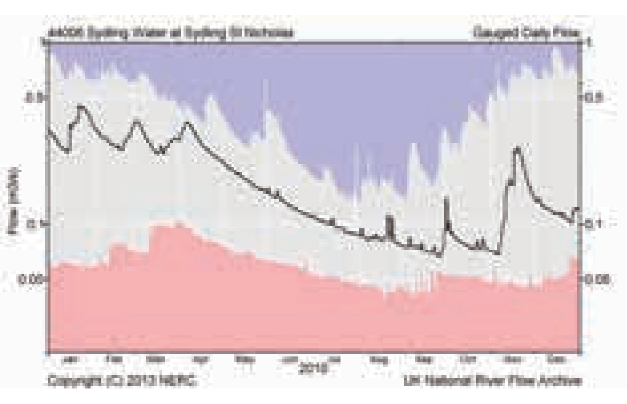
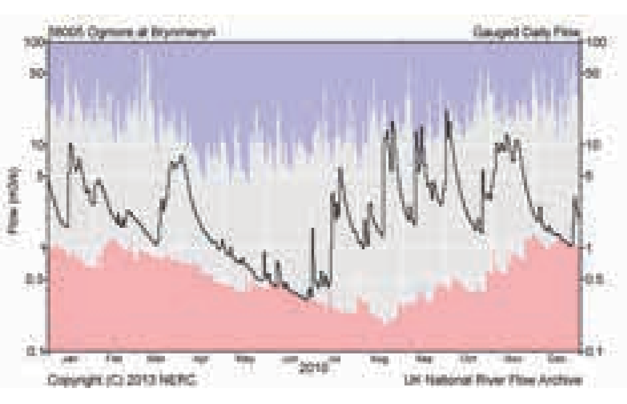


Figure 1.7
Daily river flow in the River Ogmore

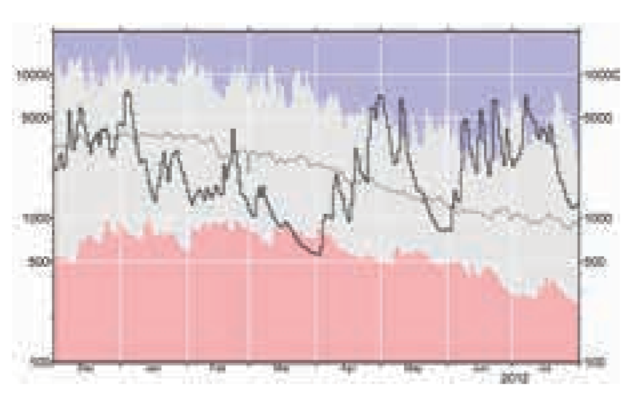


Above

The dark line shows daily gauged-flows over one year; the pale area shows the previously recorded range at the site. Sydling Water shows a smooth pattern of seasonal change (spikes on the dark line are small), which is relatively consistent between years (the dark line is within the pale area). River Ogmore responds rapidly to rainfall events and shows an erratic pattern of flow (the spikes in the dark line are large), which is inconsistent between years.

Source: CEH

Figure 1.8
Estimated daily outflows from all river in England and Wales



Above

Estimated daily outflows (m^3 s^{-1}) from all rivers in England and Wales show that 2012 was an extreme year. The blue and pink envelopes indicate pre-2012 daily maxima and minima. The dark line shows daily outflows in 2011-2012. In March-April 2012, following a prolonged drought, flows were lower than recorded previously for this time of year (in the pink zone). This was followed by a period of intense floods where flows were higher than recorded previously for that time of year (in the blue zone). The grey trace is the long-term daily average.

Source: CEH

Natural drying of ponds

To our intuitive division of fresh waters into rivers or lakes, we must add smaller standing waters such as ponds and pools (hereafter ponds). Their significance for wildlife has often been overlooked because of their small size and everyday familiarity. However, they support a diverse array of freshwater wildlife across the landscape. As the ecology of ponds is influenced by the number and spatial patterns of ponds across the landscape, it is better to think of these systems in terms of the whole 'pondscape' (i.e. all ponds across an ecologically meaningful landscape, such as a floodplain, or site, such as a nature reserve), rather than as small isolated waterbodies. In ponds, hydrologic variation may appear dramatic, for example drying out completely in summer. However, this may be a common, perhaps annual, part of their natural ecology. Indeed certain rare species are associated with ponds, rivers and lakes that are naturally prone to drying.

Rivers, lakes and ponds all depend on the availability of fresh water and this availability varies over time and space. Although the wide variety of running and standing waters may appear to be very different, each is defined by environmental factors of climate/local weather and the character and land use of their catchment, and all are exposed to natural variation.

Annual drying and rewetting is part of the natural hydrological cycle of many ponds.

Why freshwater ecosystems?

Climate change is predicted to cause profound impacts on all ecosystems. So why are we concentrating on freshwater ecosystems in this volume?

a) Extreme climatic events cause substantial changes to precipitation and hydrology. Freshwater systems are particularly susceptible to changes in the quantity and quality of water entering and leaving them.

b) There is an inherent desire to reduce the immediate effects of flooding and drought on society, typically through engineering of waterways. This presents a potential conflict where the impacts of extreme events are exacerbated by man-made modifications to the landscape and pressures on the environment.

Humans have affected many aspects of the movement of water through the landscape. Urban development and agriculture have altered the permeability of surfaces, increasing the rate at which precipitation runs off the land rather than recharging aquifers. Excessive abstraction from aquifers reduces groundwater levels and flows in rivers. Various industrial, agricultural and urban activities have increased the load of pollutants that flow into fresh waters. New pathways have been created for pollutants to follow. Land drainage and flood defence works have often reduced the ability of rivers, lakes and wetlands to retain water during floods, thus concentrating flows and increasing peak flood levels, whilst simultaneously reducing the rivers' ability to cope with the impacts of floods. Past engineering works have tended to reduce heterogeneity both within individual rivers (e.g. removing depth variation by dredging and armouring of banks, regulating flows) and between rivers (e.g. standard trapezoidal profile, straightening). Often this has constrained the natural processes that provide freshwater ecosystems with the resilience to endure extreme events without lasting damage.

Rather than working with the natural ability of ecosystems to endure extreme weather events, human intervention has often had a tendency to exacerbate the undesirable ecological consequences of such events. Here we detail the physical and chemical impacts that extreme climatic events have on fresh waters (Chapter 2). We then discuss the impact that extreme climatic events have on freshwater ecosystems, at all levels of the ecological hierarchy, from individual organisms and species (Chapter 3) to entire ecosystems (Chapter 4). Finally, we present options for management to lessen the impact of extreme events on freshwater ecosystems (Chapter 5). In particular, we highlight those options that provide both societal and ecological benefits ("win-win scenarios"). In the face of a changing climate, we will have to endure more extreme events. We cannot prevent these events from occurring but, with adequate preparation, we can lessen their impact.

2 Environmental impacts of extreme climatic events on fresh waters

Extreme climatic events affecting freshwater ecosystems include floods, droughts, storm-induced waves, heatwaves and freezing conditions.

Such events can cause the scouring or deposition of sediments, low or absent flows in rivers, water-level drawdown or desiccation of standing waterbodies, shoreline erosion in lakes, and the mortality of flora and fauna. A combination of these events, e.g. freezing during a winter drought, can have particularly severe impacts on waterbodies.

This chapter deals with the environmental impacts of extreme events on fresh waters, i.e. how extreme events affect the following four characteristics of waterbodies:

1. Water quantity
2. Water quality
3. Physical environment
4. Habitat availability and connectivity

Water Quantity

Hydrological Variation

Long- and short-term water level dynamics, including periodic floods or droughts, are part of the natural variation in the water cycle. This variation influences many ecosystem characteristics, such as waterbody and wetland morphometry, the productivity and structure of vegetation, life cycles of flora and fauna, decomposition processes, and nutrient cycling. Natural ecosystems and the species within them are adapted to the variation in flows and water levels that they experience. However, there is substantial evidence to indicate that where this variation extends beyond the 'normal' range, ecosystem structure and processes can be impaired (see Chapters 3 and 4). As a result, the quantity of water and its passage through an ecosystem during extreme events can have a major influence on freshwater ecosystems and the species and ecological processes within them. In fact, such alterations to hydrological regimes, particularly the number and severity of extreme events, may be the cause of the most pronounced effects of climate change on freshwater ecosystems.

Natural hydrological regimes in Britain are normally characterised by high water levels in winter followed by a decline in early summer, although there is often substantial variation in timing and water levels between years. Levels reach a minimum in late summer followed by a rise during the autumn, to attain the highest levels again in mid- to late winter. However, in some areas of Europe, where there is significant snowfall or glacial feed to watercourses, this pattern may be reversed, with the highest water levels occurring in early summer when snowmelt is at its maximum and with low levels during the winter 'freeze-up'.

The degree to which flows and water levels fluctuate is determined by the balance between ground water, precipitation and surface run-off on the one hand, and outflows, evaporation and plant transpiration on the other. In a waterbody managed for water supply or hydroelectric power, pumping, storage, release and abstraction can exaggerate these processes to a large degree. It is commonplace for small ponds to fall by up to 50%

during the summer and in larger, temperate lakes annual variation of 10-15% is normal, with some lakes varying a great deal more through entirely natural causes.

The seasonal pattern of water levels in a freshwater ecosystem forms a distinctive hydrologic signature that is termed the hydroperiod. It is characterised by:

- Frequency (number of flood/drought events in a given time period)
- Amplitude (vertical range or depth)
- Duration (of flooding or drought events)
- Seasonality (winter flood, spring flood)
- Predictability
- Rate of change

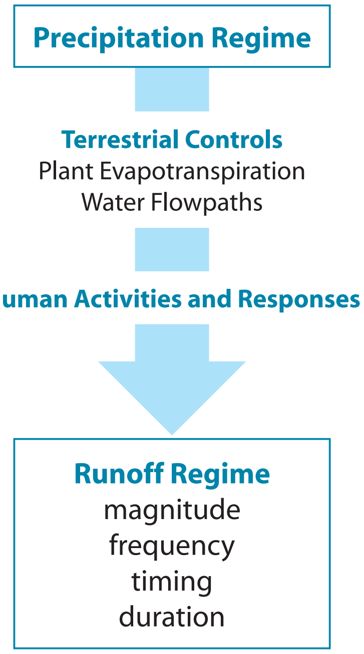
These characteristics are determined by the size of the waterbody; the catchment area and its topography; sources of water; climatic factors; underlying geology; and human modifications of the natural setting. Extreme events can affect one or more of these hydrologic characteristics, causing the hydroperiod or discharge pattern of a watercourse to be altered outside of its normal range. In addition, management of water levels can modify the hydroperiod by artificially exaggerating, dampening or shifting natural regimes.

Climate change is expected to cause, on the one hand, more frequent and extreme flooding events, while on the other hand, it is expected to increase the potential for water shortages as a result of reduced rainfall and increased evapotranspiration. This will stretch the hydrological 'envelope' in opposite directions, producing more dynamic and extreme hydrological conditions, which will become both increasingly unstable and increasingly unpredictable.

Floods

Floods are part of the natural variation expressed by freshwater ecosystems. Floods occur when hydrological inputs from precipitation, run-off and ground water result in excess water entering receiving waterbodies, whether rivers, lakes, ponds or wetlands. Extreme weather can affect the amount of precipitation occurring in a particular event. In addition, extreme climatic conditions over a long period can affect factors influencing run-off (such as ground water, river and lake levels, soil moisture, and the condition of vegetation and soil) to such an extent that normal rainfall can exceed thresholds, creating flood conditions. However, other factors, including human activities and responses to extreme weather, also affect the surface run-off regime (Figure 2.1). Whether future extreme climatic events manifest as extreme floods or not will depend on the response of management (See Chapter 5).

Figure 2.1
Linkages between precipitation and run-off regimes



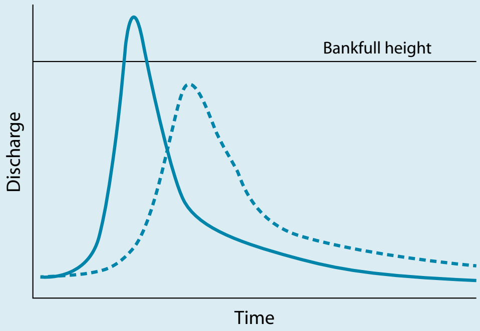
Rivers

In storm hydrology, an important consideration is the waterbody's hydrograph, a record of how discharge (i.e. the rate at which the volume of water passes downstream, $m^3 s^{-1}$) varies over time after a precipitation event. Following an initial characteristic delay, the discharge quickly rises to a peak flow after each precipitation event, and then falls in a slow recession (Figure 2.2). Flooding occurs if the volume of water exceeds the capacity of the channel to transport water downstream (overbank flooding). The shape of the hydrograph depends on the rate at which water is delivered to the channel. If water delivery from upland and upstream is slowed, the hydrograph will be broadened, and the flood peak delayed and diminished: although the same total volume may pass through the waterbody over the considered time period, overbank flooding may not occur (Fig 2.2). Flooding by ground water can also occur where the capacity of the aquifer is exceeded resulting in surface-flows (groundwater flooding). It should be noted that whilst floods and flooding are both caused by excess precipitation, flooding is influenced by features of the water body; flooding occurs when the volume of water cannot be contained within the waterbody, which results in water covering land that is normally dry.

Recent floods in Britain have demonstrated how the permeability of surfaces affects the amount of run-off and the shape of the hydrograph. In built-up areas, man-made, impermeable surfaces result in high volumes of rapid run-off in response to precipitation, producing a narrow and intense peak in the hydrograph of local watercourses and a greater likelihood of flooding.

Figure 2.2
Hydrograph showing a schematic of a flood wave

Increased flow results in an increase in discharge to peak discharge, which recedes over time as the flood passes (solid line). Overbank flooding occurs if a discharge corresponding to bankfull height is exceeded. If run-off is delayed, e.g. by upstream storage (dashed line), the flood peak may be attenuated even though the same total volume of water is passing through the waterbody.



During a flood, both the velocity (the speed at which water passes downstream) and the erosive power of the water in the channel increase with increasing discharge. Water-flows become more turbulent. The force of the water (shear stress) on the bed and sides of the river channel increases. Particles become entrained within the flow, which increases the likelihood of further particles becoming dislodged as the particles collide with the channel bed and sides. The shear stress on plants increases, potentially uprooting them, thereby reducing vegetation cover, dispersing organic material downstream and increasing erosion of the mineral substrate. There is an increase in the volume of debris being transported (both the number and size of particles) as surface-flows and erosion bring material into the river channel. Debris accumulates into blockages, diverting flows around them; erosion is greatest where flows are constrained. Material is deposited, often in substantial quantities, where flow velocities are low, e.g. behind obstructions, where overbank flooding occurs, or as the flood recedes. River beds are restructured and channels often move during these exceptional events. Where the river breaks its banks, it will connect to the floodplain, causing a range of processes to be initiated and often introducing nutrients, silt and debris to the flooded areas.

Lakes and ponds

In standing waters, floods increase the volume of inflowing water, raising water levels and increasing the rate at which water is flushed through the lake basin. Increased erosion due to flow is generally restricted to the inflows and outflows, but wind-driven wave-wash can cause erosion around the lake perimeter, particularly where high lake levels inundate new areas. Rates of deposition increase throughout the remainder of the lake basin. If the catchment is sediment-rich, infilling or delta formation may occur within the waterbody, potentially changing its morphometry. These silt inputs may accelerate terrestrialisation and can provide scope for plant establishment.

Droughts

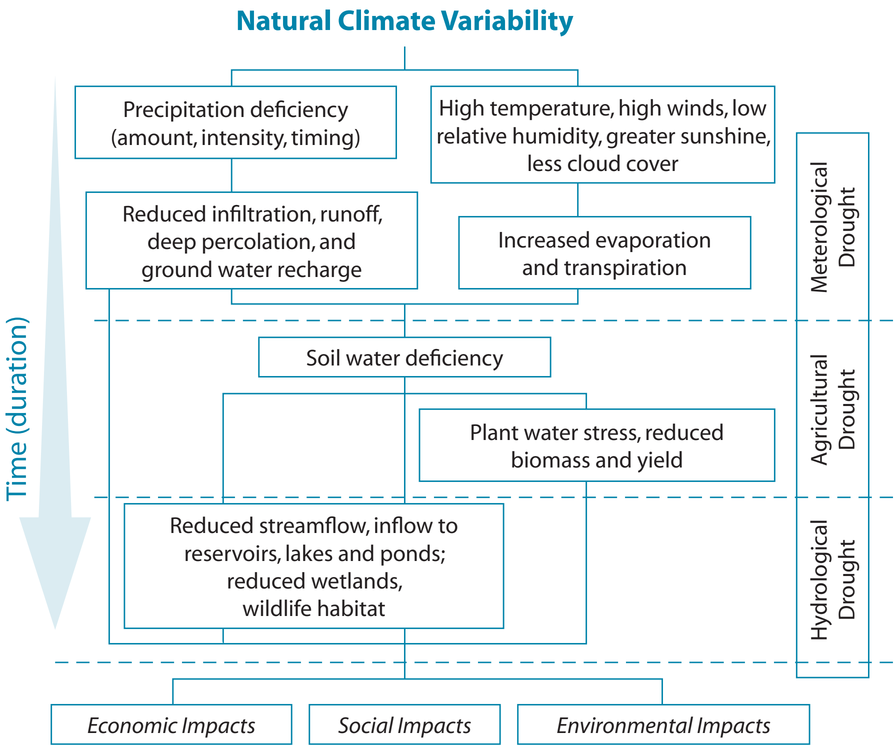
Droughts occur when there is significantly less precipitation than usual, relative to the average climate of the given region. Droughts should not be confused with aridity, which describes the general characteristic of a dry climate. Droughts can be defined variously as meteorological, agricultural, hydrological and socio-economic (Figure 2.3). The scale of the ecological, economic and social impacts of droughts differs depending on the way the drought manifests, its duration, and exposure and vulnerability to the effects of drought. The ecological impacts of droughts on fresh waters are dependent on the severity and the nature of the drought, and the extent to which waterbodies in the landscape are dependent on surface run-off and/or ground water. In running waters, drought can result in reduced water-flows, reduced depth and width, flow cessation, and eventually complete desiccation (although water may continue to flow through the substrate below the river bed). Headwaters, higher in the river network, tend to be more susceptible to drying than larger rivers downstream. In standing waters, droughts result in increased water residence time, water level drawdown and eventually complete drying.

It should be noted that although droughts are often associated with high temperatures, they can occur at any time. Winter droughts (less than usual precipitation during cold periods) may differ in their ecological impacts from summer droughts.

Reduction in flows or water levels within an ecosystem can reduce the area of freshwater habitat present; concentrate pollutants; prevent navigation by fish; expose plants to damaging ultraviolet light, heat stress or frost; and can leave aquatic organisms stranded. Furthermore, the physical structure and chemical composition of substrates that are normally waterlogged often change as they dry out. Hence, flow reduction and water level drawdown have a major influence on the biological communities of waterbodies and their fringing wetlands. Nevertheless, drying is part of the natural cycle for some aquatic ecosystems, such as groundwater-fed winterbournes, temporary ponds and seasonal wetlands, and some of the organisms that inhabit these systems are specifically adapted to the dry-wet cycle.

Figure 2.3
Sequence of drought occurrence and impacts for commonly accepted drought types

All droughts originate from a deficiency of precipitation but secondary types of drought and impacts cascade from this deficiency. Meteorological Drought is a deficit of precipitation; Agricultural Drought is a deficit of soil moisture, particularly in the root zone; Hydrological Drought is the occurrence of negative anomalies in stream flow, lake, and/or groundwater levels. Water scarcity is linked to Socio-economic Drought but is also affected by human demands on water supply.



Water Quality

How hydrology influences water quality

Rivers and standing waters are tightly connected to their catchments. As a result, the quality of the water that enters a waterbody is heavily influenced by the characteristics of the catchment. Direct precipitation often accounts for only a small amount of the water received by a waterbody: generally, surface run-off and subsurface (groundwater) flows are the major flow pathways and, hence, determine the quantity and quality of water entering waterbodies. Inputs of water bring solutes, nutrients, dissolved carbon and particulate matter, which are delivered on an annual pattern, as determined by the hydrological, biological and climatic patterns of a region. The occurrence of extreme events alters the timing and magnitude of water delivery, as well as the degree of dilution or concentration of solutes, thus altering water quality in freshwater ecosystems.

The impact of extreme high-flow (floods) events on water quality

In extreme rainfall events the volume of water entering waterbodies increases, which dilutes any solutes that are supplied from the catchment at a constant rate (e.g. bicarbonate ions), and those delivered through slow pathways. However, the increased movement of water also increases the delivery of other solutes and suspended particles, particularly those delivered through rapid pathways. The increased surface run-off causes erosion and the delivery of large amounts of soil, sediment and organic matter into lakes and reservoirs. In urban or intensive agricultural environments these inputs can be combined with high concentrations of heavy metals, pesticides and nutrients. Flow via pathways that are inactive under drier conditions results in a wider range of sources and increased loads of pollutants. The 'first flush' of storm water into receiving waterbodies (particularly rivers and streams) is known to be particularly high in pollutants. Storm drains, roadside ditches and drains often contain stagnant water, characterised by low oxygen and highly polluted with waste, which is introduced into streams and rivers ahead of the main body of floodwater that would otherwise afford a degree of dilution. A plug of pollution can also occur where waste storage facilities (agricultural or urban) are inundated or fail. Acid pollution also tends to follow this pattern; an 'acid surge' is produced by an increased influx of acidified water and/or dilution of cations that counteract acidity.

Rivers and streams are often at risk of increased sewage input from urban areas during high-flow events as a result of the design of combined sewerage overflows. In these systems, surface run-off in urban areas drains into the same sewerage systems as foul water. If a storm event puts the sewerage system at risk of reaching capacity, the excess volume of combined storm water and sewage is discharged via a storm-water overflow into a nearby watercourse. This increase in suspended solids and organic material is often followed by a decline in oxygen levels in the watercourse as a result of elevated microbial activity. If surface run-off greatly exceeds sewerage capacity or floodwaters inundate the system, sewerage systems can fail and sewage can flow out of atypical pathways (inspection covers, road drains, sinks, toilets) further adding to the pollutant load. Together with organic matter, sewage discharges can introduce a variety of pollutants from both industrial and domestic sources into rivers. These pollutants include, but are not limited to, heavy metals, detergents, pesticides and pharmaceutical compounds.

Increased delivery of water to freshwater ecosystems during flood events results in a decrease in water conductivity (a measure of the concentration of ions in the water) in tandem with a change in pH, depending on the nature of the contributing water sources. The temperature of the receiving waterbody may also be affected by extreme high-flow events, although the degree and direction of influence vary according to the nature of the source and the receiving waters. The seasonal timing and location of high-flow events can also play an important role in determining the type and degree of pollutants entering watercourses. For example, floodwaters in the winter months within urban areas are particularly high in chloride from road salting operations, resulting in elevated pH and conductivity in receiving waterbodies. In contrast, the impact of floods in rural areas will depend on the agricultural calendar, potentially delivering run-off high in nutrients (from fertilisers), fine sediments (from bare soil), faecal matter (from grazing animals) and/or pesticides.

Although extreme high-flow events predominantly result in the increased delivery of surface run-off to freshwater ecosystems, prolonged high precipitation can enhance the degree of input from groundwater sources as the water table rises. This increase in ground water contribution to freshwater ecosystems may further affect water quality by introducing contaminants and oxygen depleted waters that were previously contained within groundwater storage.

The strong erosive power of water during floods increases the movement of sediment, as well as mobilising pollutants within sediments (e.g. heavy metals, pesticides, organic compounds), which may be exposed and transported within the floodwaters. Run-off from the catchment erodes soils, gathers other particles and transports them via existing and new flowpaths (i.e. those not functional during drier periods) to river channels. Within the channel, previously deposited particles become re-suspended, and erosion of the channel sides and bed brings new material into suspension. The size range of particles that are moved (by suspension [carried within the water column] and saltation [bouncing along the bottom]) increases during the flood. Whilst exceptionally large particles are often moved, the movement of fine sediment (sand, silt and clay particles, <2 mm) increases enormously. Typically, the proportion of inorganic particles in suspension increases, although the total mass of organic material in suspension far exceeds background conditions. Floodwaters become brown and highly turbid with increased suspended sediment. Humic substances are leached from soils and other sources in the catchment, increasing the concentration of dissolved organic matter in floodwaters. Both turbidity (solid, light-scattering particles) and colour (dissolved, light-absorbing substances) increase. Increased sediment loads can have a deleterious effect on both the physical (e.g. clogging of pore spaces, infilling of pools, decrease in light penetration) and biological components (e.g. clogging and abrasion of fish gills by fine sediments) of the watercourse.

The inundation of previously dry soils during flooding results in the redistribution of nutrients and resources from the waterbody to its floodplain and vice versa. The deposition of silt introduces nutrients to the floodplain. However, the continued inundation of soils (waterlogging) can create low-oxygen or oxygen-free conditions, which strongly alter the chemical and biological conditions affecting microbial processes. These anoxic conditions slow the mineralisation of organic nitrogen compounds, prevent oxidation of ammonia and promote denitrification. This leads to a depletion of soil nitrate and the build-up of ammonia. Sulphates are reduced to sulphides such as hydrogen sulphide or insoluble iron sulphide, reduced iron and manganese become soluble, and carbon compounds may decompose to produce methane. The response of plants to these conditions varies widely among species but may include reduced shoot and root growth, decreased transpiration rate, increased susceptibility to pathogens, and eventually mortality.

Although prolonged inundation can cause terrestrial plants to die, the recharge and exchange of resources that occurs with flooding has important implications for both aquatic and terrestrial ecosystems in terms of productivity and the rates of other ecosystem processes.

The impact of extreme low flow (drought) events on water quality

Extreme low-flow events (droughts) can have a more profound effect on lakes and rivers than high-flow events (floods) due to their medium- to long-term timescale and large spatial extent. In general, however, droughts are characterised by much lower than average flow input from surface and/or groundwater sources, resulting in a decrease in the level and volume of water present within the waterbody.

Depending on the duration and intensity of the drought, the percentage contribution of surface water versus groundwater sources may alter. Surface water sources are usually the first to be affected, leading to a higher proportion of ground water supplying the waterbody. This may influence water quality, for example if the ground water is richer in nutrients or is anoxic. If drought conditions persist, groundwater sources may be affected as well, leading to a decline or loss of groundwater input. Continued licensed discharges of sewage and industrial wastewaters at this time may seriously impact receiving waters because the capacity for dilution of these discharges will be limited.

This decline in surface and groundwater delivery represents a loss of input from the catchment into the receiving waterbody, resulting in lower loads of sediment, nutrients and organic matter. However, the decreased flow also results in loss of dilution and increased concentrations of dissolved and particulate matter in the water. Conductivity increases due to an increased concentration of ions. Deposition of suspended solids is likely to increase due to decreased flow and turbulence, thereby reducing turbidity, but causing increased infiltration of fine sediments into the pore spaces of surface and subsurface sediments. Water temperature is affected by residence time, resulting in increased temperature when flows are low. In summer, dissolved oxygen concentrations are likely to decline, sometimes dramatically, as a result of elevated water temperature and decreased mixing. Lakes and ponds are particularly susceptible to temperature changes, oxygen depletion and changes in stratification during drought events, which may further impact water quality (Figure 2.4). If the waterbody is isolated from the underlying ground water, salinity may also increase.

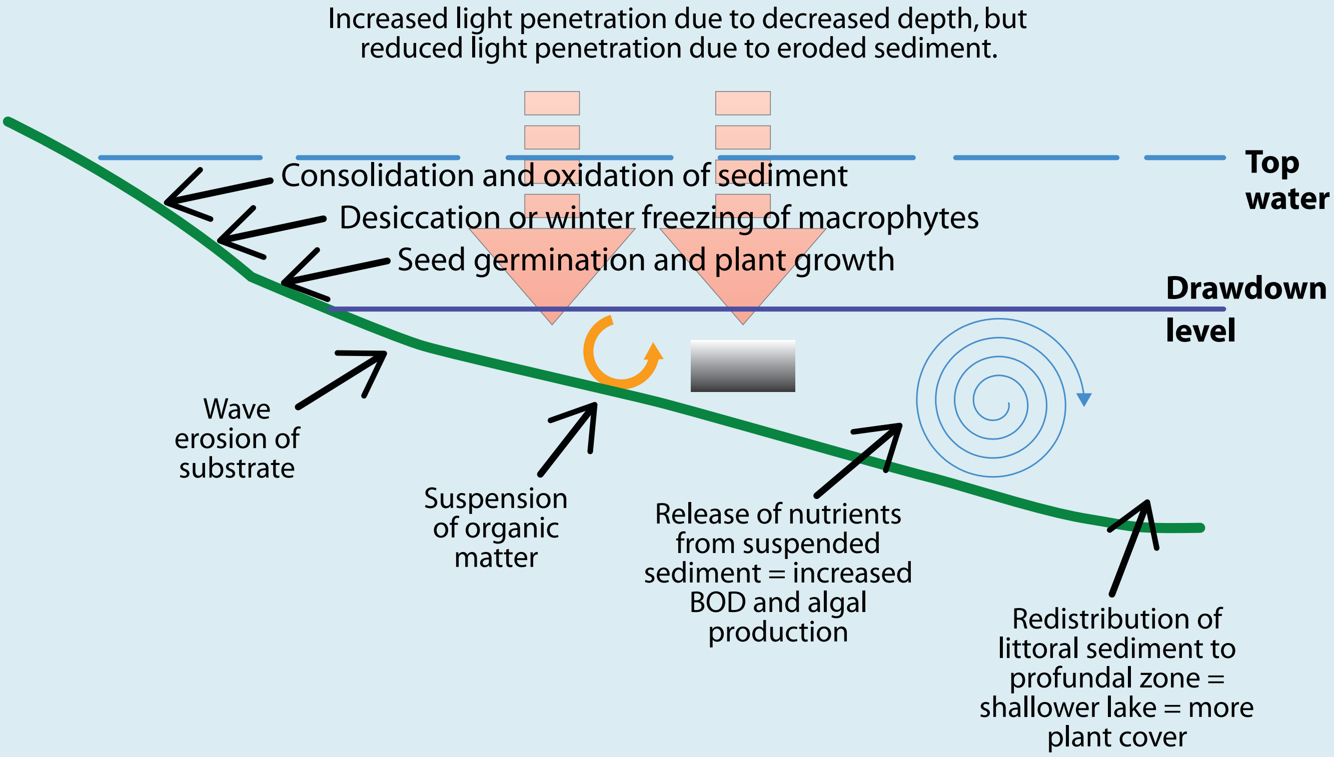
The exposure of organic bed sediments leads to changes in their chemistry and microbiology. For example, extension of the oxic (oxygenated) layer within soils causes a more rapid mineralisation of nitrogen and phosphorus through the oxidative breakdown of organic material. These nutrients then become available to plants developing on the exposed substrate or can be released on the next flood cycle, to create a flush of productivity in the aquatic ecosystem. As well as altering nutrient cycling, sediment exposure increases the rate of decomposition of deposited organic matter.

The lower reaches of rivers are particularly susceptible to prolonged, extreme low-flow events, as the lack of fresh water input from upstream reaches results in the movement of saline conditions into areas previously characterised as being fresh water. In addition to dramatically altering the living conditions for biota inhabiting these areas, the presence of dense, saline water can result in the stratification of these reaches (a salt plug), affecting water mixing and creating particularly poor quality conditions (deoxygenation of deeper saline water).

Figure 2.4

Effects of water level drawdown on the lakeshore environment

Source: Grelsson & Nilsson (1991), Blindow (1992), Gottgens (1994), Wrubleski et al (1997)



Physical Environment

Light and Temperature

Changes in water level (i.e. depth) caused by extreme events will have consequences for light penetration and water temperature. These factors influence the growth of submerged aquatic plants and benthic algae, which are confined to water depths where there is sufficient light for growth. Increased water depth, and suspended and dissolved substances will reduce the light available at depth, and negatively impact plant and benthic algal growth. In contrast, the reduced water levels that occur with drawdown allow greater penetration of light through the water column, which may benefit submerged aquatic plants and benthic algae.

The bare ground left behind by retreating water levels in drought conditions, together with the lack of shade-creating wetland and bankside plants, creates a high level of light at the sediment surface. This exposure to solar radiation can be a major cause of mortality for algae attached to stones in periodically inundated aquatic habitats. However, the increased light and temperature produced by lower water levels can have positive effects, promoting germination and growth of macrophytes on exposed substrates.

Climatic extremes can lead to unusually high air and water temperatures. Nevertheless, water depth, river discharge, groundwater inputs, riparian land use and lake mixing all influence the relationship between air temperature and water temperature. The impact of high temperatures *per se* can be substantial and can manifest itself through both direct and indirect pathways.

Organisms persist over a range of temperatures, which can be broad or narrow. Typically, the optimum temperature is towards the upper end of this range. Metabolism increases with temperature until biochemical pathways break down and (eventually) proteins denature. Yet the direct effects of temperature on metabolism alone rarely cause ecological impacts because even extreme heat spells rarely reach physiologically critical temperature levels in fresh waters. However, temperature also reduces the solubility of dissolved gases, including oxygen, and increased microbial metabolism at elevated temperatures increases oxygen consumption, often leading to acute oxygen stress. Nevertheless, many animals have evolved behavioural responses that can mitigate extreme temperature peaks at least to some extent (e.g. retreating to cooler, deep water). The ecological impact of high temperature extremes is often determined by the interplay of microbial respiration (in turn impacted by the supply of organic matter) and the availability of cool refugia (see Chapter 3).

Extreme cold can also occur, yet the direct effects on aquatic organisms are less pronounced than those at high temperatures. During periods of low temperature a layer of ice can form at the water surface, although this is less likely in rapidly flowing waters. Due to the insulating effects of ice, and the fact that water is densest at 4ºC, only shallow waterbodies subject to very low temperatures experience sub-surface temperatures of 0ºC or below. Some organisms can become fatally trapped in ice at the surface, but those that are regularly encased in ice (such as free-floating plants) can survive to -4ºC. As most aquatic organisms do not regularly experience extreme low temperatures, they are often very susceptible to damage when exposed in shallow water conditions. However, it is typically the indirect effects of low temperatures that cause ecological impacts, e.g. the presence of ice isolates the waterbodies from the atmosphere, which can result in oxygen depletion to lethal levels below the ice (see Chapter 3).

Under cold conditions, the exposure of substrates to atmospheric conditions allows frost to occur in areas otherwise protected by overlying water. The very cold conditions particularly found with winter drawdowns in high latitudes and altitudes, can cause frost heave of sediment, with consequences for vegetation. However, the stable heat-sink effect of a large waterbody can ameliorate the temperature in the saturated root zone of exposed mudflats, preventing any adverse effects of frost on the plants growing there.

Stratification

Drought conditions are usually associated with reduced inflows into lakes and, hence, reduced nutrient loading from external sources. This may improve water quality. However, internal processes within the lake may counteract the impacts of reduced inflows, leading to increased nutrient availability.

As the density of water is affected by temperature, heat exchanges within lakes and externally with their environments often produce a thermal stratification in the water column. Solar radiation penetrates into the water column, heating the uppermost layers. This upper warm layer (the epilimnion) is separated from cooler waters at depth (the hypolimnion) by a thermal boundary called the thermocline where temperature changes rapidly with depth. Once the water column is stratified, the density gradient prevents the warm, well-illuminated epilimnion from mixing with the colder, darker hypolimnion. If there is insufficient light in the hypolimnion, respiration depletes the oxygen and leads to a build-up of phosphate and ammonia that is released into the water column from the sediment. In winter, inverse stratification can occur if the lake temperature falls to, or below, the temperature of maximum density (4 °C), and further cooling may produce a surface layer of ice. Shallower lakes are more susceptible to freezing than deep lakes, because of their lower heat storage capacity and more intense heat exchange with the atmosphere. The water temperature below the ice depends on several factors, e.g. the temperature of inflowing water, the release of heat from sediments and radiation penetrating the ice sheets; under certain conditions the temperature may rise above 4 °C.

Extreme events, whether floods, droughts, heatwaves or strong winds can profoundly affect the thermal regime of lakes, influencing the formation and erosion of stratified layers, their boundaries and how lakes mix. This will go on to affect the relative volumes of the different layers, their water chemistry and ecology. For example, droughts will reduce the volume of the hypolimnion, concentrating the chemical products of organic matter decomposition released from the sediment, such as phosphorus, ammonia and hydrogen sulphide.

> Extreme drawdowns can also disrupt the normal stratification in lakes, making it easier to mix the entire water column and causing the upper parts of the water column to become enriched with nutrients from the hypolimnion.

Wave action

Wave action is one of the major environmental factors affecting lake shorelines. The intensity of wave action is normally determined by wind speed, wind duration, fetch and water depth. Larger waterbodies tend to have greater wave and current energy. The magnitude of this wave force on any shore is determined by margin slope, water depth, duration of held water levels, substrate type and vegetation cover. The level of exposure to wave action can vary with vertical position down the slope of the bank, as well as horizontally along the shoreline.

High levels of wave action cause erosion, transport, sorting and deposition of sediment, commonly resulting in lakeshore sediments with low organic matter content, low nutrient concentrations and coarse particle sizes. Exposure is strongly positively correlated with a sand-sorting coefficient and strongly negatively correlated with the proportion of silt, clay and organic matter in the substrate. This results in an exposure gradient characterized at one extreme by wave-washed, sandy, nutrient-poor beaches and at the other by sheltered bays with organic, nutrient-rich soils containing a high proportion of silt and clay.

Erosion of the substrate by wave action causes suspension of fine sediments into the water column. Lighter organic material, in particular, is transported into deeper water areas before settling, so that sediments eventually become finer with increasing distance from the lake edge. This transport is affected by the slope of the littoral zone: gently sloping areas allow deposition of fine sediments, while steeper slopes encourage erosion and sediment transport.

Extreme storms (especially if combined with water level fluctuations) cause high levels of wave action and potentially major effects on the lake's ecology including sediment redistribution, habitat alteration, release of nutrients, high turbidity (reducing light penetration) and enhanced sediment oxygen demand. The disruption is particularly pronounced in lakes with fine, organic bottom substrate, or in small, shallow lakes where a relatively large proportion of the lake is affected by drawdown. The sloughing of eroded material to deeper parts of the lake eventually reduces the maximum water depth and leads to the development of substantial shallow areas. The effects of wave exposure regimes on the abiotic environment of lakes may determine much of the within-lake variation in vegetation characteristics such as species richness, species composition, propagule transport, depth distribution and competitive interactions.

Habitat availability and connectivity

Floods often result in the inundation of floodplains, leading to an increase in habitat availability beyond the normal river channel or lake basin. In addition to the creation of lateral linkages between the waterbody and its floodplain, floods also promote vertical, lateral and longitudinal connectivity between habitats. Many migratory fish species rely on flood pulses to trigger upstream migration and to allow passage over obstacles as they move upstream to spawning grounds. A number of off-line features, such as cut-off channels and backwaters, rely on extreme events to maintain ecosystem productivity through reconnection with other features. High-flow events are also important for maintaining channel form, flushing fine sediments and mobilising or depositing timber and other organic materials.

Drought, on the other hand, reduces habitat availability for aquatic organisms and decreases connectivity, because flow between units is restricted. As a low-flow event progresses, habitats become increasingly isolated from one another in the vertical, lateral and longitudinal planes (See Chapter 4).

One potential outcome of an increase in the frequency of extreme climatic events could be the creation of new wetland habitat in the form of temporary pools or riverine wetlands in areas subject to increased flooding. Conversely, if droughts occur more often, many existing wetland features will experience an increase in the incidence and scale of summer drawdown due to reduced rainfall and increased evapotranspiration. Neither of these two outcomes is exclusive; it is possible that an increase in the number of extreme climatic events will produce dramatic changes between these two states, with habitats switching more frequently between an inundated and terrestrial condition.

3 The impact of extreme climatic events on freshwater habitats and wildlife

Fresh waters are dynamic environments that sustain a diversity of habitats rich in wildlife.

The ecological communities of our rivers, lakes and ponds are forged by the physical and chemical nature of the ecosystems in which they live and how these influences vary in space and time. Freshwater ecosystems are responsive to changing climate but vulnerability to extreme events differs among species and habitats. To understand this, we must first examine the background variability in the environment. We must first understand the role of natural disturbance regimes before we can identify any distinctly different outcomes caused by extreme climatic events.

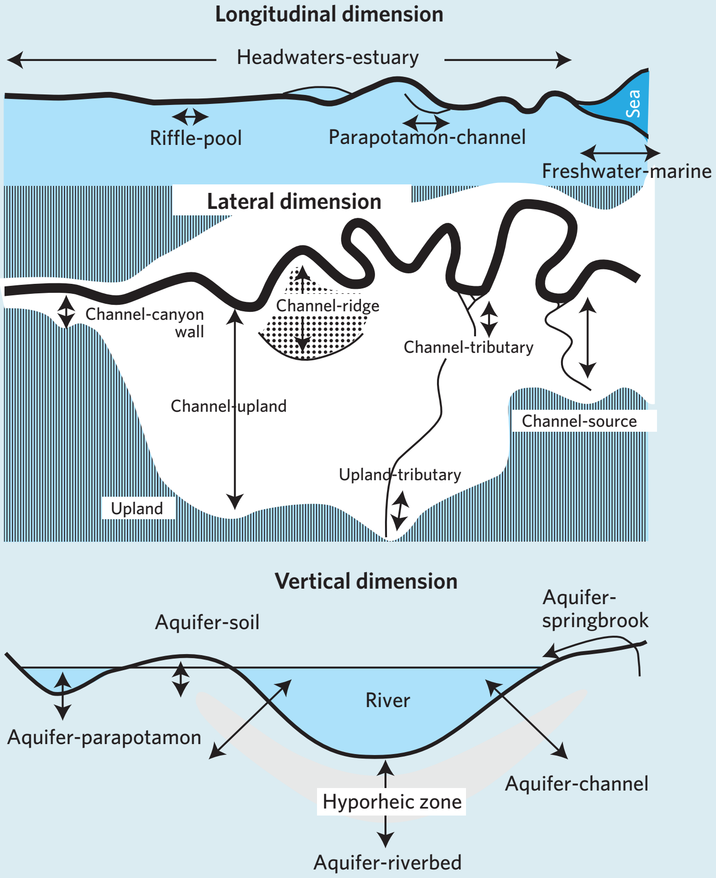
Rivers

River ecosystems are an inseparable combination of the river channel, riparian habitat, wider floodplain and subsurface water flow; the whole ecosystem being a mosaic through space and time that creates a riverine landscape or riverscape. Whilst the longitudinal gradient along the length of rivers is obvious, lateral connectivity, which may be particularly conspicuous during flooding, and vertical gradients between surface and ground water, which may never be seen, are also important (Figure 3.1).

Figure 3.1

Longitudinal, lateral and vertical connectivity in riverine landscapes

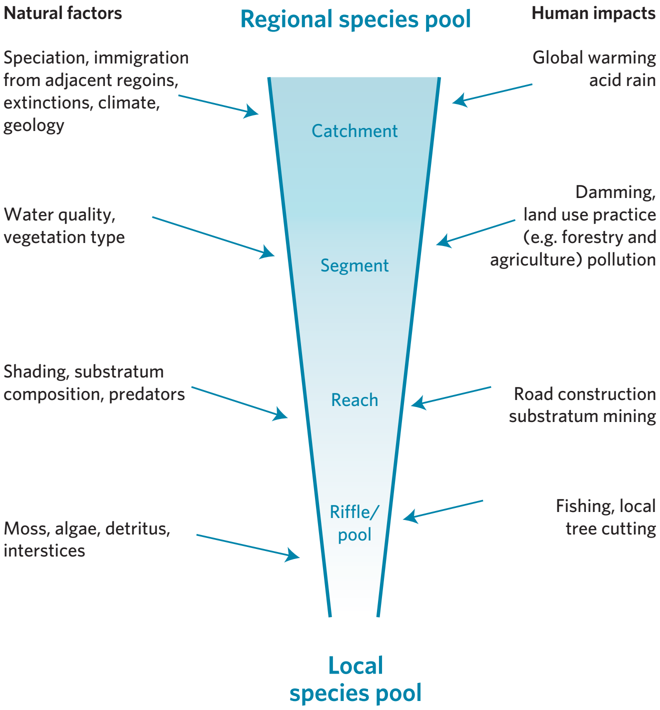
Redrawn from: J. V. Ward et al (2002) Freshwater Biology



The specific character of rivers is defined by: local climate, soils, underlying geology and other characteristics of the catchment landscape. The structural diversity of rivers, i.e. the mix of in-channel habitats, such as riffles and pools, or the distribution of pools across the wider floodplain, is created by the interplay of disturbance and geomorphology. Fluvial action (erosion, transport and deposition) is the key driver shaping these landscapes, modifying substrate, turbidity and temperature – the very factors that extreme events affect. The in-channel habitats, riparian landscapes and subterranean waters are connected by fluxes of matter, energy and wildlife. This pulsing connectivity operates over decades and centuries to create complex, wildlife-rich floodplains (Figure 3.2). Alternating states of floods, which bring nutrients and sediment to recharge systems, and clear-water stable flow, which allows breeding and development, are vital for many riverine species. Habitat variation reflects more than just differences in physical morphology; thermal regimes vary among habitats, too, often mediated by connectivity. In natural river systems, daily variation in water temperature can be pronounced in habitats such as exposed gravel beds but may be more stable in deeper patches and where ground water up-wells, collectively creating hot and cold spots on the river bed. Rivers are by their very nature open, changing systems. This creates a natural ecological regime, rather nicely phrased as "the style of a river".

Figure 3.2

Redrawn from: B. Malmqvist (2002) Freshwater Biology

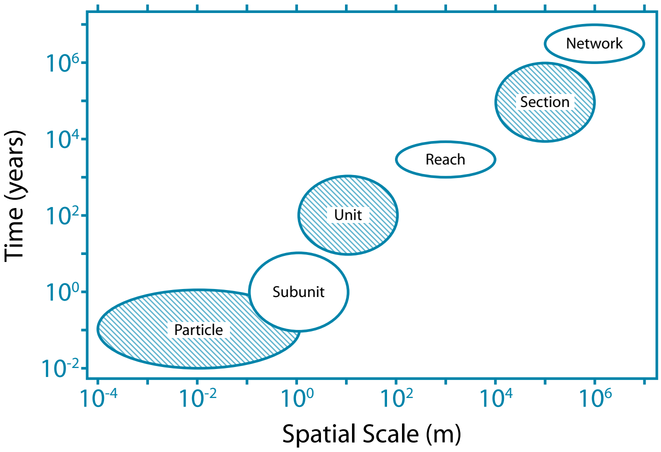


A hierarchy of scales at which natural factors and human impacts affect freshwater communities. The regional species pool is filtered by all of these influences resulting in the local species pool present at a site.

Figure 3.3

Source: Gregory 1991

The structure and processes that define rivers can be described at a variety of nested spatial and temporal scales. Natural disturbance affects all these scales, from determining the character of the overall river network to moving particles of different sizes during disturbance events of different magnitude.



Most rivers in lowland UK have been modified substantially by human intervention but studies from geomorphologically intact, unconstrained rivers from elsewhere in Europe suggest a turnover of ~30% of individual habitat features every three to five years as floods rework the riverscape. Change is normal. Once created, habitats undergo ecological succession, often becoming more biodiverse and structurally complex with time. However, meanders cut off from the main channel of natural rivers may start to infill within a decade and become temporary wetlands within fifty years. Flood disturbance acts to counter this progression, creating new aquatic habitats such as riffles and pools, which add to the diversity of habitats across the riverscape. In reality, disturbances have complex effects on rivers, altering channel morphology and nutrient levels, and influencing both natural characteristics, and those that result from human activity in the catchment. It is from these complex interactions that the inherently heterogeneous nature of river networks is borne (Figure 3.3).

The impacts of disturbance can vary markedly among wildlife groups. For example, fish species richness across floodplain waters generally increases with increasing connectedness because species are able to access more habitat in which to forage, spawn or seek refuge during floods. Nevertheless, particular river sections may become more homogenous because they increasingly hold the same mix of common species. In contrast, amphibian diversity often increases as sites become disconnected, establishing strongholds where there are less predators, especially fish.

The highest riverscape biodiversity is often associated with:

Intermediate levels of disturbance, which re-invigorate and create patches of new habitat without being destructive across the whole system.

Intermediate variety of habitat types, not just a few large uniform patches or patches that are too small for populations to be viable.

Intermediate connectivity. All wildlife needs to disperse to new sites. A lack of connectivity prevents dispersal of organisms that can exploit opportunities created by disturbance or can ameliorate damage incurred. Uniform, readily exploited connections may result in a loss of diversity as unusual sites and variety across the landscape are overwhelmed by cosmopolitan species.

Lakes

There are over 40,000 lakes in the UK with a surface area greater than 0.1 ha.

These constitute over 90% of the surface water resources. Lakes undergo natural, systematic change over long timescales (potentially thousands of years) in relation to changes in climate and catchment characteristics. They can also show considerable inter-annual variability in hydrological and physical processes over shorter timescales (10 to 100 years).

Water can enter and exit lakes via various pathways, including through ground water, sub-surface drainage, overland flow, direct precipitation and evaporation. Each of these sources varies spatially and temporally in concert with climate, catchment soils and geology, and lake basin morphology. The position of lakes in the hydrological landscape is a key factor in determining the relative importance of inputs from ground water, surface water and precipitation. Lakes that are higher in the local hydrological landscape tend to receive a greater proportion of their water from direct rainfall compared to lakes that are lower down. The relative importance of water sources, together with basin morphology, influences how lakes respond to extreme climatic events.

When compared with the dynamic and ever-changing nature of rivers, lakes apparently maintain a more permanent physical shape and position in the landscape. Nevertheless, short-term hydrological disturbances associated with very high or very low rainfall (floods and droughts) can affect lake flushing rate (a measure of how often the total volume of water in the lake is replaced – the inverse of residence time), water level, and rates of inputs of nutrients and sediments from catchments, with consequences for their ecological functioning. An eighteen-year study of Loch Leven, Scotland, showed that changes to the flushing rate altered water temperature and nutrient cycling, which in turn modified algal assemblages and the invertebrate consumers that fuel vertebrates at higher trophic levels, such as fish and birds. Thus, disturbances may have both direct and indirect effects, which can ramify through the food web. Natural variation in flushing rates also dictates the likelihood of toxic cyanobacterial blooms, with associated consequences for public health and amenity value. Low flushing rates in warm dry summers can foster blooms whereas high rainfall events wash them out.

Declining water level and volume can also disturb plant and invertebrate communities in lakes, especially around the margins (see Chapter 1). Biota with relatively long generation times (months to years), such as plants and fish, tend to be most severely affected because their populations take time to recover. Fish and aquatic birds are particularly susceptible to loss of breeding and nursery areas, even if relatively small changes in water level are involved. Recovery of predators such as fish and birds may also be constrained by the rate of recovery of species lower down the food chain on which they depend for food. By contrast, species with relatively short lifespans and generation times (days to weeks), such as open water (planktonic) communities of algae and invertebrates, tend to be least affected by water level fluctuations because their populations can respond rapidly to change.

Lake connectivity in the landscape is less affected by 'natural' floods or droughts than are the backwaters of rivers, although the passage of migratory fish to a lake may be impeded by low water levels in the rivers connected to it. Natural variation in lake water level typically has less impact on fish assemblages than is the case for river systems. Changes in lake substrate, turbidity and temperature will impact fish populations but these parameters tend to be less affected by short-term natural disturbance. Although very warm periods can lead to fish kills in some lakes, these mainly occur in anthropogenically enriched (eutrophic) waterbodies. In some lake systems, seasonal flooding of the surrounding land provides important spawning and nursery grounds for some fish species, although this is not very important for fish in UK lakes. Here, fish are more likely to be affected by the exposure of littoral areas during periods of low water level, which restricts spawning and nursery habitat. Changes in the small tributaries feeding lakes may have a much greater effect on lake fish populations than changes within the lake itself, as these are often the only spawning grounds for salmonids such as Atlantic salmon, *Salmo salar*, and brown trout, *Salmo trutta*. However, episodic, reductions in reproductive success caused by any type of disturbance may have lasting effects on fish populations.

Ponds

At least 500,000 natural and man-made ponds are peppered across the UK landscape (excluding those in gardens). Ponds are disproportionately rich in freshwater wildlife compared to other ecosystems, being home to 70% of the UK's freshwater species and supporting more endangered species than lakes and rivers. This species richness arises because of the unique combinations of many pond habitats; even ponds very close together often support conspicuously different wildlife, and this is especially the case for ponds with contrasting hydrology.

Disturbance driven by hydrology is a major source of local variation in ponds. Some ponds are permanent, never drying out, but others are temporary, either drying out occasionally, or predictably every year; a more formal classification differentiates permanent, intermittent and temporary ponds. In some habitats such as river floodplains or wetlands, the seasonal inundation is a disturbance, linking ponds, and sometimes creating new pools.

Ponds can be viewed as islands in the surrounding terrestrial landscape, and where water levels fluctuate, resident animals typically are highly effective dispersers, capable of emigration from desiccation and extremes of temperature. Many taxa produce drought- resistant propagules such as eggs, spores and seeds, which represent a refuge through time based on life history, a form of ecological memory. Propagules provide powerful resilience at a landscape scale, remaining viable for many years; seed bank experiments commonly find ~50% of species germinating seven to ten years after sites have dried out, and up to twenty years for many zooplankton. Not all propagules germinate or hatch in response to a single re-wetting event, a form of bet-hedging in case the site suddenly dries out again, but, once hatched, many species rapidly set seed or lay eggs. All of these strategies create diversity through space and time; the variety of species in the propagule bank is usually greater than the active species in the community.

The highest biodiversity across a pondscape is associated with analogous levels of disturbance to riverine systems:

Intermediate levels of disturbance. For ponds across the landscape this means that some individual sites have regular, prolonged dry phases whilst others stay wet permanently. This creates a spectrum of disturbance across the terrain; if most ponds became permanent or most dry out then overall biodiversity will fall.

Intermediate pond density. Pond wildlife benefits from a mosaic of pond clusters plus some isolated sites. This occurs in landscapes where hydrological variation and geomorphology create many ponds providing varied environments.

Intermediate connectivity. Intermediate between a few large, isolated ponds (providing a limited habitat type) and many ponds (such that wildlife homogenizes across ponds). However, inundation linking ponds can be problematic, especially for temporary ponds.

> In summary, rivers, lakes and ponds are all ecosystems that depend on natural disturbance regimes to maintain their biodiversity. Disturbance itself is not a problem. However, extreme events, spikes, threshold switches and shocks that deviate from the natural regime can have devastating consequences for life in running and standing waters.

The creativity of disturbance

Exposed Riverine Sediment

The shoals, bars and sand banks of rivers are created and destroyed by flooding, which moves sediment, strips vegetation and deposits fresh substrate. These raw, shifting habitats are usually poorly vegetated but support a specialist invertebrate fauna, particularly ground and rove beetles (Carabidae and Staphylinidae), bugs, flies and grasshoppers. Exposed Riverine Sediment (ERS) complexes offer a fine-grained mosaic of habitats created by variation in sediment size, temperature and humidity. The importance of ERS habitats in the UK has only been appreciated in the last decade; surveys have revealed 131 invertebrates as ERS specialists and of these 86 carry a conservation designation recognising their scarcity. Flow disturbance is essential for ERS habitats. The disturbance creates physical and temporal variety; species' life histories are synchronised to survive and exploit seasonal flooding, and floods provide connectivity allowing individuals to disperse between patches.

A major threat to ERS habitats and the invertebrates they support is anthropogenic flow regulation, e.g. water storage, and channel modification. This is usually intended to control the flow regime by reducing the frequency and magnitude of flood events. However, very little is known about the precise flood-habitat requirements for most ERS species, except that disturbance is at the creative core of this habitat.

Figure 3.4
Exposed Riverine Sediment

The specialist plants and animals of the bars and islands depend on natural disturbance to create and refresh these habitats, stopping the substrate from becoming vegetated and stable.

Temporary ponds

Temporary ponds are a common feature of the UK landscape but their significance for specialist and rare wildlife has only been documented in the last twenty years. Their diversity is influenced by variation in the frequency of drying and refilling. For example, a comparison of 76 temporary ponds from the Lizard Peninsular in Cornwall and the New Forest in Hampshire revealed that half the ponds supported at least one nationally rare plant (e.g. pillwort, *Pilularia globulifera*, rated as 'Vulnerable') whilst nearly three quarters were home to at least one nationally rare invertebrate (e.g. the water beetle *Haliplus variegatus*, rated as 'Endangered'). The diversity of rare and common species depended on the fluctuating hydrology: most are resilient to disturbance and many have life histories requiring dry and wet phases. The variety of hydrological disturbance over the whole pondscape created dry and wet phases of differing duration and depth, resulting in a wealth of ecological communities. Again natural disturbance underpins the natural landscape and its biodiversity.

Figure 3.5
Temporary ponds

Temporary ponds undergo drying and rewetting. As a result these ponds often look poor quality but support diverse communities with life histories well adapted to the changing environment and benefitting from the absence of permanent pond predators such as large fish.

The impact of extreme climatic events

Knowledge of the effects of extreme climatic events in fresh waters is still scarce. This is partly because we tend to lack data obtained immediately before unpredictable events such as severe floods or droughts. Hence, we rely primarily on opportunistic studies, which examine associations between these events and ecological outcomes that we can measure, such as loss of species or declines in populations. In practice, replicated experimental studies which provide more statistically robust links between cause and effect would be more efficacious. Nevertheless, a small number of examples from a range of ecosystems reveal significant impacts of extreme events on the wildlife of rivers, lakes and ponds. The examples that follow are all drawn from studies where the events are described as unusual, severe or extreme. Most are also drawn from sites within the UK, or with some biogeographical equivalence.

Rivers and streams

Floods

Extreme floods significantly reduce the cover and biomass of submerged and emergent plants. The impacts depend on the location and morphology of plant stands and swards. During a rare (1 in 100+ years) flood event on the River Wansbeck in Northumberland in 1997, stands of branched bur-reed, *Sparganium erectum*, and common club-rush, *Schoenoplectus lacustris*, were lost to erosion and scouring flows, which uprooted vegetation and destroyed plant habitat habitat (Figure 3.7). Floods can also slow plant growth, altering the normal development of plant habitats over the growing season. Species such as the fringed water-lily, *Nymphoides peltata*, whose leaves and flower stalks grow up to the water surface from a rooted base, are particularly sensitive to this sort of damage.

A long-term study (since 1978) on an Alaskan river newly formed by glacial retreat, revealed the impacts of a 1 in 100 year storm event that occurred in 2005. Humpback salmon, *Oncorhynchus gorbuscha*, eggs and juveniles suffered severe mortality: in 2007 populations were reduced to ~5% of pre-flood levels but numbers had recovered by 2011, two generations after the event. Most invertebrate species suffered significant losses. Although a few pioneer species that had become scarce in preceding years recolonised after the flood, only to disappear as other species recovered, overall abundances remained low. Large-bodied taxa (e.g. diving beetles, Dytiscidae, and the freshwater shrimp, *Gammarus* sp.) were wholly lost and had not returned by 2008. The community was being reset to an earlier successional stage, similar to that of fifteen years before. The abundance of meiofauna (small benthic macroinvertebrates 45-500 μm) was not so severely hit and their recovery was rapid, probably due to the use of refuges deep in the river bed during the event and the resilience provided by their short generation time. It is important to note that rapid recovery (particularly of salmonids) in this system was probably enhanced by the lack of human development of the catchment: there were no stressors acting on the ecosystem once the major flood had passed.

Elsewhere, research indicates that severe flooding can strongly reduce the abundance of invertebrates, but impacts are species- and habitat-specific. For example, an unusually long period of flooding on the Tiber near Rome in Italy, altered the abundance of 85% of taxa. Floods suppressed many taxa (e.g. non-biting midges, snails, leeches and flatworms) whilst others increased (e.g. caddis flies), and the wider food web was reconfigured, featuring more generalism as opportunists replaced specialised feeders. Recovery from such events can be rapid however, typically taking days to weeks. The River Wansbeck flood, which demolished some but not all stands of emergent plants, also significantly reduced the abundance and species richness of invertebrates, but within two months abundances of both had recovered.

During floods, larger fish tend to seek refuge in areas of lower water velocity, often moving into backwaters or side channels. When overbank flooding occurs, fish will use the floodplain and individuals can become trapped or stranded when the water recedes. However, it is the small fish, particularly early life stages (eggs and fry) that are most vulnerable to the impacts of floods, as they lack the strength to swim to areas of low flow.

Studies of artificial disturbance of river beds, designed to mimic the impact of floods, suggest that the rate of recovery varies depending on the severity of the flood, the heterogeneity of the river bed (i.e. availability of refugia to escape the effects of the flood) and the previous history of flooding at the site (which influences the pre-flood community). In more homogeneous environments only those species that can endure the disturbance remain, with these species tending to take longer to recolonise.

In the immediate aftermath of an extreme flood there may be a switch in community composition to r-selected benthic invertebrate species such as non-biting midges, (Chironomidae) and blackflies (Simulidae), which usually have smaller body size, faster reproduction and growth, and thus greater resilience, at the expense of larger, slower growing/reproducing K-selected species such as caddis flies (Trichoptera) and dragonflies (Odonata). In addition to the effects on productivity and energy flow within the channel, such changes also influence net energy exports into terrestrial systems, as adults emerge and fly into the wider landscape.

The impact of extreme floods goes beyond the truly aquatic flora and fauna. In 2002, the highest recorded flood of the Elbe in Germany impacted the ground beetle communities of the floodplain. Overall species richness was reduced significantly in the aftermath but had recovered within two years. However, the varied beetle communities associated with microhabitats had become more different to each other and this effect persisted; the flooding had reset the beetle communities. The distribution of common riparian plants on the Rhine suggests that extreme events may be important, but may not affect all species equally; the distribution of flood-intolerant species, e.g. false oat-grass, *Arrhenatherum elatius*, showed limits corresponding to the high water levels of floods over ten years earlier, whilst flood tolerant species, e.g. curled dock, *Rumex crispus*, showed no such constraint. Extreme floods on the Danube in 2006 are associated with a change in Lake Sakadaš, Croatia, transforming it from a turbid, phytoplankton-dominated floodplain lake to a clear-water state with a rich, submerged plant flora.

> To summarise, extreme floods can reset in-channel and riparian communities, but the effect is species- and habitat-specific.

Figure 3.6
Flood damage

A meander on the River Wansbeck in July 1996 (left, top), and following an unseasonal 1 in 100 year flood in July 1997 (left, below) showing uprooted plants. The right hand photo shows sticklebacks marooned by receding flood waters on a footpath following 2012's summer floods.

Drought

Severe droughts threaten the biodiversity of fresh waters.

River survey data has enabled scientists to evaluate the ecological effects of droughts occurring in southern England in 1989-1992 and 2005-2006. These two exceptionally dry periods can be regarded as extreme events in terms of low rainfall but also in terms of river hydrology and the persistence of low-flow conditions in rivers. The intensity and duration of these dry periods led to hosepipe bans in some areas, generating sustained media coverage and parliamentary debate.

Chalk streams, which depend on ground water to maintain flows, were conspicuously affected during the 1989-1992 droughts. Whilst the headwaters of these systems often dry naturally, dewatering in the early 1990s appeared to be extreme, extending to normally perennial lower reaches. In the Little Stour River in Kent, the overall abundance of invertebrates was markedly reduced during the dry phase, exacerbated by siltation. Flows resumed in 1993 and populations recovered over the following two years, with only one species suffering local extinction. Longer-lasting effects were seen where deposits of silt remained, with the abundance and diversity of invertebrates remaining lower in these patches. Botanical surveys of the headwater reaches of groundwater-fed streams throughout south east England, recovering from the same drought, showed that some plant communities were highly sensitive to the drought, whilst others were much more resistant. Dried-out reaches developed an extensive cover of non-aquatic grasses and herbs, which were replaced by wetland species such as marsh foxtail, *Alopecurus geniculatus*, and water-cress, *Rorippa nasturtium-aquaticum*, as flows resumed, then by the classic aquatic plants of these rivers such as pond water-crowfoot, *Ranunculus peltatus*. Again the recovery occurred within one to three years, with the river plants alternating between terrestrialised, intermittent flow and fully aquatic communities. For some species, the opportunities for recovery can be lost during prolonged drought: in the Dorset Frome, Atlantic salmon, *Salmo salar*, were lost from a tributary where low flows denied returning adults passage over obstructions for several winters in succession.

A similarly severe drought affected the Rivers Lambourn and Kennet in 1996-1997. The richness of invertebrate families was slightly reduced during the drought but most taxa persisted and recovery was rapid, within a year. Similarly, the visible impact on plants appeared severe with in-channel macrophytes such as the characteristic stream water-crowfoot, *Ranunculus penicillatus ssp. pseudofluitans*, reduced to less than 10% cover and replaced by filamentous algae, *Cladophora* sp., and exposed silt. Once again, recovery was rapid when flows resumed, with the crowfoot re-occupying over 50% of the river bed the following year.

Detailed monitoring of the loss of invertebrates from dried river sediments in a temperate French river, the Albarine, and the subsequent variety of species hatching when sediments were re-wetted, showed species-specific outcomes. The overall number of taxa declined steadily with increasing length of the dry period. The results from several studies have shown loss rates of one taxon every ten to fifty days, whilst population abundances can fall catastrophically within days.

Population crashes of invertebrates in the immediate aftermath of habitat drying are commonly recorded, typically with at least 30-60% losses. Longer-term impacts occur when the drought dry phase disrupts life cycles. In an intermittent temperate Australian stream, species of shrimp and caddis fly were lost, or their populations significantly reduced, following a severe drought because they had been unable to complete their life cycles and lacked life history stages able to survive during the dry phase. Overall, invertebrate species richness declined by between 30-50% but many taxa recolonised rapidly when the flow resumed. Drying reset ecological succession, and although most species recovered within two years, some taxa were permanently lost.

Similarly, studies of severe UK droughts in the 1970s and 1980s revealed significant, rapid reductions in invertebrate abundance during the drought and sustained changes to community structure one-to-two years post-drought, reflecting recruitment failures. These changes resulted from loss of a few, usually rare, species, although many invertebrate recovered within months of drought break. The loss of the juvenile fish year class is common during drought and, in some circumstances, this can lead to the local extinction of species. This is particularly true of migratory species, e.g. Atlantic salmon, *Salmo salar*, if subject to several consecutive years of drought.

Insights can also be drawn from experimental work that mimics natural drought conditions whilst enabling much finer control over the nature of the disturbance. A 24-month trial using artificial streams at the Freshwater Biological Association's River Laboratory, imposed regular dewatering of bed sediments as a disturbance to mimic extreme drought, with adjacent control channels for comparison. This simulated drought caused significant reductions to populations of many species including the dominant shredders (e.g. the freshwater shrimp *Gammarus pulex*), predators (e.g. the alderfly *Sialis lutaria*) and grazers (e.g. the snail *Radix balthica*), whilst a few other species of mollusc became extinct. Larger species, with life cycles lasting several years, were most vulnerable. A few small, rapidly-reproducing taxa increased under drought conditions (e.g. chironomid non-biting midges). The changes to the invertebrate community in drought conditions had significant effects on production within the system as the ratio of secondary (i.e. animal) production to biomass increased because of a shift to smaller species with faster growth and life cycles and the disproportionate loss of larger animals. The natural functioning of the community can also be disrupted because changes in water level alter the mechanical and chemical properties of aquatic plants. For example, the feeding rates and energy reserves built up by common, detritus-feeding invertebrates such as the freshwater shrimp *Gammarus pulex* and the hoglouse, *Asellus aquaticus*, are significantly lower when feeding on the leaves of lesser water-parsnip, *Berula erecta*, growing as an emergent compared with leaves from submerged plants.

The general lessons from studies of droughts are that ecological resistance is low whereas resilience is often high. Populations (or allied measures such as biomass and cover) decline strongly when rivers dry out but the long-term outcomes are species-specific. Recovery is dependent upon life history traits, strategies and body size. Most species recover within a year or two, depending on the availability of refugia and seed/propagule banks from which biota can recolonise, but some species may be lost permanently.

Figure 3.7
Wet and dry rivers

Some rivers on permeable substrate (winterbournes) frequently lose their surface flows for part of the year (a-b, c-d). For other rivers loss of flow is an unusual occurrence. The extent and duration of drying is affected by local climatic conditions and influences the biological community.

Temperature

Water temperature affects species' distribution and abundance, growth, development, and production in freshwaters, because many organisms are ectothermic (i.e. unable to internally regulate their body temperature and therefore dependent on the environmental temperature). Extreme events (both 'hot' and 'cold') can alter water temperature and may have complex effects on aquatic ecosystems, for example by altering the riparian landscape or through icing/thawing cycles.

An analysis of long-term invertebrate community data (from 1981) from the Welsh Llyn Brianne catchment has revealed how warming affects the ecology of running waters. Whilst the Llyn Brianne data emphasise gradual change (i.e. warming trend rather than an extreme event), the results nonetheless highlight the potential risk posed to wildlife by warming. Specifically, the study revealed impacts on invertebrate abundances and local extinction of some species with a 1.4-1.7 ºC rise in mean annual stream winter temperature from 1981-2005. In circumneutral streams, total abundances of invertebrates fell by 21% for every 1 ºC rise. Modelling indicated that future warming of 1-3 ºC would eliminate ten (mostly rare) taxa, representing up to 12% of the local species pool. The temperature change impacts were compounded by variations in the North Atlantic Oscillation and associated winter rainfall patterns. Nevertheless, despite such predictions of species loss, elsewhere in the UK it has not been possible to detect any negative effects of changing climate on species richness, largely due to sustained improvements in water quality, leading to species gains rather than losses.

A similar approach was taken with long-term data on fish and invertebrates from the river Rhône in eastern France. From 1979-1999, mean water temperature increased from 11.3 to 11.7 ºC, with three unusually warm years (1982, 1989 and 1994) superimposed on the gradually warming trend. During the study period, and adjusting for other local influences from power plants and dams, cooler water fish (e.g. dace, *Leuciscus leuciscus*) and invertebrates (e.g. *Chloroperla* stoneflies and *Ecdyonurus* mayflies) were replaced by warm water species (e.g. chub, *Leuciscus cephalus*, and the caddis fly *Lepidostoma*). Invertebrate data from the same river between 1985 and 2004 showed both gradual changes linked to varying oxygen and temperature but also rapid switches between species. These switches were linked to individual extreme flood and heatwave events that benefitted tolerant, invasive taxa.

Climate models predict future warming in many parts of the world, including Europe, and the challenge for scientists is to untangle the impact of shifting mean temperatures from that of growing extremes and other, co-occurring, stressors associated with climate change in fresh waters, such as shifts in water quantity and quality. Whilst both the Lynn Brianne and Rhône examples did not address individual extreme events, they are nevertheless valuable in revealing the risks posed to freshwater ecosystems by warming.

An unusual example of a specific extreme event is provided by a study of the effect of the summer 2003 heatwave on molluscs in the River Saone system in France, set against a longer-term trend of increasing temperature between 1996 and 2004. Through most of this period, maximum water temperatures reached a peak of 26.4 °C but were seldom higher than 25 °C. In summer 2003 temperatures were higher than 25 °C for seventy-five days reaching a maximum of 29.5 °C. During the heatwave, snail and bivalve richness and abundance declined significantly; for example, mean numbers of the New Zealand mud snail, *Potamopyrgus antipodarum*, fell from 156 individuals m-2 in 1996 to 1 m-2 in July 2003. Recovery after this event was slow, especially for bivalve pea mussels, *Pisidium* sp., perhaps due to catastrophic losses of adults combined with relatively low numbers of young produced per adult.

An example of the effects of low temperature extremes comes from the West Fork River, USA. The river was hit by a severe, early spring-freeze event that occurred across the south central and eastern USA in 2007, following unusually warm weather that had prompted early bud-break in riparian vegetation. The freeze killed the newly emerged leaves on riparian trees, resulting in a five-fold higher level of photosynthetically active light reaching the stream. This caused cascade effects such as two- to three-fold increases in primary production, increases in the uptake of nitrate supporting this productivity and significantly higher growth rates amongst a numerically dominant grazing snail. Knock-on effects in subsequent years were not recorded, but this is a powerful example of the connectivity between the river channel and the surrounding landscape, and the impact of short-term, extreme disruptions that may become more frequent with aseasonal weather systems.

Lakes

In general, and in comparison to rivers, the impacts of extreme climatic events on lakes are less obvious and are not well documented. They include the impacts of both floods and drought, and also of extremes of temperature and wind speed. The relatively large volume of water contained in a lake tends to buffer these effects, especially if they are only short term. Shallow lakes appear to be particularly sensitive, with marked changes in community structure potentially resulting from high intensity rainfall, drought, severe ice events, heatwaves, high winds and unusual periods of calm weather.

Floods and drought

The flushing rate fluctuates naturally in relation to variation in rainfall and is increased during flooding. Changes in flushing rate affect the species composition and abundance of primary producers (algae, plants) and, as a consequence, the biota that depend on them for food and shelter. Flooding leads to increases in surface area and volume (especially in shallow lakes), changes in habitat availability in the littoral zone, and reductions in the sensitivity of lakes to other pressures such as nutrient enrichment (eutrophication). In contrast, droughts reduce the amount of water flowing into a lake from its catchment. This is likely to be combined with increases in evaporative losses from the surface of the lake, due to the lower levels of air humidity and increases in air temperatures that are often associated with drought conditions. In combination, these factors cause lake water levels to fall and volumes to decrease.

Less inflowing water also results in less outflowing water, so flushing rate is reduced; this increases the sensitivity of lakes to other pressures such as acidification, abstraction, eutrophication and invasive species. The risk of algal blooms increases as incoming nutrients are retained for longer periods and fewer algae are flushed from the system. Lower flushing rates are likely to affect algal composition by favouring slow growing species such as cyanobacteria. Under flood conditions, when flushing rates are high, smaller algae with relatively fast growth rates will dominate the algal community. Algal species composition and succession can also be affected by the indirect impacts of lower flushing rates (such as changes in temperature regime and nutrient availability) although, if the growth of cyanobacterial populations is limited by other factors such as light or nutrient availability, increases due to reduced flushing rates may be less significant.

Lake biota have evolved life cycles that accommodate natural fluctuations in water level. However, extreme or unusually timed fluctuations in lake water levels can impair ecosystem functioning. Low water levels cause a loss of habitat, especially around the edge of the lake. Although fish are usually widely distributed within a lake, changes in water level may affect individuals that forage and/or find physical refuge from predation in littoral areas; this applies especially to younger individuals. Lower water levels during the spawning season will adversely affect the reproductive success of most fish species that spawn on plants or bottom substrates in the littoral zone or in small tributaries.

Shallow lakes are more vulnerable to extreme events than deeper lakes because small changes in water level represent a much larger proportion of their total surface area and volume. In deep, seasonally stratified lakes, the impacts of water level fluctuations are mainly restricted to changes in the littoral zone. Excessive or prolonged drawdown or flooding of lakes, beyond natural fluctuations in level, may cause major losses of aquatic plants (both species and abundance) as physiological limits are exceeded. More extreme disturbances can lead to significant change, or complete destruction, of some of these littoral communities. Examples of such impacts are often seen in lakes managed for water supply (e.g. Llyn Tegid, Loch Doon, Loch Leven and Thirlmere in the UK). However, the impacts of changes in water level are often species specific. While some species of plants such as shoreweed, *Littorella uniflora*, and the rarer floating water-plantain, *Luronium natans*, tend to benefit from variations in water level, others, such as the invasive Himalayan balsam, *Impatiens glandulifera*, do not.

The increased inorganic turbidity associated with severe storms may cause the loss of submerged plants from shallow lakes. In separate cases in New Zealand and Florida, submerged plants did not return after the storm had passed: the lakes remained in an altered state, dominated by phytoplankton rather than plants.

The loss of aquatic plants reduces structural diversity leading to fewer habitats being available to invertebrates and fish. It may also cause a regime shift in lake functioning, from plant-dominated to algal-dominated. There will be significant losses amongst the littoral invertebrate community, which, in turn, will affect species that depend on them for food, such as fish and aquatic birds. Under extreme conditions, some naturally occurring species may be lost, destabilising the ecosystem and making it vulnerable to colonisation by invasive species. Extreme reductions in water level may affect rare fish species (e.g. salmonids), which are sensitive to reductions in the volume of the hypolimnion because they require relatively low water temperatures to survive. Reductions in lake water depth may also affect habitat partitioning in lakes, affecting highly specialised aquatic birds such as divers. Associated reductions in the volume of depth-specific habitats are also a threat to wildlife, especially when this is combined with nutrient enrichment and deep-water deoxygenation.

The direct impacts of flood events on fish are very limited, but severe floods may flush large amounts of fine sediments into lakes, which could reduce the survival of incubating eggs. In European waters, including the UK, such impacts may occur over a large part of the year. This is because lake-spawned eggs of salmonids (such as Arctic charr, *Salvelinus alpinus*, whitefish, *Coregonus lavaretus*, and vendace, *Coregonus albula*) incubate from the late autumn to the following spring and are joined by eggs of percids and cyprinids from the spring through to early/mid-summer. Extreme inundation of adjoining land also carries the risk of fish becoming stranded when water levels fall, but this is unlikely to be an extensive or significant problem.

Temperature

Temperatures are, broadly, a function of geography: latitude (in terms of solar radiation), altitude (air temperature falls by about 0.6 °C per 100 m rise) and aspect. However, surface waters tend not to show such extreme fluctuations as air temperature and often lag behind it in the seasonal cycle. Superimposed on seasonal temperature cycles are daily patterns of temperature fluctuations whose magnitude is controlled by the weather. Temperatures fluctuate seasonally and diurnally, but less so in lakes than in running waters. The temperature of standing waters, other than very small and shallow lakes, follows seasonal trends with perhaps small, short-term variations that are related to significant weather events. In lakes, the main influences on temperature are from thermal interaction at the interface between water and air, and from energy input directly from solar radiation – the latter being enhanced at higher turbidity. In addition, inflows, rainfall and mixing by winds are all variably influential depending on the relative hydrology and lake morphometry.

The structure and functioning of lakes is determined by thermal regimes both directly (e.g. reproduction and development rates, the timing of fish spawning and egg incubation periods) and indirectly (e.g. oxygen content of water, thermal stratification and ice cover). There are two types of thermal regime in lakes in the UK, classified according to their biological functioning: warm monomictic and dimictic. Warm monomictic lakes are confined to Scotland and are exemplified by large deep lakes, such as Loch Ness, that never fall below the temperature of maximum water density (4° C). Dimictic lakes, on the other hand, occur throughout the UK and are characterised by water temperatures passing through 4° C twice a year (in spring and autumn) and, if deep enough, these lakes may also undergo thermal stratification in the summer.

Changes in the temperatures of lakes can cause changes in the seasonal timing of population peaks and densities. These can have significant ecological consequences, such as the mismatching of algal food supplies with planktonic grazing communities as has been observed in Loch Leven and Lake Windermere. Temperature changes may also restrict habitat availability or reproductive success for sensitive species such as the Arctic charr in Windermere.

In addition to the physical effects, gradual or relatively abrupt changes in lake temperatures will have an impact on biogeochemical cycling within the system. For example, as a lake warms, nitrogen removal processes are likely to be enhanced. This may lead to an increase in the resilience of cyanobacteria to any nutrient reduction measures aimed at reducing eutrophication problems.

Temperature tolerances of benthic invertebrates are poorly known. Some species are adapted to a narrow range of temperatures (stenotherms), while others can tolerate a broader range (eurytherms). Like most freshwater biota, benthic invertebrates are poikilothermic, and can only regulate their body temperatures through behaviour. So, their survival and success largely depends on the ambient water temperatures that they are exposed to. If water temperatures exceed the tolerance levels of sensitive species, this can be lethal; a less marked rise in temperature can affect a species' metabolic activity and other physiological processes, leading to changes in growth rate, life history, reproduction and behaviour. The life cycles of many aquatic insects are closely linked to the temperature regime of their surroundings, with different temperatures important at different stages. Water temperature also has an impact on benthic invertebrate communities indirectly through its effects on dissolved oxygen concentrations and the toxicity of pollutants.

The profundal areas of deep stratifying lakes, below the photic and wave action zones, tend to be characterised by relatively uniform and predictable environmental conditions and by low, stable temperatures. They are dominated by fine-grained substrata with low levels of physical fluctuation, predation pressure and biological diversity. These limit the benthos to relatively few animal groups: mainly larvae of the non-biting midges (Chironomidae), oligochaete worms and sphaeriid mussels. The number of individuals and production may be depth-limited. In contrast, the benthic invertebrate fauna of shallow, non-stratified lakes and the littoral areas of deeper lakes is much more diverse. This reflects the much greater variety of habitats present. Here, the benthic invertebrate community is influenced much more by ambient temperature, together with a range of other abiotic and biotic factors, such as lake morphometry, light penetration, re-suspension of substrate, variable oxygen regimes and wind exposure. Due to the volume of water involved, it is unlikely that short-term high or low temperature events will affect these habitats and the communities that they support.

For most UK fish species, such as percids and cyprinids, it is unlikely that anything other than extremely high temperatures would have direct and significant impacts on fish communities. However, in shallow eutrophic lakes, summer fish kills can be precipitated by very warm conditions resulting in low oxygen availability. In theory, even with less marked increases in temperature, such effects could affect salmonids, which prefer colder water. However, in practice, these species are almost always found in deep, stratified lakes, where any effect of temperature on oxygen concentration may influence vertical distributions but direct mortality is unlikely if an appropriate deep-water refuge is available (i.e. an area with adequate oxygen availability). In relation to extreme low temperature, extensive and prolonged ice cover has been known to cause fish kills in Scandinavia and North America; however, such protracted ice cover is unlikely to occur in the UK.

Wind speed

Wind speed can have a major effect on ecosystem structure and function in lakes.

All but the shallowest lakes are stratified from spring to autumn. This stratification separates a zone of net production and nutrient removal in the well-lit upper layer (epilimnion) from a region of net decomposition and nutrient regeneration in the darker lower layer (hypolimnion). The strength and duration of stratification, and the degree of physical transfer of material across the thermocline, is controlled largely by wind energy transmitted through the surface of the lake. In general, high wind speeds create strong surface waves and large internal waves (seiches) and currents, which redistribute sediments, uproot plants and disturb habitats around the shoreline.

A period of exceptionally calm weather can result in the thermocline becoming shallower. This improves the light climate for phytoplankton but also leads to nutrient removal. In contrast, very windy weather can deepen the thermocline and entrain nutrients from the bottom of the lake into the upper layers. In productive lakes, these entrainment events can also have a major effect on hypolimnetic oxygen concentration. This can have important consequences for the survival of organisms that need oxygen at depth and can lead to the release of phosphorus from the sediment surface into the overlying water. Some cool-adapted species that find a refuge at depth during the summer months, such as the vendace in Derwent Water, may find their habitat restricted if this niche is reduced by high winds that weaken stratification and cause the warming of the deeper water.

Wind can also affect the vertical and horizontal distribution of planktonic organisms within a lake. During very calm weather buoyant cyanobacteria can float to the surface causing surface blooms; these may be short lived, often being mixed into the epilimnion by wind when the calm period passes. This response to physical disturbance of thermal stratification has been exploited in reservoir management, where aerators have been installed to encourage destratification and discourage the development of large populations of cyanobacteria. Wind stress on the lake surface can set up water currents that distribute organisms downwind. This can lead to an accumulation of a large proportion of the cyanobacteria population in downwind areas or bays, magnifying the negative consequences of potentially toxic blooms. These impacts on planktonic organisms lead to indirect effects on other biota within the lake. For example, in Esthwaite Water, the water flea (*Daphnia* sp.) is never abundant when the lake is strongly stratified in autumn, because these conditions favour the growth of cyanobacteria.

Many effects of extreme wind events are relatively short-lived; for example, they tend to reset the seasonal periodicity of phytoplankton succession by just a few weeks. However, some examples of much longer-term effects have been documented. For example, when strong winds caused wind-throw to uproot trees in a catchment in Denmark, large amounts of humic material entered the lake. This decreased water transparency and affected the depth-distribution of aquatic macrophytes. The thermal properties of the lake were also altered. Another example is the wind-induced sediment disturbance in Lake Okeechobee, Florida, USA. Caused by a hurricane, this resulted in high levels of suspended solids and nutrients in the water column and an overall reduction in water clarity. The effects of this on the biota lasted for more than two years – mainly because the sediments that had been disturbed by the earlier event were, subsequently, much more susceptible to disturbance by smaller, but more frequent, wind events.

There are few documented studies on the impacts of wind on invertebrate communities. However, it has been shown that the community structure and spatial patterns of invertebrates in Lake Taihu, China, were strongly correlated with wind-induced disturbance.

High winds are unlikely to have significant effects on fish in lakes under most circumstances, although there have been some instances in North America where extreme winter storms may have had a negative impact on eggs incubating in the littoral zone. There is also some anecdotal information that, in very rare circumstances, a fish kill may be observed when a storm has passed; however, there are no documented scientific observations of this. Increases in turbidity due to the re-suspension of fine particles in the water column by high winds may have some negative impact on optical conditions for foraging fish, but these are unlikely to be of ecological significance unless they persist for long periods.

Ponds

Floods and drought

The impact of inundation on ponds largely depends on the length of time the water is retained, rather than any physical damage such as the scour or erosion witnessed in rivers. Many ponds dry out intermittently or regularly; drying out is not itself an extreme, although it leads to significant recasting of the ecology of the pond. The natural heterogeneity of wildlife between ponds and the often rapid ecological succession makes it difficult to identify extreme events and their impacts.

There is evidence of drought and inundation impacts from 30 small, rain-fed ponds created in 1994 in Northumberland and monitored annually for plants and invertebrates. The ponds dry out most years but since 2000 the single, several-week-long summer dry phase, which generally started in late May/June, has been replaced by multiple drying and re-wetting events, the first drying occurring earlier in the year, in March or April. The original diverse temporary pond fauna, characterised by crustaceans such as seed shrimps (ostracods) and insects, degraded to a handful of species within two years. Similarly the wetland plants (e.g. spike rush, *Eleocharis palustris*) have declined and been replaced by more amphibious grasses (e.g. marsh foxtail, *Alopecurus geniculatus*) and increasingly by terrestrial plants, a pattern that appears to be over and above natural succession as the pond basins remain physically intact. In 1997-1998 the same ponds suffered an extreme inundation when unusually high summer rainfall (at least a 1 in 300 year event) prevented the ponds drying and they stayed wet for two years. Filamentous algae (*Spirogyra* sp.) formed thick swards at the surface of most ponds. The cover of submerged macrophytes under the algae was reduced, invertebrate diversity declined and a few temporary water species (e.g. the caddis fly, *Limnephilus vittatus*) were lost. Drying of the ponds in the summer of 1999 resulted in loss of the algal cover, and plant and invertebrate diversity recovered. Permanent water species that had colonised naturally were rapidly lost from most ponds, although their ultimate local extinction took one or two years. Pond dwelling amphibians are also vulnerable to drought. An extreme drought in southern Finland in 2003 was associated with a significant reduction in the number of clutches of eggs and adult amphibians. However, the impact of the drought varied with land use, being less in more heterogenous landscapes.

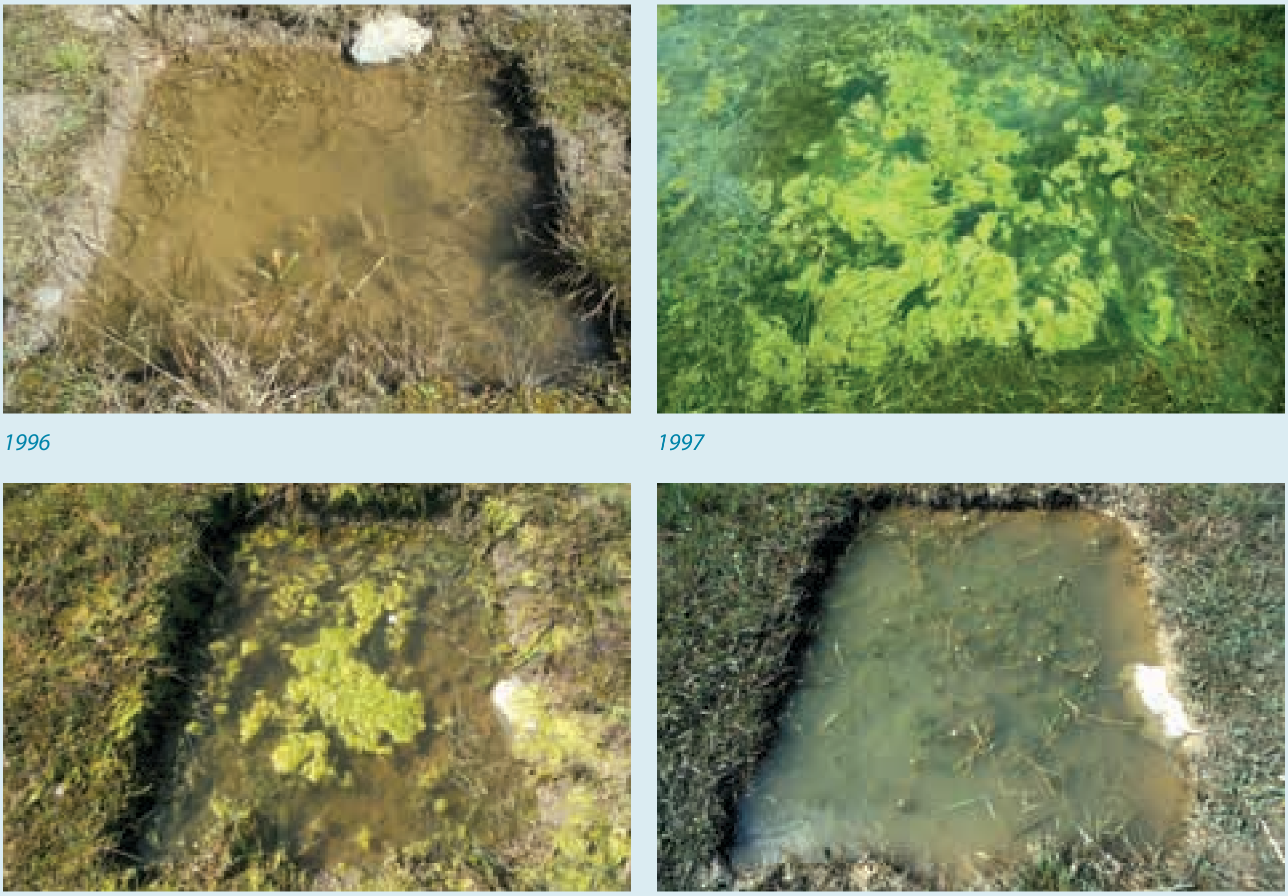
Extreme events may involve changes to the frequency and timing of inundation as well as duration. In the floodplain pools of the Ovens River in south-east Australia, the perennial flood regime benefitted the native carp gudgeon, *Hypseleotris klunzingeri*, over the non-native mosquito fish, *Gambusia holbrooki*. The life history and breeding cycle of *H. klunzingeri* is tuned to the natural inundation regime, which brings a flush of nutrients and warmer water. However, mosquito fish have become more abundant in irregularly flooded pools, able to exploit the more unpredictable regime, which is out of synchrony with the *H. klunzingeri* phenology. Other taxa may also benefit from extreme flooding of riverine ponds. The same 2002 floods on the River Elbe that caused persistent switches in ground beetle communities also significantly increased the diversity and abundance of molluscs in ponds in the area. By 2003 both species richness and abundance had returned to pre-flood levels but communities had been switched from amphibious to truly aquatic, including species such as the great pond snail, *Lymnaea stagnalis*, and the great ramshorn snail, *Planorbis corneus*, which persisted for another year at least.

Evidence from studies of ponds adds to the information from opportunistic studies of dry phases and floods in rivers. In general, there is low resistance to significant population loss during the immediate event but rapid recovery within a year or two, provided that there are refuge habitats within recolonisation range or the wildlife has effective propagule banks that outlast the crisis. However, responses are very species specific and whilst overall diversity and abundance often recover, some species can become locally extinct.

Figure 3.8

Hauxley pond extreme inundation algal degradation (1997, 1998, 1999)

The impact of extreme inundation. The images show one of thirty artificial temporary ponds in Northumberland, photographs in early summer 1996-1999. Extreme rainfall (1 in 300 years) in 1997 prevented the pond's normal summer drying out in 1997 and 1998, allowing thick mats of algae to build up. This resulted in extinctions of some invertebrates and population declines in other pond vegetation. Drying of the ponds in late 1998 allow temporary pond taxa to recover by summer 1999.



1996

1997

1998

1999

Temperature

Because of their small volume, ponds are more susceptible to changes in thermal regime than the well-buffered, larger volumes of lakes. Long-term data for the distribution of the Arctic fairy shrimp, *Branchinecta paludosa*, in Norway, shows the impact of extreme thermal changes. The shrimp is a specialist species of fishless circumpolar ponds, not found in the UK (although some sites in Norway are as far south in latitude). A comparison of 121 ponds, first surveyed in 1971 and again in 2011/12, revealed that the shrimp had been lost from 19 ponds, all but one at low altitude where thermal changes had been greatest. The losses were correlated more with an increase in particularly warm days, i.e. the extremes, than with simply the average increase in temperature. The precise cause of the losses was not identified although it was suggested that an inability of respiration to keep up with oxygen consumption demands at the thermal extremes might be responsible. The shrimp showed no concomitant colonisation of new sites.

Summary of extreme event impacts

Several common patterns emerge from across all freshwater habitats despite the difficulties of identifying and studying unusual, and hence unpredictable, floods, droughts and heatwaves. Severe population declines, local extinction of vulnerable taxa and disruption of community function have all been recorded, although long term, wholesale destruction of communities wrought by a single event have not been documented. This is because the wildlife has been able to recover. Recovery can be rapid, or it can take several years, but it depends upon having a landscape that harbours survivors somewhere. Our fresh waters face multiple stressors including abstraction, engineering and pollution. Under natural or semi-natural conditions, freshwater communities are naturally resilient and able to cope with extreme events. Wildlife may be able to recover from a single extreme event but already stressed and fragmented communities are vulnerable, and further extreme disturbance will degrade our freshwater biodiversity. Whilst we cannot prevent extreme climatic events nor effectively manage every lake, pond and river to ameliorate the impacts of these events on wildlife, we can manage landscapes to sustain and increase refuges and connectivity. This will allow wildlife to bounce back from damaging impacts. We should not respond to recent extreme events with rushed, clumsy engineering which degrades both individual ecosystems and landscape integration, otherwise wildlife will be less resilient in future.

In summary, the known effects of extreme events are:

Rapid reductions in abundance and biomass, especially during flood events. Drought causes similar overall losses but is slower acting, with declines ramping up as the duration of the dry phase lengthens.

Local extinction of species, with the number of species lost, generally increasing gradually with duration/intensity of event. Usually the species that are lost are those whose life history is out of synchrony with the timing and magnitude of the disturbance so that maturation and breeding are fatally disrupted.

Recovery of presence, abundance and diversity of most species within two or three years so long as refuges exist for individuals to escape the disturbance, which creates the potential for the species to recolonise disturbed areas from these refuges. Sanctuaries can exist both in time (e.g. resistant propagules that have survived locally) or in space (e.g. habitats supporting remnant populations from which colonists can repopulate the damaged habitat).

More pronounced effects on communities from sites that are physically homogeneous.

Events reset the ecological stage, e.g. making local communities more varied across the landscape, causing local extinction of some species and providing opportunities for invasive species.

Extreme impacts can disrupt the functioning of communities such as energy flows, feeding, nutrient fluxes, productivity and reproduction.

4 The ecosystem approach to understanding and predicting impacts of extreme events

The ecosystem approach is a key principle of sustainable management of environments, including fresh waters.

It focuses on the integrated assessment and management of land, water and living resources, the promotion of their conservation and sustainable use, and requires consideration of how human actions affect the interconnected components (e.g. fish, invertebrates, etc.) of an ecosystem. Human society benefits from processes or structures within ecosystems that give rise to a range of valuable goods and services, often collectively referred to as 'ecosystem services'. These are typically grouped into four broad categories: Supporting services which underpin the provision of the other service categories, Provisioning services such as food and water, Regulating services such as climate and flood regulation and Cultural services such as recreation, education and spiritual wellbeing (Table 4.1). In this chapter we explore how extreme events in fresh waters affect ecosystem properties and the valuable services they provide to human society.

The ecosystem services approach is based on identifying, valuing, enhancing and managing ecosystems sustainably over the long term. However, although some services can be easily quantified, for example high water quality or the economic value of freight transported on barges, understanding the processes and functions underlying the provision of other ecosystem services is more challenging. Additionally, the choice about what to measure is largely arbitrary; ethical/equity issues arise about who benefits, and where and when the benefit occurs; and finally, ecosystem services that can be monetarily valued are typically prized more than others.

These challenges are being addressed as the field of ecosystem services matures, which requires the natural, physical, and social sciences to become more closely integrated. This poses a range of challenges in itself, given the different languages, philosophical frameworks and traditions embedded within each discipline. Despite these initial hurdles that must be overcome, this emerging field is now developing rapidly. For instance, the National Ecosystem Assessment (NEA) in the UK has started to evaluate change under different socioeconomic scenarios that are projected for 2050. This is necessary in order to understand and manage freshwater ecosystems to protect nature's services, tackle key pressures, such as habitat loss, drainage and eutrophication, and to co-ordinate activities across a range of sectors.

Moderate hydrological variability is a key component of the natural structure and functioning of freshwater systems (see Chapter 3), but predictions indicate that major floods and droughts linked to extreme climatic events are likely to become more frequent in the future. Natural freshwater habitats can regulate these extreme events to some degree (e.g. floodplains storing floodwaters, thereby damping flood peaks and reducing flooding downstream), reflecting the reciprocity between the biological and physical components. However, many habitats have been so heavily modified by pollutants, drainage, vegetation removal, and engineering projects (e.g. channelization) that this capacity, and the ability of fresh waters to function normally, has been compromised. There are also tensions between different ecosystem services, for example, the often-conflicting demands of water supply and viable fisheries. The former needs clean, pristine water, whereas the latter can actually benefit from moderate levels of nutrient enrichment. Our fresh waters need to be managed in such a way that balances the provision of services with predictions of the likely impacts of increased extreme events. The difficulty at present is that the evidence-base for these higher-level ecological properties is still under-developed, so in many cases we are forced to speculate based on limited information and imperfect understanding until more detailed and reliable data and models become available.

Evaluating the impact of extreme events on biodiversity, ecosystem functioning, goods and services using food webs

The food web is a central unifying concept in ecology that connects the lower levels of biological organisation (individuals, populations) to the higher, multispecies levels (e.g. communities, ecosystems), which operates within the context of the physical environment. For instance, as extreme events intensify, the connections between species generally weaken, and the food web can start to collapse as the whole system moves to one dominated more by disturbance than by biotic interactions. Increasingly, food webs are used to address how biodiversity-ecosystem functioning (B-EF) and biodiversity-ecosystem services (B-ES) relationships respond to extreme events. These latter relationships typically operate at larger temporal and spatial scales and are less well understood than the former.

To understand how an ecosystem operates, we need to understand how species are connected, not just to their physical environment but to one another, via the food web. Within a food web numerous species combine to supply ecosystem services, and these can vary depending on which part of the web is being considered: regulating services (e.g. carbon sequestration) are often concentrated towards the base of the web, whereas certain cultural services (e.g. recreational fishing, bird-watching) tend to be located at the higher trophic levels.

The behaviour of seemingly complex systems cannot be predicted simply from the sum of their parts, so it is important that we understand not just impacts on individual species and assemblages (see Chapter 3) but how they are configured as an entire system – just as an electrical circuit must be configured in a particular way to operate effectively. For example, ecosystem resilience, or the ability to recover from an extreme event, will be determined by the length of food chains within the food web: longer chains make the system more fragile and prone to collapse when exposed to a disturbance. This means that natural systems with long food chains may be especially prone to losing their top predators (and the particular cultural services associated with them), e.g. fisheries in lowland rivers are predicted to be especially vulnerable to extreme events.

Table 4.1

Ecosystem services provided by or derived from freshwater ecosystems

Adapted from the Millennium Ecosystem Assessment

Services	Comments and Examples
Provisioning	
Food	production of fish, wild game, fruits and grains
Fresh water	storage and retention of water for domestic, industrial, and agricultural use
Fibre and fuel	production of logs, fuelwood, peat, fodder, reeds
Biochemical	extraction of medicines and other materials from biota
Genetic materials	genes for resistance to plant pathogens, ornamental species, and so on
Regulating	
Climate regulation	source of and sink for greenhouse gases; influence local and regional temperature, precipitation, and other climatic processes
Water regulation (hydrological flows)	groundwater recharge/discharge
Water purification and waste treatment	retention, recovery, and removal of excess nutrients and other pollutants
Erosion regulation	retention of soils and sediments
Natural hazard regulation	flood control, storm protection
Pollination	habitat for pollinators
Cultural	
Spiritual and inspirational	source of inspiration; many religions attach spiritual and religious values to aspects of freshwater ecosystems
Recreational	opportunities for recreational activities
Aesthetic	many people find beauty or aesthetic value in aspects of freshwater ecosystems
Educational	opportunities for formal and informal education and training
Supporting	
Soil formation	sediment retention and accumulation of organic matter
Nutrient cycling	storage, recycling, processing, and acquisition of nutrients

Table 4.2

Examples of hydrological-ecological relationships at different river flows that support the ecological character of fresh waters and their services

Adapted from the Millennium Ecosystem Assessment
(Derived from Cl9.2, C20.2)

Flow Component	Ecological Role
Low (base) flows Normal level:	provide adequate habitat space for aquatic organisms maintain suitable water temperatures, dissolved oxygen, and other chemical conditions, including salinity maintain water table levels in floodplain and plant soil moisture provide drinking water for terrestrial animals keep fish and amphibian eggs suspended enable passage of fish to feeding and spawning areas support hyporheic organisms (living in saturated sediments)
Low (base) flows Drought level:	enable recruitment of certain floodplain plants purge invasive, introduced species from aquatic and riparian communities concentrate prey into limited areas to the benefit of predators
Higher flows (small flood pulses)	shape physical character of river channel, including availability and heterogeneity of different biotopes (such as riffles, pools) and microhabitats restore normal water quality after prolonged low flows, flushing away waste products, pollutants, and proliferations of nuisance algae maintain suitable salinity conditions in estuaries prevent encroachment of riparian vegetation into the channel aerate eggs in spawning gravels, prevent siltation of cobble interstices determine size of river bed substrata (sand, gravel, cobble, boulder)
Large floods	provide fish migration and spawning cues provide new feeding opportunities for fish and waterbirds recharge floodplain water table maintain diversity in floodplain forest types through prolonged inundation (plant species have differing tolerances for flooding) and their natural regeneration processes control distribution and abundance of plants on floodplain trigger new phases of life cycles (such as insects) enable fish to spawn on floodplain, provide nursery area for juvenile fish deposit nutrients on floodplain maintain balance of species in aquatic and riparian communities create sites for recruitment of colonizing plants shape physical character and habitats of river channels and floodplain deposit substrata (gravel, cobble) in spawning areas flush organic materials (food) and woody debris (habitat structures) into channel purge invasive, introduced species from aquatic and riparian communities disburse seeds and fruits of riparian plants drive lateral movement of river channel, forming new habitats (secondary channels, oxbow lakes) provide plant seedlings with prolonged access to soil moisture drive floodplain productivity

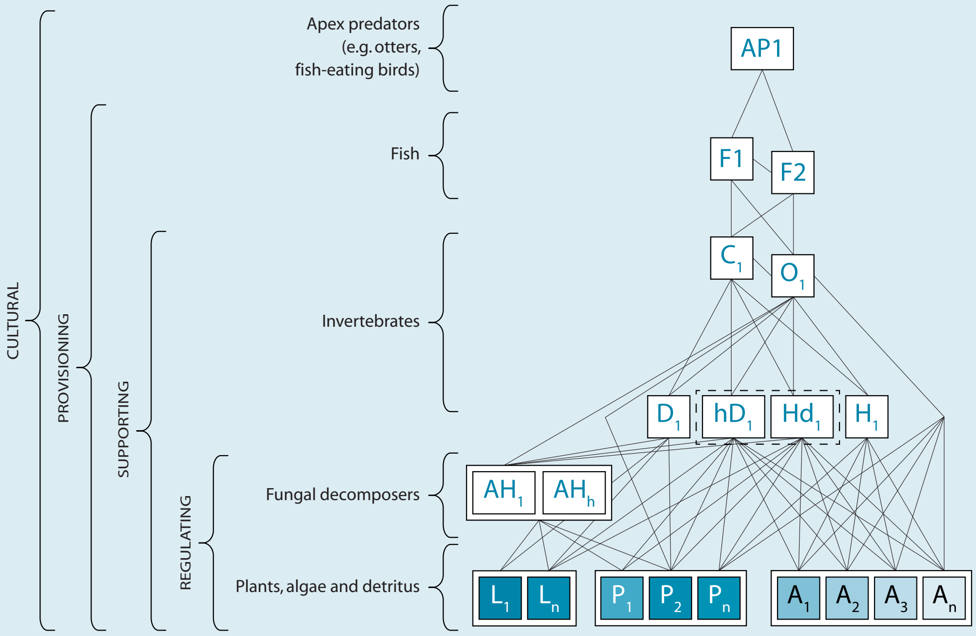
Figure 4.1

A freshwater food web showing the main contributors to ecosystem service delivery

Key:
AP: apex vertebrate predator;
F: fish;
C: carnivorous invertebrate predator;
O: omnivorous invertebrate predator;
D: detritivore;
hD / Hd: herbivore-detritivore;
H: herbivore;
AH: aquatic hyphomycete;
L: leaf-litter;
P: plant;
A: algae.

Rotated text highlights main areas of ecosystem service delivery within the components of the food web.

Redrawn from Wooward 2009, Freshwater Biology



Although certain groups of services tend to be associated with particular parts of the food web, others involve the entire system (Figure 4.1). High profile iconic species that are often the key focus of conservation bodies, such as otters and ospreys, tend to be located towards the top of the web, and these are therefore particularly sensitive to extreme events. In contrast, regulating, supporting and provisioning services (e.g. carbon sequestration, nutrient cycling) tend to be driven by less charismatic, but no less important, organisms towards the base of the web. There are always a few exceptions to any ecological generalisation, and many taxa also contribute to more than one service, but this broad scheme applies to fresh waters in general.

The food web is, thus, a useful framework within which to think about likely impacts of extreme events because species and their services are not lost at random from the system. Top predators, and their associated cultural and aesthetic values, are especially susceptible and, once lost, their populations are very slow to recover. They are also already exposed to a host of other stressors, so extreme events may push them beyond a tipping point, resulting in population crashes, local extinctions, and extensive rewiring of the entire food web. The collapse of fish populations due to acid rain is a familiar example of this and one that can also be linked to extreme events, as the acid pulses that are especially damaging to aquatic life are strongly associated with high run-off during floods. Therefore, extreme events have the potential both to cause widespread damage in their own right and to amplify the effects of existing stressors. It is not just floods that can cause these dangerous synergies: many pollutants become more concentrated during droughts because there is less water to dilute them (See Chapter 2), and this can also amplify the effects of oxygen stress and habitat loss. For instance, the extreme low flow that occurs during drought reduces the power of rivers to remove sediment to the sea. The increased deposition of silt on the river bed can reduce the availability of oxygen in the river bed and in the water, with impacts on organisms such as fish. This is often further exacerbated by the heatwaves that can accompany summer droughts, which reduce the oxygen content still further, as temperature is inversely related to oxygen. This tends to push these systems to increased CO_2 and methane emissions from the anaerobic sediments, both of which are powerful greenhouse gases. In this example, the extreme event is acting simultaneously at both the top and the base of the food web, with negative consequences for several ecosystem services (e.g. carbon sequestration, maintenance of fisheries).

A major challenge, when taking a food web approach, is to understand what happens to the lower trophic levels, which may also be profoundly affected, but in ways that are often less immediately obvious. For example, the production of fisheries and the supply of clean drinking water are ultimately underpinned by what is happening in the usually unseen microscopic world. Nevertheless, impacts on microbes can become strikingly apparent under certain extreme environmental conditions. The blooms of "blue-green algae" (cyanobacteria) that turn shallow lakes foetid green, due to a combination of high water temperature and excessive nutrients, illustrate what can happen when the microbial world intrudes visibly upon our own. Such events are likely to become more common during long, hot summer droughts caused by extreme events, again highlighting a dangerous synergy between extreme climatic events and other stressors. This exposes another important ecosystem-level phenomenon, which would be masked by focusing on single "indicator species" – namely, there are both losers and winners within the food web as a result of extreme events, with the most severe problems for human societies arising when the winners have undesirable impacts (e.g. release of toxins by cyanobacteria into waterbodies kills fish; invasive species being given a competitive advantage over native species).

Compelling evidence exists that extreme events have the strongest impacts on biodiversity at the higher trophic levels.

At the base of the food web microscopic (often single-celled) organisms are both numerically abundant and very diverse, providing greater scope for "ecological insurance" when the system is disturbed: if such a species is lost due to an extreme event, another can often fill its role and maintain ecosystem functioning, at least up to a point, beyond which catastrophic changes can occur very rapidly. Higher in the web, species populations are inherently much more fragile: there are fewer individuals of fewer species, which makes them especially prone to the vagaries of extreme events, and they take longer to recover. These species are typically more biologically complex, often with unique behavioural and other ecological traits that cannot be replaced by another species acquiring the vacant niche, and this is especially true for the top predators. Another critical point to note when taking this whole-system approach is that although droughts and floods may have similar impacts on overall food web structure, the identity and attributes of the members of the web most adversely affected will differ markedly. Thus, although all fish species may suffer to some extent, coarse fish (e.g. carp, tench) that are adapted to slower-flowing or standing waters, will be most negatively affected by floods, whereas game fish (e.g. salmon, trout) will be most strongly impacted by droughts. This means that the food web that remains after an extreme event might have a similarly degraded structure (e.g. fewer species, reduced population sizes and shortened food chains), but the identity of the remnant species will depend on whether they were was exposed to flood or drought.

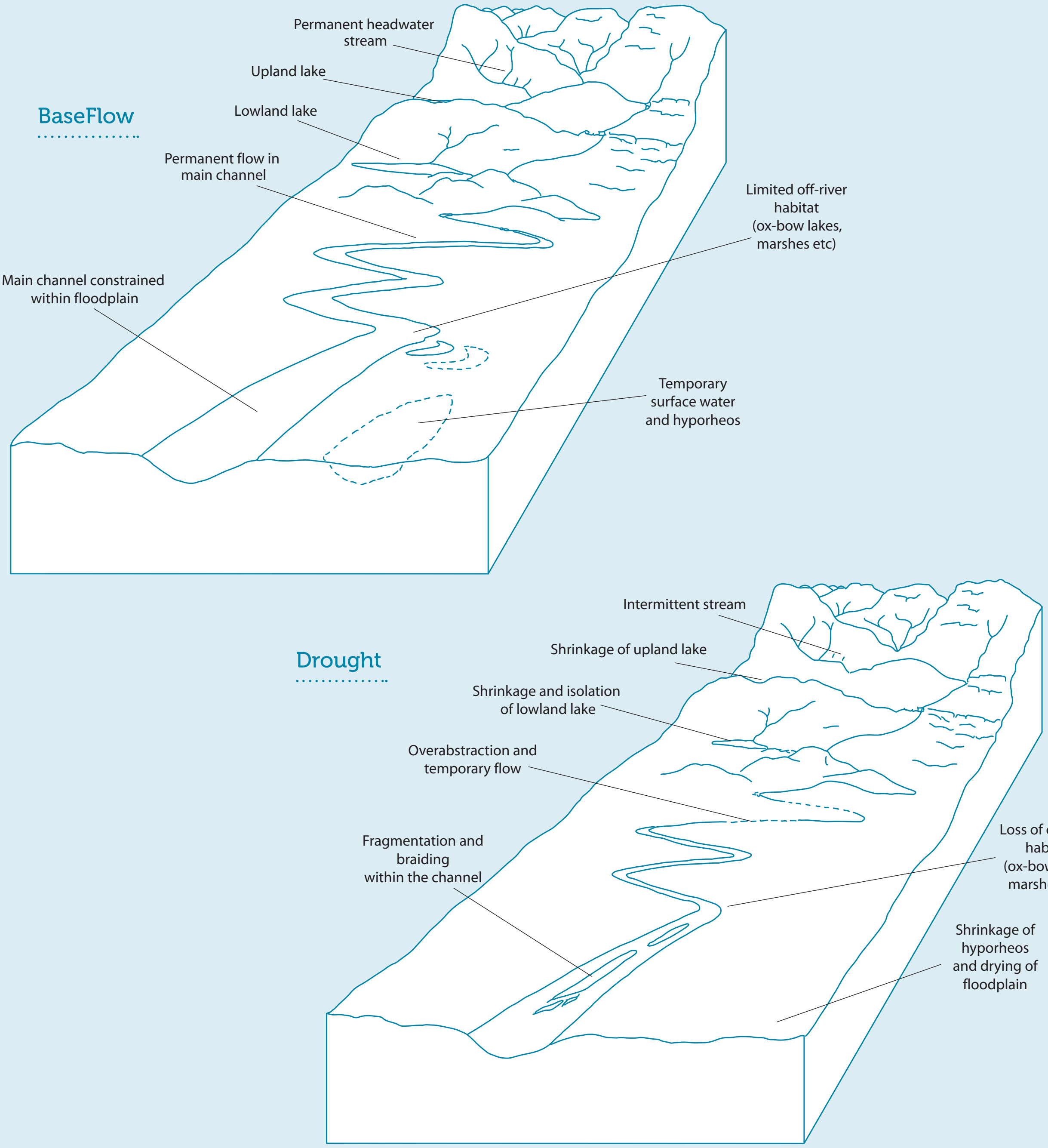
Despite these somewhat idiosyncratic effects at the species level, the effects of extreme events on ecosystem services are more predictable. The food web is primarily eroded from the top down. Therefore, the critical regulating and supporting services associated with microbes are impaired last. Note, however, that once this stage is reached then the system has most probably passed a critical, and potentially irreversible, tipping point. This could happen, for instance, if extreme high temperature and drought combine to release carbon stored in freshwater sediments back into the atmosphere. At large scales this could trigger a dangerous positive feedback loop that further intensifies the rate and amplitude of climate change, potentially leading to runaway warming. We should be on our guard, therefore, to monitor changes in species abundance and the loss of biodiversity across the food web. In addition, we should keep a close eye on the higher trophic levels because these contain the most sensitive species that act as an early warning system. Far more severe consequences are likely to follow if the seemingly more resilient basal species involved in regulating and supporting services are impacted. Healthy populations of top predators are usually reliable indicators that the lower trophic levels are functioning (relatively) normally.

Connectivity

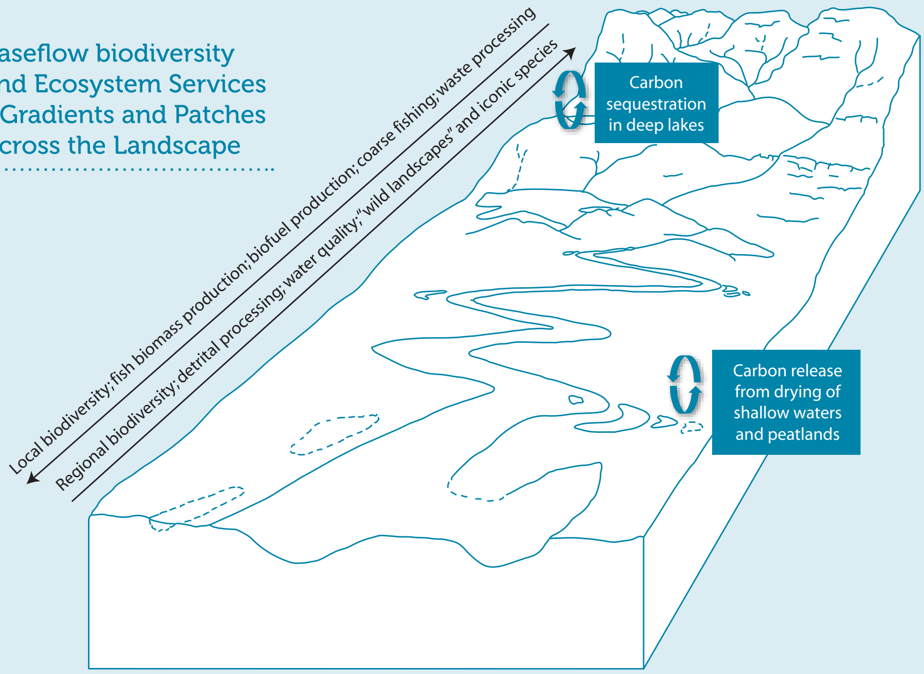
No food web in fresh waters is truly isolated so we need to consider how they are connected in time and space. Fresh waters differ fundamentally from their marine counterparts in that they are highly fragmented in a predominantly terrestrial landscape, a situation amplified by human activity (e.g. construction of dams and weirs, over-abstraction, etc.). In natural systems fresh waters are connected across four dimensions: longitudinally (along the length of the river), vertically (with the hyporheic zone and ultimately ground water), laterally (with the floodplain), and temporally (see Chapter 3). This connectivity is central to the services provided by, and the resilience of, the whole ecosystem.

Figure 4.2

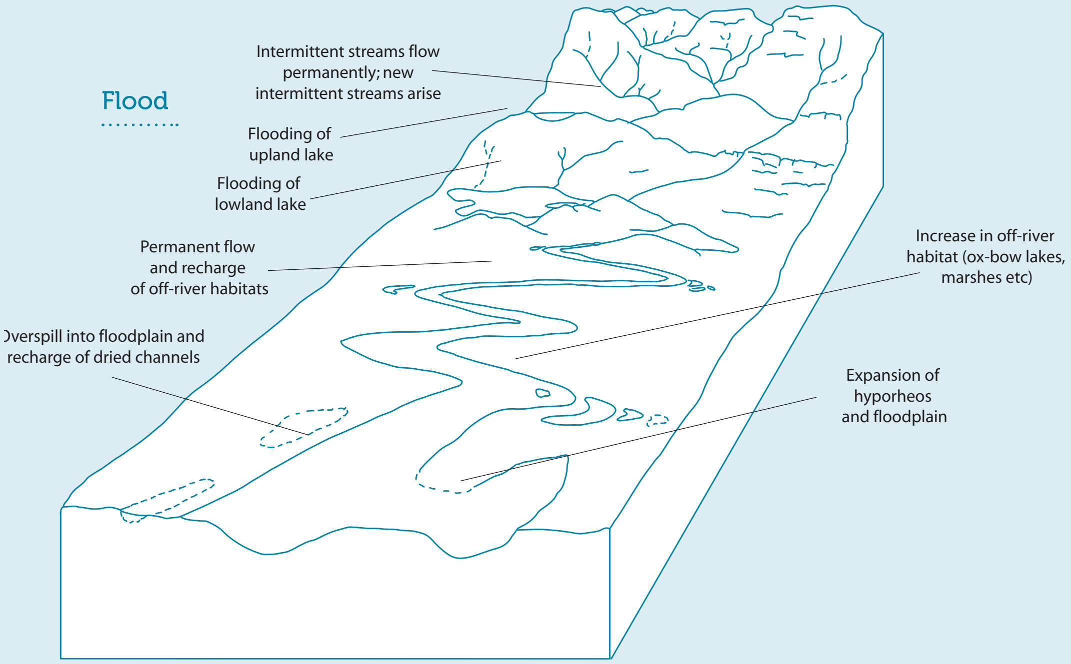
Shifting connectivity among freshwater and terrestrial habitats under normal flow conditions versus those imposed by extreme events



Baseflow biodiversity and Ecosystem Services - Gradients and Patches Across the Landscape



Flood



Longitudinal connectivity

Longitudinal connectivity is reduced by the creation of chemical barriers (e.g. pollutant gradients) to species dispersal, as well as physical barriers (e.g. disconnection or removal of floodplain habitats, construction of dams and weirs). Populations that suffer local extinctions due to an extreme event might never recover if dispersal barriers exist for (re)colonists from source populations. This is especially evident among certain taxa at the top of the food web, such as migratory fish (e.g. Atlantic salmon, sea trout, sea lamprey, eels), that require longitudinal connectivity in river systems so that they can move to their native spawning habitats. Even many wholly freshwater fish species require access to breeding sites that may be many kilometres from where they normally reside. If a generation is lost due to a disturbance (e.g. drought-induced siltation and drying, or flood-induced washout of redds where their eggs are laid), the local population may be lost or its size significantly reduced for many years. While these large predators in headwater streams are extremely mobile and able to connect marine and freshwater food webs over very large distances, they are also very sensitive to perturbations in their natal streams: there is growing evidence that salmon and trout populations in the UK may be suffering from the combined effects of habitat fragmentation and extreme events.

Several key ecosystem processes and services change along the length of a river and across the different standing waters within the catchment. For example, in the uplands methanogenesis occurs primarily in bogs and mires connected to the floodplain, whereas in the lowlands it is more pronounced within the stream channel itself, where sediment is often trapped in extensive beds of water plants. Much of a catchment's biodiversity resides in small, headwater streams, which are often chemically distinct from lower reaches and support very different suites of species from one another and from lower reaches. In contrast, in the lower reaches the species composition may be much less variable among rivers, as these systems are physically more similar to one another, due to the imposition of centuries of modification by humans. Consequently, the scope for resisting or recovering from extreme flow events may be greatest in the catchment's upper reaches, where there is a more diverse regional pool of species with a wider range of adaptive capabilities that enable them to cope with different conditions. The more homogenised flora and fauna of the lower reaches may be far more constrained and less able to respond to extreme events, so the consequences will be even more pronounced than in the headwaters.

Vertical connectivity

Vertical connectivity of the river occurs with the region beneath its bed (the hyporheic zone) where there is mixing of shallow groundwater and surface water. Hyporheic zones are not well developed in all rivers and streams, particularly where bedrock or other impermeable surfaces are close to the upper sediment layers. Where a hyporheic zone is present, surface water sinks into the sediments and travels downstream before upwelling to the surface again. The hyporheic zone plays a crucial functional role in the biogeochemistry of water and provides an important water purification service via microbial transformation of nutrients and other pollutants (acting as a detoxifier in an analogous way to an animal's liver) (Table 4.1).

Hydrological connectivity with the hyporheic zone will be compromised where extreme low flows cause surface sediments to become clogged with silt, thus blocking interstitial spaces and reducing the vertical exchange of water. Clogging of the surface sediments is a particular problem for groundwater-fed streams (e.g. chalk streams) because the high flows that flush accumulated sediments from the substrate are naturally rare in these systems. Low flows can be caused by over-abstraction as well as drought. Furthermore, increased sedimentation is associated with changes in land management in the catchment, including deforestation, urbanisation and arable agriculture, sometimes at some distance from the waterway. Therefore, both extreme events and anthropogenic activities can reduce the ability of the hyporheic zone to provide a water purification service. Relatively pristine rivers and streams, for example, have a greater potential for nitrate removal than those impacted by humans.

The hyporheic zone contributes to the resilience of the whole river ecosystem by providing a physical refuge for river fauna during extreme events. Many benthic organisms move to the hyporheic zone as surface conditions deteriorate then, once the disturbance has passed, they return to recolonise the surface waters.

The hydrogeological attributes of the catchment determine the effectiveness of the hyporheic zone to act as a refuge during extreme events. The volume of available hyporheic habitat, the pore size of the sediment and the amount of clogging, all influence the degree of connectivity between the surface and the hyporheic zone and the ability of fauna to move between them. The effectiveness of the hyporheic zone as a refugium is further mediated by bed stability (Figure 4.2).

Figure 4.3
Hyporheic zone characteristics determining its potential importance as a refugium from surface disturbances for benthic organisms. The arrows indicate the direction of increasing effectiveness of refugia

Source: Taken from Robertson & Wood 2010

Hyporheic zone characteristic			
Volume	Small	→	Large
Sediment / Pore size	Small	→	Large
Colmation / Clogging	High	→	Low
Connectivity	Low	→	High
Bed stability	Low	→	High

Where rivers or streams are frequently disturbed and where the hyporheic zone forms an effective refugium, the food web will be dominated by species possessing traits that allow them to use it (i.e. small size, mobility and burrowing ability). Thus, the hyporheic zone and its degree of connectivity with the surface water helps to shape the composition and resilience of the overall ecosystem to extreme events.

Lateral connectivity

Rivers connect laterally with their floodplain via the riparian corridor of vegetation. The floodplain provides important ecosystem services in the form of flood control: water flowing down the channel is stored so that the flood peak is reached more slowly and the floodwaters are released more gradually (Figure 4.3). Floodplain vegetation retains nutrients, such as nitrogen and phosphorus, and particulate matter carried by the floodwaters. These are subsequently deposited on the floodplain, fuelling the base of the food web. The lateral linkage, via the riparian corridor of vegetation, provides subsidies to the river in the form of leaf litter (a key carbon source in the food web) as well as terrestrial invertebrates that fall into the river to become food for fish (e.g. almost half of brown trout biomass may be derived from these terrestrial inputs). In some rivers the riparian corridor provides large pieces of coarse woody debris, contributing heterogeneity to the habitat, which is especially important for fish. However, in lowland rivers and streams this wood is frequently removed because it is believed to increase flooding in adjacent urban and agricultural habitats. The river and its floodplain also provide aquatic invertebrate subsidies to the terrestrial environment, which are consumed by beetles, spiders, bats and birds. This highlights the interconnections between fresh waters and the landscape within which they are embedded.

Many fish species depend on the lateral connections with floodplains for important spawning and rearing habitats, which are typically slower flowing, more productive water channels containing fewer predators (Table 3.2). Travel into and out of these lateral habitats by spawning adults and juvenile fish often requires high flows so, while they may act as key refugia during floods, these critical connections may be lost due to habitat fragmentation during droughts. The strength of the lateral ties between the river and its floodplain varies along the length of the river and the spatial extent of flooding increases downstream, so ecosystem services such as buffering against floods and deposition of nutrients on agricultural land occur mainly in the middle and lower reaches.

Temporal connectivity

Floods are important natural attributes of river systems when within the normal range: seasonal floods are often associated with larger rivers, whereas flooding in headwater streams is more stochastic. It is predicted, however, that climate change will lead to more frequent floods of a greater magnitude at atypical times of the year. Ecosystem recovery from such floods may take considerably longer than from those occurring at more predictable times, because they are outside the normal experience of the organisms affected. In contrast, the timing of low-flow events can be critical to connectivity because it can restrict upstream and downstream fish migration, which is typically triggered by peak flows, e.g. in salmonids. The timing of extreme climatic events will also have major implications for the reciprocal subsidies between freshwater and terrestrial systems, which are determined by the relative extent of each habitat type and would be affected by drying or flooding.

An increase in the frequency of extreme events will constrain recovery trajectories because it does not allow communities time to recover before the next event occurs. This can lead to legacy effects, whereby the remnant food web influences which species subsequently colonise and therefore the structure of the recovered community, and the ecosystem services it is able to provide.

In conclusion, extreme events have profound impacts on the magnitude and type of ecosystem services provided by fresh waters, due to alterations in the food web and its associated biodiversity-ecosystem functioning (B-EF) and biodiversity-ecosystem services (B-ES) relationships.

The strongest effects will be manifest through impacts on species at higher trophic levels, which could compromise the provision of ecosystem services such as fisheries. Species lower down the trophic structure are more abundant and diverse, and have the potential to be replaced by other species that are able to maintain ecosystem functioning and service, hence this portion of the food web is likely to be most resilient.

These networks of trophic interactions are themselves embedded in interconnected networks of habitat patches in the landscape. Connectivity is therefore central to the services provided by, and the resilience of, the whole river ecosystem and the maintenance of B-EF and B-ES relationships during extreme events. Connections among and within freshwater and terrestrial habitats can provide critical refugia from which the survivors are able to recolonise the system when conditions have ameliorated, enabling the food web to reassemble and conferring resilience on the ecosystem as a whole. Extreme events in general, and low flows in particular, can reduce both trophic and spatial connectivity, fragmenting the food web and compromising the ability of the freshwater ecosystem to recover.

Finally, extreme events cannot be viewed in isolation from other stressors in the catchment, which may combine in a "perfect storm", thereby amplifying their effects. Trophic and physical connectivity in the landscape need to be considered together, and in the context of other stressors (e.g. habitat fragmentation caused by damming; siltation of salmonid breeding grounds caused by agricultural run-off) when planning river management and restoration, especially in the context of climate change.

Figure 4.4

Relationship between processes, functions and ecosystem services of fresh waters

Processes	**Functions**	**Services**
Denitrification and other transformations of nutrients in plant cells	Uptake from water and use of nutrients by plants	Improvement in water quality through reduced nutrients
Downward movement of water by gravity from the wetland into underlying strata	Recharge of aquifers	Augmentation of groundwater resources available for human use
Movement of water from rivers during high flows to inundate a flood plain surface, fill depressions and saturate the soil	Flood water storage	Reduction in downstream flood risk
Production of peat from dead plant material in anaerobic conditions	Carbon storage	Reduction in greenhouse gases
Flow of nutrients and energy between organisms in the food web	Growth and reproduction of fish, invertebrates, plants	Fish and plants to eat, reeds for thatching, birds to watch

Source: National Ecosystem Assessment

5 Management

People don't like surprises, especially when they risk lives and livelihoods. Hence, we attempt to manage our environment in ways that reduce the impact of extreme events on society.

We have defined extreme events as rare climatic periods that push ecosystems outside what has been considered to date as normal variability. Yet, as described in the introductory chapter, disturbance events occur naturally (with a frequency, amplitude, duration, timing, rate of change and spatial extent that are within a predictable range given our previous experience) and can provide a positive and necessary 'shake-up' to ecosystems. Whilst such disturbance can have major impacts in localised areas in the short term, over longer time periods and in a wider landscape context disturbance can be a positive creative force, improving biological and habitat diversity. The challenge to management is to facilitate this natural dynamism while at the same time protecting society from the undesirable impacts of extreme climatic events.

Whilst extreme climatic events have figured prominently in IPCC assessments, extremes only contribute in part to disasters (i.e. widespread damage and severe alterations to the normal functioning of societies). The character and severity of impacts of extreme climatic events on both society and ecology emerge from the interaction of the extreme event with exposure and vulnerability, which in turn are both influenced by humans.

A long history of land management and flood control has sought to reduce the potential for extreme events to affect human developments, resulting in a general simplification of natural environments. Such attempts to control may, perversely, be reducing the capacity of fresh waters to absorb floods and replenish ground water, thus accentuating the impact of extreme climatic events.

Furthermore, it is predicted that climate change is likely to increase the frequency and magnitude of certain extreme climatic events (see Chapter 1). As a result, it is critical to increase the resilience of freshwater ecosystems, as well as to maximise the benefits that such extreme events can provide. Wherever possible, options should be taken that produce both societal and ecological benefits. For example, by ensuring efficient use of the water that we do abstract (e.g. reducing leakage, re-use of grey water, low-flush toilets), we can both reduce the costs of water treatment and, by extracting less water, reduce the exposure of freshwater ecosystems to the adverse effects of drought.

Following extreme events, ecosystems undergo a natural recovery process (see Chapter 3). Management should aim to protect the capacity for such natural recovery processes and, where it has been impaired, to actively assist recovery. However, it is possible that extreme events can force ecosystems over a threshold beyond which a different, often simpler, community of animals and plants predominates, with profound and potentially permanent effects on the ecosystem. We cannot predict when such catastrophic events are likely to occur, but we could provide ecosystems with the capacity to absorb and recover quickly from extreme events. In short, management should work to provide ecological resilience so that ecosystems are better prepared for extreme events.

In the first instance, freshwater ecosystems that have largely retained their active natural processes and water retention capacity, should be protected from any future degradation and enhanced where necessary (e.g. the Insh Marshes on the River Spey: see Box 5.1), as such systems are likely to be more resilient to extremes. Elsewhere, the impact of pollution and physical habitat damage on freshwater ecosystems should be reduced. Here, drivers of change such as the European Union Water Framework Directive (EU WFD) are already having a positive impact, with a commitment to increase the ecological quality of lakes and rivers in Europe. Such improvements are likely to increase diversity and reduce vulnerability of species and populations within waterbodies thereby increasing ecological resilience. However, the ability of species populations to recover after an extreme event will depend on the availability of refuges for individuals to escape the disturbance and the potential for the species to recolonise disturbed areas from these refuges once the event has passed. Here, management should aim to provide a coherent ecological network, with increased connectivity both within and between freshwater ecosystems. Heterogeneity, both at the habitat and landscape scales should be encouraged. This heterogeneity should also consider temporal variation, and allow freshwater and terrestrial habitats to change in response to climatic events: such scope to respond to natural disturbances and to create refuges, increases long-term ecological resilience to extreme events.

Introducing spatial and temporal heterogeneity into the waterscape may seem counter-intuitive when the aim is to reduce the impact of extreme events, but in the face of climate change there are many potential ecological, social and economic benefits to a more holistic approach to water management. There is strong pressure from society for human life and property to be protected from floods, and for reliable access to water resources during drought. Future management strategies will need to balance these socioeconomic needs with ecological needs. The EU WFD and EU Floods Directive provide the means by which such conflicting objectives can be resolved. These Directives shift the focus of water management away from compliance with chemical standards and construction of flood defence infrastructure to recognising the wider benefits to society of the natural functions provided by freshwater ecosystems, e.g. attenuation of floods, water storage and water purification. Choices on how best to manage river and lake catchments can ultimately be framed in terms of their impact on the likelihood of a waterbody achieving good ecological status or potential, the fundamental WFD target.

A key tenet of the EU Floods Directive is to ensure protection from extreme flood events by taking advantage of nature's own capacity to absorb excess waters. Natural Flood Management is the use of land management techniques and engineering strategies that work with natural ecological and hydrological processes within the framework of land use planning. This type of management is not new: most of the techniques are components of existing best practices in farming, forestry, river restoration and natural habitat management. However, a major element is the production of a catchment flood management plan enabling most of the current land uses to continue, while introducing flood controls in key areas. Incorporating Natural Flood Management into the EU Floods Directive ensures that the Directive's aims are closely aligned with those of the EU WFD. In practice, a sustainable approach should mean that management plans integrate a range of flood management requirements using best practices, and involving the economics of schemes, good planning, understanding flood generation processes, protecting natural environments, and working with communities. Identifying complementary and conflicting objectives between flood-risk management, other ecosystem services, landowner priorities and regulatory frameworks is crucial for the effective implementation of Natural Flood Management. There may still be difficult choices and trade-offs to consider but with such a co-ordinated approach, decisions will be taken from a better-informed basis thereby lessening the chance of unintended consequences.

Natural Flood Management is a catchment-based approach aimed at reducing run-off rates in the uplands, reducing rates of flow down watercourses, reducing flood peaks and restoring a more natural flow regime (Box 5.2). It selects the functional flood control areas within the catchment to modify or restore land uses that together reduce downstream flooding. The key components of Natural Flood Management comprise the suite of techniques that can be used, the spatial distribution of these applications around the catchment and the quantification of how effective they will be in the short and long terms.

Natural Flood Management techniques include:

- Reforestation of hill slopes;
- Planting dense woodlands in gullies;
- Modifying agricultural practices;
- Restoring upland wetlands, lowland wetlands and floodplains;
- Restoring river channel meanders;
- Controlling excessive erosion;
- Management of large woody debris in watercourses;
- Encouraging target low-lying areas to flood

There is an expectation that once the flow regime has been restored, the river itself will undertake the long-term maintenance works. An evidence-base for the effects of Natural Flood Management is starting to emerge from a combination of river catchment-scale experiments and models. Areas of woodland along hill slopes in the Pontbren catchment in Wales, have been shown to increase infiltration of surface run-off, relative to grazed pasture. Modelling has demonstrated that careful placement of such interventions could reduce the magnitude of flood peaks by 40% at the field scale; while at a catchment scale reductions of 2-11% were possible from optimally placed woodland shelterbelts. A recent and ongoing application of Natural Flood Management focuses on the North Pennines where areas of moorland have been drained over previous decades by the digging of ditches. This has been detrimental to the peatland landscape and has increased the likelihood of flash floods. In recent years 100,000 peat dams have been installed to block 950 kilometres of Pennine moorland ditches. This reduced the amount of water, and rate at which it flows from the moorland into receiving watercourses. A final example comes from the River Dijle, south of Leuven, in Belgium. The river regularly flooded parts of the historic city and there was pressure to build a floodwater-retaining dam upstream of the city. Such infrastructure would have destroyed many notable wetland systems, e.g. wet hay meadows, sedge complexes, ponds and alder swamp forests. Local conservation bodies convinced the authorities to adopt a Natural Flood Management approach to seeking a solution. The natural retention capacity of the floodplain upstream of Leuven was enhanced through the purchase of land, restoration of grassland habitats, re-modelling of former fishponds, blocking of drainage ditches and appropriate ongoing management in collaboration with local farmers. The results have been a win-win situation where Leuven is now better protected from flooding, large coherent blocks of wetland habitat have been restored, and all for less than the dam construction costs.

A reduction in the capacity of catchments to retain water also increases their vulnerability to drought. However, that function can be restored through appropriate management. An initiative by South West Water called "Upstream Thinking", funded projects to restore upland mires and to create wetland habitats to deliver benefits in both water quantity and quality (Box 5.3). Encouraging infiltration and conserving water are also key agricultural management activities, through measures such as creating ponds and building on-farm reservoirs; the latter is already seen as critical by bodies such as the National Farmers Union (NFU). Farmers are key stakeholders as well as potential contributors in flood-risk management. Through agri-environment schemes, farmers could be encouraged to retain certain areas of farmland for water storage, or to improve the natural retention capacity of the land, for example through targeted planting of buffer strips or the maintenance of wet meadows in floodplains.

Box 5.1

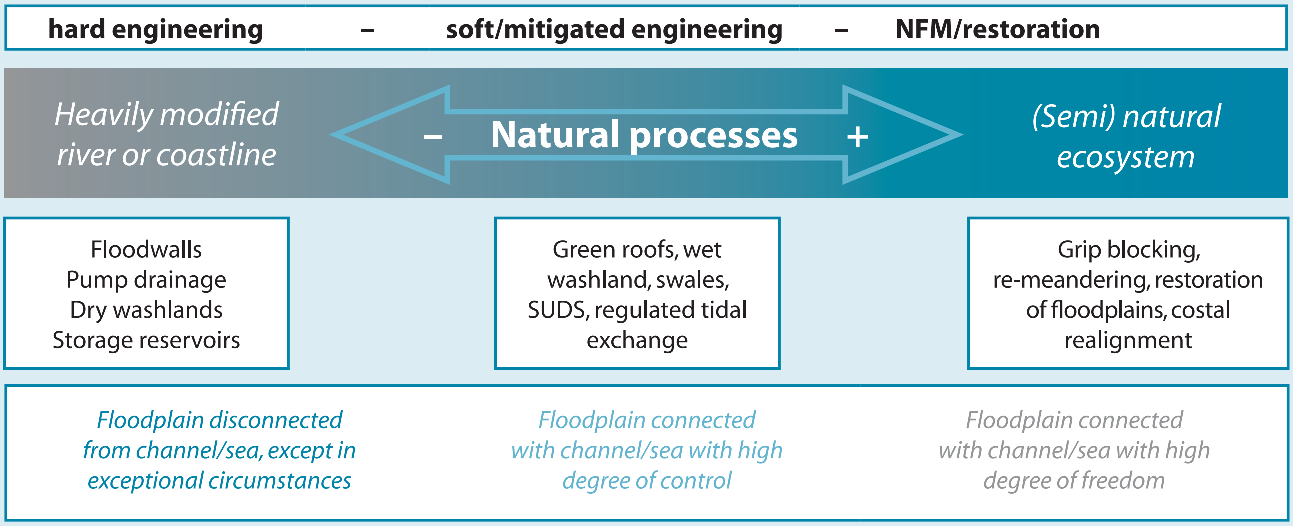
Insh Marshes on the River Spey

Natural Flood Management

In the River Spey catchment in Scotland, the Insh Marshes is an internationally-important floodplain wetland at the confluence of several energetic mountain rivers including the River Calder and River Tromie. Historically, floodplain mire systems such as Insh Marshes were once common in Britain but most similar river valleys have now been drained, and their flow regimes controlled. The conservation status of the marshes relies on the regular inundation of the land, but the downstream community of Aviemore relies on the wetland for flood protection. By carrying out a detailed study of the site, a management agreement was entered into involving the partial excavation of downstream sediment accumulations. The work was designed to reduce the extent of flooding while retaining flood water storage over the marshes and maintaining the protection of the downstream community. The Royal Society for the Protection of Birds (RSPB) Scotland now owns and manages the site for the benefit of both biodiversity and flooding. The floodplain regularly floods during winter and spring, acting as a natural flood system with floodwater covering some 1000 ha at a depth of 2 m. Flood risk is reduced to neighbouring settlements including parts of Aviemore, which is an important base for the local tourism economy. The reserve itself adds approximately £200,000 to the local economy through tourism, angling and management of the reserve. The cost of hard engineering to provide similar protection is estimated at £1.3M.

Natural Flood Management

Source: RSPB Scotland (2009): Meeting the challenges of implementing the Flood Risk Management (Scotland) Act 2009 by Andrea Johnstonova



Box 5.2
Sustainable Flood Management

Natural Flood Management and Sustainable Drainage Systems are approaches to water management that work with the natural environment to reduce the impact of floods and droughts. The overall idea of these approaches is to reduce the impact of extremes through reduction of flood peaks and recharge of aquifers. They work on simple key principals, with many of the activities listed below achieving more than one of the key principles.

Slow water down

Examples of activities include:

- Block inappropriate artificial drains and ditches
- Plant woodlands in steep gullies
- Plant and manage across-slope hedgerows along existing field boundaries
- Encourage native mixed woodland on hill slopes
- Build hard flood defences away from the channel
- Create 'leaky barriers' to disrupt flow paths over floodplains
- Manage farm tracks and tramlines to intercept flows

Encourage infiltration

Examples of activities include:

- Restore wetlands
- Use permeable materials for hard surfaces
- Position gates in up-slope field boundaries
- Restore wet grasslands in floodplains
- Create soak-aways rather than drains
- Create ponds and wetlands to intercept surface-flows in urban settings
- Reduce compaction of agricultural soils
- Use permeable structures for in-field surface water storage

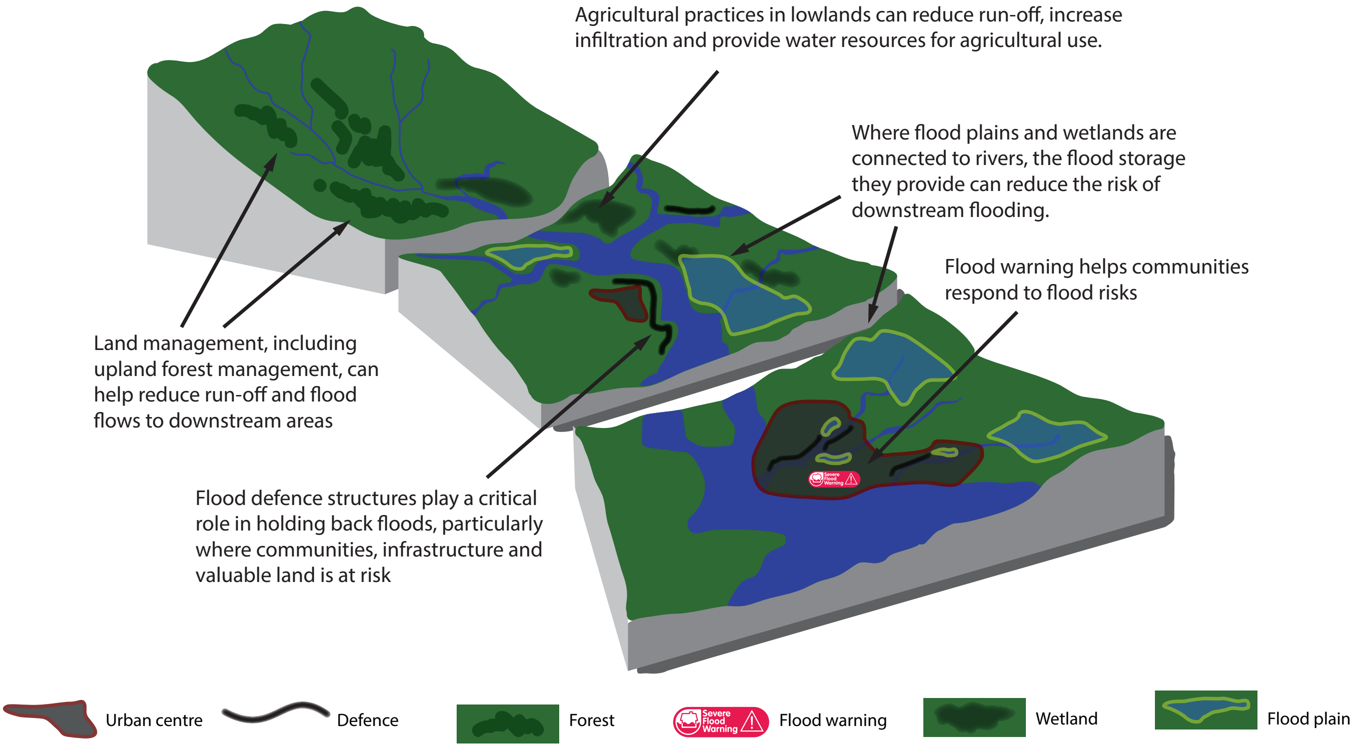
Encourage natural processes

Examples of activities include:

- Re-meander rivers
- Re-profile channels
- Create buffer strips or water margins along watercourses
- Encourage in-stream large woody debris, where appropriate
- Avoid dredging where possible
- Re-connect rivers to their floodplains
- Soften lake edges
- Allow low-lying areas to flood

Figure 5.2
Sustainable Flood Management

The Future of Flood Risk Management in Scotland: A Consultation Document http://www.scotland.gov.uk/Publications/2008/02/13095729/9



Sustainable Drainage Systems (SuDS) is an approach similar to Natural Flood Management that has been developed for urban areas. The principle behind Sustainable Drainage Systems is to manage water above ground rather than draining surface run-off from urban areas through a combined sewerage system with foul water. By incorporating water management as an integral part of urban design, the drainage "infrastructure" is no longer considered distinct from the built environment. Sustainable Drainage Systems use relatively low-cost techniques to slow water down in urban areas, including:

- Increased coverage of permeable surfaces, including permeable asphalt and paving;
- Increased numbers of ponds and wetlands;
- Green roofs;
- Recycling of roof and grey water;
- Swales, i.e. low-lying tracts of land next to impermeable surfaces;
- Filter and infiltration trenches;
- Detention basins;
- Setting hard flood defences back from the channel, if they have to be built.

The overall effect is a reduction in run-off rates and increased groundwater recharge. However, SuDS provide additional benefits through increased pollutant retention and less storm-water discharge, together with the ecosystem benefits of integrating freshwater habitats into urban environments. A recent business park development on the outskirts of Bristol provides a good example of how SuDS can be incorporated into urban design. The development included permeable paving allowing water to drain through a grit bedding layer into a porous sub-base, a detention pond which holds run-off from the business park, and silt traps. As a result of these design features the likelihood of flooding in a nearby village has changed from 1 in 30 years to 1 in 100 years. A more high-profile example of the implementation of SuDS comes from the Olympic Park development in East London. Due to the contaminated underlying soils (a legacy of past industry) it was not feasible to use infiltration drainage systems. Instead, porous asphalt pedestrian concourses were used extensively throughout the park. These gathered and carried surface water to catchpits that eventually drained into adjacent watercourses (River Lea). Wetland areas were also installed, featuring swales, balancing ponds and filter strips to limit these discharges. The Sustainable Drainage Systems and wider site flood management plan was designed to take into account the potential impacts of future climate change.

Rural Sustainable Drainage Systems (RSuDS) is an equivalent approach for areas of farming and forestry where run-off contributes to flooding, erosion and pollution. The aim is to reduce peak flows and associated diffuse pollution. The techniques used encourage the collection and storage of water, to enhance cleaning processes before slowly releasing the water back to the environment. The actual techniques are similar to SuDS, but adapted for a rural setting (e.g. retention ponds, swales, wetlands, riparian buffers, soakaways), and fall within agricultural best practice.

By making space for water using the Natural Flood Management and Sustainable Drainage Systems approaches, the cost of flood damage and the impact of droughts can be reduced, whilst simultaneously conferring the ecological benefits of increased resilience to extreme events.

However, making space for water implies a change in land use to allow more natural processes to occur. Tough choices will have to be made for example on maintaining flood defences where historic building practices have placed properties in flood-prone areas. Therefore, it is important to get local communities to appreciate the benefits of landscape-scale management in order to engender support and enthusiasm. On many occasions, there will be resistance from landowners and other vested interests keen to retain the *status quo* or to promote more hard-engineering solutions. Stakeholder buy-in will be crucial to success, i.e. being able to convince the reluctant with evidence of the long-term environmental and economic benefits of the National Flood Management and Sustainable Drainage Systems approach in the face of more frequent extreme climatic events.

Box 5.3
Upstream Thinking

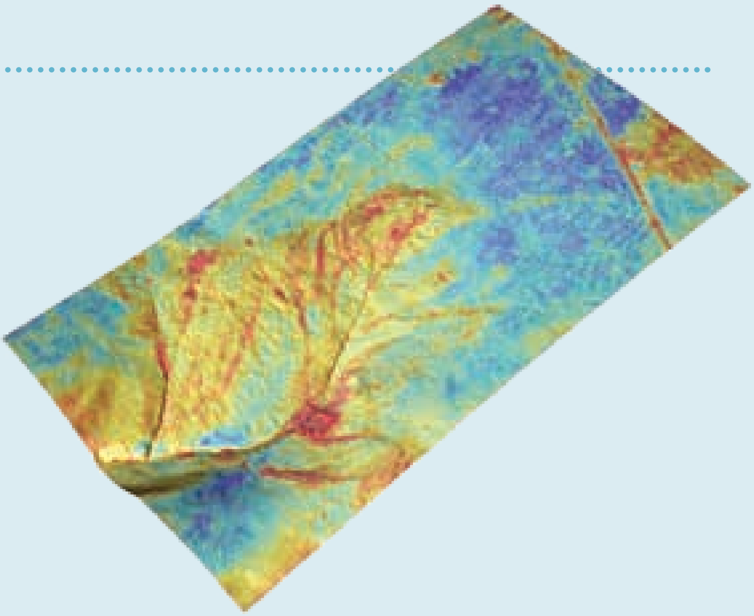
The Wimbleball Strategic Reservoir, built in the 1970s, provides water for Exeter and Devon but there have been recent concerns over its ability to provide a continuous supply of water through droughts. The cost of creating a second reservoir to meet this challenge was estimated to be in the region of £90 million, but there was a possible alternative: the restoration of the peatland mires on Exmoor to re-instate their water storage capacity, at an estimated cost in the region of £5-10 million. Drained moorlands respond quickly to rainfall and have little storage capacity because all the water runs through the ditches and into the rivers.

Blocking up the ditches slows down the flow of water and increases the time it takes to get to the river.

The Exmoor Mires Project was established (an initiative involving South West Water, the Environment Agency, landowners, commoners, universities and Exmoor National Park) to optimise water storage capacity through the natural hydrology of upland mires.

Figure 5.3

Rendered composite image of moorland surface used to detect sites for re-wetting



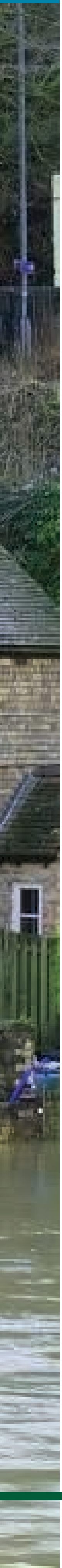
Between 2006 and 2010, on a budget of £400,000, a total of 50 km of ditch was restored (4,300 ditch blocks of baled rush/*Molinia* or wood and peat infill) resulting in the re-wetting of over 350 hectares of moorland across 17 sites. A subsequent project, worth £2.2 million, has mapped a further 120 potential sites covering over 3,500 hectares.

Hydrological modelling of the restored area predicts an increase in storage and residence times of surface waters, with in-peak flows, elevated base-flows and reduced water velocities. Secondary benefits include improved water quality, carbon sequestration and improved habitat quality within the headwaters of the River Exe. In other parts of the River Exe, catchment advice is being given to farmers by the Westcountry Rivers Trust on how to improve farm infrastructure and agricultural practice to provide better water quality and sustainable water management. Flow paths are being intercepted, and wetlands and floodplains restored. The scheme will distribute over £1.2 million of investment (at 50% grant rate). Payments are based on action and ensured through a 10- or 25-year contract and covenant. The delivery of water quality and water storage benefits are being assessed though a 'proof of concept' monitoring programme in the Caudworthy Water sub-catchment by Defra Demonstration Test Catchments.

This project demonstrates how the buffering capacity of restored wetlands can contribute locally to the reduction of environmental damage associated with extremes in flows.

Figure 5.4

Ditch restoration on Exmoor: slowing water down by re-wetting moorland



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www.susdrain.org Susdrain is an exciting new community, created by CIRIA (the construction industry research and information association), that provides a range of resources for those involved in delivering sustainable drainage systems (SuDS).

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