Environment Agency

Evidence

Monitoring and Assessment of Environmental Impacts of Droughts

Literature Synthesis

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Miranda Kavanagh

Director of Evidence

Executive summary

The objective of this report is to present a brief synthesis of a targeted literature review aimed at highlighting the long and short-term ecological impacts of drought by answering the following key questions about rivers, lakes, wetlands and ponds:

- What impacts do droughts have on ecosystems (including differentiating the impacts of winter (including flushing flows) and summer droughts)?
- Depending on the severity of the drought, how quickly do aquatic ecosystems recover?
- Can we incorporate any impacts resulting from climate change into our understanding and conceptual models?
- What are the long-term ecological impacts (if any) and can we define the threshold(s) beyond which rivers, lakes, wetlands and ponds are 'permanently' altered and deliver reduced ecosystem services?
- Are we and/or our partners collecting the right information to answer these questions?

For the purpose of this synthesis, drought is considered as a natural phenomenon defined relative to the prevailing 'normal' conditions of a locality in which 'normal' conditions refer to an agreed measure of precipitation, stream flow or water level over a long period. Predicting the ecological impacts of drought is challenging as the UK climate is naturally variable, water body response is often site-specific, every drought is unique and anthropogenic pressures modify ecosystem response. Drought impact needs to be understood as a multi-pressure problem where ecosystem resistance and resilience to drought are impaired by multiple anthropogenic factors.

Drought represents a disturbance to an ecosystem. In assessing drought impact, it is necessary to discriminate between the event of the disturbance (drought) and the responses by the abiotic and biotic components of the ecosystem to the disturbance. Drought, unlike a flood event, is a 'ramp' disturbance that starts slowly, but steadily builds in intensity and spatial extent. Ramp disturbances may dissipate gradually or break with floods. Aquatic ecosystem response to a drought is a 'ramp' response which is dependent on the resistance and resilience of the aquatic biota.

Drought reduces the volume of available water, resulting in a loss of horizontal, longitudinal and vertical connectivity between the water body and its surroundings. In river ecosystems, the impact of drought is initially the result of wetted habitat loss when the river becomes disconnected from its riparian zone. As the drought progresses, longitudinal river connectivity may also be lost, particularly in smaller upland water bodies. In rivers with hyporheic exchange flows, droughts may also cause a loss of vertical connectivity between surface water and groundwater.

The morphology of a river strongly influences the spatial pattern of drying and re-wetting. However, the majority of lowland rivers have been heavily modified by humans, particularly to control flood risk, creating a homogenised habitat. For this reason, sites characterised by habitat modification are often more sensitive to drought than those that are not. Geomorphologically diverse sites, with little or no habitat modification, provide refuges and confer resilience to drying (such as a range of flow environments, deeper pools and boulders/logs/plants). Conversely, homogenous river channels are more prone to rapid and total drying which exacerbates the impacts of drought on biota. This effect is, in part, mitigated because rivers with degraded habitats often have less biotic diversity to lose than sites in good hydromorphological condition.

Nonetheless, there is a conflict between managing flood risk and maintaining the natural resilience of a river to drought.

The impact of drought on lake ecosystems occurs through a decrease in water level and volume. Lakes may also be affected by a reduction in flushing rates and changes in nutrient inputs from diffuse sources within the catchment.

There are broad differences in the impact of drought on different wetland types, determined by the hydrological processes that feed the wetland. Three wetland types are evident: rain-fed wetlands, river-fed wetlands and groundwater-fed wetlands. In general, rain-fed wetlands respond rapidly to drought since alternative hydrological mechanisms that could buffer the response do not exist. In river-fed wetlands, fluctuating water levels are buffered by the transfer of water between the river and the wetland. Groundwater-fed wetlands are less sensitive to seasonal drought but could be significantly impacted by supra-seasonal drought. In addition to hydrological processes, other factors, such as soil properties, also affect how a wetland responds to drought.

Ponds differ somewhat from other water body types as they lie on a natural gradient of permanence, ranging from completely permanent, through semi-permanent, to truly seasonal water bodies that dry in all or most years. In the United Kingdom, it is estimated that approximately seventy per cent of ponds are permanent, twenty-five per cent are semi-permanent (drying in drought years) and the remainder are seasonal (drying annually). Studies of semi-permanent and seasonal ponds can be used to infer the impact of drought on these water bodies. These studies suggest that droughts are likely to affect pond ecosystems through a reduction in water volume and level, changes to nutrient and pollutant inputs and alterations in habitat (such as the temporary loss of aquatic habitat and corresponding increase in semi-aquatic habitat).

Rivers

Based on the best available information, the response of rivers to drought is highlighted through providing answers to the five key questions presented earlier. A brief summary is presented below:

- *What impacts do droughts have on ecosystems (including differentiating the impacts of winter (including flushing flows) and summer droughts)?*

  Drought reduces the volume of water and the wetted perimeter of a river, affecting lateral, longitudinal and vertical connectivity. Initially, water gradually recedes from the littoral zone, disconnecting the river margins. Further water loss results in riffle drying. Later, particularly in smaller, upland streams, longitudinal connectivity may be lost, resulting in flow fragmentation. Further drying results in the desiccation of the hyporheic zone (if present), disrupting vertical connectivity.

  The shape of the drying curve depends on the morphology of the river and the rate of drying. For example, in a small, upland geomorphologically diverse stream with a stepped channel cross-section, the drying curve is likely to be stepped. In contrast, a larger lowland stream with a rectangular or semi-circular cross-section would have a smoother drying curve. A response gradient exists between these two broad channel ‘types’. Therefore, channel modification has a significant impact both on aquatic ecosystem response to drought and on ecosystem recovery from drought.

  Abiotic elements also respond to increased drying. Water temperature generally increases, as does conductivity, nutrient concentrations, dissolved organic matter and particulate organic matter. Dissolved oxygen initially increases, but later significantly declines as longitudinal connectivity is lost. Turbidity declines as inputs of suspended particles from the catchment are reduced but fine sediments accumulate as flow and mixing decrease.

Biotic response to drying depends on the resistance and resilience of the biota and the availability and use of refuges. With drying, the consumption of organic debris by microbes and detritivores can drop, reducing the breakdown rate of organic matter, a primary ecosystem function. Increased green algal growth and primary production may be an initial response to increased nutrient concentrations. However, with further drying, algal biofilms may become exposed, marking a shift back to an assemblage dominated by diatoms. Drying may impact macrophyte communities by eliminating some species and creating gaps for opportunistic species to establish. There is likely to be a shift from aquatic to terrestrial plant assemblages as the channel boundary dries. The intensity and the duration of the drought will determine the extent to which this process occurs. Invertebrate response to drying may also be an initial increase in density as they become concentrated in the remaining wet habitat. However, with further drying and habitat loss, competitive and predatory interactions may intensify, and eventually lead to a decline in invertebrate numbers.

Biotic resistance to drought is substantially mediated by the use of refuges, manifested in the stepped response of the biota. These steps correspond to the sequential drying of different habitats that act as refuges as lateral, longitudinal and vertical connectivity is lost.

As with macrophytes, invertebrates and fish with adaptations to drought conditions can dominate the community between these steps until water completely disappears. Further, broad types of biota have contrasting sensitivities to each step. For example, emergent macrophytes are strongly impacted by the recession from stream margins, while fish are strongly impacted by the loss of the flow continuum. Non-native invasive species may exploit drought conditions and impair the re-establishment of native species.

Many organisms are adapted to summer low flows; as such, winter droughts have far more of an effect as many plants and animals over-winter as juveniles. Winter droughts can evolve into a supra-seasonal drought.

- *Depending on the severity of the drought, how quickly do aquatic ecosystems (including rivers, lakes, wetlands and ponds) recover?*

Recovery from drought is strongly dependent on the duration and extent of drying. The shape of the re-wetting curve depends on morphology and the characteristics of the precipitation that breaks the drought. Depending on these characteristics, connectivity is either gradually restored with stepped changes occurring as pools are refilled, riffles are re-wetted and lateral connectivity is restored (as in a return to a more ‘normal’ precipitation pattern), or in the case of a flood, connectivity is rapidly restored. Connectivity can be restored at any point during the drying process.

Abiotic response to re-wetting is strongly influenced by catchment and channel condition, antecedent conditions and the characteristics of the precipitation. However, in general, pulses of particulate organic matter, dissolved organic matter, nutrients and sediment are introduced into the water body followed by a gradual recession. The relative influence of these pulses of chemicals, nutrients and organic matter on re-wetting can be a major determinant of ecosystem recovery. Recovery may be limited by human activities including abstraction, pollution and habitat degradation (among other pressures).

There is very little published information on the biotic response to re-wetting. However, it is reasonable to assume that this is, in part, dependent on the duration and extent of drying, the morphology of the water body and whether the system is perennial or intermittent. Therefore, recovery from a seasonal drought is likely to be rapid while recovery from a supra-seasonal drought is likely to be subject to a time lag. Algae, invertebrates and fish can respond rapidly to re-wetting. This recolonisation occurs from a range of potential refuges. Macrophyte recovery is successional, though this can be rapid or take years depending on the extent of terrestrialisation that occurred during the drought. Similar to the process that occurs in the drying phase, the biotic response to re-wetting is stepped, as habitats are sequentially replenished with water.

Many non-native invasive species may exploit drought conditions and impair the re-establishment of native species when flows return.

- *Can we incorporate any impacts resulting from climate change into our understanding and conceptual models?*

  Predicted increases in air temperature translate into high water temperatures, particularly in small upland streams and in large lowland rivers with long retention times. Temperatures in flowing waters are known to have increased across Europe. Warmer temperatures may alter fundamental ecological processes (including sensitivity of river ecosystems to droughts) and change species distributions. Currently, there is insufficient information to firmly conclude just how climate change could impact on river ecosystems via hydrological mechanisms.

- *What are the long-term ecological impacts (if any) and can we define the threshold(s) beyond which rivers, lakes, wetlands and ponds are 'permanently' altered and deliver reduced ecosystem services?*

  Long-term effects are dependent on the duration and the intensity of the drought. On the whole, most systems recover within a year to two, although there can be longer-term lags in recovery, particularly for sensitive water bodies subject to supra-seasonal drought. While it is recognised that the main threshold of change in community composition is cessation of flow, it is also accepted that there are flow thresholds where fish and invertebrates present a behavioural response to drought conditions. In terms or recovery, there is a threshold where the extent of terrestrialisation of the river channel is such that the physical habitat is changed when flows return and the river will not return to pre-drought conditions. Currently, there is little evidence or information to link drought with ecosystem services.

- *Are we and/or our partners collecting the right information to answer these questions?*

  Empirical, scientifically robust data on the ecological effects of drought are rare. Many studies are opportunistic and are not designed to monitor drought (usually lacking pre-drought data). Much of the drought literature refers to the ecological impact of low flows, or is drawn from work on naturally intermittent rivers and streams, where drying phases are predictable and characterise the ecosystem. It is unclear how useful this is to our understanding of drought. Information is particularly lacking on the impacts of drought on ecosystem functioning. It is extremely hard to detect specific drought impacts in rivers or streams without carefully designed monitoring programmes. Long-term datasets are required that include information on hydraulic descriptors.

  Nationally, the Environment Agency currently assesses drought impacts using the National Drought Surveillance Network (NDSN) which monitors paired hydrological and ecological (macroinvertebrate) sites on permanent, wadable rivers. This review suggests that the NDSN should be more adaptive and account for different water body 'types'. It is suggested that sites with minimal hydrological impact and quantified impacts of other pressures (such as habitat modification and pollution) be used as references to provide before, during and after drought conditions for different water body 'types'. The additional effects of drought on hydrologically impacted catchments could then be assessed by linking to other monitoring, such as Catchment Abstraction Management Strategy (CAMS) network.

Lakes

Based on the best available information, the response of lakes to drought is highlighted through providing answers to the five key questions presented earlier. A brief summary is presented below:

- *What impacts do droughts have on ecosystems (including differentiating the impacts of winter (including flushing flows) and summer droughts)?*

  As lake inflows are reduced and evaporation increases, lake water levels and volumes decrease, resulting in a loss of habitat, especially around the perimeter of the lake. Shallower lakes are more affected than deep lakes, because small water level changes represent a larger proportion of their total surface area and volume. Flushing rates are also reduced, increasing the sensitivity of lakes to other pressures such as eutrophication and abstraction. As inflows are reduced, concentrations of dissolved chemicals increase, while nutrient inputs from diffuse sources decrease. Internal biogeochemical cycling of phosphorus, nitrogen and other chemicals may change. Lower flushing rates and decreased lake volume will reduce the level of dilution of any internal release of nutrients from lake sediments. Microbial activity is likely to increase, enhancing denitrification and ammonification. Ecosystem functioning may be affected by a switch from phosphate-limitation to nitrate-limitation.

  Algae, macrophytes, invertebrates, fish and aquatic birds have variable spatial and temporal responses to abiotic changes that occur during drought, depending on species resistance and resilience, competitive and predatory interactions and the timing and characteristics of the drought (the change in flushing rate being particularly important for lakes). Drought can alter communities by eliminating some species and creating gaps for others to establish. Small reductions in water level in shallow lakes may, for example, cause large changes in macrophyte species composition. During supra-seasonal droughts, some naturally occurring species may be lost, providing opportunities for more invasive, generalist species to become established (for example, a prolonged five-year drought in California allowed the invasive green sunfish to become established and proliferate while native fish populations declined).

  While fish can be impacted by drought in lakes, many are relatively long-lived and, unless there is a major fish kill, the impacts of drought may not necessarily affect the fish population immediately. However, a reduction in successful reproduction during a supra-seasonal drought could cause a significant decline in fish populations.

  Many lake biota are adapted to natural water level fluctuations. Supra-seasonal droughts can impact ecosystem functioning, which may impact species composition and abundance of primary producers and, as a consequence, the biota that depend on them for food and shelter.

- *Depending on the severity of the drought, how quickly do aquatic ecosystems (including rivers, lakes, wetlands and ponds) recover?*

There is little or no information on the recovery of lake biological communities from drought. Recovery is dependent on the resistance and resilience of aquatic species. Recovery from seasonal drought can be rapid for many species, with a predictable and distinct sequence of return, unless species have been lost completely. Information on ecosystem recovery from supra-seasonal droughts is difficult to determine.

- *Can we incorporate any impacts resulting from climate change into our understanding and conceptual models?*

  Climate change may affect lake ecology through changes to inflows and water temperature.

- *What are the long-term ecological impacts (if any) and can we define the threshold(s) beyond which rivers, lakes, wetlands and ponds are 'permanently' altered and deliver reduced ecosystem services?*

  It is difficult to provide information on thresholds beyond which the ecology of lakes is 'permanently damaged' as a result of drought as this is an under-studied area of freshwater ecology. Response to drought will depend on site-specific factors such as geographical location, bathymetry, trophic status, resilience and anthropogenic pressure.

- *Are we and/or our partners collecting the right information to answer these questions?*

  Lake monitoring is a developing area for the Environment Agency. This review suggests that water levels and indicator species should be monitored at lakes where the hydrological processes are well understood.

Wetlands

Based on the best available information, the response of wetlands to drought is highlighted through providing answers to the five key questions presented earlier. A brief summary is presented below:

- *What impacts do droughts have on ecosystems (including differentiating the impacts of winter (including flushing flows) and summer droughts)?*

  As the supply of water is reduced to wetlands, areas of open water reduce and eventually dry altogether. Wet corridors or fringes that connect sections of open water similarly decrease in area and dry, leaving isolated patches of open water, resulting in a progressive loss of habitat. As soil moisture is reduced, extended drying can lead to a loss of soil structure and erosion. Organic soils can oxidise and release carbon into the atmosphere. As water availability is reduced, concentrations of dissolved nutrients and pollutants may increase, while the supply of water-borne species via rain or river water decreases.

  Birds, terrestrial wetland vegetation, vascular plants and bryophytes, mosquitoes and invertebrates indicate a variable spatial and temporal response to abiotic changes, depending on species resistance and resilience, competitive and predatory interactions, availability of food and the timing and characteristics of the drought. Drought can alter communities by eliminating some species and creating gaps for other species to establish. For example, where there is a concentration of nutrients, alkalinity and pollutants, wetland plant species adapted to eutrophic or alkaline species are favoured. Similarly, reduced moisture availability will disadvantage shallow-rooted species and those without physiological adaptations to drought. Supra-seasonal drought may cause a shift in the floral assemblage.

Many wetland biota are adapted to natural water level fluctuations. In general, river-fed wetlands experience a wide range of water levels and support communities which are adapted to such fluctuations. Comparatively, groundwater-fed wetlands experience a smaller range of water levels, supporting communities which have a narrow range of preferred water levels. Groundwater-fed wetlands are more vulnerable to the effects of supra-seasonal drought.

- *Depending on the severity of the drought, how quickly do aquatic ecosystems (including rivers, lakes, wetlands and ponds) recover?*

  The recovery of wetland ecosystems following drought is dependent on the resistance and resilience of aquatic species and the duration and severity of the drought. Recovery from seasonal drought can be rapid for many species, with a predictable and distinct sequence of return. A supra-seasonal drought could result in a shift in vegetation structure. Changes in the vegetation structure are likely to result in a corresponding change in wetland fauna. The permanence of such a new community depends on their resilience to post-drought conditions.

- *Can we incorporate any impacts resulting from climate change into our understanding and conceptual models?*

  Rain-fed wetlands are more vulnerable to climate change than river-fed or groundwater-fed wetlands. However, changes in the frequency or extent of disturbance may increase opportunities for invasive species to become established.

- *What are the long-term ecological impacts (if any) and can we define the threshold(s) beyond which rivers, lakes, wetlands and ponds are 'permanently' altered and deliver reduced ecosystem services?*

  Long-term impacts are possible, particularly if changes in the abiotic nature of the wetland occur. There is limited information on thresholds beyond which wetlands are permanently damaged and deliver reduced ecosystem services.

- *Are we and/or our partners collecting the right information to answer these questions?*

  This review suggests that a wetland (drought) monitoring programme should assess water levels, indicator species and the main inflows and outflows from the system.

Ponds

Based on the best available information, the response of ponds to drought is highlighted through providing answers to the five key questions presented earlier. A brief summary is presented below:

- *What impacts do droughts have on ecosystems (including differentiating the impacts of winter (including flushing flows) and summer droughts)?*

  The impact of drought on ponds is dependent on their permanence. Periods of drought create opportunities for plants and animals that have mechanisms for exploiting or tolerating drought. Unlike rivers, drought can reduce predation pressures and competition while increasing habitat diversity. Pond water temperatures will often increase (though shaded ponds may be buffered from this) which can lead to rapid growth rates for some organisms. Gradual pond drying may lead to the concentration of some pollutants or the oxidation of sediments.

- *Depending on the severity of the drought, how quickly do aquatic ecosystems (including rivers, lakes, wetlands and ponds) recover?*

  Recovery is dependent upon permanence and location. Temporary ponds which refill often recover rapidly. Ponds located within denser networks of freshwater habitats are likely to be more resilient and recover rapidly from drought. However, some ponds never recover their special interest feature(s) as a result of local extinction

- *Can we incorporate any impacts resulting from climate change into our understanding and conceptual models?*

  Higher water temperatures are likely, particularly in smaller, un-shaded ponds. These may alter fundamental ecological processes, which may change species distributions. However, currently there is too little understanding of the likely impact of climate-mediated changes in ponds to make useful predictions of the impacts of droughts.

- *What are the long-term ecological impacts (if any) and can we define the threshold(s) beyond which rivers, lakes, wetlands and ponds are 'permanently' altered and deliver reduced ecosystem services?*

  There are no studies available to assess whether droughts have long-term effects on ponds in the UK. It is not possible at present to define thresholds at which ponds are permanently altered by drought.

- *Are we and/or our partners collecting the right information to answer these questions?*

  The Environment Agency does not monitor ponds; however, some organisations are collecting observational data.

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1 Introduction

The objective of this report is to present a brief synthesis of a targeted literature review aimed at highlighting the long- and short-term ecological impacts of drought by answering the following key questions:

- What impacts do droughts have on ecosystems (including differentiating the impacts of winter (including flushing flows) and summer droughts)?
- Depending on the severity of the drought, how quickly do aquatic ecosystems (including rivers, lakes, wetlands, ponds and wetlands) recover?
- Can we incorporate any impacts resulting from climate change into our understanding and conceptual models?
- What are the long-term ecological impacts (if any) and can we define the threshold(s) beyond which rivers, lakes, wetlands and ponds are 'permanently' altered and deliver reduced ecosystem services?
- Are we and/or our partners collecting the right information to answer these questions?

The report is structured to answer each of these key questions for rivers, lakes, wetlands and ponds in turn (Sections 3, 4, 5 and 6 respectively). Section 7 presents a brief discussion on the need for clarifying the objective / purpose of monitoring drought impacts, while Section 8 presents the synthesised conclusions. Report references are provided in two formats. In Section 9, a conventional reference list is provided for the references listed in the text. A list of references that have been consulted for this synthesis but have not cited directly are presented in Section 10. These references are mainly 'grey' literature.

It is important to recognise that the answers to the five aforementioned questions need to be interpreted within a context; this context is provided in Section 2 below.

2 Context

2.1 Drought as a natural phenomenon

Drought is a naturally occurring phenomenon that can contribute to maintaining the diversity of aquatic ecosystems (Everard, 1996; Lake, 2011). Climate models predict that drought will increase in frequency, intensity and spatial extent in the future (Dai, 2011; Environment Agency, undated a). Understanding and predicting drought impacts on aquatic ecosystems and society is a challenge as the climate in the United Kingdom is naturally variable, every drought is unique, the degree and extent of ecosystem impact is often water body specific and existing anthropogenic pressures modify ecosystem response. Further, drought frequency, duration, intensity and severity all vary with locality and with time at any one location (Lake, 2011). Hence, drought impact needs to be viewed as a multi-pressure problem where ecosystem resistance[1] and resilience[2] to drought are impaired by multiple anthropogenic factors.

While a universal definition of drought is an unrealistic expectation[3] (Wilhite, 2000), drought is usually defined relative to the prevailing ‘normal’ conditions of a locality. For the purpose of this literature synthesis, we necessarily consider drought a natural phenomenon, while recognising the legitimacy of the definition of drought as a ‘hazard to human activities’. A useful definition of drought as a natural phenomenon is ‘… an extended period – a season, a year or several years – of deficit rainfall[4] relative to the statistical multi-year mean for a region’ (Druyan, 1996). For this definition to be useful it is necessary to have long-term datasets and to make the assumption of no significant change in long-term mean values. Long-term records are also required to account for response to meteorological and hydrological variability so that extreme events can be placed in the context of natural variability. The current lack of long-term drought studies[5] means that we have a poor understanding of the cumulative effects of drought, recovery from drought and of the lags and long term changes that drought may have on populations, communities and ecosystems (Lake, 2011). Short-term studies cannot simply be scaled-up to understand the long-term, large-scale phenomenon that is drought.

There are five recognised forms of drought (after Lake, 2011):

- Meteorological drought – a deficit between the amount of precipitation received and the amount that may normally be expected for an extended duration.
- Hydrological drought – where the amount of precipitation in a region is insufficient to maintain surface water in lotic and/or lentic systems.
- Agricultural drought – where soil moisture is inadequate to meet evapotranspiration demands so as to initiate and sustain crop growth.
- Ecological drought – where the shortage of water causes stress on ecosystems, adversely affecting the life of some plants and animals but benefitting others.
- Socio-economic or operational drought – where there is a shortage of water for human activities.

[1] The capacity of biota to withstand stresses of disturbance (Lake, 2011).
[2] The capacity of biota to recover from disturbance, even if biota and ecological processes are diminished (Lake, 2011).
[3] Lake (2011) makes the point that in an ideal world, drought indices could be used to compare droughts from region to region, compare current droughts with those of the past, identify drought prone areas and determine trends in drought with time. Poor characterisation of droughts makes it difficult to undertake rigorous, quantifiable comparisons between different studies and between different droughts occurring at the same place.
[4] The word ‘rainfall’ in this definition can be substituted with the words ‘stream flow’, ‘groundwater levels’, ‘soil moisture’ and so on.
[5] Lake (2011) emphasises that focusing on site investigations limits our understanding of drought and ecosystem processes at the appropriately large spatial extent relevant to drought.

This synthesis focuses mainly on hydrological and ecological[6] drought.

Droughts exhibit spatial coherence (Parry *et al*., 2012), as rainfall deficits typically affect large areas simultaneously. In many landscapes, as droughts develop, water bodies form a mosaic that alters in pattern as drought lowers water availability at a regional level (Lake, 2011). Accordingly, the impacts of drought can be variable at a landscape-level, determined in part by landscape-level properties and processes, the history of water bodies and their interconnectedness[7]. Hence, sampling a single or a few sites may reveal assemblage changes that may not be evident at a larger spatial scale. The assessment of drought impact therefore requires explicit consideration of spatial scale.

Different parts of the United Kingdom are vulnerable to droughts of different typical duration and seasonality, owing to their different hydrological responses (Hannaford *et al*., 2011; Lloyd-Hughes *et al*., 2011). This introduces the important distinction between short-term within-year water deficiencies (seasonal droughts) and multi-year water deficiencies (supra-seasonal droughts). Supra-seasonal droughts progressively develop from meteorological drought to hydrological drought in surface water, and finally to groundwater drought (Figure 2.1).

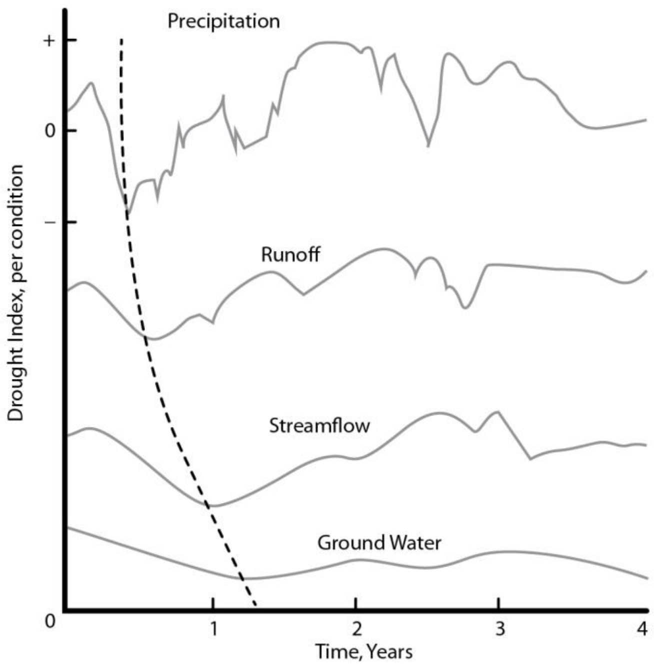

Figure 2.1 The development of a supra-seasonal drought from a meteorological drought to a hydrological drought in surface water and finally in groundwater (adapted from Lake, 2011).

Both the hydrological (for example Parry *et al*., 2012) and ecological (for example Wood and Armitage, 2004) literature recognise that supra-seasonal droughts have significantly greater impacts on water resources and ecosystems than seasonal droughts; that is, in dealing with drought, 'history matters'[8] as antecedent conditions[9] can greatly influence the effects of drought (Lake, 2011). In the United Kingdom, supra-seasonal droughts[10] have a significant impact on aquifer recharge and storage and

[6] It should be noted that the manifestation of drought in the UK is very different to the predictable seasonal droughts typical of Mediterranean/semi-arid regions which dominates much of the literature.
[7] For example, wetland recovery is strongly dependent on the nature and distribution of neighbouring wetlands.
[8] The importance of the past history of droughts in shaping the effects of a contemporary drought is an example of ecological memory (Lake, 2011).
[9] Timing also matters, particularly in relation to the life cycle of the inhabitants (Lake, 2011).
[10] Since 1970 there have been five supra-seasonal droughts in the UK: 1975/6, 1988/92, 1995/7, 2004/6 and 2011/12.

hence on security of supply and on ecosystems, particularly in the south and east where supply and ecosystems are predominantly groundwater-dependent. In chalk streams, for example, seasonal droughts may be buffered by the continuous provision of groundwater provided abstraction is properly managed. However, if droughts are close together or are accompanied by over-abstraction, impacts can be severe and recovery impeded. The assessment of drought impact requires explicit consideration of temporal scale.

Accordingly, assessing drought impacts on aquatic ecosystems must use appropriate indices for detecting and assessing meteorological and hydrological drought. Indices must be capable of discriminating between low flows/levels (or base flows/levels) and drought flows/levels. This also requires the application of agreed hydrological thresholds to define (or at least standardise where appropriate) when droughts start and end.

Lake (2011) suggests that in examining the impact of any disturbance (drought in the context of this assessment) on an ecosystem, it is necessary to discriminate between the event of the disturbance (drought) and the response of the abiotic and biotic components of the ecosystem to the disturbance. Here, it is useful to distinguish between three types of disturbance (Lake, 2000):

- a ‘pulse’ disturbance, such as floods, which are sharp, rapid events which also dissipate rapidly;
- a ‘press’ disturbance which starts sharply but maintains pressure (pollution, for example);
- a ‘ramp’ disturbance which starts slowly, but steadily builds in strength and spatial extent (Figure 2.2). Ramp disturbances may dissipate gradually, or break with floods.

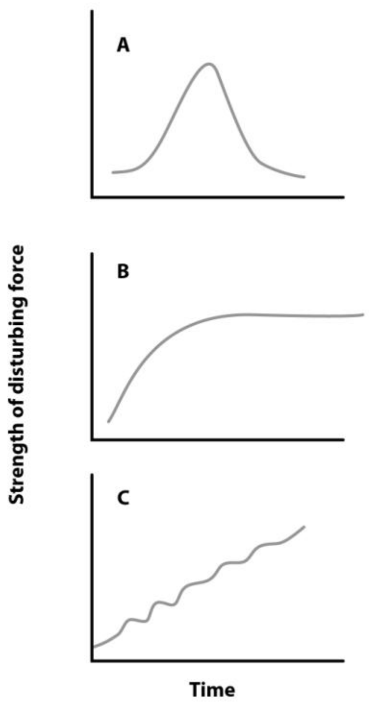

Figure 2.2 Conceptual diagram of A) pulse, B) press and C) ramp disturbances (adapted from Lake, 2000).

Aquatic ecosystem response to drought is a 'ramp' response with step changes. Response depends on the resistance and resilience of the aquatic biota shaped by the legacies of past events (ecological memory).

Available data from published sources (see Lake, 2011 for a full review) indicates that different water body 'types' do not respond in a similar way to drought and that the response varies depending on the types of drought. For example, Lake (2011) noted that the 'biotic effects of drought are strongly influenced by the type of aquatic ecosystem' and that studies 'revealed different effects that drought may exert on streams of different bioregions'. There appears to be a consensus that the biotic effects of drought are easier to detect within ephemeral or temporary streams due to the loss of surface water, although the change to community structure may be more marked within perennial systems, particularly if the duration of the drought extends over more than one winter as in the case of supra-seasonal droughts (cf. Armitage and Petts, 1992; Castella *et al*., 1995; Wood and Armitage, 2004). In addition, there appears to be marked differences in the sensitivity and response of upland and lowland streams in the United Kingdom (Hynes, 1958; Cowx *et al*., 1984; Extence, 1981; Wood and Armitage 2004). Monk *et al*. (2008) suggest that characterising rivers based on the shape and magnitude of the flow regime (hydrograph) provides an objective way of classifying rivers and a means of increasing the predictive capacity of models to quantify biotic responses.

2.2 Rivers and drought

Drought reduces the volume of water and affects lateral, longitudinal and vertical connectivity (Lake, 2011). For streams and rivers, the impact of drought on ecosystems is initially the result of wetted habitat loss. During the early stages of a drought, flow and velocities are reduced, as the drought progresses, water may become disconnected from the stream or river margins, disrupting the linkage with the riparian zone. Later, particularly in smaller, upland streams and rivers, longitudinal connectivity may be lost, with the bed becoming a mosaic of trickles, remnant pools and drying patches. When the bed starts to dry, the underside of boulders and woody debris provide important areas of moist habitat for some fauna. Further drying results in loss of free water within the hyporheic zone (if present), disrupting vertical connectivity. In severe supra-seasonal droughts, all remnant pools may dry up completely, as may the hyporheic zone. With increased drying, water quality deteriorates (generally temperature increases, dissolved oxygen (DO) decreases, conductivity increases, nutrient concentrations increase or decrease, suspended solids decrease, turbidity decreases, particulate organic matter (POM) increases), while biological activity (such as competition, predation) intensifies (Labbe and Fausch, 2000; Caruso, 2002; Boulton, 2003; Dahm *et al*., 2003; Suren *et al*., 2003a; Dewson *et al*., 2007; Zwolsman and van Bokhoven, 2007; Bond *et al*., 2008; van Vliet and Zwolsman, 2008; Wilbers *et al*., 2009 and Zielinski *et al*., 2009). In estuaries, saline water can move upstream changing water quality (Peirson *et al.*, 2001; Elsdon *et al.*, 2009; Baptista *et al*., 2010; Dolbeth *et al*., 2010).

The morphology of a water body strongly influences the spatial pattern of drying and re-wetting (Figure 2.3). Therefore, habitat loss is site-specific, related to the hydraulic geometry and bed topography of a water body (Environment Agency, undated b). Geomorphologically diverse sites may be more resilient to drought because they present more refuges (Chester and Robson, 2011). However, once drying occurs, there is a greater diversity of habitats and species to be lost. Comparatively, homogenous sites have less diversity to lose; however drying is likely to occur more rapidly and to be more severe.

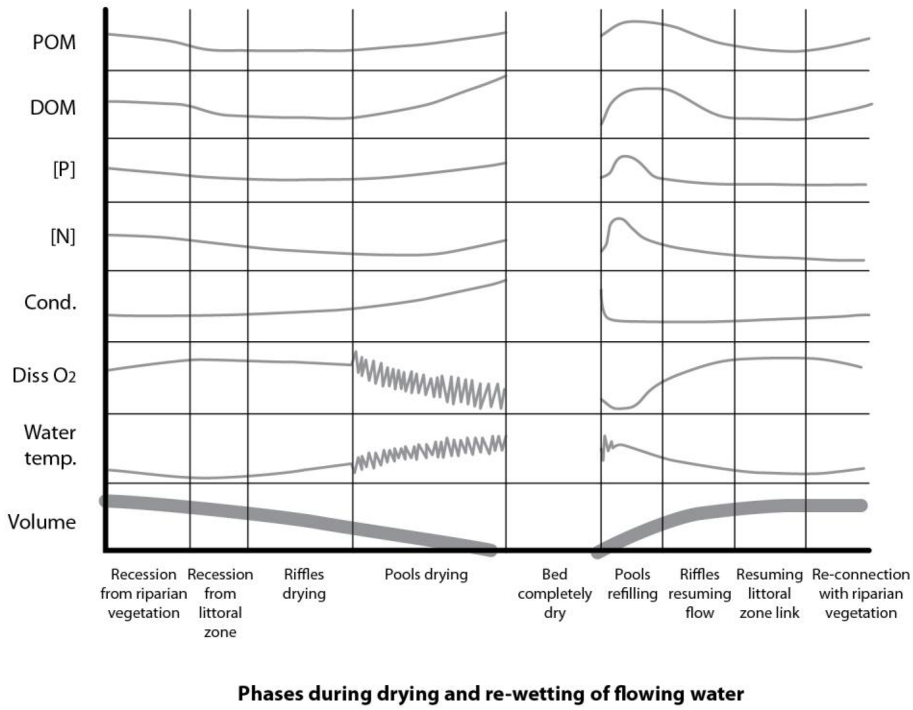

Figure 2.3 Phases during drying and re-wetting of flowing water (adapted after Lake, 2011).

Sites which are characterised by habitat modification, through for example, river engineering works, are more sensitive to low flows, and hence by implication, drought (Dunbar *et al*., 2010a; 2010b). Further, habitat modification would appear more important than water quality in determining the ecological impacts of drought (Caruso, 2002). Improved water quality as a result of advances in the treatment of effluent can, however, enable streams and rivers to better tolerate the effects of reduced flows and the increased temperature associated with drought.

2.3 Lakes and drought

In comparison to rivers, there is limited information in the published literature on the hydrological impact of drought on lakes. However, in general, drought reduces the volume of water in all types of water bodies (Lake, 2011). The response of a lake to drought is likely to be determined by its position within the landscape (Figure 2.4), because this affects the relative proportions of its hydrological inputs which range from direct precipitation to overland flow and groundwater (Webster *et al*., 1996).

Droughts are likely to affect lake ecosystems through: a decrease in water levels and volumes (Webster *et al*., 1996; Lake, 2011); reduced flushing rates; lower inputs of nutrients from diffuse sources within the catchment (although inputs from point sources, which are not driven by rainfall, would probably remain almost unchanged), and increased nutrient rich inputs from groundwater (Webster *et al*., 1996). In general, seepage lakes tend to be more affected by drought than drainage lakes (Webster *et al*., 1996).

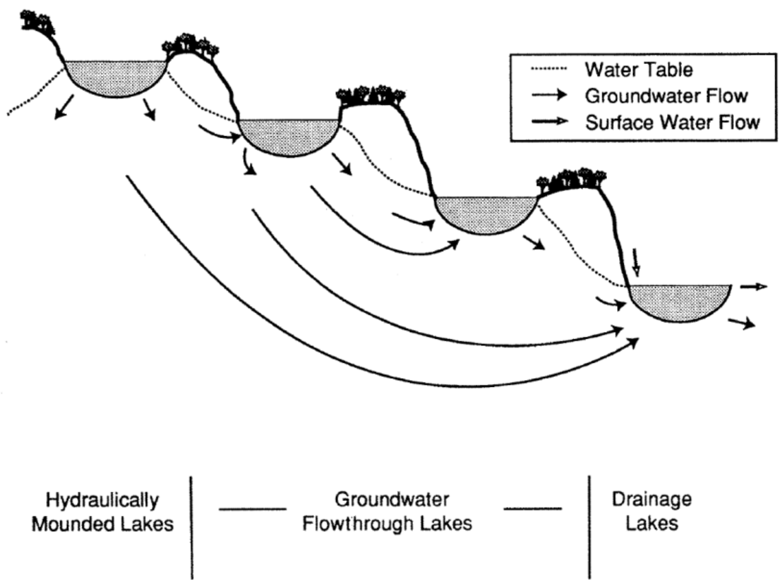

Figure 2.4 Relationship between lake position in the landscape and lake hydrological type in a groundwater flow system (adapted from Webster *et al*., 1996)

Initially, the impacts on lake ecology are likely to occur in response to loss of habitat (Lake, 2011). However, as a drought progresses, the volume of the lake will decrease and associated increases in water temperature, coupled with changes in the chemical composition of the water, will have increasing impacts (Figure 2.5; Lake, 2011).

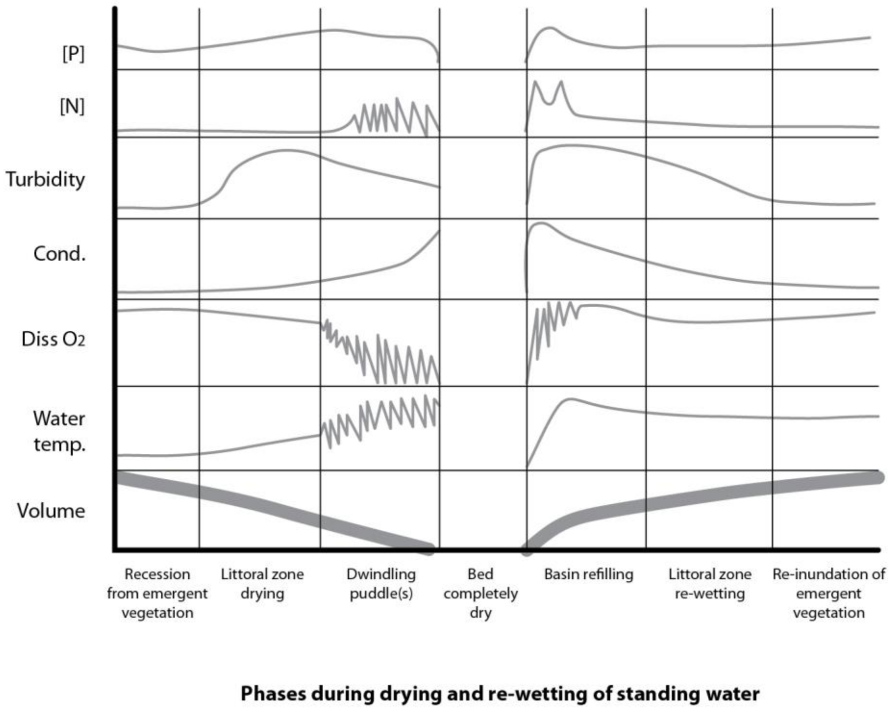

Figure 2.5 Phases during drying and re-wetting of standing water (adapted after Lake, 2011).

The response of any particular lake will depend on its size and shape, position in the landscape, typology and hydrogeology (Webster *et al*., 1996; Lake, 2011). Particularly important aspects of this are catchment area and lake volume, because these are the most important factors in determining lake flushing rate. Lakes are fed by water from a combination of sources: surface water, groundwater and direct precipitation. So the impact of drought on these systems depends on the relative importance of these sources to the overall hydrological balance. In a lake that is predominantly surface water-fed, the inflowing supply of water will reduce and the level of the lake will fall below the level of the outflow, creating a feedback loop that will tend to conserve the remaining water. In predominantly groundwater-fed lakes, a reduction in groundwater levels will reduce the water supply to the lake and may also turn the groundwater from a source to a sink, effectively increasing water losses from the system (Winter, 1976).

The proportional input from direct precipitation onto the lake surface will increase with increasing lake surface area to volume ratio. Relative evaporative losses will tend to be greater in shallower systems with large surface area to lake volume ratios. As a drought progresses, evaporative losses will increase due to higher water temperature and reduced humidity. At low levels of rainfall, evaporative losses may become a net loss to the lake and cause water levels to drop further; however, as water levels fall, the area of the lake will decrease alongside evaporative losses.

In the early stages, shallow lakes will be more sensitive to drought than deeper lakes. This is because the same reduction in water level in a shallow system corresponds to a much greater proportion of the lake volume than in a deeper system (Lake, 2011). For this reason, the impact of evapo-concentration on dissolved chemicals is also likely to be greater in shallow lakes than deeper lakes (Webster *et al*., 1996). Lake bathymetry will also affect the impact of a reduction in lake volume on the amount of lakebed exposed. This will be a relatively small in a lake with steeply sloping sides, but much larger in a lake with a more gently sloping bed. Continued drawdown may also result in the lake becoming subdivided into separate basins (Lake, 2011).

2.4 Wetlands and drought

Hydrology is the major factor controlling wetland form and function, hence climatically induced loss of wetland habitats, such as droughts, can have significant implications for UK biodiversity (Acreman and Jose, 2000). There are broad differences in the impact of drought on different wetland 'types' such as the different drought tolerance of vegetation communities (Wheeler *et al.*, 2004). To understand this impact, it is necessary to understand how hydrological conditions within a wetland may change in response to drought. This is largely determined by the hydrological processes feeding the wetland (Acreman and Miller, 2007). Three wetland 'types' are considered: rain-fed wetlands, river-fed wetlands and groundwater-fed wetlands. In general, impacts of low rainfall on rain-fed wetlands will be greater than on those dominated by river inflows (Acreman *et al*., 2009).

2.4.1 Rain-fed wetlands

In general, primarily rain-fed wetlands will respond rapidly to a change in rainfall since alternative hydrological mechanisms that could buffer the response do not exist. The rain-fed wetland will only respond to rain falling directly on it and therefore the size of the wetland and spatial heterogeneity of the rainfall will both influence the extent to which the site is affected. Rainfall patterns typically vary between winter and summer with more regionally consistent frontal rainfall occurring in winter and more localised convective rainfall occurring in summer. The risk of a rainfall event not falling on a wetland may therefore be greater in summer.

2.4.2 River-fed wetlands

In addition to direct rainfall, river-fed wetlands receive a significant portion of their water from a nearby river or watercourse (Duranel *et al.*, 2007). The fluctuation of water level within the wetland is buffered by the transfer of water between the river and the wetland, which can happen either in the sub-surface and/or overland. As a result, there is likely to be a lagged response to change in rainfall. Since the hydrological response of the river is driven by rainfall and recharge processes happening over the whole catchment, there is less sensitivity to small-scale spatial and temporal variation (seasonal droughts).

2.4.3 Groundwater-fed wetlands

Groundwater-fed wetlands receive a groundwater input in addition to direct rainfall and sometimes also receive water from a nearby river. Buffering of the hydrological conditions within the wetland is pronounced and there is a significant lag between changes in rainfall and hydrological response within the wetland. The groundwater system is driven by recharge processes occurring over a large ‘recharge zone’ so like river-fed wetlands, there is less sensitivity to small-scale spatial and temporal variation (seasonal droughts). As with river-fed systems, land cover has a dramatic impact on recharge and it is often the case that very little rain falling in the summer months recharges the underlying aquifer. As a result the groundwater system may not be very sensitive to seasonal drought whilst being much more sensitive to a change in autumn and winter rainfall when decreased interception leads to greater recharge (supra-seasonal drought).

2.4.4 Soil properties

In addition to hydrological processes, other variables, such as soil properties, affect how a wetland responds to drought. In permeable soils, the water table in the wetland will reflect the variations in the water supply mechanism (Acreman and Miller, 2007). For example, the water table in a permeable floodplain wetland will follow (with varying degrees of proximity) the water level in the river. In low permeability soils there is only a weak connection between the water supply mechanism and the moisture available in the wetland, and the conditions in the wetland may not reflect the conditions in the wider catchment (Acreman *et al*., 2009).

As the water level within a wetland drops, the hydraulic gradient towards the outflow point may also decrease (Bradley, 2002). This is dependent both on the nature of the wetland and of the outflow point. The result of this reduction in gradient is a negative feedback process in which the volume of water flowing out of the site declines and slows the subsequent rate of drying within the site. In addition, as the root zone of the wetland vegetation dries out, the rate of actual evapotranspiration drops to a point where ultimately little water is lost by transpiration (Coudrain-Ribstein *et al.,* 1998). These mechanisms can act to lessen the impact of supra-seasonal drought.

Additional differences exist between soil types and these can be significant in determining the way in which the wetland responds to changing hydrological conditions. For example, it is possible that in some rain-fed systems the soil matrix is compressible or that the vegetation mat ‘floats’ on the saturated ground beneath. In these systems, a lowering of the ground surface compensates for the decline in rainfall, and as a result the depth from the ground surface to the water table may not change significantly until the point at which the underlying system dries out.

Further, some mineral soils will crack during hot and dry spells, and the cracks become effective preferential pathways for the flow of water. When rainfall does occur, it can infiltrate more deeply into the soil than if the cracks had not been present.

2.5 Ponds and drought

Ponds can be defined as standing waters between $1m^2$ and 2ha, permanent or seasonal, man-made or natural, which hold water for at least four months of the year (Brown *et al*., 2006). Ponds lie on a gradient from completely permanent through semi-permanent to truly seasonal water bodies that dry in all or most years (Brown *et al*., 2006). In Great Britain the proportions are roughly 70 per cent permanent, 25 per cent semi-permanent and 5 per cent truly seasonal.

There is relatively little information in the published literature on the impact of drought on permanent and semi-permanent ponds, which make up the majority in the UK. However, there is a substantial body of information on temporary ponds, which necessarily includes information on drying out, although the regular annual change associated with loss of water in seasonal ponds is not precisely analogous to extended periods of drought.

From studies of semi-permanent and seasonal ponds it seems likely that droughts affect pond ecosystems through:

- A decrease in water levels and volumes and concomitant change in the physico-chemical environment, including exposure of sediments to the atmosphere which may lead to substantial differences in sediment quality on re-wetting.
- Extension of marginal drawdown zones, often substantially, which may both limit some biota and provide opportunities for others.
- Pronounced biotic changes, for example elimination of fish.
- Short-term reductions in inter-water body distances (both pond to pond and pond to other water body types) in habitat networks, which increase the risk of local biotic extinctions.

It is likely that substantial differences exist in the responses of impaired compared to un-impacted ponds. It is possible that there may be lower levels of water-borne pollutant inputs from the surrounding catchment, but unlike larger waters there is little evidence available to assess the significance of this phenomenon.

3 Rivers

3.1 What impacts do droughts have on ecosystems (including differentiating the impacts of winter (including flushing flows) and summer droughts)?

3.1.1 Abiotic effects

- As flow is reduced, air temperature and solar radiation have a greater influence on water temperature, which increases (Poff *et al.*, 2002; Meier *et al.*, 2003).
- Increased water temperature causes heat stress to biota but also increases decomposition rates and reduces DO, which may cause hypoxic conditions, particularly at night (Suren *et al*., 2003b).
- In the case of small streams with high groundwater input, temperature may drop as the contribution of warmer surface flows is reduced (Dewson *et al*., 2007).
- As flows decrease so does dilution, so the concentration of solutes increases and conductivity and pH may also increase (van Vliet and Zwolsman, 2008; Wilbers *et al.*, 2009; Zielinski *et al*., 2009).
- Increases in nutrient concentrations due to water loss are partly compensated by the reduced input from the catchment as well as the higher contribution of nutrient-poor groundwater (Caruso, 2002; Dahm *et al*., 2003; Golladay and Battle, 2002).
- There is a lowering of ratio of inorganic to organic nutrients (Dahm *et al*., 2003).
- As flow decreases so do suspended particles and turbidity (Bond, 2004; McKenzie-Smith *et al*., 2006).
- Particulate organic matter can accumulate in the channel (Pinna and Basset, 2004).
- As flow decreases, more fine sediments will drop out of suspension onto the bed and into interstitial spaces, though this is in part compensated for by the reduced input of sediment from the catchment (McKenzie-Smith *et al.*, 2006).
- Once dry, exposed benthic soft sediments may crack and fissure, causing changes in microbiology, chemistry and mineralogy. The anoxic layer of the bed retreats deeper, reducing microbial biomass and denitrification, increasing phosphate retention and potentially re-oxidising sulphur to sulphates (Baldwin and Mitchell, 2000; Lamontagne *et al*., 2006).

3.1.2 Algal biofilms

- At drought onset, low flows and higher nutrient concentrations can initially promote algal growth (Wade *et al.*, 2002).
- Low flows cause a shift from assemblages dominated by diatoms to assemblages dominated by filamentous green algae; there is thus a net increase in algal biomass (Suren *et al*., 2003b).
- Once flows decrease past a threshold, the higher concentrations of nutrients and elevated temperatures can lead to algal and bacterial blooms, leading to eutrophication (Kinzie *et al*., 2006).
- As the wetted habitat decreases, biofilms become exposed and desiccation starts to occur (Ledger *et al*., 2008).
- At this stage there is a shift back to assemblages dominated by diatoms (Caramujo *et al*., 2008).
- Algal biofilms resist desiccation using extracellular mucilage layers, and the formation of cysts provides an avoidance strategy (Stanley *et al*., 2004).
- Remnant pools may also provide refuges (Robson and Matthews, 2004).
- The rate of drying is critical: rapid drying kills algal cells and impairs desiccation-resistant strategies (Ledger and Hildrew, 2001).

3.1.3 Macrophytes

- Drought can substantially alter macrophyte communities by eliminating some species and creating gaps for opportunistic species to establish (Lake, 2011).
- As the river or stream ecosystem dries, remaining plants can provide an important refuge to invertebrates and juvenile fish (Wright *et al*., 2002a).
- Plants have a wide range of strategies to resist drought, particularly changes in osmotic physiology, cell turgor, stomata opening and leaf orientation (Touchette *et al*., 2007; Romanello *et al*., 2008).
- Plants also have avoidance strategies such as reliance on propagules and seeds. Seeds remain viable for a long time and are stored in benthic sediments, providing a refuge from drought in the form of a seed bank (Brock *et al*., 2003; Touchette *et al*., 2007; Romanello *et al*., 2008).
- Seeds may not necessarily germinate on re-wetting, so provide a refuge from supra-seasonal droughts (Brock *et al*., 2003).
- As aquatic plants die, organic material is deposited on the bed and river or stream margins, which can act as a source of moist habitat patches, providing some refuge for other biota (Lake, 2011).
- As the bed dries, there is a shift from aquatic to terrestrial plant assemblages; the intensity and duration of the drought determine the extent to which this process occurs (Wright and Berrie, 1987; Westwood *et al*., 2006).
- This shift modifies channel morphology, particularly when combined with the deposition of sediment and plant litter (Franklin *et al*., 2008).

3.1.4 Invertebrates

- Reduced flows can initially increase invertebrate density as they are concentrated in the remaining wet habitat (McIntosh *et al*., 2002; Dewson *et al*., 2003) .
- Competitive and predatory interactions intensify and eventually lead to a decline in invertebrates (Wood *et al*., 2000).
- The response of food resources, in particular algae, to drought conditions can have strong influence on the response of invertebrates (Smakhtin, 2001).
- If habitats such as riffles and cascades are lost with drying, invertebrate biodiversity can decrease. If habitat diversity persists then invertebrate species richness is little affected (Ruegg and Robinson, 2004; Boulton and Lake, 2008).
- Channel morphology has a strong influence on how the wetted habitat changes as droughts develop. Heterogeneous reaches provide a variety of flow and depth environments and may be more resilient to drought because drying rates are slower and they present more refuges for the biota. However, once drying sets in there is potentially a greater diversity of species to be lost. Comparatively homogeneous reaches have less diversity to lose, but drying is likely to occur more quickly and be more severe thus having a strong impact on biota (Smith *et al*., 2003; Lake, 2011).
- In cases where some flow remains, total abundance and richness are similar pre- and post-drought. There is usually a change in community composition as droughts progress, as habitat suitability increases for some species and decreases for others (Everard, 1996).
- The rate of drying is important to community structure. In small streams rapid drying acts as an environmental filter to produce a robust set of surviving species. In larger rivers and streams drying takes longer and may be less extensive, so produces a less stable and specific community (Wood and Armitage, 2004; Wood *et al*., 2005; Bonada *et al*., 2006; Bonada *et al*., 2007; Lake, 2011).
- Taxa with preferences for low velocities and fine sediment can dominate during drought years, whereas species with preference for high velocities and gravel would normally dominate (Everard, 1996).
- Rheophylic taxa such as filter feeders are rapidly eliminated with decreasing flows or confined to the few remaining riffle/cascading habitats (Dewson *et al*., 2007).
- Taxa with shorter life cycles are favoured as their exposure to drought is limited (Bonada *et al*., 2006; Bonada *et al*., 2007; Dewson *et al*., 2007).
- Species specialised in shallower habitats like riffles risk becoming stranded as water levels drop, particularly those with limited motility such as mussels (Gagnon *et al*., 2004; Golladay *et al*., 2004).
- Due to increasing concentrations of nutrients in the remaining water (especially remnant pools), and physical processes such as the deposition of fine sediments and litter with dropping flows, taxa that are

well adapted to low water quality and degraded river/stream conditions are often well adapted to tolerate drought (Boulton, 2003; Lake, 2011).

- Larger bodied taxa are more susceptible to drought, particularly when drying sets in, due to their higher rates of evaporation and their greater requirement for wetted habitat (Dewson *et al*., 2007; Ledger *et al*., 2011).
- Invertebrate fauna have a low resistance but high resilience to drought (Boulton, 2003; Lake, 2003; Fritz and Dodds, 2004; Bonada *et al*., 2007).
- Resilience is substantially mediated by the use of refuges (Boulton, 2003; Dewson *et al*., 2007; Lake, 2008; Poff *et al*., 2010) .
- Invertebrate refuges consist of remnant pools, moist areas (such as under boulders) (Fenoglio *et al*., 2006), the hyporheic zone (Wood *et al*., 2010; Stubbington, 2012) or wetted reaches further downstream.
- Drift enables some invertebrates to avoid drought and can be the first and strongest response to drought. Active drift of invertebrates increases during drought, whereas passive drift is reduced. Once a flow threshold is reached, drifting is no longer possible (Poff and Ward, 1991; Kinzie *et al*., 2006; Dewson *et al*., 2007).
- Some taxa emerge earlier than they would normally to avoid drought (Stubbington *et al*., 2009), but some will need wet habitat to lay their eggs. Some have desiccation resistant eggs which serve to delay the next generation until drought conditions have passed (Morrison, 1990; Brock *et al*., 2003; Briers *et al*., 2004; Harper and Peckarsky, 2006).
- Thus for many insects the true impact of a drought may remain unclear until the following year's recruitment (Lake, 2011).
- Non-drifting, low motility invertebrates such as worms, molluscs and some crustaceans use sedentary refuges (Dewson *et al.*, 2007) .
- In the early stages of drying some wet habitat is available under stones and woody detritus (Covich *et al*., 2003; Golladay *et al*., 2004).
- In rivers and streams with hyporheic zones, invertebrates may migrate into the wet sediment, though this may eventually dry out too. There is some debate over the use of the hyporheic zone by benthic taxa as a refuge, as this varies greatly between river/stream ecosystems. In some cases there is no hyporheic zone at all (Datry *et al*., 2010; Wood *et al*., 2010; Dole-Olivier, 2011; Young *et al*., 2011; Stubbington, 2012).
- The biota of intermittent streams have evolved to contend with sometimes severe seasonal drought and may provide an insight into the adaptations that could increase resistance and resilience to drought (Wright and Berrie, 1987; Smith *et al.*, 2003; Fritz and Dodds, 2004; Robson and Matthews, 2004; Acuna *et al.*, 2005; Fonnesu *et al*., 2005; Bonada *et al*., 2006; Bonada *et al*., 2007; Chessman *et al*., 2010; Chester and Robson, 2011). These include laying eggs in vegetation, free isolated eggs, parthenogenesis, diapause, spiracular respiration, tegument respiration, flying adult stage, passive aquatic dispersal, use of cocoons, endobenthic habit, surface swimming and fine detritus as food (Bonada *et al*., 2006; Bonada *et al*., 2007).

- In the 1988 to 1992 supra-seasonal drought, in the Little Stour River, Kent, perennial reaches dried out, large volumes of fine sediment were deposited on the bed and invertebrate abundance was lowered (Wood and Petts, 1994; 1999).
- During the 2004-2006 UK drought, in the same Little Stour River, invertebrate abundance varied greatly but was lowest during the summer, in particular for insects with aquatic larvae. Lowest species richness did not coincide with periods of lowest flows, but was governed by insect emergence, which occurred earlier than in non-drought years. Hyporheic taxa abundance increased in autumn, indicating different responses of benthic and hyporheic invertebrates, which can be explained by their relative exposure to drying. The authors concluded that factors other than flow had a strong influence on invertebrate response, in particular thermal characteristics (Stubbington *et al*., 2009).

3.1.5 Fish

- As flow drops, fish change behaviour, and habitat, dominance hierarchy and territoriality disappear (Elliott, 2006).
- Initially fish will redistribute at the reach-scale seeking shaded pools in particular (Elliott, 2000; Matthews and Marsh-Matthews, 2003; Dekar and Magoulick, 2007; Pires *et al*., 2010).
- Drought causes a shift from density-dependant population regulation to density-independent mechanisms in salmonid populations (Elliott, 2006; Nicola *et al., 2009)*.
- Benthic fish are more tolerant of low flows than pelagic fish (Elliott, 2006; Lake, 2011).
- Fish are affected by the depletion of invertebrates, their main food source (Hakala and Hartman, 2004).
- Fish, in particular pelagic fish, can become stranded in remnant pools once a flow threshold is reached. This can increase predation risk from terrestrial animals and the risk of parasitism and disease (Magalhaes *et al*., 2002).
- Water quality of pools may also be low (Labbe and Fausch, 2000; Antolos *et al*., 2005; Dekar and Magoulick, 2007; Magalhaes *et al*., 2007; Maceda-Veiga *et al*., 2009).
- Remnant pools can thus act as an environmental filter shaping the composition of the remnant fauna and the post-drought assemblage (Matthews and Marsh-Matthews, 2003; Lake, 2011).
- As the bed dries, deteriorating water quality in pools means fish will need to attempt migration to a perennial reach or run the risk of being trapped in a pool that may eventually dry out (Magoulick and Kobza, 2003; Dekar and Magoulick, 2007; Conallin *et al*., 2010).
- The timing of drought is important with respect to life cycle. Juvenile fish are more susceptible to predation in remnant pools and eggs may die if fine sediments are deposited during low flows (Hakala and Hartman, 2004; Magalhaes *et al*., 2007).

- Supra-seasonal drought may prevent the migration of anadromous and catadromous fish, particularly in systems with weirs and other artificial structures (Vadas, 2000; Fukushima, 2001; Jonsson and Jonsson, 2002; de Leaniz, 2008).
- In Welsh rivers, the 1975/6 supra-seasonal drought led to fish kills, mediated by elevated water temperatures. However, for salmon, the effect was limited to that year's juveniles (Brooker *et al*., 1977; Cowx *et al*., 1984).

3.1.6 Ecosystem functioning

- Because of the effects on habitats and species described earlier, drought has the potential for large effects on ecosystem functioning, dependent upon the extent and duration of drying (Lake, 2011).
- Consumption of organic debris by microbes and detritivores can drop substantially, thus impacting the breakdown of organic matter (Schlief and Mutz, 2011).
- Primary production is impacted. It can at first increase greatly because of temperature and nutrients, even causing blooms. It can then drop dramatically and even cease as drying takes place (Ledger and Hildrew, 2001; Wade *et al*., 2002; Suren *et al*., 2003b; Ledger *et al*., 2008).
- Secondary production of invertebrates and fish is reduced by low flows and extensively reduced by drying (Matthews and Marsh-Matthews, 2003; Lake, 2011; Ledger *et al*., 2011).
- A shift from heterotrophy to autotrophy in stream metabolism is possible, as there is less dissolved organic carbon (DOC) and less algae to take up nitrogen (Dahm *et al.*, 2003).
- Streambed desiccation has been shown to have a clear effect on the functioning of benthic biofilms, as autotrophs (primarily unicellular algae and cyanobacteria) were reduced by 80 per cent but heterotrophs (bacteria) were reduced by only 20 per cent. This was associated with a drop in N degradation, while carbon and phosphorous breakdown were maintained (Timoner *et al*., 2012).

3.1.7 Winter and summer droughts

- Summer droughts can be severe, however they often occur at a predictable time of the year when water resources are most depleted.
- Many organisms are adapted to summer low flows, particularly regarding the timing of life cycles of fauna and flora.
- Winter droughts are far more damaging for the reasons listed below:
    - Many plants and animals over-winter as juveniles and may be more sensitive to low flows.
    - Winter is when aquifers recharge so a winter drought can evolve into a supra-seasonal drought.

- Flushing flows at the end of winter are extremely important for channel morphology maintenance, sediment dynamics, organic matter distribution and microhabitat formation.
- There is some evidence that the lack of these flushing flows has an impact in itself (Power *et al*., 2008).

3.2 Depending on the severity of the drought, how quickly do aquatic ecosystems (including rivers, lakes, ponds and wetlands) recover?

3.2.1 Drought breaking

- Drought recovery represents a major gap in research.
- Drought effects and recovery from drought are strongly mediated via catchments (Lake, 2011). Recovery appears to be strongly influenced by water body type, state of the catchment, groundwater levels, the nature of the precipitation and ecological memory.
- Abiotic changes caused by drought are much better known than abiotic changes that occur when droughts break and recovery sets in (Lake, 2011).
- Increases in bare ground if plant cover has been reduced reduces water retention capacity of the catchment when run-off returns after the drought, increasing entrainment of sediment, organic matter and nutrients into the water (Lake, 2011).
- If droughts break with a heavy spell of precipitation, large amounts of sediment and nutrients[11] may be entrained and ultimately lost from the catchment (Lake, 2011).
- The re-wetted riparian zones and floodplains release Dissolved Organic Carbon from the soil and litter which is flushed into stream or river water and can increase microbial activity and reduce water quality (O'Connell *et al*., 2000; Worrall *et al*., 2006; Howitt *et al*., 2007).
- Soils also accumulate nitrates during drought and re-wetting causes a pulse of these nitrates in streams and rivers and thus an increase in nitrate concentrations and nitrogen loading. Dried bed sediments may also release nitrates on re-wetting. (Watmough *et al.*, 2004; Whitehead *et al*., 2004; Zwolsman and van Bokhoven, 2007).
- The increased nitrates can stimulate microbial activity, algal activity and macrophyte growth (Baldwin *et al.*, 2005).
- Re-wetting soils may also release sulphates as sulphuric acid, causing an acid pulse and potentially mobilising metals, which can reach toxic concentrations (Tipping *et al.*, 2003; Eimers *et al.*, 2008).
- If particulate organic matter (POM) and leaf litter has accumulated on the stream or river bed during drought, there is a pulse of Dissolved

[11] Apart from the work of Romani *et al*. (2006), the biogeochemistry of ecosystem recovery after drought remains unexplored

Organic Carbon and nutrients which may be taken up into the food web contributing to recovery (Artigas *et al*., 2009; Lake, 2011).
- The relative influence of these pulses of chemicals, nutrients and organic matter on re-wetting at the catchment and stream/river reach scales can be a major determinant of ecosystem recovery (Romani *et al*., 2006).

3.2.2 Ecosystem recovery

- There is limited quantitative information which can relate drought severity to the length of recovery (Lake, 2011).
- Recovery is dependent on the duration and extent of drying and the nature of the system (perennial or intermittent). River/stream ecosystems recover relatively quickly from droughts, and if recovery is delayed, systems still recover eventually (Lake, 2011).
- For supra-seasonal droughts, recovery is subject to a time lag and is less predictable because there will have been some species turnover and changes in microhabitat distribution (Lake, 2011).
- Recovery is limited by some human activities, in particular water abstraction, river regulation, pollution and habitat degradation (Lake, 2011).
- Many non-native invasive species may exploit drought conditions, and impair the re-establishment of native species when flows return (Lake, 2011).

Algae

- Re-wetting often sees rapid recovery of the algal biofilm from surviving cells, cysts, and propagules in the drift if upstream reaches have remained wet. If remnant pools persisted throughout the drought they also act as recolonisation foci (Ledger and Hildrew, 2001; Robson and Matthews, 2004; Stanley *et al*., 2004; Robson *et al*., 2008).
- Timoner *et al*. (2012) observed a rapid recovery of the autotroph component of benthic biofilms (primarily unicellular algae) at flow resumption, despite reductions in biomass of 80 per cent with streambed desiccation.

Macrophytes

- The recovery of higher plants is important for ecosystem recovery as they provide habitat as well as a food resource (Wright *et al*., 2002b).
- Recovery of higher plants consists of a gradual succession back to an aquatic assemblage. This recovery to pre-drought assemblages can take years depending on the extent of terrestrialisation that occurred during the drought (Holmes, 1999; Westwood *et al*., 2006).

- However some systems recover rapidly; for example, winterbourne stream flora re-establishes itself soon after inundation (Holmes, 1999; Wright *et al.*, 2002b; Westwood *et al.*, 2006).
- Recovery of plant assemblages can be in part limited if fine sediments have been deposited on the river/stream bed during drought and shade seedlings (Franklin *et al*., 2008).
- Holmes (1999) found that some plant communities shifted after drought, but that this was dependent on site characteristics and on the pre-drought community structure.

Invertebrates

- As long as some flow persists, recovery of invertebrate assemblages is usually rapid. If the channel dries completely, recovery will be slower and may be incomplete (Boulton, 2003; Acuna *et al*., 2005; Boulton and Lake, 2008).
- Some insects recolonise via highly mobile adult flying stages from remnant pools, wetted reaches or other water bodies (the availability of these latter two will be affected by the spatial extent of the drought). (Fritz and Dodds, 2004).
- Drought favours species with good colonising traits, such as multivoltinism, but for many insects recolonisation may not take place until the following year (Hynes, 1958; Hynes, 1961; Morrison, 1990, Ruegg and Robinson, 2004; Bonada *et al*., 2007).
- Therefore, the timing of drought in terms of animal life cycles is crucial in determining the speed of recovery (Boulton, 2003).
- Recolonisation also occurs from surviving individuals in remnant pools (Suren *et al.*, 2003a; Fritz and Dodds, 2004; Boulton and Lake, 2008) and the hyporheic zone (Dole-Olivier *et al*., 1997; Stubbington *et al*., 2009; Wood *et al.*, 2010; Dole-Olivier, 2011; Young *et al*., 2011; Stubbington, 2012).
- Recolonisation can also occur from drought-resistant eggs (Boulton, 2003).
- The recovery trajectory is similar in perennial and intermittent streams. The first colonists have short lifecycles and are usually small bodied, species richness increases as bigger, longer-lived taxa re-appear, with larger predators usually returning last (Lake, 2007).
- Important traits in early recovery are small body size, sclerotisation, tubular shape and ability to drift. As recovery progresses, these traits give way to soft bodies, poor resistance to desiccation, rarity in drift and the ability to crawl and cling (Griswold *et al.*, 2008).
- For supra-seasonal droughts, the pre- and post-drought communities can be different if key species such as grazers and shredders are lost and the trophic structure has changed (Lake, 2011).
- In the 1988/92 supra-seasonal drought in the Little Stour River, Kent, perennial reaches dried out and large volumes of fine sediment were deposited on the bed. Invertebrate abundance was low but recovered

over two to three years. Few invertebrate taxa were eliminated due to use of refuges, particularly the hyporheic zone (Wood and Petts, 1999; Wood and Armitage, 2004).

- In the 1975/6 supra-seasonal drought, two studies in Wales indicated that invertebrate density and diversity was strongly affected by drought but these recovered within a year (Brooker *et al.,* 1977; Cowx *et al*., 1984).
- In seasonal droughts in UK chalk streams, abundance of invertebrates, plants and fish are all negatively affected but quick recovery has been observed (one to three years) particularly of macrophytes, then invertebrates, then fish (Ladle and Bass, 1981; Wright *et al*., 2000; Wright *et al*., 2002a; Wood and Armitage, 2004).
- Only one UK study observed increases in invertebrate abundance, probably due to increased resources (Extence, 1981).

Fish

- As long as wetted areas are available and accessible, fish recolonisation is rapid because they are highly mobile (Magoulick and Kobza, 2003; Elliott, 2006).
- Recruitment is often strongest following a drought year (Keaton *et al.*, 2005).
- Recovery from a supra-seasonal drought is less predictable for fish and ranges from rapid recovery to no recovery at all (Lake, 2007).

3.3 Can we incorporate any impacts resulting from climate change into our understanding and conceptual models?

- Predicted increases in air temperature translate into higher water temperatures, particularly in small upland streams and possibly in large lowland rivers with long retention times (Des Clers *et al*., 2010; Simpson *et al*., 2010). In line with this, the temperatures of flowing waters have increased across Europe. For example, water temperature in the Danube River has increased by up to 1.7^{o}C since 1901 (Webb and Nobilis, 2007), by 2.6^{o}C in French rivers between 1979 and 2003 (Daufresne and Boet, 2007) and by 1.4^{o}C in Welsh streams between 1981 and 2005 (Durance and Ormerod, 2007).
- Warmer temperatures may alter fundamental ecological processes and change species distributions (Poff *et al*., 2002).
- Warmer water temperature is a stressor to aquatic biota, and could change the sensitivity of stream ecosystems to droughts (Poff *et al*., 2002).
- Changes to air temperature could cause shifts in the timing and intensity of precipitation and rates of evapotranspiration (Milly *et al*., 2005;

Intergovernmental Panel on Climate Change (IPCC), 2007; National Oceanic and Atmospheric Administration (NOAA), 2011).

- Thus the timing and volume of runoff, snow melt and groundwater recharge may change, bringing about changes to the hydrology of river/stream systems.(Bates *et al*., 2008).
- This includes a greater frequency, duration and intensity of extreme events such as droughts and floods, increased peak flows and reduced base flows (Allen and Ingram, 2002; Alcamo *et al.*, 2007; Kundzewicz, 2009) .
- More frequent floods and droughts are both expected, which may have a strong influence on ecosystem recovery from these extreme events (Christensen and Christensen, 2003).
- Seasonal droughts will be more severe, supra-seasonal droughts will become more likely (Allen and Ingram, 2002).
- Currently, there is insufficient evidence to firmly conclude just how climate change could impact on river/stream ecosystems via hydrological mechanisms.

3.4 What are the long-term ecological impacts (if any) and can we define the threshold(s) beyond which rivers, lakes, wetlands and ponds are 'permanently' altered and deliver reduced ecosystem services?

- Long-term effects are dependent on the duration and intensity of the drought.
- Acuna *et al*. (2005) state that the main threshold for change in community composition is cessation of flow.
- There is a flow threshold at which fish and invertebrates present a behavioural response to drought conditions, modifying activity rates and habitat use. Beyond this generic understanding, no further information is currently available.
- There is a flow threshold at which drifting invertebrates and fish will migrate from drought impacted reaches. Beyond this generic understanding, no further information is currently available.
- There is a flow/depth threshold where the river or stream becomes a series of isolated pools. There will clearly not be generic hydraulic thresholds, rather they will be influenced by channel morphology, both natural and with human impacts overlain. Pools can act as refuges for taxa able to exploit them. Beyond this generic understanding, no further information is currently available.
- There is a water quality threshold in remnant pools beyond which biota cannot survive. Beyond this generic understanding, no further information is currently available.

- There is a threshold at which the terrestrialisation of the dried bed may be such that pre-drought conditions cannot be fully regained as microhabitat distribution is changed.
- Every species of invertebrate and fish has its own critical thermal limit, a temperature threshold beyond which they will die. Beyond this generic understanding, no further information is currently available.
- Currently there is little evidence or information to link drought with ecosystem services (not that there is not be a link, rather there is no evidence currently to assess whether this link does indeed occur).
- Boulton (2003) states: 'Although drought acts as a sustained 'ramp' disturbance, impacts may be disproportionately severe when critical thresholds are exceeded. For example, ecological changes may be gradual while a riffle dries but cessation of flow causes abrupt loss of a specific habitat, alteration of physicochemical conditions in pools downstream, and fragmentation of the river ecosystem. Many ecological responses to drought within these habitats apparently depend on timing and rapidity of hydrological transitions across these thresholds, exhibiting a 'stepped' response alternating between gradual change while a threshold is approached followed by a swift transition when habitat disappears or is fragmented.'
- Groffman *et al.* (2003) state: 'Ecological thresholds: the key to successful environmental management or an important concept with no practical application?'

3.5 Are we and/or our partners collecting the right information to answer these questions?

- Empirical, scientifically robust data on the ecological effects of drought are scarce.
- Many studies are opportunistic.
- Studies with proper before-and-after data specifically targeting the ecological impacts of drought are extremely rare.
- Experimental manipulations in mesocosms or in the field are even rarer, even though they are the only true source of robust before/after control impact (BACI) data. By necessity they are often limited to studying one aspect of the ecosystem (such as fish).
- Part of the drought literature draws on the ecological impacts of regulated low flows, though it is unclear how useful this is to our understanding of drought.
- Part of the literature is also drawn from work on naturally intermittent rivers and streams, where drying phases are predictable and characterise the ecosystem. It is unclear how relevant this is to the episodic drying of normally perennial waters.
- The ideal situation for gathering data is when droughts occur during a long-term monitoring campaign, providing before-during-after evidence and information.

- Data are particularly lacking on the impacts of drought on ecosystem functioning, despite the fact that basic ecosystem functions such as algal grazing and organic matter breakdown can be easily quantified using simple field techniques.
- Further data are needed on the relationship between hydromorphological degradation and resilience to drought.
- The dynamics of re-wetting of catchment soils and stream/river beds, and the effect on water quality, are poorly studied.
- It is extremely hard to detect specific drought impacts in rivers and streams without carefully designing monitoring programmes.

4 Lakes

4.1 What impacts do droughts have on the ecosystems (including differentiating the impacts of winter (including flushing flows) and summer droughts)?

4.1.1 Abiotic effects

- Less inflowing water from the catchment, plus any increase in evaporation rates caused by any associated increases in air temperatures and decreases in levels of humidity will cause lake water levels and volumes to fall.
- Lower water levels will cause a loss of habitat, especially around the perimeter of the lake.
- Shallow lakes are affected more than deeper lakes, because small water level changes represent a much larger proportion of their total surface area and volume.
- In deep, seasonally stratified lakes the impacts of water level fluctuations will be restricted to changes in the littoral zone.
- Less inflowing water results in less outflowing water, so the flushing rate is reduced; this increases the sensitivity of a lake to other pressures such as eutrophication, acidification, abstraction and invasive species.
- Flushing rate fluctuates naturally in relation to rainfall (Bailey-Watts *et al*., 1990).

4.1.2 Water chemistry

- Lower levels of inflowing water from the catchment and any secondary increases in evaporation rate (see above) may cause concentrations of dissolved chemicals to increase.
- Decreased inputs of nutrients from diffuse sources within the catchment, although inputs from point source will remain almost unchanged.
- Changes in environmental conditions in lakes may alter internal biogeochemical cycling of phosphorus, nitrogen and other chemical species that are regulated by redox conditions (such as metals and metalloids) (Bostrom *et al*., 1988).
- Increased likelihood of anoxia and stagnant, warm waters will increase the likelihood of phosphorus release from sediments (Spears *et al*., 2009); however, this may be offset by increased cover by sediment dwelling plants and algae (Spears *et al*., 2010; 2012).
- Lower flushing rates and decreased lake volume will reduce the level of dilution of any internal release of nutrients from lake sediments.

- Microbial activity is likely to increase in warmer waters, enhancing denitrification and ammonification, causing an overall increase in NH_4-N concentrations in bottom waters and accelerating the loss of NO_3-N from the system to the atmosphere as N_2.
- A general switch from P limitation to N limitation will be expected due to the increased supply of P relative to N from bed sediments; this will affect ecosystem functioning (May *et al., 2010*).

4.1.3 Algae

- A reduction in flushing rate tends to reduce the resilience of lakes to eutrophication; there is a greater risk of algal blooms because incoming nutrients are retained for a longer periods and less algae are flushed from the system; a range of lake management models reflect this (Vollenweider, 1975; Dillon and Rigler, 1974; Vollenweider and Kerekes, 1982).
- The direct impact of lower flushing rates (increased retention times) on algal composition is likely to favour slow growing species such as cyanobacteria (Reynolds and Lund, 1988; Reynolds, 2006; Carvalho *et al*., 2011; Elliott, 2010); when flushing rates are high, smaller algae with relatively high growth rates tend to dominate the algal community (Dickman, 1969; Bailey-Watts *et al*., 1990).
- Indirect impacts of lower flushing rates (such as changes in temperature regime and nutrient availability) affect algal species composition and succession (Bailey-Watts *et al*., 1990; Elliott, 2010; Carvalho *et al*., 2011; Jones *et al*., 2011; Reynolds *et al*., 2012).
- If the growth of cyanobacterial populations is limited by other factors (such as light, nutrient availability), increases due to reduced flushing rates may be less significant.

4.1.4 Macrophytes

- Littoral macrophytes have developed coping strategies to survive in the areas they inhabit, where changes in water level occur naturally; motile species avoid potential desiccation while some amphibious species have developed tolerance.
- Small reductions in water level in shallow lakes may cause large changes in macrophyte species composition.
- Lower spring water levels may encourage the growth of submerged plants in shallow systems (Coops *et al*., 2003).
- Excessive or prolonged drawdown in lakes and/or altered timings of low water levels (beyond natural water level fluctuations) causes significant losses of macrophyte species and abundance as physiological limits are exceeded (Hellsten and Dudley, 2006; Zohary and Ostrovsky, 2011).
- In extreme conditions, some naturally occurring species may be lost, making lakes vulnerable to colonisation by more invasive generalist

species; these may out-compete the remaining native species resulting in a loss of biodiversity.

4.1.5 Invertebrates

- Littoral macroinvertebrates inhabit a region with natural changes in water level; some species can cope with changing water levels while other, more motile, species will use avoidance strategies.
- Loss of macrophytes will reduce the habitat available to macroinvertebrates; this causes significant reductions in biodiversity within the littoral community (for example see Arvoviita and Heiki, 2008; Baumgartner *et al*., 2008; White *et al*., 2008).
- Drought conditions may cause a shift in primary production from macrophytes to planktonic algae; consequent changes in habitat and food availability are likely to affect the abundance and species composition of the macroinvertebrate community (for example see Gunn *et al*., 2012).
- Under extreme drought conditions some species may be lost, providing opportunities for more invasive, generalist species to become established and proliferate (Zohary and Ostrovsky, 2011).

4.1.6 Fish

- Fish are usually widely distributed within a lake; however 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 (Winfield, 2004).
- Lower water levels during the spawning season will adversely affect the reproductive success of most fish species because they spawn in the littoral zone on suitable macrophytes or bottom substrates (for example see Winfield *et al*., 2004).
- Extreme lowering of water levels may reduce the volume of the hypolimnion; this will affect fish that require relatively low water temperatures and could lead to fish kills. Some of the UK's rarest fish are likely to be most affected (Maitland and Lyle, 1992; Jones *et al*., 2008).
- Lower water levels outside of the spawning season can affect the suitability of the littoral zone for many fish species by reducing food availability (for example see Winfield *et al*., 1998).
- Many fish are relatively long-lived so, unless there are major fish kills, the impacts of droughts may not necessarily affect population levels immediately; however, a reduction in successful reproduction over a number of seasons would cause a significant decline in fish populations.

4.1.7 Aquatic birds

- Aquatic birds use lakes typically to feed on macrophytes, macroinvertebrates or fish, so drought impacts that depress these potential food sources may also impact on these bird populations.
- Birds that can only forage to limited depths (such as swans, dabbling ducks) would be the most affected by these changes. Diving ducks (such as the tufted duck), which feed at greater depths, would be less affected.

4.1.8 Ecosystem functioning

- Lake biota have evolved life cycles that accommodate natural water level fluctuations. Under drought conditions, extreme or unusually timed fluctuations in lake water levels are likely to result in impacts on the biota, impairing ecosystem functioning.
- Changes in flushing rate affect temperature regimes and nutrient availability; these, in turn, 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 (for example see Bailey-Watts *et al*., 1990; Reynolds *et al*., 2012).
- Loss of macrophytes will result in a reduction in structural diversity that will lead to less habitat being available for macroinvertebrates and fish.
- Loss of macrophytes may cause a regime shift in lake functioning, from macrophyte-dominated to algal-dominated.
- Loss of macrophytes will result in significant losses amongst the littoral macroinvertebrate community (for example see Arvoviita and Heiki, 2008; Baumgartner *et al*., 2008; White *et al*., 2008); this will affect species that depend on this food supply, such as fish and aquatic birds.
- Under extreme conditions, some naturally occurring species may be lost, making the ecosystem unstable and vulnerable to colonisation by invasive species with consequent loss of ecosystem functions.
- Changes in lake depth will affect sensitive fish species (trout, salmon and coregonids) and highly specialised aquatic birds (such as divers), because of its role in habitat partitioning (for example see Ferguson and Mason, 1981). Reduced water levels can restrict the volume of depth-specific habitats and are a particular threat when combined with nutrient enrichment and deep water deoxygenation.

4.2 Depending on the severity of the drought, how quickly do aquatic ecosystems (including rivers, lakes, ponds and wetlands) recover?

- There is little or no literature on the recovery of lake biological communities from drought.

- Capacity to recover depends on the ability of aquatic species to withstand drought conditions (resistance) and/or recover from them (resilience).
- Recovery from seasonal droughts is likely to be relatively rapid for many species, with a predictable and distinct sequence of return, unless species have been lost completely (such as fish) (Lake, 2003).
- Species specific traits, such as an ability to recolonise from refuges or from resting or resistant forms (such as seeds or turions), will be important in terms of recovery processes. Some benthic macroinvertebrates may survive by becoming physiologically inactive or burrowing into sediments (Coops *et al*., 2003).
- Biotic response to the more supra-seasonal droughts is likely to be characterised by low to moderate resistance and variable resilience, because it is more difficult to evolve the adaption strategies required to respond to unexpected conditions.

4.3 Can we incorporate any impacts resulting from climate change into our understanding and conceptual models?

- Climate change will affect lake ecology through impacts on nutrient delivery, water temperature, wind-induced mixing and flushing rate.
- Lake response model PROTECH has been used to predict the impacts of climate change on fish (Vendace) (Elliott and Bell, 2011) and algal response (Jones *et al*., 2011).
- Zohary and Ostrovosky (2011) provide a conceptual model that summarises the likely changes to the ecology of stratified lakes in relation to increasing water level fluctuation beyond natural: littoral resources and native or keystone species decrease, while invasive species and internal nutrient cycling increase. Climate change will affect the degree of water level fluctuation (Figure 4.1).

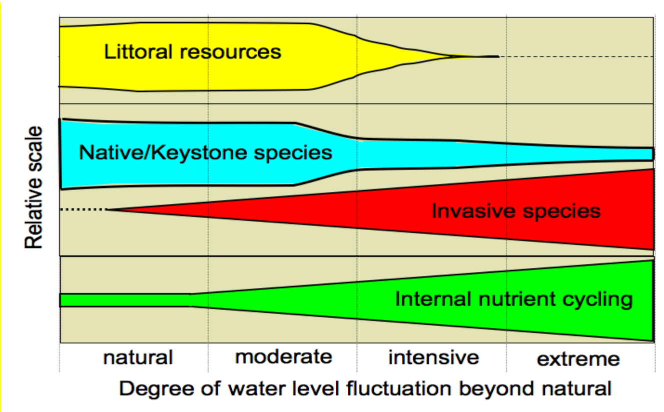

Figure 4.1 Changes likely to occur in stratified lakes as a function of water level fluctuations beyond natural (after Zohary and Ostrovosky, 2011)

4.4 What are the long-term ecological impacts (if any) and can we define the threshold(s) beyond which rivers, lakes, wetlands and ponds are 'permanently' altered and deliver reduced ecosystem services?

- It is difficult to provide information on thresholds beyond which the ecology of lakes are 'permanently' altered as the result of drought; this is an under-studied area of freshwater ecology (Zohary and Ostrovosky, 2011).
- Ecological response to 'extreme' reductions in water level and flushing rate will depend on site-specific factors that affect their sensitivity; these include geographical location, bathymetry, trophic status, resilience and type of disturbance to the natural water level regime (Zohary and Ostrovosky, 2011).

4.5 Are we and/or our partners collecting the right information to answer these questions?

- No information has been provided on lake monitoring by the Environment Agency. In view of this, the following is suggested:
    - Select a range of large and small lakes with different depth characteristics, water sources and water residence times.
    - Develop hydrological budgets for each lake using existing data such as catchment characteristics, bathymetric maps and meteorological data.
    - Identify the hydrological 'type' of each lake according to the proportional input of water from direct precipitation, surface runoff and groundwater, and its position in the landscape.
    - Monitor water levels.
    - Monitor the main water inputs to and losses from the system using rain gauges, river stage/flow gauges, groundwater level monitors, surface runoff, outflows and evaporation rates.
    - Monitor ecological 'indicator' species that depend on the hydrological integrity of each lake or affect its ecological status.

5 Wetlands

5.1 What impacts do droughts have on ecosystems (including differentiating the impacts of winter (including flushing flows) and summer droughts)?

5.1.1 Introduction

- There are very few specific studies on the effects of droughts on wetlands.
- Those that do exist tend to be in more traditionally drought-prone regions (Mediterranean and the Murray-Darling basin in Australia) and tend to deal with impacts of drought that are not particularly relevant to the UK. For example, in the Murray-Darling there is a lot of work on increased groundwater salinity resulting from drought.
- The information on wetlands presented below is therefore based on information from other studies which relate species (or abiotic) information to the availability of water (or secondary consequences).

5.1.2 Abiotic effects

- As the supply of water is reduced, areas of open water within the wetland (such as puddles, pools, ditches and so on) reduce in area and eventually dry up all together.
- The wet corridors or fringes that connect areas of open water similarly decrease in area and eventually dry out. This results in remaining areas of open water becoming isolated.
- As the depth to the water table increases, there is a reduced supply of water to the soil surface, which combined with increased evaporation from the soil surface, results in development of a soil moisture deficit.
- Drying of the soil (particularly over an extended period) can lead to a loss of soil structure. Soils become very prone to erosion, which can occur either on re-wetting or in some cases due to high wind velocity.
- Organic soils are likely to oxidise under drought conditions and there can be a significant loss of carbon to the atmosphere. In extreme cases some highly organic soils have ignited, again resulting in a substantial carbon loss.
- Drying of the soil surface makes the soil less penetrable. Associated with this hardening is a reduced ease of re-wetting.
- As surface and groundwater quantities reduce, there is a concentration of dissolved nutrients and pollutants. The supply of water-borne species via rain or river water reduces.

5.1.3 Birds

- As open water features are lost, population numbers of aquatic species (such as ducks and grebes) and of semi-aquatic species (such as Moorhen), decline and ultimately fall to zero.
- Reduced viability of fringing vegetation could impact a range of species, (such as the Reed Warbler and Sedge Warbler) by damaging the food supply.
- Shrinkage of water bodies can increase exposure of nests to terrestrial predators. The safety of roost sites, including non-aquatic species such as swallows and martins, may also be reduced.
- Reduced connectivity between water features (such as ponds and pools) may increase risk of mortality and loss of body condition if species are forced to disperse from degraded or dried-up water bodies.
- Much of this is associated with a reduction in availability of food, particularly aquatic invertebrates and vertebrates, and this will drive a deterioration of viable feeding habitat for wetland and non-wetland birds.
- Increased concentration of water-borne nutrients and pollutants may both have a direct toxic effect and may bioaccumulate. Increased turbidity could reduce hunting success in visual pursuit predators such as grebes.
- The impact of reduction in soil moisture can lead to a reduced food supply for herbivores and reduced cover for nesting, as there is reduced plant biomass accumulation.
- Reduced penetrability of the soil surface will have a direct effect on bird species feeding on soil invertebrates as the prey become inaccessible. This applies to species such as snipe and thrush.

5.1.4 Terrestrial wetland vegetation

- An initial and temporary increase in the proportion of drawdown species (mainly annuals or ephemerals with a ruderal strategy) that colonise the drying soil occurs.
- More open habitat is colonised by competitors with a strategy for rapid vegetative spread (rhiomatous or stoloniferous grasses such as *Agrostis stolonfera*, for example) assuming they are present locally or have a viable seedbank.
- Where there is an increase in the concentration of nutrients (nitrogen, phosphorus and potassium), alkalinity and pollutants, wetland plant species adapted to eutrophic or alkaline species are favoured.
- Increased nutrient concentrations are also likely to favour various algae which may produce ‘blooms’ under drought conditions in receding pools, reducing light to aquatic vascular plant species and shrouding terrestrial plants.
- Some plants may be unable to abstract water (and nutrients) from the soil, and will reach their wilting point, close their stomata and hence not perform gaseous exchange. If this were to continue, the permanent wilting point may be reached followed by death. The impact on plant

assemblages will be to disadvantage shallow-rooted species and those without physiological adaptations to drought, altering the community structure.

- Where drought leads to vegetation death, organic soils are exposed accelerating oxidation and soil loss. In extreme supra-seasonal droughts, ‘fen blows’ result in soil wastage and exposure of the underlying mineral layer.
- Wetland microbial activity is suppressed during a drought, leading to reduced consumption of inorganic nutrients. The direct stress of drought on vascular plants leads to reduced release of DOC further reducing microbial activity.
- Erosion and loss of soil (and soil carbon and nutrient store) creates conditions inimical to vascular plant growth, impacting obligate wetland plants. In extreme cases, this might lead to wetland destruction and the development of a new vegetation type.

5.1.5 Vascular plants and byrophytes

- Species of permanent open water will be impacted adversely but species that are well adapted to withstand fluctuating water levels will probably experience little impact in response to seasonal drought. There may even be some benefit to ephemeral species which are adapted to complete life on exposed mud.
- Reduced availability of soil water may have a temporary effect on wetland species of marshes or swamps but the magnitude of this impact will be related to the extent, frequency and duration of the drought.
- Supra-seasonal drought would likely bring about a shift in vegetation community if the wetland water levels fall below the 'absolute minimum' water level which varies according to vegetation community (Wheeler *et al*., 2004; Wheeler *et al*., 2009; Davy *et al*., 2010). Trajectory diagrams which give detailed information about the response of vegetation communities to changing conditions are available (for example, see Wheeler *et al*., 2004).

5.1.6 Mosquitoes

- For species which lay their eggs in permanent water bodies, a reduction in open water would decrease available habitat and might increase competition between larvae.
- For species which lay their eggs on land and wait for water levels to rise, a supra-seasonal drought may result in eggs dying at a rate that is species dependent. This might reduce mosquito abundance.
- As drought intensifies, reduced connectivity between water features may enhance larval survival since many species prefer isolated water features that may have a reduced number of predators of larvae.
- Adult mosquito survival rate is related to air moisture which has a relationship with soil moisture. In general, reduced moisture will

decrease adult survival, though effects will be different for individual species.

5.1.7 Invertebrates

- During drought, soil invertebrates (such as earthworms, springtails) move to deeper soil layers or enter diapauses. This affects survival and reproduction rates resulting in longer term declines in population size.
- With loss of soil structure, soil microbial activity becomes inactive. This affects rates of carbon mineralisation, rates of cycling of key nutrients including nitrogen and phosphorus, potential degradation of complex organic chemicals including deposited air pollutants and pesticides, and soil food web and energy flows.

5.1.8 Ecosystem functioning

- Reduced productivity of wetland plants and crops will provide less cattle feed and associated products. Similarly, the knock-on effect of reduced numbers of wetland species (both flora and fauna) will result in a more widespread reduction in food and greater pressure on dependent species.
- Loss of soil structure, in particular in organic soils, may permanently compromise the ability of the soil to store water. It therefore will have reduced ability to both store water in times of flood (potentially increasing downstream flood risk) and release water in times of drought.
- Mineralisation of organic soil may result in a considerable release of carbon to the atmosphere.

5.1.9 Habitat selection

- In general, wetlands supplied with water by rivers, often in conjunction with rainfall, experience a large range of wetland water levels, potentially supporting vegetation communities which have a wide range of preferred water levels (summer and winter). The minimum water level requirement for these communities is generally some depth below the surface (Wheeler *et al*., 2004).
- In general, wetlands supplied by groundwater, sometimes in conjunction with surface water runoff, are likely to experience a smaller range of wetland water levels, potentially supporting vegetation communities which have a narrow range of preferred water levels (summer and winter). The minimum water level requirement for these communities is generally close to the surface (Wheeler *et al*., 2009).
- Most wetlands supported by groundwater fluxes will have developed vegetation communities which prefer minimal variations in water level commensurate with a relatively unvarying groundwater flux.

- However, under drought conditions it is possible that the supply of water to wetlands fed by groundwater could cease as the aquifer water level falls below a particular threshold.
- Such thresholds are difficult to define as they will be influenced by the aquifer scale, specific yield, geometry in relation to the wetland and more particularly in the case of semi-confined aquifers by the volume of the aquifer in relation to the size of its recharge area.
- This is supported by Winter (2000), who suggested that in the context of climate change, wetlands whose hydrology is dependent on precipitation are more vulnerable than those fed by groundwater. However, it can be hypothesised that if under a supra-seasonal drought a threshold is passed and groundwater fluxes cease, then the impact on the groundwater-fed wetland will become very significant indeed.
- Several wetland mire vegetation communities take the form of a (semi-) buoyant vegetation 'raft' (Wheeler *et al*., 2009). This implies a degree of vertical mobility which will provide some hydrological stability; that is, until the floating vegetation is grounded it will not be fully affected by water level variations.
- A similar effect can occur on those mires with a compressible substrate (such as peat). In this case, as the water level in the peat falls, the peat consolidates (shrinks), which in effect compensates for the water level decline to a degree (for example see Price and Schlotzhauer, 1999). This means that water levels measured with respect to the surface may well not decline as much as expected on peat substrates.
- Dune slack wetlands, although fed by rainfall with localised groundwater fluxes, actually have a wide range of preferred summer water levels and minimum water level requirements some depth below the surface (Davy *et al*., 2010). This may well be due to the influence of deep rooting vegetation which continues to transpire through the summer resulting in a greatly reduced recharge of the sand aquifer.
- Ditch communities, fed by rain and runoff, are floating communities and as such are far less sensitive to water depth, having a wide range of preferred water levels (Wheeler *et al*., 2004). The key threshold for these communities will be whether the ditch totally dries out during drought.
- It should be emphasised that communities comprise an assemblage of different species and individual species in these communities will have differing tolerances to varying water levels and hence drought.

5.2 Depending on the severity of the drought, how quickly do aquatic ecosystems (including rivers, lakes, ponds and wetlands) recover?

- The response of a wetland following a period of drought will be dependent on the duration and severity of drought.

- As discussed previously, it is often the case that wetland species are well adapted to the likely range of conditions that will occur and many will therefore be able to withstand seasonal drought.
- A supra-seasonal drought is likely to result in a shift in the vegetation community structure if the wetland water level falls below the 'absolute minimum' water level, which varies according to vegetation community (Wheeler *et al*., 2004; Wheeler *et al*., 2009; Davy *et al*., 2010). Trajectory diagrams exist for many vegetation types, describing how vegetation communities respond to pressures including lack of water.
- If a shift in the vegetation community has occurred then the community structure of associated wetland fauna is also likely to change.
- The permanence of the new community will depend upon how resilient they are to the post-drought conditions.

5.3 Can we incorporate any impacts resulting from climate change into our understanding and conceptual models?

- Winter (2000) undertook a hypothetical assessment of wetlands in different hydrological and landscape settings and concluded that wetlands whose hydrology is dependent on precipitation are more vulnerable to climate change than those fed by groundwater.
- Acreman *et al*. (2009) calculated that under United Kingdom Climate Impacts Programme (UKCIP) 02 climate change scenarios, reduced summer rainfall and increased summer evaporation will put stress on wetland plant communities in late summer and autumn with conditions becoming too dry in the south of England for some rain-fed communities. In addition, these impacts are likely to be less for wetlands fed by river flows than for rain-fed wetlands.
- 'Rapidly changing climates and habitats may increase opportunities for invasive species to spread because of their adaptability to disturbance,' (Erwin, 2009).
- As part of the current Environment Agency’s 'Wetland Vision and climate change' project, the approach developed by Acreman *et al*. (2009) has been extended to evaluate the impact of probabilistic (UKCP09) climate change scenarios on wetlands across the regions of England and Wales.

5.4 What are the long-term ecosystem impacts (if any) and can we define the threshold(s) beyond which rivers, lakes, wetlands and ponds are 'permanently' altered and deliver reduced ecosystem services?

- The concept of an ecosystem being 'permanently' altered is dependent on the timescale considered.
- Hydrological thresholds have been defined to varying degrees for many wetland flora and fauna. Some of these are semi-quantitative (for example, National Vegetation Classification (NVC) hydro-ecological water level requirements such as Wheeler *et al.*, 2004) while others are more qualitative (minimum area of open water required for wading birds).
- Short-term alteration of plant and animal communities way well occur in response to drought, and these may recover to their previous state (many factors affect this, including presence of a viable seed bank or local population, resilience of the newly established species, occurrence of trajectory reversal event (such as flood)).
- As the severity of drought increases, long-term alteration may occur, particularly if changes in the abiotic nature of the wetland take place. For example, in an extreme case there could be a complete loss of organic substrate (due to oxidation and wind-blown losses of peat) and it could take many centuries for the peat to reform under suitable hydrological conditions.

5.5 Are we and/or our partners collecting the right information to answer these questions?

- In the absence of information from the Environment Agency, and with due regard for financial, practical and analytical constraints, the most important actions to consider are as follows:
    - Development of a conceptual hydrological understanding of the site in question. This can initially be done using a variety of existing data sets including geological and topographic maps, results of previous vegetation surveys (analysed in reference to hydro-ecological guidelines), locations of nearby water sources (such as rivers, springs, ponds and surface seepage zones).
    - Monitoring of water levels in the wetland. Frequency and spatial density of measurement will be site dependent. This would include both open water bodies and the local water table.
    - Monitoring of the water supply mechanisms. These should have been identified in the conceptual hydrological understanding. Monitoring may include: a rain gauge, river stage, groundwater level, surface runoff, and is likely to extend beyond the area of

the wetland. Some of this data is available from the Centre for Ecology and Hydrology's (CEH's) National River Flow Archive (NRFA) and from the British Geological Survey's (BGS's) National Groundwater Level Archive (NGLA). Other potential data sources include the Environment Agency and/or Water Company monitoring networks.

  - Monitoring of ecological 'indicator' species. This could potentially include many species of flora and fauna, and will depend on the site in question.

6 Ponds

6.1 Introduction

- There is a large international literature describing the biota and ecology of temporary ponds which necessarily experience regular drought.
- There are, however, very few studies of the effects of drought on ponds which are permanent or semi-permanent (that is, which dry out only in drought years). However, those that have been undertaken suggest that droughts are as likely to be beneficial as harmful.

6.2 What impacts do droughts have on the ecosystems (including differentiating the impacts of winter (including flushing flows) and summer droughts?

- Water body permanence is one of the major shaping forces on ponds (Welborn *et al*., 1996).
- Periods of drought can be seen as creating opportunities for plants and animals. Many species of plants and animal have mechanisms for exploiting or tolerating drought.
- Drought eliminates fish and other predation pressures, reduces inter-specific competition, can contribute to habitat diversity and may create conditions where growth can proceed very rapidly as water levels drop and water warms up (Schneider and Frost, 1996; Lott, 2001; Werner *et al*., 2007; Ewald, 2008; Chase *et al*., 2009).
- Semi-permanent ponds have for some time been known to be the richest of pond ecosystems (and therefore by implication, amongst the richest freshwater systems) (Collinson *et al*., 1995).
- For species dependent on permanent water, mainly animals, drought is fatal. However, even within these groups, local extinctions may be tolerated at the population level if there are suitable locations from which the species can recolonise.
- This is especially true of all animal groups which have life histories where one or more stage is terrestrial, and another stage aquatic (for example, many aquatic insects, amphibians).
- Currently there are no specific data available to distinguish between impacts of summer and winter drought on ponds.

6.2.1 Abiotic effects

- The broad abiotic trends associated with drying down in ponds can be described in generic terms (Williams *et al*., 2004; Davies *et al*., 2009).

- As water volumes decline, air temperature and solar radiation will probably increase water temperature, although this may be mediated by local factors such as shading and hydrology (that is, groundwater ponds and wooded ponds may heat up less rapidly than surface water fed ponds).
- Increased water temperature leads to rapid growth rates, with some species (such as amphibian tadpoles) seeking out warm shallows (Bancroft *et al*., 2008).
- As water volumes decrease, the concentration of solutes increases (reflected in higher conductivity) (Arle, 2002; Magnusson and Williams, 2006); there is no evidence available to suggest that in unpolluted systems these changes are detrimental, perhaps reflecting the predictability of the seasonal drying cycle and the co-evolution of biotic responses.
- In mildly contaminated systems it is possible that during dry weather, concentrations of nutrients and other pollutants may reach biologically critical levels leading to impacts that would not occur during wetter conditions. In severely contaminated ponds where pollutants are routinely above levels that cause biotic impacts, further drying may create extreme pollution conditions.
- Droughts may exacerbate the impact of biocides on pond systems as reduced water volumes reduce the potential for dilution (Biggs *et al*., 2000).
- Oxidation of sediments when water bodies are dry may lead to biologically beneficial reductions in organic matter content as many wetland plants grow best on mineral substrates; mineralisation of carbon rich sediments may reduce the value of any carbon storage in normally wet basins.

6.2.2 Vegetation

- Many wetland plants benefit from or have adaptations to exploit, periods of drought.
- Aquatic species of waters up to 2-3m deep are unlikely to be impacted; many (such as water lilies) survive growing on wet mud unless there is a prolonged supra-seasonal drought.
- Many aquatic plants are annuals which germinate from seeds or spores and are likely to be reasonably resistant to periods of drought. Sites with a more developed seed bank seem likely to resist drought stress better.
- In waters where stress on fish populations leads to fish kills, drought could liberate aquatic plants from fish-enhanced eutrophication stresses.
- Marginal species are potentially able to extend their range into areas they are normally excluded from by deeper water.
- There is likely to be relatively little impact on species of shallow water as these either depend on (for example, Starfruit) or are adapted to tolerate fluctuating water levels (Water-violet, for example).

6.2.3 Invertebrates

- In near-natural, unpolluted ponds, many pond-associated invertebrates benefit from or are adapted to drought. This may be either through having life cycles adapted to exploit seasonal or intermittent absence of water, release from competition, release from predation pressures or increased availability of habitat.
- The main risks to invertebrates from droughts are likely to come from:
    - Drought-induced changes in ecosystem structure which lead to substantial detrimental changes in habitat quality, for example switching between alternate stable states such as clear water, vegetation-rich to floating lemnopyte-dominated vegetation.
    - Poorly informed management responses in which ponds perceived to be drying out are deepened.
    - In impacted landscapes small water body chemical quality typically shows greater heterogeneity than in larger running waters, especially rivers. Thus whilst ponds often include some of the least polluted systems across landscapes, they also normally include the worst, with low dilution potential and small volumes leading to very poor water quality. Droughts may preferentially enhance this risk, creating severe stress on invertebrate assemblages.
    - As many ponds suffer substantial nutrient pollution and are known to have particularly depauperate submerged aquatic plant communities, invertebrate assemblages in polluted ponds (the majority) may be detrimentally impacted by drawdowns in which marginal aquatic habitat is temporarily lost, with little compensatory habitat in deeper water as a result of the lack of submerged aquatic vegetation.
    - Studies of boreal lake littorals suggest that fluctuations in excess of 2m in water level might be damaging (White *et al*., 2011).

6.2.4 Fish

- Fish in ponds are unlikely to survive drought as they lack physiological survival mechanisms or resistant resting stages.
- However, periods of drought and re-wetting are not automatically damaging to fish populations as ponds in more natural systems, especially in river floodplain and wetland systems, are highly productive for young fish.

6.2.5 Birds

- In summer, breeding water birds are largely concentrated on bigger ponds (0.5ha and above) which typically show the least variation in water levels, so direct effects on habitat extent are likely to be modest.

- On smaller ponds, breeding water birds are typically limited to Moorhen and wetland associated passerines (such as Reed Bunting and Sedge Warbler).
- If water levels drop significantly, islands used as breeding sites may become connected to the mainland, increasing predation risk.

6.2.6 Ecosystem functioning

- Ponds provide a range of ecosystem services which may be affected by drought:
    - *Pollutant interception*: Periods of drought may reduce the ability of pond systems to intercept pollutants, particularly post recovery. Although during dry weather water-borne pollutant transport is reduced to near or close to zero, on the breaking of the drought the system may function less effectively as a result of the disturbance to the ecosystem. For example, aquatic vegetation may have died back and therefore be unable to function as a filter or biological treatment system through surface film processing. Such treatment systems could therefore perform less consistently. It is also possible that periods of drying out could lead to previously trapped pollutants remobilising more readily when treatment ponds re-wet.
    - *Sediment trapping*: Small water bodies are widely used to trap sediment. As with chemical pollutant interception, it is possible that the shutting down of biological, water-based, functions during the drought could reduce the effectiveness of sediment interception post re-wetting.
    - *Carbon sequestration*: Small ponds can trap carbon. Drought may substantially impair this process, especially if deeper waters which are normally permanent dry down and expose organic rich sediments to the atmosphere.

6.3 Depending on the severity of the drought, how quickly do aquatic ecosystems (including rivers, lakes, ponds and wetlands) recover?

- Broadly it seems likely that unimpaired ponds will have a greater potential for recovery than degraded sites. Water bodies in denser networks of freshwater habitats, where there is greater resilience in the system of habitats, also seem likely to recover more rapidly. Stream and ditch fed ponds may also recover more quickly although this may be offset by the fact that inflows typically transport pollutants into ponds.
- It is known that ponds in proximity to other wetlands are richer in species (Williams *et al.*, 2010).

- Recovery appears, therefore, to have at least four possible trajectories, all of which have some supporting evidence:

    - Temporary ponds which refill often recover rapidly with clear and largely predictable sequences of species.
    - Ponds do not recover their special interest as a result of local extinction.
    - Ponds recover but potentially to a quite different endpoint.
    - Ponds recover to a system close to, or with effectively all the original, pre-drought species/function.

  At present it is not known which of these alternatives is most likely.
- Species that are obligate temporary water specialists have strategies for coping with supra-seasonal droughts, for example resting eggs which do not all hatch on first rewetting. They seem most likely to survive supra-seasonal droughts.

6.4 Can we incorporate any impacts resulting from climate change into our understanding and conceptual models?

- There are a number of documented examples of climate change influencing pond biota which may contribute to the development of a conceptual model of drought impacts on ponds.
- Predicted increases in air temperature seem likely to lead to higher water temperatures, particularly in smaller waters. However, there are as yet no observational data on ponds with which to test this prediction.
- Warmer temperatures may alter fundamental ecological processes and are almost certainly changing some species distributions. For example, northward range extensions of some aquatic invertebrates with broadly southern distributions have been noted and advances in spawning dates in Common Frog and Smooth Newt have been correlated with warmer springs (Beebee, 1995).
- Warmer water temperature is a stressor for some aquatic biota, principally those which are entirely dependent on dissolved sources of oxygen. For animals which breathe air (about 50 per cent of all macroinvertebrates, for example) lower water oxygen levels are less obviously stressful.
- At present there is inadequate understanding of the likely impact of climate mediated changes in pond environments to make useful predictions of the impacts of droughts.

6.5 What are the long-term ecological impacts (if any) and can we define the threshold(s) beyond which rivers, lakes, wetlands and ponds are 'permanently' altered and deliver reduced ecosystem services?

- There are no studies available to assess whether droughts have long-term effects on ponds in the UK. However, pond biological richness declined over the period 1996 to 2007 in lowland Britain (Williams *et al*., 2010), a period when there were droughts which may have contributed to biological declines.
- However, primary candidates for causing the observed decline in pond quality are pollutant stressors, and possibly isolation of water bodies and increased shade.
- At present it is difficult to separate the effects of drought stress from other stressors.
- In light of this, the main long-term impacts of drought appear to be:
    - *Increased risk of ponds switching to alternate less desirable stable states*: Freshwater ecosystems, especially those under stress, are well-known for their ability to transition from one stable state to another. It is possible that droughts could trigger or exacerbate this process, causing systems to flip from one state to another (Scheffer *et al*., 2003).
    - *Increased risk of creeping erosion of biodiversity*: Droughts are random (stochastic) events which could contribute to local extinctions of species. In water bodies supporting the only local population of a generally scarce species with no opportunity for recolonisation, droughts may contribute to creeping loss of biodiversity.
- To evaluate the risk of thresholds it would be valuable to further explore recent concepts of 'critical slowing down' which is emerging as a technique for testing the likelihood of collapse of ecosystem function.
- It is not possible at present to define thresholds at which ponds are permanently altered by drought.
- Overall measures to increase system resilience (likely to include better water quality, less isolation of populations, measures to protect critical stocks of biodiversity such as scarce species vulnerable to random extinction) are likely to be the best way of dealing with the risks of drought during a period of uncertainty when the significance of drought impacts is not well understood.

6.6 Are we and/or our partners collecting the right information to answer these questions?

- Partner organisations are collecting some of the observational data which provide an insight into the effects of droughts on ponds.
- We particularly lack data on the risks of regional species extinctions, one of the potentially most significant risks of drought in stressed environments.
- To gain a better understanding of the impacts of droughts at local (water body) scale, experimental manipulations of ponds to simulate drought are required.

7 What is the purpose of monitoring?

There is a large gap in our understanding as to how different rivers respond to drought[12] . This lack of targeted data collection and inconsistent sample periods makes it harder to provide the 'right' information on the impacts of drought on aquatic ecosystems. The Environment Agency states that the development of the National Drought Surveillance Network (NDSN) is required for 'the right type of evidence to aid drought reporting and to help us understand changes in WFD classification status during a drought[13]'. It will also help the Environment Agency advise water companies in setting up their drought monitoring[14].

The Environment Agency states that the objectives of the network are to:

- Bring together selected existing flow-responsive ecology monitoring sites with high quality flow gauging stations.
- Cover all major geologies, so that surface and groundwater catchments of different character are captured.
- Include a range of catchments from near pristine (for example, High WFD status) as well as known flow-impacted sites (non-compliant sites based on current Environmental Flow Indicator) as well as rivers of varying size.
- Where possible, link ecology sites with existing water resource situation reporting sites (indicator flow sites).

An initial attempt has been made by the Environment Agency to select monitoring sites (n=89) that reflect the above objectives, undertaken using 'expert opinion' and local knowledge, rather than a consistent, robust and repeatable approach. The selected sites are therefore unlikely to be representative of the range of drought impacts that might be expected in different water bodies and aquatic ecosystems (as described earlier). Similarly, without the selection of representative sites, monitoring and reporting will reflect the inherent bias of the selected sites.

However, what the monitoring seeks to achieve and how the results will be used are less clear. These are important questions, as they will determine the parameters and frequency of the monitoring programme. It is proposed that the NDSN network should *contribute* to monitoring whether selected UK water bodies, which have been defined by the Water Framework Directive (WFD) classification process, achieve the 'Good Ecological Status' (GES) / 'Good Ecological Potential' (GEP) / 'no deterioration' requirement set during river basin planning (in the River Basin Management Plan (RBMP)). This assumes that the existing UK Technical Advisory Group (UKTAG) UK Environmental Standards and Conditions[15], which, when combined, represent society's view on what is considered to be good status or good potential for different water

[12] The existing network is based only on rivers and does not include other habitat types (lakes, wetlands and ponds).
[13] Note that this pre-supposes and would require nested standards and conditions for different water bodies specifically for drought, an unrealistic expectation at present. Further, drought impacts can only be fully understood and assessed retrospectively.
[14] The Environment Agency has undertaken a 'Drought Monitoring Best Practice Project' (Akande, 2006), which proposes a four-step drought monitoring procedure. It provides interim advice on setting environmental triggers
[15] http://www.wfduk.org/sites/default/files/Media/Environmental%20standards/Environmental%20standards%20phase%201_Finalv2_010408.pdf; http://www.wfduk.org/sites/default/files/Media/Environmental%20standards/Environmental%20standards%20phase%202_Final_110309.pdf

bodies[16], has set standards and conditions for drought, and that the standards and conditions take into consideration the fact that different water bodies respond differently to drought. The current UKTAG Environmental Standards and Conditions do not do this, neither are standards and conditions specifically set for droughts. This makes monitoring drought compliance impossible. This requires either revising the Standards and Conditions (to accommodate drought standards and conditions), or changing the objective of the monitoring.

We suggest that monitoring for the exclusive purpose of furthering our understanding of the ecological impacts of drought, although important, should not be the objective of the NDSN. Under natural or pristine conditions, the ecological impacts of drought (its duration, intensity, location, timing, and seasonality) are only of importance to science and to set a reference condition against which other impacts may be measured or targets set. As such, this review suggests that the NDSN should be an adaptive network, which focuses on a core of catchments with minimal hydrological impact and quantified impacts of other pressures. This will provide a reference for before, during and after drought. The additional effects of drought on hydrologically impacted catchments could then be brought in by linking to and potentially tweaking other networks (such as Catchment Abstraction Management monitoring programme). A full understanding of drought impacts would also require landscape-scale level monitoring for the reasons given earlier.

It is therefore critical that the Environment Agency clarifies its monitoring goals and objectives, once this is clear, further suggestions can be made to strengthen and enhance the NDSN.

[16] The assumption is that the 'status' of the water body will sustain ecosystem structure and function at a desired level and therefore deliver valued ecosystem services.

8 Conclusions

The following key messages are presented as conclusions:

- Drought is a natural disturbance that can contribute to ecosystem diversity.
- Drought intensity, duration and frequency is predicted to alter with climate change.
- Drought is usually defined relative to the prevailing ‘normal’ conditions of a locality; in other words, drought definitions necessarily assume system stationarity.
- Long-term data are required to account for ecosystem response to meteorological and hydrological variability so that drought can be placed in the context of natural variability.
- However, as many drought studies are opportunistic, there are few long-term datasets to provide this context.
- Accordingly, we have a limited understanding of the effects of drought, recovery from drought and of the lags and long-term changes that drought may have on populations, communities and ecosystems.
- Droughts exhibit spatial coherence as rainfall deficits typically affect large areas simultaneously. Hence, the impacts of drought are highly variable at a landscape-scale, determined, in part, by landscape-level physical properties and processes, antecedent conditions and water body connectivity.
- An important distinction can be made between short -term within-year water deficiencies (seasonal droughts) and multi-year water deficiencies (supra-seasonal droughts).
- Supra-seasonal droughts have significantly greater effects on water resources and ecosystems than seasonal droughts.
- In the UK, for example, supra-seasonal droughts have a significant effect on aquifer recharge and storage and hence on security of supply and on ecosystems, particularly in the south and east where water resources are predominantly groundwater-dependent.
- The assessment of drought effects must include appropriate indices for detecting and assessing drought. Indices must be capable of discriminating between low flows or levels and drought flows or levels.
- This also requires application of agreed hydrological thresholds to define when droughts start and end.
- Drought represents a disturbance to an ecosystem.
- A drought event, unlike a flood event, is a ‘ramp’ disturbance which starts slowly, but steadily builds in intensity and spatial extent.
- Ramp disturbances may dissipate gradually, or break with floods.
- Aquatic ecosystem response to a drought is a ‘ramp’ response with step changes. Response depends on the resistance[17] and resilience[18] of the

[17] Ecosystem resistance refers to the ability of biota to withstand the stresses of disturbance.
[18] Ecosystem resilience refers to the capacity of biota to recover from disturbance, even if biota and ecological processes are diminished.

aquatic biota, which is, in part, shaped by the legacies of past events (ecological memory).

- Response also depends on how the diminishing water volume reduces the available wetted habitat.
- The spatial pattern of wetted habitat loss is dependent on channel morphology and bed topography.
- The temporal pattern of habitat loss (rate of change) is dependent on the timing, intensity and duration of the drought.
- Drought reduces the volume of water and the wetted perimeter of a water body, affecting lateral, longitudinal and vertical connectivity.
- It is important to recognise that connectivity can be restored at any point during the drying process.
- However, during a supra-seasonal drought, lateral, longitudinal and vertical connectivity is lost, so that drought breaking is required for the restoration of vertical, longitudinal and lateral connectivity.
- In the case of a seasonal drought, generally only lateral connectivity is lost (although occasionally in severe seasonal drought, longitudinal connectivity may be lost); hence drought breaking generally only requires the restoration of lateral connectivity.
- The shape of the drying curve depends on the morphology of the water body and the rate of drying.
- Thus, for example, in a small, upland geomorphologically diverse stream with a stepped channel cross-section, the drying curve is likely to be stepped.
- In contrast, a larger lowland stream with a rectangular or semi-circular cross-section would have a smoother drying curve.
- A response gradient exists between these two broad channel 'types'.
- Similarly, the shape of the re-wetting curve would depend on morphology and the characteristics of the precipitation that breaks the drought.
- Channel modification therefore has a significant impact both on aquatic ecological response to drought and on ecosystem recovery from drought.
- Abiotic elements respond to the increased drying.
- In the case of rivers, water temperature generally increases, as does conductivity, nutrient concentrations, dissolved organic matter and particulate organic matter.
- Dissolved oxygen initially increases, but later significantly declines as water bodies fragment.
- Suspended particles and turbidity also decline, reflecting a reduced input from the catchment.
- Fine sediments accumulate as flow and mixing decrease.
- Abiotic response to re-wetting is strongly influenced by catchment and channel condition, antecedent conditions and the characteristics of the precipitation.
- Generally, however, pulses of particulate organic matter, dissolved organic matter, nutrients and sediment are introduced into the water body followed by a gradual recession.

- The relative influence of these pulses of chemicals, nutrients and organic matter on re-wetting can be a major determinant of ecosystem recovery.
- The biogeochemistry of ecosystem recovery following a drought remains largely unexplored.
- Biotic response to drying will depend on the resistance and resilience of the biota and the availability and use of refuges.
- With drying the consumption of organic debris by microbes and detritivores can drop, reducing the breakdown rate of organic matter, a primary ecosystem function.
- Increased green algal growth and primary production may be an initial response to increased nutrient concentrations. However, with further drying algal biofilms may become exposed, marking a shift back to an assemblage dominated by diatoms.
- Drying may impact macrophyte communities by eliminating some species and creating gaps for opportunistic species to establish.
- There is likely to be a shift as the channel boundary dries from aquatic to terrestrial plant assemblages.
- The intensity and the duration of the drought will determine the extent to which this process occurs.
- Invertebrate response to drying may also be an initial increase in density, as they become concentrated in the remaining wet habitat.
- However, with further drying and habitat loss, competitive and predatory interactions may intensify, and eventually lead to a decline in invertebrate numbers.
- Biotic resistance to drought is substantially mediated by the use of refuges, manifested in the stepped response of the biota. These steps correspond to the sequential drying of different habitats which act as refugia.
- As with macrophytes, invertebrates and fish with adaptations to drought conditions can dominate the community in between these steps until water completely disappears.
- Further broad types of biota have contrasting sensitivities to each step; for example, emergent macrophytes are strongly impacted by the recession from stream margins, while fish are strongly impacted by the loss of the flow continuum.
- Non-native invasive species may exploit drought conditions and impair the re-establishment of native species.
- Many organisms are adapted to summer low flows; winter droughts have far more of an effect as many plants and animals over-winter as juveniles. Winter droughts can evolve into a supra-seasonal drought.
- There is very little published information on the biotic response to re-wetting. It is reasonable to assume, however, that this is, in part, dependent on the duration and extent of drying, the morphology of the water body and whether the system is perennial or naturally intermittent.
- Hence, recovery from a seasonal drought is likely to be rapid; for supra-seasonal droughts, recovery is likely to be subject to a time lag and is less predictable.

- Algae, invertebrates and fish can respond rapidly to re-wetting. This recolonisation occurs from a range of potential refuges.
- Macrophyte recovery is successional, though this can be rapid or take years depending on the extent of terrestrialisation that occurred in the drought.
- Similarly to the process that occurs in the drying phase, the biotic response to re-wetting is stepped, as habitats are sequentially replenished with water.
- Different forms of biota respond differently; for example, fish mainly recolonise once flowing water returns, but invertebrate recolonisation occurs in each of the steps listed above.
- It should be noted that different water body 'types' have distinct responses to different 'types' of drought.
- Biotic effects of drought are easier to detect in naturally intermittent streams due to the loss of surface water, although the change to community structure may be more marked in a perennial stream or river.
- Naturally intermittent streams and rivers will also undergo fundamental changes in community structure if the duration of the drought extends over more than one winter as in the case of supra-seasonal droughts.
- In addition, there appears to be marked differences in sensitivity and response of upland and lowland streams in the UK.
- Many UK streams and rivers are heavily modified to limit flood risk, greatly homogenising the available habitat and reducing connectivity.
- For this reason, sites characterised by habitat modification are often more sensitive to drought than those that are not.
- Geomorphologically diverse sites, with little or no habitat modification, display the features that provide refuges and confer resilience to drying: a range of flow environments, deeper pools and boulders, logs and plants.
- Conversely, homogenous stream or river channels are more prone to rapid and total drying, augmenting the effects of drought on biota.
- This effect is, in part, mitigated because streams and rivers with degraded habitats often have less biotic diversity to lose than sites in good hydromorphological condition.
- Nevertheless, it is apparent that there is a conflict between managing flood risk and maintaining a stream or river's natural resilience to drought.
- Similarly, there is evidence to suggest that response (and recovery) is impacted by other pressures, including abstraction and pollution.
- Accordingly, the National Drought Surveillance Network (NDSN) should be an adaptive network that accounts for different water body 'types' which includes sites with minimal hydrological impact and quantified impacts of other pressures (mainly habitat modification and pollution).
- This will provide a reference for before, during and after drought for different water body 'types'.
- The additional effects of drought on hydrologically impacted catchments could then be brought in by linking to and potentially tweaking other

networks such as Catchment Abstraction Management Strategy (CAMS) network.

- For lakes, drought impacts are affected through a decrease in water levels and volumes, reduced flushing rates and the lower input of nutrients from diffuse sources within the catchment.
- There are broad differences in the impact of drought on different wetland ‘types’. These differences are determined by the hydrological processes feeding the wetland.
- Three wetland ‘types’ are evident: rain-fed wetlands, river-fed wetlands and groundwater-fed wetlands.
- In general, rain-fed wetlands will respond rapidly to drought since alternative hydrological mechanisms that could buffer the response do not exist.
- In river-fed wetlands, the fluctuation of water levels within the wetland is buffered by the transfer of water between the river and the wetland.
- In groundwater-fed wetlands buffering of the hydrological conditions of the wetland is pronounced.
- Hence, groundwater-fed wetlands are less sensitive to seasonal drought but could be significantly impacted by supra-seasonal drought.
- In addition to the aforementioned hydrological processes, other factors affect how a wetland responds and one of the most important of these is soil properties.
- In permeable soils, the water table in the wetland will reflect the variations in water supply mechanisms.
- In low permeability soils there is only a weak connection between the water supply mechanism and the moisture available in the wetland.
- Ponds lie naturally on a gradient from completely permanent, through semi-permanent, to truly seasonal water bodies, which dry in all or most years.
- In the UK, around 5 per cent of ponds are truly seasonal, approximately 25 per cent are semi-permanent and the remainder are permanent.
- It can be inferred from studies of semi-permanent and seasonal ponds that droughts are likely to affect pond ecosystems through: 1) lowering of water levels and volumes, 2) habitat loss, 3) reduced flushing rates and, 4) lower inputs of nutrients from diffuse sources within the catchment.

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