



**Literature review of short-term flow reduction ecological impacts
and recovery: R16115QQ**

Scottish Environmental Protection Agency

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1. Introduction

1.1 Background

The UK Technical Advisory Group on the Water Framework Directive (WFD) (UKTAG)¹ first developed water resources standards for rivers in 2008 (UKTAG, 2008). These were based on river typology developed by Holmes et al. (1998) and were expressed as maximum allowable percentage deviations from natural flow percentiles. Different percentage deviations were defined for rivers of High, Good, Moderate and Poor WFD status. The standards for Good, Moderate and Poor status varied depending on season and were designed to protect macrophytes in spring and early summer, and macro-invertebrates and fish in the late summer and early autumn (providing additional protection at times of the year when species are at key stages of their life cycles).

These standards were reviewed in 2012 and updated recommendations were published in 2014 (UKTAG, 2014). The review concluded that there was no new quantitative information that could be used to refine the existing standards for low flows ($<Q_{n95}$)², although it was noted that this topic would be kept under review. In contrast, the UKTAG did conclude that there was a need to revise recommendations on flow standards for medium and high flows. These affected the environmental standards for the Moderate and Poor WFD status categories, but did not affect those for the High and Good status categories. The revised environmental standards were again expressed as maximum allowable percentage deviations from natural flow percentiles, with different percentage deviations defined for rivers of different types.

These current environmental standards have been developed to help assess the risk of deterioration in ecological status which may arise from proposed changes in river flow, estimate the status of rivers already subject to flow alterations in cases where no suitable biological methods are available and inform investigations into the potential causes of biological damage. However, the standards take no account of the duration and return period of exceedance; in theory exceedance of a standard for one day in a year gives the same outcome as continuous exceedance. In terms of impact on river ecology these two scenarios may be very different.

¹ A working group of experts drawn from the UK environment and conservation agencies, also including representatives from the Republic of Ireland: Natural Resources Wales (NRW), Natural England (NE), Environment Agency (EA), Northern Ireland Environment Agency (NIEA), Joint Nature Conservation Committee (JNCC), Scottish Environment Protection Agency (SEPA), Scottish Natural Heritage (SNH), Republic of Ireland's Department of Environment, Community and Local Government (DECLG).

² Flows that are smaller than the flow exceeded for 95% of the time (347 days per year on average) in a natural river with no abstractions and discharges.

The current standards are considered to be adequate for abstractions that operate for all, or most of the time. However, for temporary, occasional abstractions they may be over-precautionary, with scope for introduction of a temporal and spatial element allowing short-term deviation, if it can be demonstrated that this can be allowed without causing significant environmental impacts.

The Joint Nature Conservation Committee (JNCC) has recently published an updated version of its Common Standards Monitoring Guidance for Rivers (JNCC, 2016)³. The guidance sets mandatory flow targets which are taken as the minimum expected for SAC rivers where locally agreed targets are not already in place. In a similar way to the UKTAG (2008 and 2014) guidelines, these are expressed as maximum allowable percentage deviations from natural flow percentiles, with different percentage deviations defined for rivers of different sizes. In assessing compliance with these standards, some allowance is made for spatial and temporal variation. The wording of the guidance provides some allowance for judgement based on experience and site knowledge, allowing for a maximum of:

- 10 days of continuous non-compliance in any one year, or 20 days of non-compliance overall in any one year, as long as the increased impact on naturalised flows is not dramatic (e.g. greater than twice the deviations allowed for by the flow targets that apply); and
- non-compliance over a total river length of no more than 5% of an assessment unit, again, as long as the increased impact on naturalised flows is not dramatic.

The focus of this study is to investigate whether there is evidence to support similar temporal variation from the current standards recommended by UKTAG. The temporary, intermittent type of abstraction this is pertinent to typically operates for the purposes of irrigation, or emergency water supply, during dry periods when river flows are naturally low. Thus, the focus of interest is on abstractions at the low flow end of the flow duration curve.

1.2 Aims

This project aims to review evidence of the impacts of short-term low flow events on riverine ecology, and subsequent recovery, with particular focus on the implications for WFD classification and regulation using river flow standards.

³ Prepared by the Inter-agency Freshwater Group, comprising representatives of SNH, NE, NRW and NIEA. The guidance is intended to cover condition assessment of river Site of Special Scientific Interest (SSSI), Area of Special Scientific Interest (ASSI – applies in Northern Ireland only) and Special Area of Conservation (SAC) habitat.

1.3 Objectives

The specific objectives of the project are to:

- Conduct a literature review of both published and grey literature relating to temporal aspects of short-term (typically <2 weeks and <Q95) low-flow impacts in rivers, to include the influence of magnitude and duration of low-flow events on both degree of ecological impact and recovery period. This will include impacts of abstraction when flows are already low and complete drying up.
- Conduct telephone interviews with key regulatory agency staff to capture their knowledge of particular events.
- Summarise and evaluate quantitative or semi-quantitative evidence of low-flow exposure-period impact and subsequent recovery relevant to flow standards development.

The expected outcomes of the project are to:

- Establish a better understanding of the impacts of short-term extreme low-flow events in rivers; and
- Enable revision of river flow standards to better reflect actual flow pressure impacts.

1.4 Report structure

This report is structured as follows:

- Section 2 presents the conceptual framing for this literature review;
- Section 3 presents the methods used and a summary of the results of the telephone interviews and literature search;
- Section 4 presents the results of the review in relation to ecological effects of short duration abstraction on rivers, based on changes to physical habitat;
- Section 5 presents the results of the review in relation to other factors influencing ecological response, specifically typology and confounding/compounding pressures;
- Section 6 presents a summary of the review and remaining knowledge gaps;
- Section 7 evaluates the efficacy of existing environmental flow standards for licensing short term abstraction;
- Section 8 presents a decision framework and evidence base to aid future licensing decisions;
- References are presented in Section 9; and
- Summaries of the telephone interviews are given in the appendices.

2. Framing the literature review

2.1 Conceptual framework

2.1.1 Conceptual overview

Water flow is important because it is the primary control of the physical character of river channels, which in turn is a major influence on the organisms living there (Bunn and Arthington, 2002; Petts, 2009). The connections between changes to river flow and ecological impacts are complex, involving multiple interacting parameters operating at different spatial and temporal scales. To be able to manage river flows to meet ecological objectives, a working conceptual understanding of these connections must be established.

Whilst conceptual models of dynamic systems like rivers can be made almost arbitrarily complex (Feld et al. 2010), the functional connections and feedbacks amongst discharge, hydraulic and geomorphological parameters are well-described in the literature (e.g. Hynes, 1979; Lewin, 1981; Allan, 1996). Three examples of conceptual frameworks are particularly relevant in framing the terms of this review (Boulton, 2003; Mainstone, 2010; and SNIFFER, 2012).

The relationship between abstraction-induced hydrological change and properties of the physical habitat is exemplified in a conceptual model proposed by Boulton (2003) (Figure 2.1). As discussed in Section 2.2, Boulton's model was developed in the context of drought progression; however, it emphasises the importance of the magnitude of extreme low flow events, with successive threshold changes in habitat availability proposed, and associated changes to habitat quantity, character, connectivity and water quality. Reduction in flow initially results in proportionate reductions in habitat quantity and quality, but as the magnitude of reduction increases, a series of thresholds are reached; the loss of riparian habitat, the loss of longitudinal connectivity and dewatering of the channel (the absence of surface water throughout the channel). In Boulton's model, the step changes in habitat availability correspond with the loss of macroinvertebrate taxa; as water level drops, sharp reductions in richness occur where marginal habitat (littoral or riparian zone) becomes isolated (1-2); then as riffles become dewatered resulting in loss of connectivity, there is a reduction in flow velocity and deterioration of water quality (2-3); then, complete loss of surface water (dewatering), resulting in the loss of all but the most tolerant taxa (3-4). Equivalent models could be developed for other receptors, and in this case the use of macroinvertebrates is intended to illustrate the broader linkages between habitat and biological response.

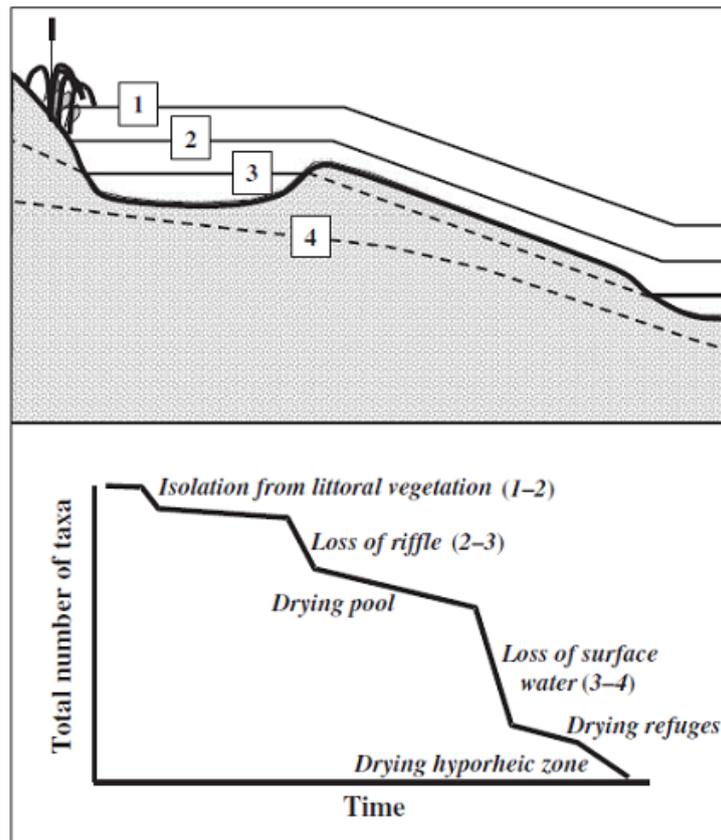


Figure 2.1 Conceptual model of the response of macroinvertebrate taxon richness to changes in habitat character and connectivity associated with a drought event, in relation to its duration (source Boulton, 2003)

Mainstone (2010) offers a further conceptualisation of the changes in macroinvertebrate density and abundance with time, following a reduction in habitat quantity associated with a low flow event (Figure 2.2). This model describes the physical effect of macroinvertebrates becoming concentrated in the shrinking habitats and the subsequent biotic effects (principally predation). A reduction in habitat quantity results in the concentration of macroinvertebrates in the remaining space, resulting in initial increases in the recorded densities (time-point a). However, density dependent increases in predation rate and mortality, as well as increased drift rates, result in a decrease in the density of prey species (time-point b). As with Boulton's (2003) model, equivalent models could be developed for other receptors, and in this case the use of macroinvertebrates is intended to illustrate the broader linkages between habitat and biological response.

A simple low flow response model can be constructed around the life history features that control fish population dynamics and fitness (Figure 2.3), combining the primary abiotic factors, biotic factors due to interactions with other biota and the internal stress factors that respond variously to almost everything else. Quantitative links between these interacting factors with regard to low flow effects have not yet been established in the scientific literature.

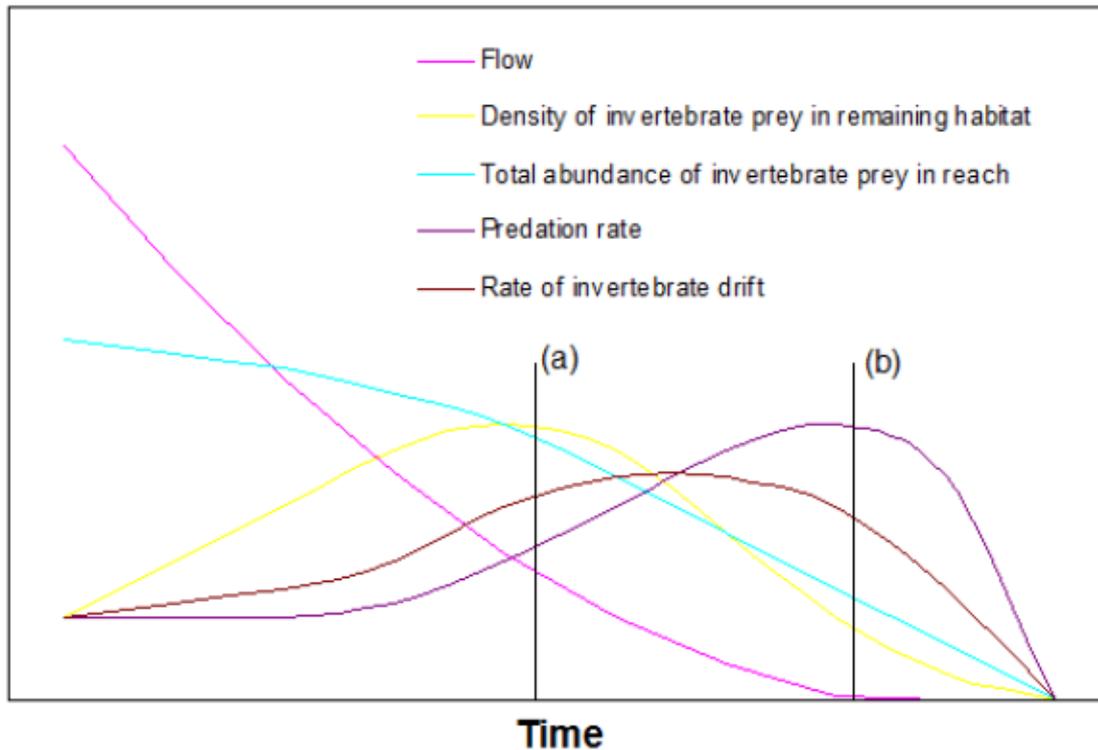


Figure 2.2 Conceptual model of macroinvertebrate response to reduced habitat quantity associated with a low flow event, in relation to duration. Observation of community at time point (a) – high invertebrate prey density, low predation rate; time point (b) - low prey density, high predation rate (reproduced from Mainstone, 2010)

Flow-related factors that affect life history features (survival, reproduction and movement) beyond the fishes' natural adaptive capacity (Lytle and Poff, 2004) will lead to demographic changes. The introduction of stress into such models, which normally include survival and fertility, explicitly recognises that repeated low level, short-term impact might, on the basis of strong experimental evidence, induce changes in the more conventional traits such as growth, maturation and fecundity. These effects, whilst complex to describe, nevertheless represent potentially important mechanisms in the context of this review.

Low flows generate many individual stressors (e.g. crowding, starvation, exposure to predators and pathogens, alteration of temperature, connectivity loss and water quality changes). General responses of fish to such stressors, separately or in combination, have been studied independently of flow and therefore some inferences with respect to the likely effects of low discharge can be developed through a conceptual framework that links impact to population (and community) level responses.

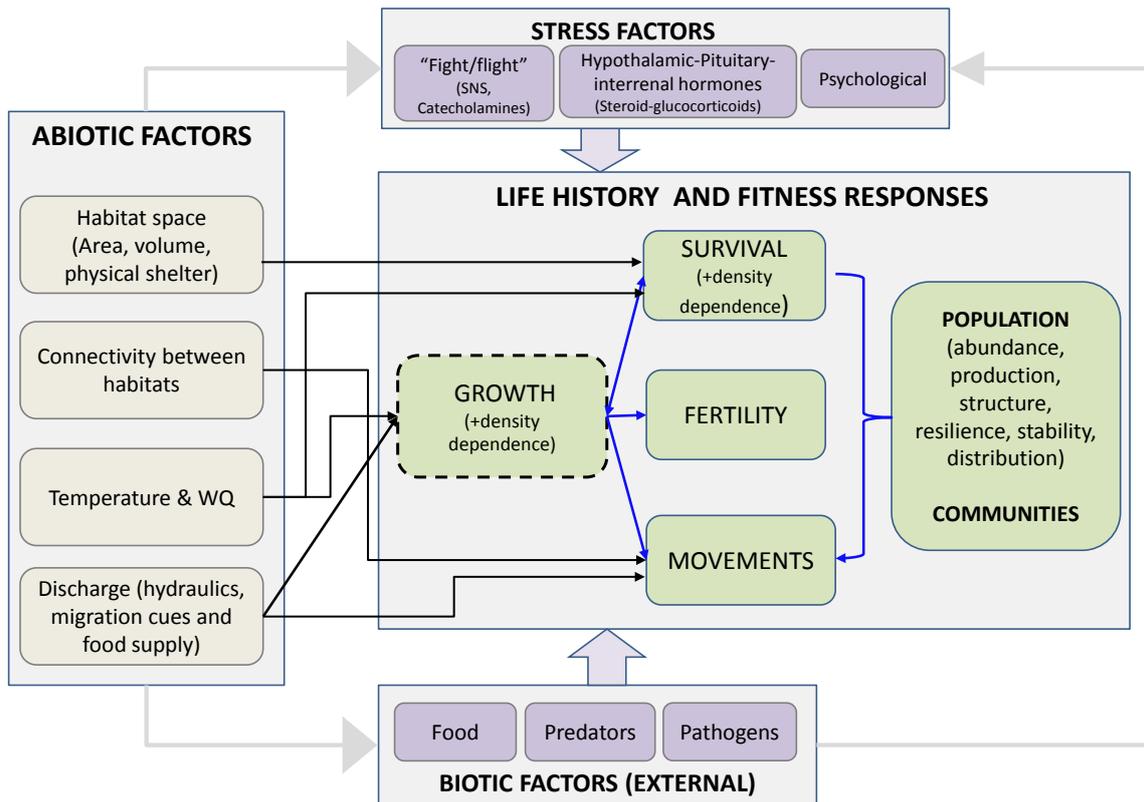


Figure 2.3 Conceptual model of the effects of short-term low flow events on fish population dynamics. Abiotic factors are directly caused by flow reduction. Biotic factors reflect changes in other taxa and consequential direct interactions with fish. Stress effects represent internal biochemical and hormonal changes that are in addition to, but may act synergistically with, the direct effects through behavioural and physiological responses. Density dependence is noted, being a space-related factor affecting survival and growth.

In the simplest of terms, abstractions affect water flow which in turn alters the hydraulics and physical structure of river channels, and adjacent riparian zones: the combination of which forms the river channel landscape occupied by organisms and their ecosystems.

SNIFFER (2012) presented a series of conceptual models and a supporting evidence base which simplified these interconnections, presenting the most important linkages between pressures and impacts. One of these, for 'extreme and extended low flows', forms an appropriate basis for assessing likely changes that may result from short-duration abstraction (see Appendix I).

As described in SNIFFER (2012), other reviews (e.g. Acreman et al. 2008) and the underpinning scientific evidence base (e.g. Richter et al. 1996, Olden and Poff 2003), hydrological changes⁴ have attributes of magnitude, duration, timing, frequency and rate of

⁴ Hydrological change in this context refers to changes in river discharge.

hydrological change. Sequencing of hydrological events (i.e. the order of events relative to one another rather than to the time of year) is also sometimes differentiated from timing.

2.1.2 *Duration and extent*

For this review, it is short-term events that are of interest. Typically these are caused by intermittent abstraction for irrigation, emergency water supply, or a lack of flow release from reservoirs, and are often operated during dry periods when river flows are naturally low. Such events are typically expected to be of durations of one month or less and, therefore, low flow events of durations of between <1 day to approximately one month are the primary focus of this review. Where examples of events lasting for >1 month are deemed relevant to the review, these are included, with the longer timescales noted.

One important feature of such abstractions is that, because by their nature (the abstractions being intermittent and of short duration), their effects may be overlooked or greatly diminished by reliance upon the flow duration curve; changes to the flow duration curve may be negligible, but impacts on ecology may be out of all proportion to their hydrological effects when summarised in this way.

As a general rule, the spatial extent of hydrological changes associated with these abstraction activities may also be localised: spatial extent increases with increasing abstraction volume, relative to stream size, and decreases with the degree of downstream flow accretion. The hydrological effects of these types of abstraction are often quite localised, but this does not mean that the ecological impacts cannot extend further.

2.1.3 *Magnitude, frequency, timing and rate of change*

Aside from the defining feature of duration, the property of short-term low flow events considered to be of greatest relevance to this review is magnitude: the most studied cause of ecological impact relating to flow (Monk et al. 2007). This review is primarily concerned with extreme low flows (primarily flows <Q95).

Frequency, timing, sequencing and rate of change are considered in this review primarily in terms of their interaction with duration and magnitude effects. With regards to frequency, short-term abstractions for irrigation or similar are unlikely to be isolated events; rather, they may be repeated on a weekly, or more frequent, basis. The significance of the frequency of short-term low flow events relates primarily to the resilience of ecological communities, i.e. whether the community is able to recover between short-term low flow events, or whether the community remains impacted owing to repeated disturbance associated with the frequency of disturbances.

In relation to timing, severe low flows from short-term abstractions (such as spray irrigation) are most likely to occur during the late spring to early autumn period, which, in the case of groundwater dominated catchments, might coincide with the period when low flows are naturally most likely (autumn) and to which biota are most likely to be adapted (and hence most resistant to impacts). Nevertheless, severe low flows that are infrequently or never encountered naturally may still cause significant stress, and the effects of low flows and high temperatures (or other seasonal effects) may reinforce one another. Neither can abstraction

induced low flows be discounted at other times, when biota may be less resistant or resilience may be compromised by other factors.

2.1.4 *Habitat and biological response*

Organisms in rivers typically respond only indirectly to the hydrological changes described above. They do so via the hydraulic conditions created by the interaction of river discharge and the geomorphology of river channels, and by interactions of discharge and the chemical quality of the water. Together, SNIFFER (2012) terms these effects as the 'habitat state', and the hydraulic and geomorphological (hydromorphological) aspects as the physical habitat.

The properties of the physical habitat state that affect biota are its quantity, connectivity, character and diversity. Impacts upon biota depend upon the nature (magnitude, duration, timing, frequency and rate of change) of the changes in the habitat (hydromorphology and water quality) state, and upon the sensitivity of the organism to these changes at a given stage of its life: Can the organism resist the changes through physiological or behavioural changes, and maintain its ability to survive, breed and disperse? If it cannot, can others of its kind recolonise, recovering the population quickly and affording resilience in the face of change?

At an organism level, change and adaptation is achieved through the biological processes of mortality, competition, predation, movement and reproductive success and such changes may favour one organism (or type of organism) and impact on another. Such changes at organism level aggregate upwards to changes at a community or an ecosystem level; affecting abundance, diversity, succession and ecosystem functioning. It is these properties and how they are measured using standard assessment and classification tools that determine the ecological status of a surface water body.

Thus, the effects of hydrological change are themselves multi-faceted, and their relationship to the changes that matter to biota – changes to habitat – may be non-linear and complex. They further highlight the importance of biotic interactions, which may be even more complex. Amongst other factors, these introduce considerations of timing with respect to life stage, the ability of organisms to learn and populations to adapt, the importance of antecedent conditions (and therefore of history and frequency) and the potential for lagged responses. Broadly, these responses fall on a spectrum between ramp and threshold effects, which operate differently even over the short timescales of interest to this review (Miller et al. 2007; Verdonschot et al. 2015). For ramp effects (effects with a gradual increase in impact over time), impacts to which biota may be resistant over the very short term may have a greater impact over the longer periods under consideration as physiological or behavioural adaptations cease to be as effective (Verdonschot et al. 2015). For threshold effects (or step changes), impacts may be initially minor, but as time progresses there is an increased probability of more sudden change. These effects are illustrated in Figure 2.4.

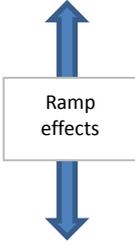
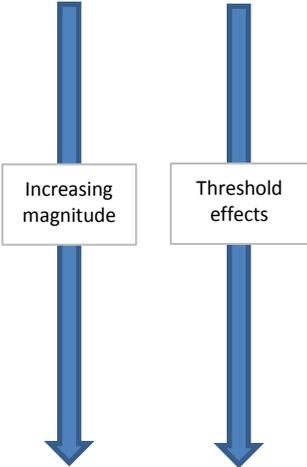
	Effect	Alteration of habitat state	Interaction with duration
	Reduced habitat quantity	<ul style="list-style-type: none"> - Reduced depth - Reduced wetted area 	n.a.
	Reduced habitat quality	<ul style="list-style-type: none"> - Reduced velocity/ stagnation - Possible reduction in WQ 	Limited. However possible increasing deterioration in WQ with time
	Exposure of riparian zone	<ul style="list-style-type: none"> - Loss of riparian habitat 	n.a.
	Loss of connectivity (loss of riffles, formation of disconnected pools)	<ul style="list-style-type: none"> - Loss of riffle habitat - Severe reduction in wetted area - Possible severe reduction in WQ - Loss of connectivity 	Strong interaction with duration - water quality can undergo drastic changes within time periods of hours/ days
	Channel dewatering	<ul style="list-style-type: none"> - Severe loss of habitat - Severe reduction in water quality in channel substrate/ interstitial spaces 	Strong interaction with duration - whether the substrate remains wetted is dependent on duration and might be measured in hours/ days

Figure 2.4 Changes to the habitat state associated with the magnitude of short-term low flow events and their interaction with duration

2.2 Potential effects of short duration abstraction

The models of SNIFFER (2012), Boulton (2003) and Mainstone (2010) were developed in consideration of events of longer duration than those of primary interest to this review, measured in months or years, rather than days or weeks. The rate of change may govern the speed at which threshold effects are reached, but even so some of the effects described may be more important for permanent changes and less so for intermittent, short-term abstraction effects. It is likely, for example, that of the changes to habitat, hydraulic stress, localised sedimentation and short-term effects on oxygen exchange within the river bed would be more important than longer-term landform changes (which are likely to be negligible). Likewise, it is uncertain whether sufficient time elapses for the postulated biotic effects to manifest and be observed in the context of short-term low flow events. This is the purpose of the review; to determine the evidence for impacts over short durations, for which the conceptual models frame the questions but do not, on their own, provide the answers:

- What is the effect of reduction in habitat quantity?
- What is the effect of reduction in habitat quality (character and diversity)?
- What is the effect of loss of connectivity?
- What is the effect of channel dewatering?

These questions are arranged along a gradient of increasing magnitude of effect, following the model of Boulton (2003), although it is acknowledged that effects may happen concurrently, or the sequence may differ, depending upon specific local circumstances.

In addressing each question, the literature review must also account for duration (even over the short duration abstraction of interest to this review) and for the interacting effects of frequency, timing/sequencing and rate of change.

And finally, a number of other, subsidiary questions must also be addressed if the review is to fully inform regulation of short duration abstraction:

- What is the effect of typology?
- What is the effect of confounding factors?

3. Review methods

The approach of this review was to explore the literature available on the basis of both telephone interviews with regulatory staff members and a global scientific literature search.

3.1 Telephone interviews

Telephone interviews with regulatory body staff were conducted in order to facilitate access to quantitative and semi-quantitative examples of the effects of short-term low flow events held within the respective agencies. Seven members of staff from the Environment Agency (EA) and Natural Resources Wales (NRW) volunteered to contribute on the basis of having experience in areas of work relevant to the theme of this review. These were:

- Richard Chadd (EA);
- Mike Dunbar (EA);
- Judy England (EA);
- Paul Greest (NRW);
- Dominic Longley (EA);
- Graeme Peirson (EA); and
- Mark Warren (EA).

Interviewees were provided with a briefing note in advance of the interviews to allow for appropriate preparation and to request that any reports/ data of relevance be provided before the interview took place. The briefing note also contained the primary questions to be covered. The briefing note is included in this report as Appendix II.

3.2 Literature search

The literature search was conducted in a systematic way using specific search terms, but it was not a formal systematic evidence review. The majority of quantitative and semi-quantitative evidence was identified from within the peer-reviewed scientific literature.

A global scientific literature search was undertaken in April 2017 using computerised searches of the ISI Web of Knowledge which includes the following databases: Web of Science (1990-), BIOSYS Citation Index (1969-), BIOSYS Previews (1969-), Data Citation Index (1900-), MEDLINE (1950-) and Journal Citation Reports. The search was based on combinations of the search terms that were discussed and agreed with the project steering group (Table 3.1). The search terms were combined to include hydrological effect and ecology, plus in some cases a term relating to the cause of the stressor, compounding pressure, or environmental flow standards.

Table 3.1 List of search terms

A) Relating to stressor	B) Relating to hydrological effect	C) Relating to ecology	D) Relating to compounding/ confounding stressors	E) Relating to flow standards
Drought	Temporary flow (s)	Ecological impacts	Multiple pressures	Flow standards
Abstraction	Short-term	Ecology		Environmental flow standards
Irrigation	Low flow (s)	Recovery		
	Duration	Resilience		
	Intermittent flow (s)	Resistance		
	Low velocity	Seasonality		
	Ponding	Stranding		
	Predictability			
	Flow permanency			
	Winterbourne			
	Ephemeral			
	Depleted reach			

3.3 Results of telephone interviews

The interviews produced mainly anecdotal evidence of short-term low flow events and quantitative/ semi-quantitative reports were limited. Examples of the types of events reported included cessation of augmentation flows; where temporary bypass channels were installed for maintenance works to be carried out; the temporary draining of online fishing lakes for maintenance and temporary damming of streams in order to fill newly dug ponds. Only two examples were provided that were supported by quantitative or semi-quantitative data. However, further to the examples that were given, the interviews allowed for conceptual discussion which helped to focus the search of the wider literature. Where relevant this report refers to anecdotal examples provided and provides examples from the literature of relevance to the example. The telephone interviews were invaluable for discussion of flow standards and licencing/ regulation challenges pertaining to short-term low flow events.

The paucity of quantitative or semi-quantitative examples available from the regulatory agencies was discussed within the interviews and it was thought possible that such events are themselves rare, owing to effective regulation of water resources in the UK (Dominic Longley, pers com), and/ or that standard regulation and monitoring does not record such events (which are likely to be limited in spatial scale) (Graeme Peirson, pers com). Of particular note was the highlighted need for improved access to information stored in the EA’s repository for categorised incidents, as extreme short-term low flow events are most likely to be brought to the attention of the EA via this route (Mike Dunbar, pers com).

3.4 Summary of the results of the literature search

The search term combinations and the number of results returned (total 632) are presented in Table 3.2. Of these 632 references 28 were screened in on the basis of the content of the abstract of the paper and its relevance to this review. As low numbers of relevant papers were returned for most search term combinations, and owing to redundancy of search

results, it was considered that further relevant papers would be better identified from within the literature itself. Furthermore some papers and grey literature reports were provided directly by the project steering group and staff within APEM. The primary sources identified from both peer-reviewed and grey literature sources are presented in Section 4, together with further references identified from several important review papers.

Table 3.2 List of search results. The number of results excludes recounts of the same papers returned under multiple search term combinations.

Search Term	No. of results
"temporary flow (s)" ecology	11 (1)
"intermittent flow (s)" ecology	158 (15)
"low flow (s)" ecology temporary	35 (15)
"low flow (s)" ecology short-term	91 (40)
"low flow (s)" ecology intermittent	58 (23)
"low flow (s)" "ecological impacts" temporary	0
"low flow (s)" duration recovery ecology	4 (8)
"low flow (s)" duration resilience ecology	4 (4)
"low flow (s)" duration resistance ecology	4 (3)
"temporary flow (s)" recovery ecology	0
"temporary flow (s)" resilience ecology	0
"temporary flow (s)" resistance ecology	0
"intermittent flow (s)" recovery ecology	12 (0)
"intermittent flow (s)" resilience ecology	6 (1)
"intermittent flow (s)" resistance ecology	6 (1)
"intermittent flow (s)" "low flow (s)" "flow standards"	0
"intermittent flow (s)" "low flow (s)" "environmental flow standards"	0
"temporary flow (s)" "low flow (s)" "flow standards"	0
"temporary flow (s)" "low flow (s)" "environmental flow standards"	0
"intermittent flow (s)" ecology "flow standards"	1 (0)
"intermittent flow (s)" ecology "environmental flow standards"	1 (0)
"temporary flow (s)" ecology "flow standards"	0
"low flow (s)" ecology "flow standards"	4 (1)
"intermittent flow (s)" "ecological impacts" predictability	0
"intermittent flow (s)" ecological impacts predictability	0
"intermittent flow (s)" ecology predictability	0
"temporary flow (s)" "ecological impacts" predictability	0
"temporary flow (s)" ecological impacts predictability	0
"temporary flow (s)" ecology predictability	0
"low flow (s)" ecology predictability "intermittent flow (s)"	0
"low flow (s)" ecology predictability "temporary flow (s)"	0
"low flow (s)" ecology predictability "short-term"	0
"low flow (s)" "ecological impacts" predictability	0
"low flow (s)" ecological impacts predictability	1 (0)
"low flow (s)" ecology predictability	18 (6)
"intermittent flow (s)" ecology predict	17 (1)
"temporary flow (s)" ecology predict	0
abstraction "short-term" "low flow (s)" ecology	2 (2)
irrigation "short-term" "low flow (s)" ecology	0 (2)
drought "short-term" "low flow (s)" ecology	12 (5)
abstraction "intermittent flow (s)" ecology	3 (1)
irrigation "intermittent flow (s)" ecology	5 (0)

Search Term	No. of results
drought "intermittent flow (s)" ecology	23 (4)
abstraction "temporary flow (s)" ecology	1 (0)
irrigation "temporary flow (s)" ecology	0
drought "temporary flow (s)" ecology	5 (0)
"low flow (s)" ecology temporary seasonality	2 (0)
"low flow (s)" ecology short-term seasonality	5 (4)
"low flow (s)" ecology intermittent seasonality	5 (1)
"low flow (s)" ecology temporary "transitional zone"	0
"low flow (s)" ecology short-term "transitional zone"	0
"low flow (s)" ecology intermittent "transitional zone"	0
"low flow (s)" ecology "transitional zone"	0
"low flow (s)" "transitional zone"	0
"low flow (s)" ecology temporary "multiple pressures"	0
"low flow (s)" ecology short-term "multiple pressures"	0
"low flow (s)" ecology intermittent "multiple pressures"	0
"low flow (s)" ecology "multiple pressures"	0
"low flow (s)" "multiple pressures"	0
"short-term" "low velocity" ecology	3
abstraction "low velocity" ecology	1
irrigation "low velocity" ecology	5
"short-term" "ponding" ecology	10
abstraction "ponding" ecology	2
irrigation "ponding" ecology	68
"low flow(s)" "predictability" ecology	19 (6)
"flow permanency" ecology	3
"depleted reach" ecology	1
"low flow (s)" winterbourne temporary	0 (0)
"low flow (s)" winterbourne "short-term"	0 (0)
"low flow (s)" winterbourne intermittent	1 (0)
"low flow (s)" ephemeral ecology	20 (8)
"low flow (s)" stranding ecology	7 (6)

The search identified most primary sources from Australasia, the UK and the rest of Europe as well as North America. Research interest in New Zealand regarding the ecological effects of short-term low flow events was notable; specifically the PhD work of Dewson (Dewson, 2007) and subsequent papers explored the theme of this literature review. Multiple papers of relevance to this review are associated with the work of Dewson and her associates (Dewson et al. 2007a; Dewson et al. 2007b; James et al. 2007; James et al. 2008; Death et al. 2009) and concern the ecological impacts of irrigation related abstraction. Two European experimental studies were identified as particularly relevant where the experimental set-up tested the effect of magnitude of short-term low flow events, with stagnation, pooling and dewatering being tested concurrently. These were conducted in lowland rivers of Denmark (Hille et al. 2014) and the Netherlands (Verdonschot et al. 2015).

4. Ecological effects of short duration abstraction on rivers

The effects of habitat changes resulting from short-term low flow events are considered for the different WFD biological quality elements for classifying river water bodies (macroinvertebrates, fish, macrophytes and phytobenthos) and ecosystem functioning. The majority of the literature describing the ecological impacts of short-term low flow events however focuses on riverine macroinvertebrates.

Evidence of the ecological impacts of short-term, extreme flow reductions is presented in sub-sections with specific reference to the conceptual model that frames the literature review:

- reduction in habitat quantity;
- reduction in habitat quality (character and diversity);
- loss of connectivity; and
- channel dewatering.

It is noted that these habitat effects were often not explicitly considered in the literature. Synthesis has therefore been undertaken in ascribing impacts to specific mechanisms and knowledge gaps are highlighted as appropriate.

The focus of the literature review is on the interacting effects of the magnitude and duration of low flow events with an emphasis on identifying quantitative or semi-quantitative information on the effect of duration of one month or less. Evidence for the interacting effects of frequency, timing/ sequencing and rate of change have also been considered. This is distinct from the effects of typology and confounding/ compounding factors are presented in Section 5.

Evidence has been categorised according to its strength to give a measure of certainty associated with each effect: from low certainty (supported by conceptual understanding/ anecdotal evidence only); moderate certainty (qualitative evidence, observational data and/ or some experimental studies but with conflicting findings); to high certainty (supported by a number of experimental studies with consistent findings).

4.1 Effects of reduced habitat quantity

4.1.1 Macroinvertebrates.

A review of observational and experimental studies of the effects of reduced flows on macroinvertebrates indicated that there was generally either no impact or increased abundance/ density of macroinvertebrates within the sampling units, where the habitat was miniaturised, but disconnection of pools and dewatering was not reported.

Dewson et al. (2007a) undertook an experimental manipulation of flow reduction in three New Zealand streams to mimic the hydrological effects of short-term (<one month duration) abstraction for irrigation and to investigate the resulting impacts on macroinvertebrates in

relation to control streams. The hydromorphological effect of the flow reductions (89-98% reduction in discharge) in all three streams was to miniaturise the aquatic habitat, but not to change the quality, character or connectivity of the habitat. Macroinvertebrate densities increased in all streams in the month following flow reduction, even though macroinvertebrate drift increased in the first few days after flow reduction. The proportion of mayflies, stoneflies and caddisflies increased in the low gradient stream in an agricultural catchment after flow reduction. There was no change in taxonomic composition of macroinvertebrates in any of the streams, indicating that when the effect of short-term flow reduction is to reduce the size of the habitat, but not to change the quality, character or connectivity of the habitat, for a duration of one month, the impact on macroinvertebrates was minimal other than increasing their densities.

A follow-on study (James et al. (2008)) of the same stream sites reported by Dewson et al. (2007a) indicated that the short-term (<one month duration) extreme flow reduction had no effect on hyporheic macroinvertebrates, suggesting that macroinvertebrates were not sufficiently stressed by extreme low flows of just one month duration. James et al (2008) concluded that macroinvertebrates in the three study sites (that were comparable to range of lowland and upland catchment in the UK) were resistant to short-term, severe flow reduction, as long as some water remained.

This study reported on the effects of the magnitude and duration of short-term, extreme low flow events; however, the study did not consider the timing of the event and the authors acknowledged that this could be important and requires further work. The three streams used in this experiment in New Zealand are considered to be suitable analogues for streams in the UK. Booth's Creek was a low gradient, meandering stream in an agricultural catchment classified as moderately polluted, considered to be similar to many low gradient streams in the UK that are subject to short-term abstraction for irrigation. The Kiriwhakapapa Stream was similar to modified streams in the UK with extensive stock grazing. The Reef Creek was typical of pristine, high gradient upland streams in the UK, within a native forest catchment. The effect of short-term, extreme flow reductions, mimicking abstraction for irrigation, was fairly universal across these streams (although the increase in macroinvertebrate density in Reef Creek was slightly less than the other streams), suggesting that the effects of short-term abstraction might be consistent across different river types in the UK, as long as it does not result in changes to the quality, character and connectivity of the habitat.

A field study on the effects of irrigation abstraction induced low flow in a large lowland river of Oregon, USA, reported that macroinvertebrate communities were generally highly resistant to the effects of short-term abstraction for irrigation purposes, but this depended on the duration of the abstraction (Miller et al. 2007). The USA study site is considered to be fairly comparable to a large lowland, agricultural catchment in the UK, with a high demand for water for irrigation in the summer. Consistent with Dewson et al (2007a), high intensity, short-term abstraction of less than two months during the summer changed the relative abundance of macroinvertebrate communities, but had little effect on the taxonomic composition. However, longer-term abstraction, spanning three months during the summer, did change the composition of the community, shifting the dominance of Ephemeroptera, Trichoptera and Plecoptera to predatory insects, non-insect taxa and elmids beetles. The reasons for this impact on macroinvertebrates were suggested as due to physico-chemical changes that presumably exert an effect on macroinvertebrates after more than two months (the effect of changes to habitat quality and character are described in the following section).

Where the macroinvertebrates were not resistant to high intensity abstraction for irrigation that spanned more than three months in a drought year, the communities were resilient and recovered as long as the hydrological and physico-chemical conditions lasted for more than one month after the abstraction. The recovery mechanisms were suggested as primarily recolonisation by drift from upstream habitats under high flow conditions. This indicates that the frequency of short-term, extreme low flow events is important in allowing recovery of macroinvertebrates and should allow more than one month between abstraction events during the summer. There is no information in the literature to deduce whether the frequency of short-term, extreme low flow events affects the resistance of macroinvertebrates via the cumulative (ramped) effects of successive events.

There is evidence from experiments in Western Europe that corroborates the conclusions described above that macroinvertebrates in lowland rivers are generally resistant to the effects of short-term, extreme flow reduction for less than one month in the summer, as long as some water remains and the physico-chemical habitat quality/ character is not drastically altered (which tends to occur after one month of effect anyway) (Moth Iverson et al. 1978; Verdonschot et al. 2015). It was suggested in these studies that macroinvertebrates in low gradient rivers are generally resistant to the effects of short-term extreme low flow events except when it results in the disconnection of pools, drying of the channel or major physico-chemical changes; these effects are described in the following report sections.

There is evidence from UK rivers of macroinvertebrate density and/ or abundance increasing in response to reductions in wetted habitat area. Extence (1981) reported that during the UK drought of 1976, most macroinvertebrate species in a lowland river increased in numbers over the course of several months in the summer, compared to the previous year. This effect was, in part, attributed to a reduction in habitat size causing an increase in the concentration of organisms, consistent with Mainstone (2010; Figure 2.2). Extence (1981) did not report a subsequent decrease in any of the taxa that increased in numbers during the drought, indicating that after a duration of several months of extreme low flows (longer than the defined short-term low flow periods of this review), points (a) and (b) in Figure 2.2 (Mainstone, 2010) were not reached. Other factors were suggested by Extence (1981) as contributing to the reported increased numbers of macroinvertebrates and these are described under the relevant sections below.

Wood and Petts (1994) reported increases in some macroinvertebrate species during severe low flow conditions in September 1992 compared with the following year when flow returned to normal. This study however reported increases in the abundance of gastropods and reductions in the abundance of Ephemeroptera and Trichoptera in the low flow period, in contrast to Extence (1981) that reported a decrease in the abundance of gastropods (but an increase in most other taxa) during the 1976 drought. It is not clear from Wood and Petts (1994) or Extence (1981) whether the reported contrasting impacts of severe low flows on gastropods were due to a reduction in habitat size or other factors and there is no evidence of how the duration of the severe low flows might have caused these impacts.

In the perennial section of a UK Chalk stream, Wright and Berrie (1987) reported that the density of the overall macroinvertebrate community increased whilst taxon richness remained unchanged during the summer drought of 1976. The increased density was largely attributed to Chironomidae and it was not clear whether this effect was due to reduced habitat size and concentration of organisms as in Figure 2.2 (Mainstone, 2010) or due to changes in habitat character. This study was conducted over a three month period

during the drought, suggesting that points (a) and (b) in Figure 2.2 (Mainstone, 2010) were not reached by this timescale.

By contrast, in an upland river, during the same UK drought period of 1976, Cowx et al. (1984) reported a reduction in macroinvertebrate density. However the interval between flow reduction and the measurement of these effects is unclear and it is uncertain whether the reductions in density occurred within a month of reduction in flows.

4.1.2 *Fish*

Studies relating to the responses of fish to short-term low flow events are rare, however a field experiment carried out in a chalk stream in southern England investigated habitat use and mortality of salmon, trout and grayling following abrupt reductions in flow to <30 and <10 % of the baseline flow condition, 21 days in duration (Riley et al. 2009). Whilst a number of species and age-group specific changes to habitat (relating to depth and velocity) and increases in ranges of movement were recorded, no net downstream displacement of any species under reduced flow was recorded. Mortality rates of 0+ salmon, trout and grayling were observed to be at or above those of reference conditions; however these were not reported as being statistically significant. Increase in mortality was thought to be related to the small size and increased vulnerability to predation under low flow of these fishes.

Several studies report movement of fish in response to reduced flows (Kraft, 1972; Armstrong et al. 1998; Huntingford et al. 1999). Experimental studies have demonstrated that fish can rapidly recolonise disturbed stream habitats, returning to pre-disturbance richness and abundances often within 40 days (Peterson and Bayley, 1993; Sheldon and Meffe, 1995). Speed of recovery does depend on distance to refugia however (Lonzarich et al. 1998) and potentially on channel modification (barriers to recolonisation).

4.1.3 *Macrophytes and phytobenthos*

The one study that considers the impact of short-term (<one month duration), extreme low flow events on phytobenthos, due exclusively to the effects of reduced habitat size, reported no effect of flow reduction across three streams in New Zealand. The three New Zealand streams encompassed examples that are considered to be broadly comparable to lowland streams in the UK that are subject to agricultural pressure as well as more pristine upland streams (Dewson et al. 2007a).

4.1.4 *Ecosystem functioning*

Conceptually, short-term increases in macroinvertebrate abundance following flow reductions (Dewson et al. 2007a; Verdonschot et al. 2015) could result in increased biotic interactions, in particular predation (Boulton and Lake, 1992; Mainstone, 2010). However no evidence to support such an effect has been found within the literature for river reaches that do not become disconnected by low water levels, over the timescales of less than a month.

Increased food supply for detritivores was reported in response to a drought that extended over several months in the summer of 1976 in a lowland UK river and was suggested as a possible mechanism for increased invertebrate abundance (Extence, 1981). It is not clear from the literature, however, whether this effect can occur within timescales relevant to this

study of less than one month after the onset of an extreme low flow event. A study in the Ebro catchment (Spain) suggests that if detritivores themselves are reduced by the effects of extreme low flows, the leaf litter decomposition in streams can be reduced (Monroy et al. (2016).

4.1.5 Summary

In summary, the key points to emerge from the literature regarding the impacts of short-term, extreme low flow events due to the effects of reduced habitat quantity are:

- Macroinvertebrates and phytobenthos are generally resistant to extreme, short-term low flow events lasting up to one month, as long as some water remains in the channel.
- Reductions in habitat size due to extreme low flow events lasting up to a month in the summer almost universally resulted in increases in macroinvertebrate density, but no effect on taxonomic composition. With reference to the conceptual model of Mainstone (2010; Figure 2.2), evidence suggest that point a) is not reached by one month duration.
- These effects were shown in a range of rivers in New Zealand, USA, Denmark, Netherlands and the UK that were considered to be broadly comparable to lowland rivers in the UK in agricultural catchments with channel modifications and more pristine upland streams.
- There are indications that extreme low flow events that last for more than three months in the summer result in changes in macroinvertebrate taxonomic composition and relative abundance, compared to events of similar magnitude on the same river lasting up to two months in the summer. However, the mechanism for causing impacts on macroinvertebrates after three months is due to physico-chemical changes induced by reduced water levels and these are described in the following section.
- Reductions in habitat size due to short-term flow reductions up to 21 days has caused fish to move between habitats and to increase their range of movement, but has not resulted in a net downstream displacement. Increased mortality was observed as a result of reduced habitat size due largely to increased predation.

Table 4.1 Summary of the ecological effects of reduced habitat quantity

Effect	Alteration of habitat state	Duration	Ecological effects	Certainty	References
Reduced habitat quantity	Reduced depth Reduced wetted area	Up to one month ¹ Effects extending over a month or timescale not clear	Increase in macroinvertebrate density	High	Extence (1981); Wright and Berrie (1987) ¹ ; Wood and Petts (1994) ¹ ; Dewson et al. (2007a); James et al. (2008)
			No change in macroinvertebrate species richness or evenness. Slight change in community composition at one site. No change in periphyton	High	Dewson et al. (2007a); Miller et al. (2007) ¹
			Reduction in macroinvertebrate density in an upland river in Wales	Low	Cowx et al. (1984) ¹
			Increased range of movement of salmon, trout and grayling between habitats, but no increase in downstream displacement. Higher mortality due to increased predation	Med	Riley et al. (2009)

4.2 Effects of change to habitat quality

4.2.1 Macroinvertebrates

Whereas changes in the size of habitat due to extreme low flow events up to one month duration are expected to affect just the density of macroinvertebrates, changes in the physico-chemical quality and character of the habitat can affect the taxonomic composition of macroinvertebrate communities.

Some studies have reported increases in macroinvertebrate richness and diversity in response to short-term low flow events as a consequence of changes in habitat quality. Increased diversity of macroinvertebrates (Verdonschot et al. 2015; Moth Iversen et al. 1978) in response to short-term reduced flows is considered to not only relate to a decrease in habitat, as noted above, but might also result from temporarily altered conditions being suited to new colonist taxa, in particular because of reduced flow velocities. Extence (1981) suggested that increases in the overall abundance of macroinvertebrates and taxon richness during a drought could be due to decreased spate flows, increased bed stability and the creation of more lentic habitat conditions, suited to new colonists such as Asellidae and Corixidae. Wright and Berrie (1987) demonstrated that increased siltation resulting from drought caused increases in chironomid density. Increased sedimentation associated with short-term low flow events has been shown to impact macroinvertebrates, as outlined in Section 5.2.3.

Few studies have reported overall decreases in taxon richness or diversity of macroinvertebrates in response to extreme short-term (< one month duration) reductions in flow, but some studies have reported changes in taxonomic composition as a result of changes to the quality of habitat. Experimental short-term flow reduction resulting in stagnation (flow velocities at or near zero) has been associated with the loss of rheophilic taxa; an absence of LIFE Flow Group II taxa *Hydropsyche pellucidula* (caseless caddisfly), *Limnius volkmari* (riffle beetle) and *Lype reducta* (caseless caddisfly) was recorded in Verdonschot et al. (2015); although the Flow Group I taxon *Silo nigricornis* (cased caddisfly) did persist. In this study, the flow regime of a lowland stream channel in the Netherlands was manipulated using two dams to produce distinct treatments; a stagnant reach, followed by a dewatered reach with residual pools (discussed in subsequent sections), with an unaffected upstream control reach. Stagnation resulted in a decrease in taxon richness after one week, that was suggested as not due to the loss of rheophiles but the onset of biotic effects, such as pupation/ emergence of insects or increased predation rate. Taxon richness however then increased sharply after two weeks of stagnation, due to the immigration of new taxa exploiting the lentic conditions. The end result of the experiment, after one month, was an overall increase in taxon richness in the stagnant treatment compared to pre-flow reduction and the control treatment.

The experimental field study of Hille et al. (2014), reported alteration to the macroinvertebrate community of stagnant reaches, primarily driven by changes in the abundance of five taxa; *Baetis* spp (mayfly), *Gammarus pulex* (freshwater shrimp) and three fly larvae (including Simuliidae (black fly larvae)). In the field survey of Moth Iversen et al.

(1978), reductions in the abundance of two species were noted, namely *Baetis rhodani* (mayfly) and *Hydropsyche angustipennis* (caseless caddisfly).

It should be noted that studies reported in the literature focus on measures such as species richness and abundance, and therefore the loss of specific taxa sensitive to flow might have occurred due to changes in habitat quality but may not have been reported upon. Whilst there is little evidence for this in the literature, it is likely that these effects of extreme, short-term flow reductions will affect the values of biotic indices used in the UK for assessing the biological effects of flow alteration (LIFE) and classifying the ecological status of surface water bodies under the WFD (WHPT-ASPT and NTAXA).

There is some experimental evidence that short-term (< one month duration), extreme low flow events might reduce macroinvertebrate abundance and diversity in specific stream habitat types, indicating that macroinvertebrates might be impacted if the effect of flow reduction is to simplify the habitat to specific patch types. The 18-day experimental study of Matthaei et al. (2010) found that total macroinvertebrate abundance was affected on specific substrata in artificial channels. Abundance on algal colonisation tiles and in leaf packs (leaves bolted together) decreased under an 80% reduction in flow (macroinvertebrate taxon richness was not found to be affected). James and Suren (2009) reported that densities of macroinvertebrates were reduced in gravel filled colonisation baskets (attributable to the abundance of just a few taxa) following velocity reductions one month after experimental treatment. However densities recovered at two months post-manipulation and a possible impact of applying the treatment condition cannot be discounted in explaining the initial decrease in abundance.

Flow reduction can result in indirect impacts on biota due to reduced water quality (for example though reduced dilution of pollutants, increased residence time can result in increased temperature, decreased turbulence can result in reduced dissolved oxygen concentration). This effect has only been reported for low flow events that have lasted longer than one month, including during a summer period with ambient temperatures >30°C (e.g. Miller et al. 2007). The potential compounding/ confounding effects of poor water quality in determining the impacts of short-term, extreme flow reduction on aquatic organisms is considered further in Section 5.

4.2.2 Fish

No evidence was found in the literature search of the impacts of short-term, extreme low flow events on fish, as a specific consequence of changes in habitat quality as distinct from habitat quantity, connectivity and dewatering.

4.2.3 Macrophytes and phytobenthos

Short-term experimental reduction of flow velocity has demonstrated that a shift in periphyton patch type can result (Hart et al. 2013). *Phormidium* patch types (which mainly consisted of two filamentous cyanobacteria) were dominant at > 0.4 m/s whereas filamentous green patch types (mainly chlorophyte taxa along with various diatom epiphytes) dominated at <0.2 m/s. A seven-day experimental reduction in velocity (reduced on average by 58%) resulted in a reduction in the cover of *Phormidium* patches from 84 - 21% and a corresponding increase in filamentous green patches from 16 - 79%. This was considered a

strong and rapid response to a short and relatively modest event by the authors. It should also be noted that patch-specific macroinvertebrate assemblages were recorded, i.e. specific taxa were associated with the different algal types. However, 85% of taxa were sampled from the substrata below algal mats and were not considered to be affected by patch type.

Beyond the context of studies relating directly to short-term low flow events, a comparative study considering flow intermittency and diatom communities in northern Italy identified flow velocity (maintenance of a minimum of 0.2 m/s) as the main factor in explaining abundance of endangered species (Falasco et al. 2016).

The influence of water flow on macrophyte growth in relation to short-term (< one month), extreme low flow events has not been the subject of academic research. Water velocity is a crucial factor in determining macrophyte growth: Chambers et al. (1991) demonstrated that at velocities of between 0.01 – 1 m/s macrophyte biomass decreases with increasing velocity and that at velocities of greater than 1 m/s macrophytes are rare. Generally, submerged fine-leaved macrophytes and mosses occur in faster water (>0.5 m/sec); submerged broad leaved macrophytes in deeper moderately fast water (~0.4 m/sec); and emergent macrophytes in slower water (0 – 0.05 m/sec) (Hatton-Ellis et al. 2003).

It might therefore be expected that reduced depths and flow velocities associated with short-term low flow events might favour macrophyte growth. However, in consideration of the growth rates of macrophytes, changes to velocity lasting for a month or less are not expected to result in substantial impacts to the plant community.

A study of macrophyte assemblages in lowland Danish streams found that, although macrophyte cover was found to increase with long duration of low flow and low flow variability, no relationship was found between the presence of disturbance-tolerant species and hydrological disturbance, suggesting that plant community composition developed independently of stream hydrology (Riis et al. 2008). Whilst this is not specific to short-term low flow events, it indicates that such events might not be an important driver.

4.2.4 Ecosystem functioning

The experimental study of Hart et al. (2013) has implications regarding ecosystem functioning with regard to the effect of short-term, extreme low flow events: *Phormidium* biomass was significantly greater than that of filamentous greens; therefore, reduction in flow velocity appeared to result in reduced instream productivity. The study of Matthaei et al. (2010), also found algal biomass decreased at reduced flow velocity whilst leaf packs lost more biomass at reduced flow velocity; i.e. allochthonous (matter derived from outside of the instream environment) productivity appeared to increase. Reduction in periphyton biomass following short-term flow reduction is not in agreement with the wider literature pertaining to reduced flows. Longer-term low flow events are associated with shifts from low-biomass diatom assemblages to high-biomass filamentous algal assemblages which occur in response to increased temperatures, higher nutrient concentrations, and reduced current velocity (Dewson et al. 2007b and references therein). Although this apparent difference is not well understood duration of low flow events is likely to be of importance in determining the response.

Impacts of reduced flow on the phytobenthos is complicated by the effect of grazing by macroinvertebrates, i.e. top-down as well as bottom-up processes result in the observed biomass of phytobenthos at a given time point. Velocity has been shown to be a significant factor in the facilitation and removal of algae by macroinvertebrate grazers (Hintz and Wellnitz, 2013). In this study, in the absence of macroinvertebrate grazers algal biomass increased with velocity, whereas more algal biomass was removed by grazers under higher velocity treatments.

4.2.5 Summary

In summary, the key points to emerge from the literature regarding the impacts of short-term, extreme low flow events due to the effects of reduced habitat quality are:

- Consistent with the effects due to reduction in habitat size, macroinvertebrates, macrophytes and phytobenthos are generally resistant to extreme, short-term low flow events lasting up to one month, as long as some water remains in the channel. This corresponds to step 2 in Boulton's (2003) model of habitat change in response to the progression of an extreme low flow event through time (Figure 2.1).
- Few studies have reported decreases in overall abundance, density and taxon richness of macroinvertebrates due to habitat changes occurring within one month that do not involve channel dewatering or isolation of pools. Several studies have reported overall increases in abundance and taxon richness of macroinvertebrates due to habitat changes as a consequence of extreme low flow events over the course of a month, because of new colonists overcompensating for any losses.
- However, changes in taxonomic composition as instream habitats change from lotic to lentic character within one month might have been underreported in literature that focuses on reporting total taxon richness. It is possible therefore that changes in habitat quality due to short-term, extreme low flow events that do not affect overall abundance and taxon richness of macroinvertebrates might affect the biotic indices used in the classification of ecological status under the WFD in the UK.
- Aquatic macrophytes are unlikely to respond to changes in the quality of habitats as a result of short-term, extreme low flow events lasting no more than one month.

Table 4.2 Summary of the ecological effects of reduced habitat quality

Effect	Alteration of habitat state	Duration	Ecological effects	Certainty	References
Reduced habitat quality	Reduced velocity/stagnation Possible reduction in water quality (reduced dissolved oxygen; increased water temperatures)	Up to one month	No apparent change in macroinvertebrate richness and taxonomic composition	High	Extence (1981) Hille et al. (2014) Moth Iversen et al. (1978) James et al. (2008) Matthaei et al. (2010) Miller et al. (2007) ¹
		¹ Effects extending over a month or timescale not clear	Increase in macroinvertebrate density or abundance	High	Extence (1981) Verdonschot et al. (2015)
			Increase in macroinvertebrate species richness	Med	Verdonschot et al. (2015)
			Change in taxonomic composition with loss of some rheophilic macroinvertebrate taxa, replaced with lentic taxa	High	Verdonschot et al. (2015) Hille et al. (2014)
			Increase in macroinvertebrate drift	Med	Dewson et al. (2007) James et al. (2007)
			No change to the proportion of macroinvertebrate functional feeding groups	Med	Miller et al. (2007)
			Change to fish habitat associations. Possible increased mortality of 0+ fish	Med	Riley et al. (2009) ¹
			Shift in periphyton patch type	Med	Hart et al. (2013)
			Decrease in periphyton biomass	Med	Hart et al. (2013) Matthaei et al. (2010)
			Increased leaf litter breakdown	Med	Matthaei et al. (2010)

4.3 Loss of connectivity – formation of disconnected pools

4.3.1 Macroinvertebrates

The model of Boulton (2003) is considered to apply to short-term low flow events, although reduction in richness following loss of longitudinal connectivity is not universally supported by the literature. The predicted reduction in species richness is dependent on the duration of the low flow event. The continuum proposed by Mainstone (2010) is also valid under this scenario, with initial increases in abundance and richness observed owing to a concentration effect (Verdonschot et al. 2015).

Concentration effects are short lived (recorded one day subsequent to the onset of impact conditions in the case of Verdonschot et al. 2015). For periods of up to approximately two

weeks richness and total abundance have been recorded as comparable to control conditions (Verdonschot et al. 2015; Hille et al. 2014). However, after approximately two weeks, richness is either significantly reduced (total abundance increased owing to immigration of mosquito larvae) (Verdonschot et al. 2015), or unaltered, but assemblage composition and evenness is significantly affected (Hille et al. 2014).

The interaction between loss of connectivity and event duration is of crucial importance regarding deterioration in water quality. As recognised in relation to longer-term drought in intermittent streams, reduction in species richness and alteration of the composition of assemblages resulting from short-term low flow events are attributed to reductions in water quality (Boulton and Lake, 1992); specifically, reduced dissolved oxygen levels, coincident with the compositional change. Verdonschot et al. (2015) observed a steep decline in macroinvertebrate richness coincident with hypoxia (and increasing conductivity). Paradoxically, the crash in richness observed in Boulton and Lake (1992) did not begin until approximately one month following disconnection of pools, in contrast to impacts observed in western European systems after approximately two weeks. However, the results reported in Verdonschot et al. (2015) and Hille et al. (2014) are likely relatively extreme, owing to the experimental setup used; isolated pools were artificially created through burying buckets into the sediment of experimentally dewatered reaches. These pools were therefore completely impermeable, which likely exacerbated/ accelerated water quality deterioration, and small relative to natural pools, which again likely exacerbated/ accelerated water quality deterioration.

Loss of connectivity, loss of flow and associated deterioration of water quality are considered to be the primary drivers of the impacts observed. However, an increase in predatory interactions might also result in impacts on the macroinvertebrate community, as observed in isolated pools of intermittent streams in Australia (Boulton and Lake, 1992). However, in order for sufficient time to elapse for such a response to manifest, this is only considered likely for short-term events of relatively longer duration. The relative importance of poor water quality and predatory effects will depend not only on duration of an event, but also factors pertaining to river typology and compounding or confounding factors.

Measures of macroinvertebrate communities reported on in the peer-reviewed literature are focussed on direct ecological measures, such as abundance, richness and evenness. These measures are not designed to reflect impacts of reduced flow, and therefore might obscure flow induced changes to communities, that are likely to be picked up by pressure-specific indices used by the regulatory bodies, i.e. LIFE scores (Extence et al. 1999). An event of approximately one week in duration can result in an abrupt decrease in LIFE scores, indicating a loss of rheophilic taxa (Richard Chadd, pers com, see Appendix 3.1 for a full description). This example is a rare case where long-term biomonitoring provides semi-quantitative evidence relating to the resilience of a community. LIFE scores showed an abrupt decrease following the event but appeared to have recovered to pre-disturbance values by spring of 2008 (the event having occurred in November 2006).

Loss of vertical and lateral connectivity as a result of a short-term low flow event can affect macroinvertebrates. Following the model of Boulton (2003), the first habitat to be lost with decreasing flow is that of the littoral or riparian zone. However, the greater significance of this scenario is the potential for impacts on biota resident within this zone. The riparian zone is of particular importance to macroinvertebrate taxa as well as fish fry (e.g. Ormerod et al.

1997; Rose et al. 2008). Despite the potential for impacts on these taxa, no studies have tested this in relation to short-term low flow events.

Loss of lateral connectivity could affect exposed riverine habitats and the macroinvertebrate communities that they support. Exposed riverine sediments (ERS) are given brief consideration here owing to the unique communities of specialised invertebrate taxa they support, in particular spiders and beetles. These communities are of particular conservation interest; there are 131 specialist ERS beetles, 86 of which (66%) have either Red Data Book, or Nationally Scarce status (Bates and Sadler, 2005).

These communities live at the aquatic-terrestrial interface and are dependent on the disturbance regime mediated by seasonal water-level changes. Less disturbed ERS habitat becomes degraded through compaction and stabilisation of sediment and as a result the invertebrate fauna becomes less specialised and more dominated by generalist species (Sadler and Bell, 2000). Stabilisation attributable to a lack of high flows and vegetation is considered to be a major threat to these communities (Henshall et al. 2011).

The high flow disturbance events considered crucial to the maintenance of ERS communities can be considered independent of short-term low flow events. The short-term nature of low flow events of interest to this review are not considered likely to result in stabilisation of sediment or changes to the macrophyte communities of exposed sediments and are therefore considered to pose minimal risk to ERS communities.

One exception is considered probable where the frequency of low flow event is high enough that the ERS habitat can alter. Total duration of exposure of sediment across successive events might result in a wetting regime within the range of tolerance of more generalist plants.

4.3.2 *Fish*

As fish are highly mobile taxa, habitat connectivity, allowing access to alternative suitable habitat or refugia, is a major mitigating factor of the impacts of low flows on fish populations in rivers. Conversely, riverine fish populations can be impacted by low flows if suitable habitats become disconnected. Fish survival in disconnected stream pools is described in Labbe and Fausch (2000) and Magoulick (2000).

The formation of disconnected pools occurs naturally in some New Forest streams (Dominic Longley, pers com). It was reported that once this occurs a short space of time elapses before resident fish die from asphyxiation. However, this example was not supported by data. The ability of salmonid fishes to survive in pools during drought and in intermittent streams has been linked to thermal and dissolved oxygen limits of tolerance (Elliott, 2000; Woelfle-Erskine et al. 2017), however, examples reporting on the interaction with time, specifically the short time-scales of interest to this review have not been identified.

Although of longer duration than the events of primary interest to this review a three month experimental manipulation of streams in north east USA that resulted in a minimum daily flow in two reaches of <Q99 and <Q95 in a third led to sections of the manipulated reaches drying completely, with isolated deeper pools remaining (Walters and Post, 2008). Although

large individuals were lost, no loss of fish species was observed, which the authors attributed to the presence of the deep pool refugia.

4.3.3 *Macrophytes and phytobenthos*

No evidence was found in the literature of the specific effects of disconnection and the formation of isolated pools as a result of low flow events on macrophytes and phytobenthos. The effects of low flow events on this combined WFD quality element is described under habitat quality and channel dewatering. However, given the literature reviewed in the preceding section, the temporary dewatering of the littoral zone associated with short-term low flow events is not expected to result in the loss of plant species, owing to the short duration of these events and the unlikely outcome of complete soil drying and plant die-back.

4.3.4 *Ecosystem functioning*

In the study of Walters and Post (2008) food chain length, as determined by stable isotope analysis, was not altered. Although disturbance did remove the largest individuals, body size was not strongly related to trophic position and therefore no decrease in food chain length was observed. It should be noted however that piscivorous fish were not present.

4.3.5 *Summary*

In summary, the key points to emerge from the literature regarding the impacts of short-term, extreme low flow events due to the loss of longitudinal and lateral/vertical connectivity are:

- In contrast to the general effects of reduced habitat quantity and quality, riverine macroinvertebrates and fish are not resistant to the impacts of the isolation of habitats within a river due to extreme low flow events over timescales up to one month.
- Loss of connectivity is therefore regarded as a critical threshold where short-term (< one month duration), extreme low flow events can cause significant ecological impacts and abstraction licences should be regulated to avoid the risk of such effects.

Where longitudinal connectivity is lost and habitat is reduced to disconnected pools, an interaction with duration is observed as per the continuum of Mainstone (2012). Initial concentration of macroinvertebrates is observed (time point a, Figure 2.2), however diversity of macroinvertebrates is severely reduced (time point b) within approximately a couple of weeks (Verdonschot et al. 2015; Hille et al. 2014). The duration at which a catastrophic alteration is observed will depend on river/ community type, as discussed in Section 5. However, the two week period is possibly a worse-case scenario owing to the experimental set up used to study these events.

Table 4.3 Ecological effects of loss of longitudinal connectivity

Effect	Alteration of habitat state	Duration	Ecological effects	Certainty	References
Loss of longitudinal connectivity (loss of riffles, formation of disconnected pools)	Loss of riffle habitat Severe reduction in wetted area Possible severe reduction in WQ Loss of connectivity	< c.24 hours	Increases in macroinvertebrate abundance and richness	High	Verdonschot et al. (2015)
		< c.14 days	No apparent change to macroinvertebrate communities total abundance or richness	High	Verdonschot et al. (2015) Hille et al. (2014)
			Temporary loss of rheophilic taxa (depressed LIFE scores)	Low	Richard Chadd (pers com)
		> c.14 days	Large reductions in macroinvertebrate richness coincident with hypoxia (total abundance unchanged or increased)	High	Verdonschot et al. (2015) Hille et al. (2014)
			No change in fish species richness	Med	Walters and Post, (2008) ²
			No change in food chain length	Med	Walters and Post, (2008)

4.4 Channel dewatering

4.4.1 Macroinvertebrates

Dewatering of the channel affects a number of measures of the macroinvertebrate community, as reported in some fully controlled mesocosm experiments in artificial channels. It is axiomatic that channel drying leads to mortality of resident biota and this is supported by the small body of literature on the effects of short-term extreme low flow events demonstrating large reductions in macroinvertebrate species richness (Ledger et al. 2011; Ledger et al. 2013; Lancaster and Ledger, 2015; Verdonschot et al. 2015).

Despite such large reductions in species richness, some taxa, such as fly larvae and oligochaetes, are able to exploit conditions resulting from dewatering events and increase in abundance (Ledger et al. 2011; Ledger et al. 2013; Lancaster and Ledger, 2015; Verdonschot et al. 2015). Consequently, dewatering events do not always result in reductions of total macroinvertebrate abundance or diversity (Hille et al. 2014), although this is dependent on duration of the event. In this example, total abundance was reduced one week following the dewatering of the channel; however, by three weeks post-treatment, total abundance was comparable to that of the control condition.

A contrasting interaction with duration was observed in the field experiment of Verdonschot et al. (2015). The day following the loss of surface water macroinvertebrate richness and abundance was apparently unaffected, 19 taxa were recorded after 11 days of streambed dewatering and eight survived up to 25 days (a mean number of 26 taxa were found, per sample, in the control treatment at the end of the experiment).

As implied by reductions in species richness, the susceptibility of macroinvertebrate taxa to dewatering is variable. A field experiment has demonstrated that some chalk stream taxa are highly susceptible to drought, with significant reductions in some mayflies, snails, caddisflies and beetles (Ledger et al. 2013). It is expected that body size traits will influence the ability of macroinvertebrates to survive dewatering events through the ability of taxa with a smaller body size to use interstitial spaces below the channel surface which can remain wet following exposure of the sediment surface (Lancaster and Hildrew, 1993). Although this has not been tested directly, the differential survival of taxa observed in the experiment of Ledger et al. (2011) was thought to be attributable, at least partly, to this process.

The hyporheic zone can act as an important refuge during low flow disturbance and this is therefore noted as a potential mechanism by which macroinvertebrates might demonstrate resistance to short-term low flow events (Stubbington, 2012). The hyporehic zone has been shown to act as a refuge during channel dewatering with invertebrates actively following the decreasing water table into deeper sediments (Delucchi, 1989, Clinton et al. 1996) and passive inhabitation allowing taxa to persist (Clifford, 1966). Verdonschot et al. (2015) reported that 19 taxa survived buried in the sediment for 11 days of dewatering and eight taxa survived after 25 days of dewatering, indicating that this is an important mechanism by which macroinvertebrates might be resistant and resilient to the impact of short-term, extreme low flow events. Sediment moisture content is an important determinant of macroionvertebrate survival in dewatered stream channels (Verdonschot et al, (2015 and references therein) and that a stream bed dominated by fine-grained sediments provides a suitable refuge for macroinvertebrates after dewatering (Stubbington et al. 2009).

4.4.2 Fish

It is clear that channel dewatering can result in the local loss of fish; however, loss may be incurred either through mortality or the migration of fish to reaches that remain perennial. Although conducted in a stream naturally intermittent in its middle reaches, and although drying events were in general longer than those of primary interest to this review, the field study of Davey and Kelly (2007) demonstrated that whether fish migrate or are stranded can depend on the spatial position of refugia in the landscape. In the upper river, the evidence suggested upstream emigration of fish in response to drying, whilst in the lower reaches fish did not appear to migrate downstream in response to drying and presumably were stranded. Recolonization was faster in an upstream than a downstream direction.

Resilience was also measured in the study of Davey and Kelly (2007): in the upper reaches of the intermittent river, recolonization was slow and attributed to the frequency of drying events as well as species specific behavioural traits. The assemblage of the upper reaches of the intermittent section did not return to one equivalent to that of the upstream perennial reaches, even after 100 days. In contrast, in the lower reaches of the intermittent section of river, less frequent drying events and species specific faster recolonisation rates resulted in convergence with perennial communities following prolonged periods of rewetting. This

study also demonstrated that rate of recolonisation declined strongly with increasing distance to refugia; rapid colonisation occurred where localised pools remained.

An experimental channel study conducted in New Zealand investigated the effect of riffle dewatering on two species of benthic fish, upland bullies (*Gobiomorphus breviceps*) and Canterbury galaxias (*Galaxias vulgaris*) (Davey et al. 2006). With dewatering upland bullies tended to move to upstream runs, whilst Canterbury galaxias tended to burrow into the substratum. Burrowing was more frequent on coarse substrata (cobble) than on gravels and owing to the species specific responses observed substratum size affected Canterbury galaxias more than upland bullies. Both species showed a tendency to move in an upstream in response to dewatering.

Long-term monitoring data provides a rare example where impacts on fish regarding both resistance and resilience can be considered (Mark Warren, pers com, see Appendix 3.2). Cessation of a compensation flow for approximately six hours resulted in loss of all surface flow for a time measured in hours. A reduction in 1+ brown trout density was recorded in the spring following the event, highlighting that even a brief short-term low flow event can result in an impact on ecology. It is believed that fish in pools, or sufficiently close to pools, were able to take refuge; however, juveniles in the preferred, shallow, mixed riffle/ run habitats most likely did not move in response to the reduced flow and therefore most likely were stranded. Other age classes were not found to be affected and post-survey data showed that redds appeared to have survived, ascribed to innate site selection and the short-term nature of the event. The brown trout community was considered resilient to the event, with no differences seen between control and impact cohorts the autumn following the event.

4.4.3 *Macrophytes and phytobenthos*

Experimental short-term low flow events have demonstrated impacts on algal communities resulting in changes to the dominance of algal assemblages. Short-term drying events have been shown to result in reduction of dominance by encrusting alga and increased diatom richness and abundance (Ledger et al. 2008). This response was, however, dependent on the frequency of disturbance and succession effects.

Dewatering associated with short-term low flow events of interest to this review are expected to be of brief duration. Where sub-surface moisture remains, macrophytes are in general expected to be resistant to such events, assuming die-back does not occur. No studies pertaining to short-term events of direct relevance to this review were identified; however, headwaters and winterbournes that naturally dry can be used as an analogous scenario. In apparent support of an expected resistance of macrophytes to short-term dewatering, Holmes (1996) reported no difference in macrophyte assemblages in headwaters and winterbournes between locations classified as 'always perennial' and '± perennial' (occasionally dry), based on surveys of >120 sites. Sites that dried for between 0.5 – 1.5 months of the summer (a distinct category to those sites classified as 'always perennial' and '± perennial') were reported to see the loss of six aquatic macrophyte taxa, suggesting that short-term dewatering events of relatively long duration might result in loss of some taxa.

4.4.4 *Ecosystem functioning*

Unsurprisingly channel dewatering has been shown to result in reduction of secondary production (macroinvertebrate biomass). Monthly six-day dewatering has been shown to reduce secondary production by more than half (Ledger et al. 2011). Responses within functional feeding groups were contrasting, ranging from extirpations to irruptions. Taxon specific responses related to body mass and voltinism with a shift towards a community comprised of small taxa with fast life-cycles (notably chironomids (non-biting midge larvae) and other Diptera). The possible relevance of this example to occurrences in natural systems is noted, owing to the relatively extreme nature of disturbances in the experiment.

4.4.5 *Summary*

In summary, the key points to emerge from the literature regarding the impacts of short-term, extreme low flow events due to channel dewatering are:

- Channel dewatering is considered to have severe impacts on macroinvertebrate and fish following periods of dewatering of approximately 24 hours.
- Some macroinvertebrates might be resistant to the impacts of short-term (< one month duration) dewatering by seeking refuge in the wet stream bed. Paradoxically, the dominance of fine-grained sediments that might initially compound the impacts of extreme low flow events on macroinvertebrates, might actually increase the resistance of surviving macroinvertebrates after the dewatering event has occurred.

Table 4.4 Ecological effects of channel dewatering

Effect	Alteration of habitat state	Duration	Ecological effects	Certainty	References
Channel dewatering	Severe loss of habitat Severe reduction in water quality in channel substrate/interstitial spaces	< c.24 hours	Macroinvertebrates potentially resistant to dewatering	High	Verdonschot et al. (2015)
			Mortality of some fish (1+ brown trout in example)	Low	Mark Warren, pers com
		> c.24 hours	Potential for large reduction in macroinvertebrate richness and abundance		Verdonschot et al. (2015) Ledger et al. (2011) Ledger et al. (2013) Lancaster and Ledger (2015)
			Reduction in macroinvertebrate secondary productivity	Med	Ledger et al. (2011)
			Shift in periphyton patch type	Med	Ledger et al. (2008)
			Decrease or increase in diatom richness and abundance dependent on succession effect	Med	Ledger et al. (2008)
			Potential for no change in macroinvertebrate total abundance or richness, however significant alteration to assemblage composition.	Med	Hille et al. (2014)

4.5 Frequency / return period

Interpretation of the effects of a short-term low flow event on a given community would ideally take into account information regarding the disturbance history, including the nature and frequency of antecedent disturbances. The sequencing of events is potentially important and flow conditions following a short-term low flow event can also have consequences for ecology.

The potential for repeated short-term low flow events to occur is considered relatively great, as summertime spray irrigation by farmers might be repeated in time scales measured in days or weeks. However, examples of the ecological effects of such frequent events do not appear to be available. The body of literature pertaining to the effect of frequent drying (channel dewatering) is largely based on a single experiment conducted in artificial channels located in Dorset, UK (Lancaster and Ledger, 2015; Ledger et al. 2008; Ledger et al. 2011; Ledger et al. 2013). The channels are fed by an adjacent chalk stream and therefore the consensus of findings from this body of work have not been corroborated by experimental

work across river typologies. However, they have been shown to be representative and realistic as regards the chalk stream systems they represent (Ledger et al. 2009).

The interaction between the frequency of short-term low flow events and their duration has not been investigated. As noted in Section 4.1, conceptually, duration is of increased significance for increasingly frequent events and relates to resilience of the biota. There is potential for the impacts on biota to be greater for events of longer duration (in consideration of the interactions between magnitude and duration outlined in Section 4.1). Whether or not biota are resilient to events of a given frequency can therefore potentially be dependent on the duration of the events.

The importance of the frequency of short-term low flow events to biotic responses is given in Table 4.5; where the ecological relevance of isolated, seasonal (quarterly) and monthly events are presented.

4.5.1 *Macroinvertebrates*

Declining resilience of macroinvertebrate assemblages occurs with increasing disturbance frequency (Ledger et al. 2013). In this example macroinvertebrates were relatively resilient to low frequency disturbance (quarterly dewatering events of six days); with no significant difference observed regarding richness or abundance relative to control streams (although more fly larvae and fewer mayflies and gastropods were recorded). The assemblage developed over time as per those of the controls (the experiment ran for 693 days). In contrast the high frequency disturbance (monthly dewatering events of six days) exceeded the capacity of macroinvertebrate assemblages for recovery. These were impoverished (reduced taxon richness), static communities dominated by fewer species (primarily fly larvae and oligochaetes).

The susceptibility of taxa to short-term low flow events can depend on event frequency; in the example of Ledger et al. (2013) amphipods, leeches, several caddisflies and beetles were sustained under low frequency treatment but markedly reduced under the high frequency condition.

4.5.2 *Fish*

Although pertaining to a stream naturally intermittent in its middle reaches, and although drying events were in general longer than those of primary interest to this review, increased frequency of drying event was reported to be an important factor in the rate and extent of recolonisation by fish following channel dewatering (Davey and Kelly, 2007).

4.5.3 *Macrophytes and phytobenthos*

Experimental work has demonstrated that the frequency of short-term (six days) low flow events can affect the successional dynamics of algal communities. Across a two-year experiment short-term drying events were shown to result in a reduction of dominance by encrusting alga with increasing disturbance frequency (Ledger et al. 2008). Low frequency (monthly) and high frequency (three monthly) drying events resulted in a shift from an algal community dominated by green encrusting algae to one dominated by mat-forming diatom communities. Disturbance increased diatom richness and abundance, but this was

dependent on time, with lower abundance in the high frequency treatment early in the sequence. Abundances of 11 diatom species either peaked in the high disturbance treatment and/ or decreased in the control treatment late in the sequence. Differing resistance and resilience of diatom assemblages across years was attributed to species composition.

It was noted in Section 4.2 that short-term flow reductions that result in reduced flow velocities are unlikely to result in impacts to macrophyte communities. However, it is acknowledged that if short-term low flow events were to occur at high frequency throughout the macrophyte growing season, this might result in a wetting regime within the range of tolerance of more terrestrial plants.

4.5.4 Ecosystem functioning

Taxon specific traits are likely to be of importance in determining the significance of the frequency of short-term low flow events. Aquatic macroinvertebrate taxa display considerable variation as regards voltinism (the number of generations that occur within a year). Experimental work has demonstrated how a high frequency (monthly) short-term (6 day) low-flow event differentially affected macroinvertebrate groups classified on the basis of voltinism. Productivity of multivoltine taxa increased relative to the control whilst productivity of semivoltine and univoltine taxa decreased (Ledger et al. 2011). Overall, secondary production in the impacted channels was less than half that of controls.

4.5.5 Summary

In summary, the key points to emerge from the literature regarding the impacts of short-term, extreme low flow events due to the frequency of short-term, extreme low flow events are given in Table 3.5.

Table 4.5 The importance of the frequency of short-term low flow events to biotic responses

Frequency	Biotic responses	Certainty	References
Isolated event	n.a.		n.a.
Seasonal event (quarterly)	Small changes to macroinvertebrate community composition following dewatering events	Med	Ledger et al.(2013)
	Alteration in algal dominance following dewatering events	Med	Ledger et al. (2008)
Monthly event	Large and significant impact on macroinvertebrates following dewatering events - reduced richness and resilience	Med	Ledger et al. (2013)
	Decreased macroinvertebrate productivity following dewatering events	Med	Ledger et al. (2011)
	Alteration in algal dominance following dewatering events. Increased diatom abundance and richness (given time, abundance reduced early in sequence)	Med	Ledger et al. (2008)

4.6 Timing/ seasonality

Examples of quantitative or semi-quantitative data relating to the importance of seasonality/ timing in determining the impacts of short-term low flow events are rare within the peer-reviewed literature. Therefore, the interaction between the timing of a short-term low flow event and its duration is largely conceptual. Interaction with duration is believed to be of greater importance for events of relatively greater magnitude, namely the formation of disconnected pools and channel dewatering. The impacts associated with these events are expected to progress more rapidly during warmer periods of the year (when short-term abstractions are more likely), for example increased macroinvertebrate mortality following channel dewatering (Ledger et al. 2011; Lancaster and Ledger, 2015; Richard Chadd, pers com).

The importance of timing/ seasonality in relation to biotic responses to short-term low flow events is given in Table 4.6. Biotic responses are categorised by season.

4.6.1 Macroinvertebrates

It was considered that apparent resilience of the macroinvertebrate community highlighted by the River Glen example related to the timing of the event and life-history traits of affected taxa (Richard Chadd, pers com). The approximately week-long event occurred in November, when many aquatic taxa might persist as eggs or small instars in wet sediment. It was considered that if the event had occurred in spring the larvae of many taxa may have been more greatly affected by the disturbance, as subsequent emergence and therefore reproduction of the cohort would likely have been more greatly affected. There is also the potential that physiological stress affecting macroinvertebrates within wet interstitial spaces would have been greater if the event had occurred during a warmer period. It should also be noted that colonisation via drift will have at least partially driven the recovery of the community, and this process is not related to the timing of the low flow event. It has previously been suggested that if a low flow event coincides with the presence of small instar larvae they are more likely to be able to take refuge in wet interstitial spaces (Ledger and Hildrew, 2001).

The example of the River Glen highlights that impacts of short-term low flow events on macroinvertebrate insect taxa requires consideration of life-stages; namely egg stages, a succession of instars associated with an increase in body size, emergence to a flighted stage and oviposition. Emergence and oviposition can be considered as critical time points regarding the sequencing of events relative to a short-term low flow event. It seems clear that for a given taxon a short-term event occurring post-oviposition or pre-emergence will have markedly different consequences than events occurring pre-oviposition or post emergence. The direct physical effects of short-term low flow events are expected to be of greatest significance regarding possible impacts, but indirect effects on water quality are also potentially of significance. A field study conducted across the summer in north-eastern Oregon found no difference in the emergence time of three insect taxa (two cased caddisflies and a moth), despite abstraction induced increases in water temperature of up to 4.6 °C (Brown et al. 2012). This suggests that short-term low flow events are unlikely to affect emergence through increased water temperature.

There is the potential for physiological stress affecting macroinvertebrates within standing water of wet interstitial spaces to be greater if short-term low flow events occur during a warmer period relative to a cooler period. An increase in macroinvertebrate mortality in experimental channels has been attributed to an increased intensity of disturbance events; the exposure of sediments in warm periods resulted in more rapid drying and greater mortality than in cooler periods (Ledger et al. 2011; Lancaster and Ledger, 2015). Despite increased mortality in this experimental setup, total abundance of macroinvertebrates was increased in summer and reduced in autumn/ winter in channels experiencing monthly dewatering disturbances (Ledger et al. 2013).

4.6.2 *Fish*

Fish are ectotherms with body temperatures close to that of water and thus reliant on water temperature for control of their metabolism, although they display some ability to regulate temperature (Elliott, 1981). They have optimal temperatures for growth, from which increasing deviation will reduce growth, an effect that is modified by the availability and nature of their food supply (Elliott and Hurley, 1997). Low summer flows will tend to increase water temperature on average, as the water body's thermal capacity reduces, and in the absence of other changing factors will increase or decrease growth depending on the thermal preferences of fish species. Fish can detect water temperature changes of around 0.5°C (Murray, 1971). Juvenile (Elliott, 2000; Breaux et al 2007) and adult (Moore et al 2012) salmonids have been shown to select cooler thermal refuges at times of low flow, a process that causes aggregations (Breaux et al, 2007) and thus the potential for increased density-dependent mortality and growth (Elliott et al 1997) and probably predation. Disease outbreaks are comparatively rarely observed in wild fish, but increasing fish densities and temperatures increase the risk of infection (Marcogliese, 2001).

An anecdotal example of a late summer irrigation abstraction made in a southern England stream highlights the importance of event timing; extreme low flows resulted in a fish kill of adult sea trout in the lower reaches (see Appendix 3.2). Timing was crucial: the low flow event being coincident with the migration of sea trout. The late summer timing was also likely of significance as salmonids have a particularly high oxygen demand and are sensitive to increased temperatures.

The timing/ seasonality of low flow events are of particular importance to fish regarding migration and spawning. Variable sensitivity is expected both between taxa and between life-stages of a given species. The timing of a short-term low flow event might determine whether one life-stage is negatively affected, but the same timing might confer a positive effect on a different life stage. Upstream migration is a critical life stage that is particularly affected by river flow because of the specific hydraulic conditions needed to pass partial obstruction of waterfalls and riffles. Low flows can often be a source of obstruction and if the spawning times are missed then the reproductive physiological window may be also missed, leading to loss of eggs and in some cases mortality of the spawners (de Gaudemar and Beall, 1998). However, the short-term nature of the events of primary interest to this review are, in general, unlikely to result in effective obstruction of upstream passage for long enough periods to result in the reproductive physiological window being exceeded.

Low-flow events can also cause a loss of cues for fish reproduction (Bonner and Wilde, 2000). However, the potential for the loss of cues in consideration of the time scale of short-term low flow events of primary interest (less than two weeks) is considered small and

unlikely to have substantial consequences for fish reproduction, i.e. cues for initiating reproduction might be slightly delayed, but are unlikely to occur for long enough that the period suitable for reproduction has passed.

Spawning salmonids choose sites with particular conditions of bed profile, gravel size, depth and velocity to deposit their eggs in redds. The selection is size-specific: large fish select larger gravel sizes, deeper water and higher velocity (Crisp, 2000). The spawning migration and activity are highly flow dependent. In small streams (e.g. <0.5 cumecs) passage to spawning sites may be very quick, sometimes overnight, and requires a certain range of flows to enable tributary entry, passage to spawning areas and egg deposition (Tetzlaff et al, 2005; Moir et al, 2006). Absence of suitable flows at critical times (e.g. October to December for many spate rivers, November to January in groundwater fed rivers) therefore have the potential to affect successful egg deposition. Other fish species also have critical spawning habitats of gravels and vegetation which need to be accessible for spawning to occur (Tetzlaff et al, 2005).

Oxygen concentration is crucial for fish egg survival and it was hypothesised that a short-term low flow event in the Bradshaw Brook, North West England, that occurred in December would have resulted in brown trout egg exposure and an impact on recruitment (see Appendix 3.2). However, there was no evidence for such an effect as no difference was observed the following year for the 0+ cohorts relative to those of the control locations. It was thought this might reflect the natural history of brown trout and density dependent effects; normal brown trout life-strategy involves production of large numbers of eggs with proportionately low numbers surviving to the fry stage.

The timing of low flow events in relation to fish should also be considered on a diurnal basis. NRW identified the potential for an impact on salmon where licence holders were abstracting to daily limits over a short period of time during the night, coinciding with salmon migration (see Appendix 3.4).

4.6.3 *Macrophytes and phytobenthos*

No evidence was found in the literature search of the impacts of short-term, extreme low flow events on macrophytes and phytobenthos due to the timing of these events.

4.6.4 *Ecosystem functioning*

No evidence was found in the literature search of the impacts of short-term, extreme low flow events on ecosystem functioning due to the timing of these events.

4.6.5 *Summary*

In summary, the key points to emerge from the literature regarding the impacts of short-term, extreme low flow events due to the timing of these events are given in Table 3.5.

Table 4.6 The importance of timing/ seasonality in relation to biotic responses to short-term low flow events

Timing/ seasonality	Biotic responses	Certainty	References
Spring	Macroinvertebrates relatively more sensitive owing to lower resistance of larger instars	Low	Conceptual only.
Summer	Increased likelihood of impact on macroinvertebrates owing to increased severity of low flow events (eg faster rate of drying, greater increases in temperature) and peak oviposition/emergence	Med	Ledger et al. (2011); Lancaster and Ledger (2015)
Autumn	Macroinvertebrates relatively less sensitive owing to greater resistance of egg stages and smaller early instars. Salmonid fish more sensitive because of spawning	Med	Conceptual only. Ledger and Milner (2015)
Winter	Decreased likelihood of impact on fish and macroinvertebrates owing to reduced severity of low flow events (eg reduced rate of drying, reduced temperature increases). Salmonid fish more sensitive because of spawning	Med	Ledger et al. (2011); Lancaster and Ledger (2015) Ledger and Milner (2015)

4.7 Rate of change

Rate of change of a short-term flow reduction is a particular consideration pertaining to magnitude of change effects described in Section 4.1. The rate of loss of habitat, and the speed at which the threshold is reached where riffle habitat is dewatered, can potentially result in the stranding of mobile taxa, namely fish and macroinvertebrates. Therefore, the rate at which short-term abstractions are implemented should be considered as part of their regulation.

Anecdotal examples of fish stranding occurring in relation to short-term low flow events were reported in the telephone interviews, however these related to temporary damming events which can be considered extreme in nature.

Stranding of fish and macroinvertebrates as a result of flow reductions are relatively well established in the literature (e.g. Kroger, 1973; Bradford et al. 1995; Bradford, 1997; Perry and Perry, 1986; Extence, 1981). Most research has focussed on the stranding of fish caused by hydropeaking (Nagrodski et al. 2012). Rate of change can determine whether fish are able to respond behaviourally and seek refuge (Bradford et al. 1995; Nagrodski et al. 2012), however, rate of flow decrease has not always been shown to be a significant factor in the incidence of stranding of fish (Bradford, 1997).

Experimental manipulation of the rate of change has demonstrated increased stranding rates under higher recession rates (Davey et al. 2006). Benthic fishes can also show variable behavioural response to differences in flow rate reductions with burrowing a more frequent response where flow recession is rapid (Davey et al. 2006). Furthermore, rate of recession can affect taxa differentially and is likely to reflect differences in behavioural responses of species (Davey et al. 2006).

The experimental study of Bradford et al. (1995) not only demonstrated increased frequency of stranding at higher rates of dewatering, but demonstrated that the timing of flow reduction can be of significance; fish were active in the water column at night and therefore rate of stranding was greatly diminished as compared with daytime trials.

Whether the rates of flow recession associated with the abstraction events of primary interest to this review are sufficient to result in the stranding of fish and macroinvertebrates is unknown. Based on the experimental results reported above it is considered that rate of flow loss should be a consideration in the regulation of short-term low flow events.

Rate of flow accession following a short-term low flow event is also of significance, in particular to less mobile taxa. This potential impact was raised for the designated freshwater pearl mussel following a short-term low flow event in the River Ehen (Mike Dunbar and Mark Warren, pers comm (including an extract from the River Ehen SAC Site Action Plan Addendum December 2013)). In response to an abrupt reduction in flow freshwater mussels emerged to the substrate surface. The low flow period was followed by a high flow event that peaked at mean daily flow of 2652 Ml/d. It was considered highly likely that this will have caused additional stress and resulted in mussels, made vulnerable owing to the partial emergence caused by the low flow conditions, being washed downstream.

Regarding fish, Flodmark et al. (2006) observed no differences in the growth or condition of brown trout parr subjected to daily flow fluctuations of up to 350 % in experimental stream channels. They concluded that providing stranding can be avoided, the effects of daily flow fluctuations on salmonids are relatively small. This is reaffirmed by Flodmark et al. (2002) who observed that, despite initial peaks in stress hormones in brown trout parr subjected to daily flow fluctuations, no differences between control and treatment groups were noted by the fourth day of exposure, indicating rapid habituation to fluctuations in flow on a physiological level.

Valentin et al. (1994) assessed the impacts of flow fluctuations on juvenile (two month old) grayling within an experimental stream. Baseline stream discharge was established at 25 m³/h (providing maximum velocities of 0.3 m/s). Discharge rates were subsequently increased to 90 m³/h (maximum velocity 0.55 m/s) on three successive days for a period of 2.5 hours per day. Observations of 400 individual fish indicated that *“fish response was very rapid, within the first 10 min of each spate”* regarding movement to more optimal refuge and transitional areas of the stream channel. Valentin et al. (1994) concluded *“that in moderate changes in flow, young grayling can quickly locate available and suitable areas.”*

The majority of studies that review impacts upon fish from flow regulation focus upon hydropower hydropeaking and the immediate areas below dam structures.

5. Other factors influencing ecological response to short duration abstraction from rivers

5.1 River typology and community characteristics

The biotic communities of rivers vary in their sensitivity to short-term low flow events. Impacts might be more or less pronounced dependent on the composition of a given community and the ability of a particular assemblage to show resistance and/ or resilience to a short-term low flow event. Categorisation deemed appropriate to inform flow standards are outlined below. Where sensitivity is highlighted it is considered that ecology will be impacted by events of relatively shorter duration to those outlined in Section 4, i.e. the progression along Mainstone's (2012) continuum will be more rapid than otherwise expected.

5.1.1 Chalk streams

Chalk streams are relatively unlikely to suffer from natural short-term extreme low flow events (as they are base-flow dominated with generally stable flow) and are therefore considered to be less well adapted to such events, headwater winterbournes notwithstanding. Short-term low flow event impacts are therefore expected to be greater in chalk streams versus streams associated with other geologies.

Macrophyte communities of chalk streams are likely to be more sensitive to short-term low flow events than those of other geologies. Spring and early summer have been identified as the critical seasons when some macrophytes are most sensitive to flow (Acreman et al, 2008). Sensitive macrophytes of conservation interest associated with chalk streams in particular are the water crowfoots. *Ranunculus penicillatus* subsp. *psuedofluitans* is considered to require a minimum of 0.1 m/s to maintain growth (Cranston and Darby, 2004) and could be sensitive to short-term low flow events of relatively longer duration through the spring and summer months.

5.1.2 Upland/ lowland

Upland streams in general exhibit good water quality and, in general, these systems do not suffer from the intense agricultural and urban catchment-use related pressures of lowland streams. Water temperature is also likely to be lower owing to altitude. Such streams are therefore expected to be less sensitive to short-term low flow events. Taxa sensitive to poor water quality, such as stoneflies and mayflies, have been observed to persist in such streams following the formation of disconnected pools (David Bradley, pers com). Low flow events are a more common occurrence in flashy upland catchments in the UK (Dominic Longley, pers com) and therefore impermeable catchments are further expected to be relatively resistant/ resilient to short-term low flow events, where these occur at times of the year that such natural events occur.

It might be expected that ecology would be more sensitive in upland streams compared to lowland, low gradient streams; as species found will in general be adapted to higher flow

velocities. However, Dunbar et al. (2010a) noted a distinct difference in the response of macroinvertebrate LIFE scores to flow between upland and lowland rivers, with scores from routine monitoring being more affected by low flow conditions in lowland rivers. This was believed to result from differences in channel profile (natural morphology upland-lowland differences, and additionally the effects on habitat of channel resectioning) and whether higher velocities are maintained under reduced flows.

It has been demonstrated that ecological communities encompass a high degree of diversity regarding species-specific sensitivity to the pressures outlined in Section 4. It should be noted that macroinvertebrate communities considered in the relatively sparse literature on experimental field and mesocosm experiments have not tended to be highly flow-sensitive in advance of the application of treatment, with control velocities of, for example, c. 0.9, 0.3-0.6 0.15 and 0.2 m/s (Miller et al. 2007; Dewson et al. 2007a; Verdonschot et al. 2015 and Ledger et al. 2011, respectively). In the context of LIFE Flow Groups these flow velocities are generally typical of those associated with taxa with preferences for moderate to fast flows (Extence et al. 1999). However, the lower end of these flow velocities would be associated with taxa preferring slow to sluggish flows and none of these velocities are equal to the threshold used by LIFE to indicate taxa primarily associated with rapid flows (>1 m/s). Despite this observation, as noted above, literature pertaining to broader time scales indicates that lowland macroinvertebrate assemblages are relatively sensitive to low flows (Dunbar et al. 2010b).

5.1.3 *Stream size*

Smaller streams are considered more likely to be affected by small scale local abstraction, as the volume of such abstractions is generally small and are therefore unlikely to have much effect on larger rivers. Habitat and hydraulic models have shown that smaller streams require a greater proportion of their flow to maintain the same amount of habitat as would be required in larger streams (Jowett, 1997; Lamouroux and Souchon, 2002).

5.1.4 *Relative position of an ecological community within a catchment*

The headwaters of streams can be distinguished from lower reaches regarding the potential for recolonisation following disturbance events, such as short-term, extreme low flows. Where no upstream source of colonists exists, such as in headwaters, recolonisation and recovery following a short-term, extreme low flow event might take longer than in downstream reaches, depending on the degree of isolation (e.g. Resh, 1992), or may not be expected to occur at all in the case of macrophytes in particular.

5.1.5 *Salmonid and coarse fish*

In the case of fish, a general distinction can be made between salmonid and coarse fish. Differences between these two groups present differing susceptibilities to possible effects of short-term low flow events.

Anadromous salmonid fish adults (those that migrate up rivers from the sea to spawn) are likely to avoid a large proportion of the period when irrigation or emergency water supply induced short-term low flow events are most likely to occur; inhabiting the sea for the majority of the summer months and returning to rivers on the basis of cues of appropriate

flow conditions. Where salmonids are subject to low flow events they are considered more sensitive to associated pressures such as low dissolved oxygen and increased temperature.

Coarse fish (and resident salmonids) are more likely to be subjected to the effects of anthropogenic short-term low flow events as they are resident all year round. An important correlate for the recruitment of coarse fish is temperature and the number of degree days of $>12^{\circ}\text{C}$ (Dominic Longley, pers com). Therefore a non-linear relationship between magnitude of flow reduction and the effect on coarse fish might be expected concerning short-term events. As low flow conditions are sometimes associated with elevated temperature, increasing magnitude of low flow events might improve recruitment, but only up to the point where other factors become limiting, for example depressed dissolved oxygen levels, which will vary depending the tolerance range of specific taxa.

As salmonids in general mature at a younger age than coarse fish they can be considered relatively more resilient, as populations can quickly re-establish following a low flow event; especially where a river is accessible via migration from the sea. As coarse fish tend to mature later than salmonids if extreme low flow events result in mortality, the recovery of populations would be expected to take longer than for salmonids in the absence of immigration. Therefore salmonids can, in general, be considered relatively less resistant, but more resilient as compared with coarse fish, which are relatively more resistant, but less resilient.

5.2 Confounding/ compounding pressures

As discussed in the conceptual framework to describe the pathways through which different types of water resource use affects aquatic organisms (SNIFFER, 2012) an important concept regarding the understanding of how short-term low flow impacts might affect ecology includes the effect of indirect pressures. These can act in isolation (to confound the impacts of abstraction) or in-combination with the effects of abstraction (to compound the impacts of abstraction) and include morphological changes, water pollution and invasive species. These pressures are discussed below in relation to the impacts of short-term low flow events.

5.2.1 Morphological alteration

The relative impact of short-term low flow events is likely to have considerable correlation with the degree of local morphological alteration. Substantial physical modification of streams is associated with flattening of the channel bed, straightening, loss of riparian margins, loss of connectivity with the floodplain, loss of pool/ riffle sequences, loss of shading, amongst others. Further to a reduction in habitat diversity, a common consequence of such modifications is that when flows become reduced, refuge availability can be limiting, for example a lack of pools results in absence of deeper water refugia, a flat channel bed can result in a lack of localised more concentrated flow, which otherwise would be associated with increased flow velocities and higher dissolved oxygen concentrations.

It is therefore expected that the degree of impact on ecology will be somewhat dependent on local degree of morphological alteration, with greater impacts, or thresholds being reached, following shorter duration events in more modified river systems than in less altered systems. In fact, the degree of morphological alteration might determine whether or not a

threshold of low flow magnitude that impacts ecology is reached or not for a given short-term low flow event. More complex, well connected, habitat is expected to result in both greater resistance and resilience of biota to the effects of short-term low flow events.

Macroinvertebrate communities are more flow sensitive in morphologically altered rivers as compared to more natural rivers (Dunbar et al. 2006; Dunbar and Mould, 2008; Dunbar et al. 2010a; Dunbar et al. 2010b). This effect is thought to occur primarily because of a lack of refugia in morphologically altered channels, in particular under low flows. Whether the same principal applies to short-term low flow events is untested, however, it is considered likely that impacts will be stronger in modified water bodies; reduction in flow velocity is likely to be exacerbated where longitudinal connectivity remains, and where longitudinal connectivity is lost the presence or quality (for example reductions in depth and shading (influencing temperature)) of habitat is likely to be proportionately more reduced. Although modified rivers are likely to show a greater response to low flow events, the potential for impact is likely to be greater in more natural rivers, where ecology is less impacted in advance of the disturbance. This might be especially true for ecology of the riparian zones, with natural rivers in general exhibiting shallower bank profiles, with associated biota.

For fish the issue of morphological alteration and connectivity are of particular importance, as where natural diversity of habitat is present and/ or connectivity is not impeded by manmade barriers, fish can move away from localised impacts (assuming rate of change is not too rapid and as long as flows are not low enough to result in drying of the channel). Although not of direct relevance to this review, an example that supports these assumptions was given for two brown trout chalk rivers in southern England (Dominic Longley, pers com). Long-term monitoring data have suggested that juvenile brown trout respond to seasonal variation in flow in these rivers with similar patterns observed between the two rivers. The two rivers are similar barring their degree of morphological alteration and the amplitude of reduction in abundance is consistently greater in the heavily modified river relative to the more natural river.

5.2.2 *Water quality*

Poor water quality disproportionately impacts macroinvertebrate taxa sensitive to low flow velocities (or requiring higher flow velocities) and affected communities might therefore be expected to show less response to reduced velocity/ stagnation than those that are unimpacted by poor water quality. This appears to be supported in the study of Hille et al. (2014), where reduced diversity of macroinvertebrates in artificially created pools within a dewatered channel was observed in a relatively pristine stream but not in a stream with elevated nutrients. The impacted stream of this example was also morphologically altered; however, the example demonstrates reduced sensitivity of biota to short-term low flow events in already impacted systems.

An 18 day experimental study in artificial channels tested directly the interaction among sediment addition, nutrient enrichment and water abstraction (Matthaei et al. 2010). Interactive effects of reduced flow and fine sediment were of particular importance and are discussed in the following section. Flow and nutrient status interactions were rare relative to interactions between reduced flow and fine sediment. However, the abundance of two macroinvertebrate taxa in leaf packs (leaves bolted together to assay breakdown rates) increased under higher nutrient conditions when flow was normal, but remained unchanged or reduced when flow was reduced. Ephemera, Plecoptera and Trichoptera (EPT) richness

in leaf packs showed no response to nutrients at normal flow but peaked at intermediate nutrient levels coincident with reduced flow. The final significant interaction observed between nutrient status and flow was that nematode numbers were greatest at the highest nutrients levels under normal flow, but were greatest at intermediate nutrient levels at reduced flow. These interactions are considered relatively subtle and unlikely to be of great importance to the overall impact of a short-term low flow event on macroinvertebrates.

The same field experiment as that reported on in Dewson et al. (2007a), but following flow reduction of >1 year, demonstrated that the impact of reduced flows is dependent on the presence of water quality pressure and the existing sensitivity of macroinvertebrate communities (Death et al. 2009). A number of measures of the macroinvertebrate community were found to be reduced in the pristine site, whilst only a single measure was reduced at the mildly impaired site and no effects were observed in the stream with the poorest water quality. These effects did not manifest at a shorter (1 month) time scale.

A number of studies investigating the effects of short-term low flow events have measured water quality parameters alongside the sampling of macroinvertebrates in the context of relatively low magnitude events where habitat quantity and character are affected, but longitudinal connectivity maintained (Dewson et al. 2007a; Verdonschot et al. 2015; Miller et al. 2007). Small decreases in DO have been recorded but have not been associated with effects on macroinvertebrates (Dewson et al. 2007a; Verdonschot et al. 2015). Increases in conductivity (used as a proxy for pollution) have also been recorded under this scenario with either no effect being observed (Dewson et al. 2007a) or a correlation with short-term alteration of the relative abundance of taxa observed (Miller et al. 2007). No relationship was observed between macroinvertebrates and direct measures of change in physical habitat in the latter example and the alteration to community structure was short lived, communities appearing to have recovered following high winter flows (10 months after cessation of abstraction). The change in relative abundance of taxa was not associated with change in ecosystem functioning, changes in relative abundance occurred among functional equivalents within the same taxonomic families; suggesting that impacts to ecosystem processes were minimal.

It is considered therefore that where the ecology is known to be impacted by poor water quality, the impacts associated with short-term low flow events outlined in Section 4 will be reduced or will occur following longer duration of low flow event.

5.2.3 *Excessive fine sediment*

Short-term low flow events are likely to have greater impacts on ecology in streams subjected to significant fine sediment inputs. A number of experimental studies have highlighted the potential for this interactive effect (Dewson et al. 2007a; James et al. 2008; Hille et al. 2014; Verdonschot et al. 2015). However the effect of fine sediment was not directly tested in these studies. The study of Matthaei et al. 2010 noted in the above section found that algal biomass accrual declined with reduced flow and sediment addition. Total macroinvertebrate abundance on algal colonisation tiles decreased more at low flows with increasing sediment addition. Interactions between sediment and flow influenced six of the eight common taxa on tiles and three of the taxa found in leaf-packs. Flow affected EPT richness via an interaction with sediment addition; EPT richness declined with rising sediment levels. Macroinvertebrate community composition also differed among sediment and flow treatments, with a significant interaction seen.

Whilst excessive fine sediment deposition can compound the impacts of short-term low flow events on macroinvertebrates, fine sediment can improve the resistance of some macroinvertebrate groups to short-term channel dewatering by providing wet refuges (Stubbington et al. 2009; Richard Chadd, pers com).

5.2.4 *Invasive species*

It has been said that the invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes (Bunn and Arthington, 2002). All examples given within the review of Bunn and Arthington (2002) pertain to either; the loss of wet-dry cycles in floodplain wetlands; establishment of non-native fish in regulated rivers (long-term effects resulting from, for example, flow stabilisation); and the establishment of invasive non-native macrophytes and fish where habitats have been permanently converted from lotic to lentic environments. The review therefore highlights the importance of permanent changes to flow regime resulting in favourable conditions for non-native species. None of the pressures listed are considered to apply to short-term low flow events and, because of their short-term nature, short-term low flow events do not result in permanent changes to prevailing hydrological conditions. No examples of the responses of non-native invasive species to short-term low flow events have been identified in this review (note that longer-term drought conditions might favour establishment of non-native invasive macrophyte species (Dollar et al. 2013)). Non-native invasive species are therefore not considered to be a major concern as regards short-term low flow events.

6. Summary and knowledge gaps

6.1 Summary

Whilst the conceptual understanding of the effects of flow reduction on ecology is well-established, quantitative and semi-quantitative evidence of ecological impacts and recovery following short-term flow reduction was found to be relatively rare, both within peer-reviewed and grey literature and examples provided directly by the regulatory agencies via interviews. The majority of examples of ecological impacts of short-term flow reduction came from peer-reviewed studies undertaken in Western Europe (e.g. Netherlands, Denmark, UK), Australia, New Zealand and the USA.

Examples regarding impacts on ecology can be drawn from the literature relating to naturally drying and intermittent streams. For example, macroinvertebrates in arid-land streams of the USA (Lytle and Poff, 2004; Bogan et al. 2015). However, as such biota are likely to have developed resistance/ resilience as regards life history traits, the findings of such studies are considered to be of somewhat limited use as regards short-term drying in naturally perennial systems, typical of the UK situation.

6.1.1 Impacts

In terms of the **magnitude** of change, the available evidence suggests that aquatic organisms are generally resistant to short-term (<1 month) low flow events that result in the reduction of habitat quantity and/ or quality, but not in the loss of longitudinal connectivity or channel dewatering, in the absence of compounding/ confounding pressures and considerations of river typology and community characteristics, as discussed in Section 5.1, notwithstanding.

The formation of disconnected pools may have variable effects on ecology, depending on a number of factors; firstly, the duration of the event, with severity of impact increasing at scales of between days or weeks; secondly, environmental factors that influence physio-chemical changes of importance to biota, for example shading of pools, pool depth, ambient temperature; thirdly, the sensitivity of a given biotic assemblage (the importance of species specific tolerances to abiotic change/ extremes).

The dewatering of a channel which is naturally perennial has severe short-term consequences for a number of biotic elements:

- Fish in particular may face mortality where emigration from the dewatered reach is not possible. **Rate of change** in flow, the presence of barriers to movement and channel morphology are considered to be of particular importance in this context, although quantitative evidence for rate of change effects on ecology in the UK context are limited.
- Macroinvertebrates tend to be less mobile and may also therefore face mortality, although some taxa are able to survive in substrate if it remains wetted. Survival is expected to be largely dependent on event duration and timing which affect how quickly drying of the substrate occurs.

- Phytobenthic communities have been shown to alter as a result of repeated dewatering, resulting in shifts from algal communities dominated by green encrusting algae to communities dominated by mat-forming diatoms. Nevertheless recovery is thought to be relatively rapid.
- Macrophytes are believed to be largely resistant to short-term dewatering, although evidence to support this is scarce. By contrast, if communities are lost, recovery may be very slow.

The **frequency** of flow reduction events is of importance insofar as it affects recovery of biota following a disturbance event, with full recovery typically less likely and occurring more slowly with increased frequency of disturbance. Less than one month between repeated extreme low flow events in the summer is likely to prevent the recovery of macroinvertebrates.

The **timing** of flow reduction events is of importance insofar as it affects abiotic factors which may influence survival (ambient temperature, water temperature and dissolved oxygen saturation), and the life-stages of fish and macroinvertebrates present (for example, macroinvertebrate eggs and smaller instars are expected to be better able to exploit wetted substrate as a refuge, relative to larger instars). Atlantic salmon are more resistant to short-term low flow events that occur in the summer (when they are most likely to naturally occur) and brown trout are more resistant to the effects of extreme hydrological events if they do not coincide with spawning in autumn/ winter.

6.1.2 Resistance

A number of factors may affect the resistance of aquatic organisms to short-term, extreme reductions in flow:

- Owing to their normally stable flow regime and associated biota, chalk rivers are considered to be highly sensitive to short-term low flow events.
- Macroinvertebrate communities in slow flowing lowland European rivers (examples cited from the UK, Denmark and the Netherlands) appear to be relatively resistant to the effects of low flow events extending up to periods of several months during the summer, as long as pools do not become isolated or the channel dewatered. A reason for this could be that mean current velocity is naturally relatively low in low gradient rivers and many of the taxa present are more tolerant of low flow events than rheophilic taxa that are rarer.
- There is less evidence in the literature about the resistance of aquatic organisms to short-term, extreme low flow events in upland rivers. Evidence is also inconsistent for upland rivers: one study in Wales reported a reduction in macroinvertebrate abundance during an extreme drought event (although it is unclear whether the invertebrate response occurred within a month or after several months); whilst another study suggested that macroinvertebrate communities in upland rivers might be more tolerant of extreme flow variation.
- Fish are naturally adapted to living in a temporally heterogeneous environment. Therefore, single low flow events are probably of low detrimental effect, unless their magnitude leads to severe temperature change, total desiccation, excessive predation or disease outbreak. However, cumulative effects of repeated impacts may be more significant; but the actual impacts have not been directly studied.

Effects will be dependent upon the particular environmental flow components and individual circumstances of location, season and species.

- Salmonids are expected to be less resistant to short-term low flow events than coarse fish, owing to their greater sensitivity to any resulting changes in water quality.
- The life stages potentially most vulnerable are those short duration stages that are short-term and dependent upon suitable flow at specific times, such as spawning migration, spawning and smolting. Of these, the effects of flow reduction on smolting are more equivocal because water temperature change may be more important than hydraulic variables.
- Over-crowding in small habitats, such as cool temperature refugia for cold water species in summer. Salmonids select such areas and increased density-dependent mortality and growth would be anticipated through resource and interference competition.
- Morphological alteration is expected to increase the severity of impacts of short-term low flow events owing to reductions in occurrence and/ or quality of refugia, and in some cases their absence. As noted above, fish are particularly sensitive to modification that affects their ability to migrate away from low flow, or to recolonise reaches affected.
- The biota (in particular macroinvertebrates) of water bodies with chronic poor water quality are expected to be relatively insensitive to short-term low flow events owing to the limiting pressure of poor water quality.
- The interactions between reduced flow and elevated sediment inputs have been tested experimentally. Negative impacts on ecology resulting from reduced flow will be significantly worsened where excessive fine sediment inputs are also present.
- Increased channel habitat diversity will improve the resistance of aquatic organisms to the impacts of short-term, extreme low flow events by providing more wet refuges.

Regarding ecosystem functioning, possible effects of short-term low flow events on productivity are likely to differ markedly between events that create drying of the stream channel and those that do not. There are indications from the peer-reviewed literature that short-term low flow events can result in decreased productivity. Reduction in flow velocity can result in shifts in algal patch type dominance which can result in significantly decreased biomass. Secondary productivity (macroinvertebrates) might be reduced by half following short-term low flow events (however this was observed only where a disturbance was frequent in nature, occurring monthly and lasting for six days at a time).

6.1.3 Recovery

Although studies identified within the peer-reviewed literature tend to focus on the impacts of experimental treatments and not on subsequent recovery, available evidence supports the hypothesis that aquatic organisms are relatively resilient to short-term low flow events (except where they occur at high frequency (>monthly or quarterly)), even those of sufficient magnitude to cause dewatering. This is in part because such events tend to be relatively localised in spatial scale, such that organisms may re-colonise following the disturbance. The telephone interviews demonstrated an apparent consensus amongst interviewees that, where short-term low flow events are limited regarding spatial extent, and in the absence of compounding/ confounding pressures, recovery of ecological elements is likely to be rapid, i.e. resilience to such events is expected to be high.

Recovery from the impacts of short-term, extreme low flow events occurs because:

- Macroinvertebrate taxa are able to recolonise through downstream drift after the low flow event and especially under spate conditions. Winged insects are also able to recolonise from adjacent catchments (these mechanisms presume short-term low flow events are relative localised).
- The availability of wet refuges in a dewatered channel can affect the persistence of certain macroinvertebrates and therefore the recovery rate of the community following cessation of a short-term, extreme low flow event.
- Fish are relatively mobile taxa and can recolonise from both upstream and downstream directions following restoration of suitable habitat/ restoration of connectivity.
- Phytobenthos appears to respond quickly to changes in flow and following continual rewetting are not expected to be limited.
- Macrophytes are unlikely to be impacted by short-term low flow events.

Recovery from the impacts of short-term, extreme low flow events might be delayed or prevented when:

- Short-term low flow events occur at high frequency (>quarterly); monthly drying events have been shown to result in an inability of the macroinvertebrate community to recover.
- The position in the catchment and spatial extent of the impact (e.g. in catchment headwaters and/ or relative to natural or anthropogenic barriers) restricts the ability for re-colonisation (e.g. by downstream drift or upstream migration).
- The establishment of new colonists during the low flow event that gain a foothold in the available ecological niches and block the recovery of the original community.
- The channel is uniform with few wet refugia on the surface of the substratum and/ or the sediment under the dry stream bed loses sufficient moisture.

6.2 Knowledge gaps

Overall there is a paucity of peer-reviewed literature regarding the effects of short-term abstractions on ecological receptors of perennial streams. Whilst studies that compare the magnitude of low flow event are available, studies relating to other important characteristics of low flow events and to potentially confounding factors are rare (with some notable exceptions). Furthermore, although some of these examples provide data points measured in days post initiation of a low flow event, more often data is reported on following multiples of weeks following initiation of the event. Abstraction activity of shorter duration than these time periods is of interest to this review and uncertainty therefore remains regarding events of short duration.

The effects of event frequency have received little attention and this factor is considered crucial in determining the effect of short-term low flow events on resilience of biota.

There is a paucity of peer-reviewed literature regarding the effects of rate of change of short-term abstractions, particularly on fish.

This review has assumed that the scale of impact of the abstraction activity of interest is limited spatially. Examples of ecological impacts in the peer reviewed literature pertaining to short-term low flow events in general do not take into account spatial extent of impacts. Furthermore, no anecdotal examples supported by quantitative or semi-quantitative evidence were provided for these kinds of abstractions.

The peer-reviewed literature on the effects of reduced flow on ecology uses inconsistent terminology regarding the magnitude of flow reductions. Measures used include discharge, velocity and percentage reduction from control conditions. Whilst large proportional reductions might be reported, this does not necessarily mean that the reductions investigated were extreme. This possibility is highlighted by macroinvertebrate studies where the measured flow velocities in the reduced condition did not appear to be very low (Dewson et al. 2007; Miller et al. 2007). Very rarely are flow reductions put in the context of historic flows, for example expressed as flow percentiles of a long-term record for a river. This is to some degree problematic as regulation of water abstraction considers these kinds of summary statistic. However, as this review has focussed on extreme low flows, the general absence of historic context is not considered of too great importance, as absolute flow conditions can be referenced, for example stagnation, formation of disconnected pools and dewatering.

Of the WFD biological elements identified as being of primary interest to this review, the majority of peer-reviewed studies investigating short-term low flow events considered macroinvertebrate responses. Few studies considered the effect of short-term low flow events on fish and phyto-benthos and no studies considered macrophytes.

The majority of peer reviewed studies consider in-channel habitat. In the case of macroinvertebrates this normally involves the direct sampling of the substrate. However, flow reductions are likely to have different effects on different instream habitats. It is quite possible that macroinvertebrates of the riparian zone and exposed riverine sediments may be more greatly affected than those of in-channel habitat. However, in practice this is not known because of a lack of routine monitoring of these biota. Furthermore riparian habitats are important to fish fry, and effects of low flow events might affect this group disproportionately through loss of habitat. A further knowledge gap results from the fact that experimental studies do not sample macroinvertebrates of in-channel macrophytes. In an English chalk stream and its tributary, Wright (1992) reported that taxon richness, numerical abundance and biomass of invertebrates was significantly higher on three macrophyte biotopes (*Ranunculus*, *Berula*, *Callitriche*) than on gravel or silt.

Measures of macroinvertebrate communities reported in the peer-reviewed literature are focussed on sum community metrics, such as, abundance, richness and evenness. These metrics do not measure changes in taxonomic composition that are likely to be picked up by standard indices used by the regulatory bodies in the UK to assess the impacts of different pressures and classify the ecological status of water bodies under the WFD (as demonstrated in the example of the River Glen; Richard Chadd pers com). The literature does however report the loss of rheophilic taxa and this is explicitly reported on in some cases.

Questions which further research might address:

- What are the ecological impacts of short-term low flow events at a time scale measured in days? Peer-reviewed studies rarely report data for time points < 1 week following flow reduction.
- How does the timing of short-term low flow events affect ecological impact? Peer-reviewed studies have not directly investigated this.
- How does frequency of short-term low flow event affect ecological impact? Peer-reviewed studies are currently limited to results of the artificial channel experiment reported on by Ledger and associates.
- How does ecology respond to short-term extreme low flow events in relation to the rate of change in flow? It is not well understood whether the types of short-term abstraction of interest are likely to result in impacts directly attributable to the rate of change, i.e. stranding.
- At what spatial scale do ecological impacts associated with short-term abstractions manifest? This review has assumed that effects are limited spatially, however evidence is currently lacking.
- How do duration and frequency of short-term low flow events impact fish communities?
- How, if at all, do macrophyte communities respond to short-term low flow events? How do macroinvertebrates specifically associated with macrophytes respond to short-term low flow events?
- How do ecological communities specific to riparian zones (in particular macrophytes, macroinvertebrates and fish fry) respond to short-term low flow events?
- How does morphological alteration interact with characteristics of short-term low flow events in determining ecological impacts? This requires consideration in regards to habitat quality and diversity more generally, but also specifically regarding the riparian zone and exposed riverine sediments. These habitats are, in general, less likely to be present at morphologically altered sites compared with more pristine sites.
- How do the biomonitoring metrics used by regulatory agencies respond to short-term low flow events?

7. Evaluation of environmental flow standards in relation to short-term low flow events

The UKTAG first developed water resources standards for rivers in 2008 (UKTAG, 2008). These were based on river typology developed by Holmes et al. (1998) and were expressed as maximum allowable percentage deviations from natural flow percentiles. These low flow standards defining High and Good status are given in Table 7.1 and Table 7.2, respectively. Standards defining the Moderate/ Poor and Poor/ Bad were recommended as incremental bands of 25% on the Good standards. This was considered to reflect that where abstractions are of the scale of 60-70% of the QN95, river flows are likely to fall to zero for a few days per year. The categorisation of river typologies is given in Table 7.3

Table 7.1 Water resources standards for rivers and High Status (Source UKTAG, 2008)

Types	Flows greater than QN95	Flows less than QN95
	(allowed per cent change from the natural flow)	
All Types	Up to 10	Up to 5

Table 7.2 Water resources standards for rivers and Good Status (Source UKTAG, 2008)

Types	Season	Flow > QN60	Flow > QN70	Flow > QN95	Flow < QN95
	(% change allowed from the natural flow)				
A1	April –Oct	30	25	20	15
	Nov –March	35	30	25	20
A2 (downstream), B1, B2, C1, D1	April –Oct	25	20	15	10
	Nov –March	30	25	20	15
A2 (headwaters), C2, D2	April –Oct	20	15	10	7.5
	Nov –March	25	20	15	10
Salmonid spawning and nursery areas (not Chalk rivers)	April –Oct	25	20	15	10
	Nov –March	20	15	flow > QN80 10	Flow < QN80 7.5

Table 7.3 Typology for water resources standards for rivers (Source UKTAG, 2008)

		Type	Gradient	Altitude	Description
			(Metres per kilometre)	(metres)	
Type A	Clay and/or Chalk; low altitude; low slope Eutrophic; silt-gravel bed	A1	0.8+/- 0.4	36 +/- 25	Predominantly clay. South East England, East Anglia and Cheshire plain
		A2*	Slightly steeper 1.7 +/- 0.8	low altitude 55 +/- 38	Chalk catchments; predominantly gravel beds; base-rich
Type B	Hard limestone and sandstone; low-medium altitude; low-medium slope; typically mesotrophic with gravel-boulder or pebble-cobble) bed	B1	4.1 +/-9.9	93 +/- 69	Hard sandstone, Calcareous shales; Predominantly South and South West England and South West Wales
		B2	Shallower than B1 2.7 +/- 10.7	71 +/- 58	Predominantly North West and East Scotland
Type C	Non-calcareous shales, hard limestone and sandstone; medium altitude; medium slope; oligomeso-trophic with pebble, cobble and/or boulder bed	C1	5.4 +/- 6.5	101 +/-84	Hard limestone; more silt and sand than C2; mesotrophic
		C2	Steeper than C1 7.3 +/- 10.8	130 +/- 90	Non-calcareous shales; pebblebedrock; Oligomeso-trophic
Type D	Granites and other hard rocks; low and high altitudes; gentle to steep slopes; ultra-oligo Oligo-trophic, with cobble, boulder, bedrock, and/or pebble bed	D1	Medium gradient 11.3+/- 15.6	low altitude 93+/- 92	Oligotrophic, substrate finer than D2 (including silt and sand); more slow flow areas than D2
		D2	High gradient 25.5 +/- 33	High Altitude 178 ± 131	Stream order 1 and 2 bed rock and boulder; ultra-oligo trophic torrential
* To reflect the different sensitivities of the headwaters of chalk streams to the downstream reaches, type A2 was split into two – A2 (headwaters) and A2 (downstream)					

These current environmental standards have been developed to help assess the risk of deterioration in ecological status which may arise from proposed changes in river flow, estimate the status of rivers already subject to flow alterations in cases where no suitable biological methods are available and inform investigations into the potential causes of biological damage. However, the standards take no account of the duration and return period of exceedance; in theory exceedance of a standard for one day in a year gives the same outcome as continuous exceedance. In terms of impact on river ecology these two scenarios may be very different.

For temporary, occasional abstractions it is considered that the current standards may be over-precautionary, with scope for introduction of a temporal and spatial element allowing

short-term deviation, if it can be demonstrated that this can be allowed without causing significant environmental impacts.

Any recommendations allowing short-term deviations must sit within the current flow standards framework in order to be readily implemented and regulated. A precedent for introducing further criteria/ allowable deviation is seen in the JNCC updated version of its Common Standards Monitoring Guidance for Rivers (JNCC, 2016). The guidance sets mandatory flow targets which are taken as the minimum expected for SAC rivers where locally agreed targets are not already in place. In a similar way to the UKTAG (2008 and 2014) guidelines, these are expressed as maximum allowable percentage deviations from natural flow percentiles, with different percentage deviations defined for rivers of different sizes. However, compliance assessment is based on flow time series, not flow duration curves, and some allowance is made for spatial and temporal variation. The wording of the guidance provides some allowance for judgement based on experience and site knowledge, but, in essence, allows for a maximum of:

- 10 days of continuous non-compliance in any one year, or 20 days of non-compliance overall in any one year, as long as the increased impact on naturalised flows is not dramatic (e.g. greater than twice the deviations allowed for by the flow targets that apply); and
- non-compliance over a total river length of no more than 5% of an assessment unit, again as long as the increased impact on naturalised flows is not dramatic.

On the basis of the literature review undertaken, the existing UKTAG standards are deemed precautionary, and there is likely to be some scope for deviation from the standards for short time periods under certain circumstances. Deviation in line with the recommendations of the updated version of the JNCC Common Standards Monitoring Guidance for Rivers (JNCC, 2016) would be consistent with the evidence identified in the literature, and with the approach applied at Habitats Directive sites.

Based on the evidence assessed in this review, ecological impacts of short-term abstraction have been characterised in terms of risk of impact and certainty of effect (based on number of relevant experimental and observational studies, degree of conflicting evidence, and conceptual understanding) to develop a matrix to guide where short-term deviation from the current guidelines (in line with the above bullet points) may be allowable. This risk-based assessment is presented below (Table 7.4). Monitoring would be recommended in all cases which ideally would be conducted as part of a robust investigation utilising hypothesis testing, experimental design with control locations and replication, and an analysis plan conceived in advance of monitoring, as appropriate. Circumstances where even temporary deviation from the standards is likely to be inadvisable are flagged in red.

This risk matrix is intended to be used alongside the evidence-based decision framework presented in Section 8. In this framework, the quantitative and semi-quantitative evidence has been synthesised into a framework underpinned by conceptual understanding, supported by anecdotal observations where no quantitative evidence is available.

The framework is intended to highlight under what circumstances:

- there is no or low risk of ecological impacts of short-term deviation from UKTAG standards, and how strong the supporting evidence is;
- there is medium or high risk of ecological impacts of deviating temporarily from the current standards, what those impacts are, and how strong the supporting evidence is; and
- a risk of ecological impacts is suspected but there are gaps in the supporting evidence to support this.

In the latter case, further investigation in subsequent studies may be merited to close the gap(s).

Table 7.4 Risk and certainty matrix

		Certainty		
		Low	Mod	High
Risk of impact	Conceptual understanding only			Several non-conflicting peer-reviewed experimental studies
	Low			
Medium				
High				
Unknown				

High value receptors present
Receptors of limited sensitivity/value

	Deviation probably acceptable, limited monitoring recommended as a minimum
	Deviation may be acceptable but risk of impact higher, detailed monitoring recommended
	Deviation from current standards unlikely to be acceptable

8. Decision Framework

See separate file.

9. References

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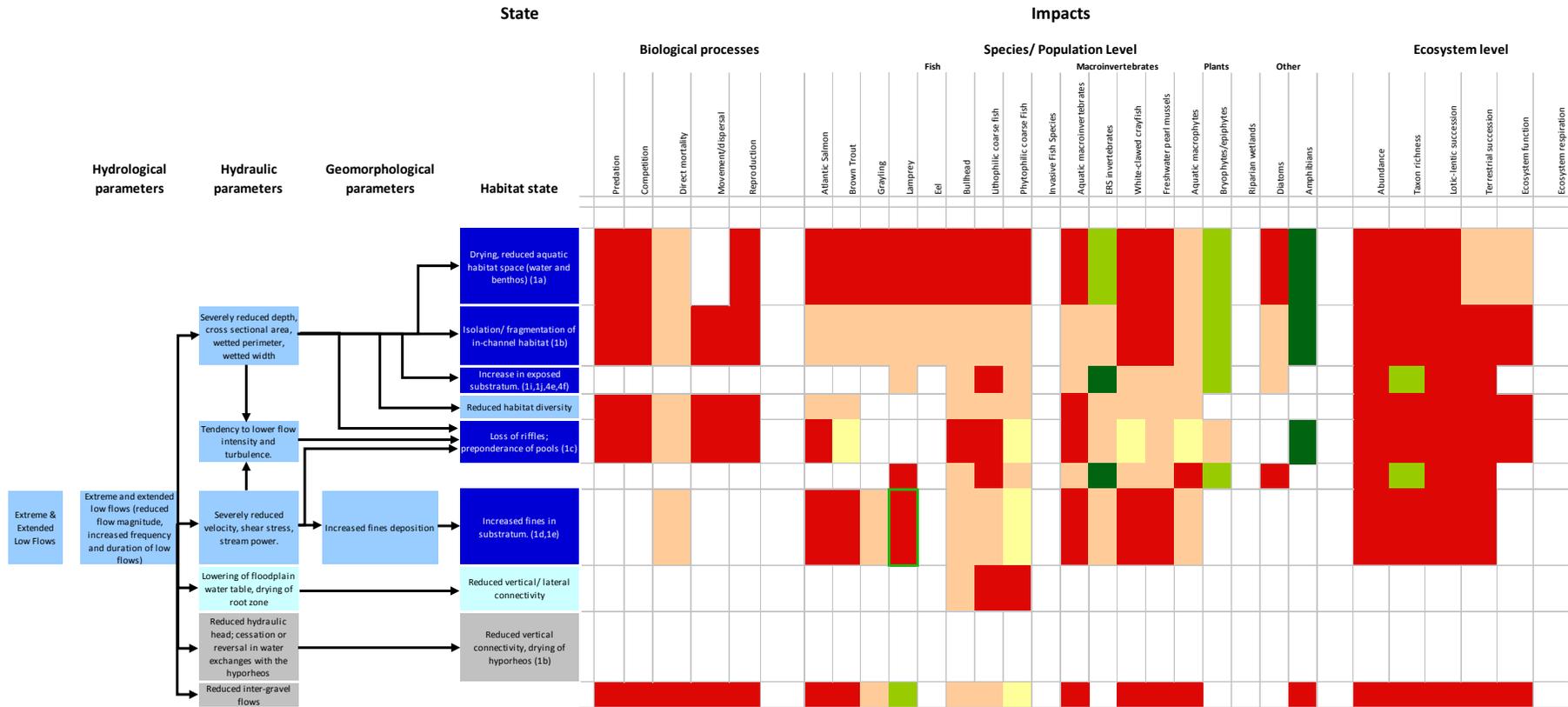
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Appendix I: Generic conceptual model of impacts arising from extreme and extended low flows

1. Generic conceptual model of impacts arising from extreme and extended low flows

The generic conceptual model of impacts arising from extreme and extended low flows developed presented in SNIFFER (2012) is given below and forms an appropriate basis for assessing likely changes that may result from short-duration extreme low flow events caused by abstraction.



Appendix II: Telephone interview briefing note

Telephone Interview Briefing Note: Literature review of short term flow reduction ecological impacts and recovery

Water Resources Task Team

APEM Ref: P00001488

2. Introduction

2.1 Background to the project

The current river flow standards, developed by the UK Technical Advisory Group (UKTAG) for the Water Framework Directive (WFD), are in the form of maximum allowable percent deviations from natural flow at different points on the flow duration curve (UKTAG (2008) and UKTAG (2013)). However, these take no account of the duration and return period of exceedance; in theory exceedance of a standard for one day in a year gives the same outcome as continuous exceedance. In terms of impact on river ecology these two scenarios are clearly very different.

The current standards are considered to be adequate for abstractions that operate for all, or most of the time. For temporary, occasional abstractions they may be over-precautionary, with scope for introduction of a temporal element allowing greater short-term deviation. The temporary, intermittent type of abstraction this is pertinent to typically operates for the purposes of irrigation, or emergency water supply, during dry periods when river flows are naturally low. Thus the focus of interest is on abstractions at the bottom end of the flow duration curve.

This project has been commissioned to review the available evidence on impact of short term abstractions at low flows.

2.2 Aims and objectives

This project aims to review evidence of the impacts of short-term low flow events on riverine ecology, and subsequent recovery. The specific objectives of the project are to:

- Conduct a literature review of both published and grey literature relating to temporal aspects of short-term (typically <2 weeks and <Q95) low-flow impacts, to include the influence of magnitude and duration of low-flow events on both degree of ecological impact and recovery period. This will include impacts of abstraction when flows are already low and complete drying up.

- Conduct telephone interviews with a small number of key agency staff to capture their knowledge of particular events.
- Summarise and evaluate evidence of low-flow exposure-period impact and subsequent recovery relevant to flow standards development.

The outputs of this project will help to:

- Establish a better understanding of the impacts of short-term extreme low-flow events; and,
- Enable revision of river flow standards to better reflect actual flow pressure impacts.

2.3 Who is involved?

The project is being undertaken by APEM. It is being administered by SEPA on behalf of the other UK regulatory agencies. The project steering group includes representatives from SEPA, EA, NRW, Natural England and NIEA.

2.4 Why we need your help

One of the objectives of the project is to conduct telephone interviews with a small number of key agency staff to capture their knowledge of particular events.

We are looking for **quantitative** and **semi-quantitative** information to demonstrate how the **magnitude** and **duration** of **abstraction-induced low flow** events influence **ecological response** and **recovery** time.

Interviewees should ideally have insight/knowledge of events supported by quantitative evidence and/or reports. Either detailed knowledge of effects across multiple sites or understanding of a particular catchment response to a range of different events. Ideally the interviewees selected should be representative of a range of types of habitats.

We are particularly interested in:

- Understanding of the impact on biota of short-term low flow events
- The duration and timing of short-term low flow events
- The predictability of short-term low flow events
- The resistance and resilience of organisms to short-term low flow events
- Organisms at the aquatic-terrestrial interface
- Consider effects of short-term low flow events on diversity and species richness
- Ecosystem functioning
- Compounding and confounding factors
- Invasive non-native species

Questions

What types of short-duration effects of abstraction on rivers do you have experience of?

Do you have any particular regulatory/licencing challenges associated with short duration effects of abstraction on rivers?

What are the strengths/weakness of current flow standards in regulating short duration abstraction effects?

Do you have evidence/examples of the impact of artificially-induced and/or natural short term low flow events on ecology, as well as subsequent recovery?

Do you have evidence/examples of events of different magnitude, duration, timing and frequency/sequencing?

How have these event characteristics affected the degree of ecological impact and speed of recovery?

Do you have any evidence of impacts and recovery relating to aquatic biota, including macroinvertebrates, fish, macrophytes, diatoms?

Do you have any specific observations of degree of impact and recovery in relation to event intensity/timing/rate of change e.g. in relation to specific species life-stages?

Do you have any evidence of different impacts and recovery relating to different types of rivers e.g. high vs. low gradient, chalk streams, impermeable catchments etc?

Do you have any evidence of impacts and recovery relating to naturally perennial, temporary and intermittent rivers?

Do you have any evidence of different impacts and recovery relating to drying events as opposed to events where there is ponding rather than complete drying of the river channel?

Do you have any evidence of impacts and recovery being affected by other pressures/confounding/compounding factors, such as altered morphology, the presence of invasive non-native species, water pollution, water temperature etc.

Next Steps and Timescales

Telephone interviews will be held by Rick Hayes (APEM) during early May.

Please send any quantitative or semi-quantitative information and/or reports in advance where possible.

Each interview will take approximately 1 hour.

Appendix III: Telephone interviews summaries

3.

3.1 Macroinvertebrates

The majority of examples of short-term low flow events and consequences for macroinvertebrates were anecdotal and were not backed up by quantitative or semi-quantitative data or reports. Such examples included where temporary bypass channels were installed for maintenance works to be carried out; the temporary draining of online fishing lakes for maintenance and temporary damming of streams in order to fill newly dug ponds. The lack of data associated with such events highlights that short-term localised low flow events are relatively rare and when they do occur opportunistic monitoring is unlikely to occur (but it should also be noted that such events are likely to be responded to by the EA through the NIRS and therefore there may be more data in existence, however locating and accessing it is not currently possible).

A highly pertinent example where follow-up semi-quantitative data was collected (timed macroinvertebrate samples) was available for a short-term low flow event that occurred in the River Glen, Lincolnshire, in November 2006 (Richard Chadd, pers com). The Glen catchment geology is chalk and limestone with overlaying clay. The river is inclined to be flashy but is ultimately driven by base-flow and is considered over-abstracted and over-engineered. The abrupt cessation of a water transfer that normally operates between the Rivers Gwash and Glen resulted in a drying event of approximately one week on the normally perennial River West Glen, with only isolated pools of standing water persisting.

Two long-term macroinvertebrate monitoring locations are located on the River Glen, one immediately downstream of the transfer (Banthorpe Lodge). The impact of the low flow event could therefore be put in the context of the historic data-set and, furthermore, in this instance opportunistic follow-up sampling of macroinvertebrates was undertaken (post-event, so pertaining to resilience). The data was interpreted through consideration of commonly used indices, including the Lotic-invertebrate Index for Flow Evaluation (LIFE), and the number of Biological Monitoring Working Party scoring taxa (NTAXA).

Immediately downstream of the transfer LIFE scores showed an abrupt decrease following the event (first sampled 03/01/2007). LIFE scores then showed a steady increase throughout 2007 (further samples collected March, May, July and October). The invertebrate community was considered to be resilient to the drying event as LIFE scores appeared to have recovered to pre-disturbance values by spring 2008 (sample collected late March).

A second example was provided regarding a macroinvertebrate species of high conservation interest, the freshwater pearl mussel, in the River Ehen (pers com, Mike Dunbar). Although quantitative or semi-quantitative data/ reporting was not provided to support the example it is described here owing to the overall lack of examples available and because the example highlights important considerations regarding short-term low flow events.

The River Ehen is fed by Ennerdale Water, a natural lake that has been built-up at the downstream end to increase capacity. Owing to this artificial raising of the outfall, when flows in the River Ehen drop below certain level water is pumped out of the lake to feed the river. The site is designated as a SAC and under the Habitats Directive for its freshwater pearl mussel population.

On the 7th June 2012 an accidental cessation of the pumps occurred. Although the exact duration was unknown the event was short-term; the duration was thought to be a day or two at most. Although neither quantitative nor semi-quantitative data was provided, a description of the impact was given as follows (Mike Dunbar and Mark Warren, pers com) and was supported by an extract from the River Ehen SAC Site Action Plan Addendum December 2013.

The water level was very low and widespread low velocities were observed in the river. The majority of mussels were either stressed, moribund or dead with the exception of 5-10% of the animals in the fastest velocity areas of the river. In response to the abrupt reduction in flow all the mussels emerged to the substrate surface level. It was noted that rising to the surface increases vulnerability of mussels to being washed downstream, should flow rise at a sufficient rate, particularly in the case of smaller juvenile mussels.

Layers of fine sediments and algae had developed which were expected to have prevented the flow of oxygen through the sediment and resulted in the death of juveniles. The stressed mussels were associated with low velocities and accumulated algae, diatoms and fine sediment. Stressed animals displayed a poor digging response, which would have made them increasingly vulnerable to high flows. Juvenile searches found no mussels less than 30mm in size in any of the wider juvenile habitats. A small number of 20mm sized mussels were found in the fastest flowing riffles.

The observation that all mussels had migrated to the substrate surface was used to inform licencing of the upstream compensation flow. Prior to the event freshet trials had been implemented to prevent build-up of particulate matter and algae on the river bed as part of a proposed licence change to satisfy the Habitats Directive. The observation of mussels coming to the surface during the low flow event indicated that spate flows could cause additional stress owing to the rapid change in velocity over the mussels. One outcome from the 2012 incident was that the provision of artificial freshets was found to be potentially damaging and could not be used as mitigation for the loss of flow variability.

Findings regarding a single species highlight the importance of species specific traits, in this case the behavioural response to a change in flow conditions. Furthermore the example highlights the importance of the succession of events, and in this case, perhaps paradoxically, that the return of flows, if managed inappropriately, has the potential to negatively impact ecology.

Factors likely to affect the response of macroinvertebrates

Further considerations highlighted, but not associated with quantitative or semi-quantitative examples, were the importance of:

- Timing of short-term events

It was considered that the apparent resilience of the macroinvertebrate community (as regards LIFE scores) highlighted by the River Glen example related to the timing of the event and life-history traits of affected taxa (Richard Chadd, pers com). The approximately week-long event occurred in November, when many aquatic taxa might persist as eggs or small instars in wet sediment. If the event had occurred in spring the larvae of many taxa may have been more affected by the disturbance as subsequent emergence and therefore reproduction of the cohort would likely have been more greatly affected.

The importance of the predictability of short-term low flow events was stressed. Where ecology is subjected to events to which it is adapted, i.e. the low flow events occur at a similar time year-to-year, it is likely to be more resistant and resilient. Where low flow events occur of an atypical timing the ecology is more likely to be affected. For example if the event occurred just before an emergence or just following oviposition, a macroinvertebrates might be particularly affected.

The importance of timing of low flow events in combination with possible water quality effects of low flows was also noted; oxygen levels being crucial for egg survival.

- Confounding/ compounding factors

Morphologically altered waterbodies were considered to be particularly sensitive to short-term low flow events. Poor water quality and deposition of fine sediment were also highlighted as confounding/ compounding stressors (and not independent of low flows or morphological alteration).

- Resilience

Where a short-term low flow event is genuinely limited regarding spatial and temporal extent it was considered that recovery is likely to be rapid, i.e. resilience to such events is expected to be high, driven by drift from upstream (Judy England, pers com). The Glen example appeared to support this.

- Stream typology

The importance of stream typology was stressed. For example, chalk streams are perhaps relatively unlikely to be affected by short-term extreme low-flow events (as base-flow dominated generally stable flow) and might therefore be less well adapted to such events, headwater winterbournes notwithstanding.

Differences between permeable and impermeable catchments were highlighted regarding lateral connectivity (and by implication the presence of low flow refugia). Impermeable catchments will possibly be more affected by short-term low flow events owing to relative lack of connection to a floodplain. However it should be noted that low flow events are a more common occurrence in more flashy upland catchments (Dominic Longley, pers com) and therefore impermeable catchments might be more sensitive specifically where a short-term low flow event occurs outside of the normal timing of such an event.

The headwaters of streams were distinguished from lower reaches regarding the potential for recolonisation from upstream. This might affect resilience and result in slower recovery of macroinvertebrate communities.

- The importance of measures of impact

It was highlighted that records of impacts, such as the degree of impact, or the resilience of a community, are dependent on the measures used to measure such phenomena. This is of relevance to the regulation of activities that might cause short-term low flows and translation into meaningful environmental standards.

Future developments

Whilst not relevant to flow standards directly (i.e. use of the UKTAG flow standards at Q95 flows), discussion was made regarding the potential for low-flow events to affect macroinvertebrate index outputs that currently do not, but moving forwards might, influence WFD classification. An index has been developed, Drought Effect of Habitat Loss on Invertebrates (DEHLI), which might prove to be a more sensitive indicator of the impacts of low flows that result in loss of habitat than LIFE (Richard Chadd, pers com; Chad et al. 2017).

DEHLI is designed to be responsive to the habitat change associated with low-flows (*sensu* Boulton, 2003), rather than flow velocity. Although this index has been developed for longer-term events, i.e. droughts, it is considered that it might be suitable for indicating impacts of the kinds of short-term events of primary interest to this review. The index has been developed as LIFE is considered to be insufficient for quantifying impacts at the lowest end of the flow spectrum, i.e. once velocities become very low/ standing, the metric is not sensitive to changes in habitat availability.

An example of the use of DEHLI to indicate the impact of a drought event was given for the River Tham (Richard Chadd, pers com). Metric output was clearly depressed as a result of a low-flow event, showing subsequent recovery to pre-disturbance values approximately three months after the disturbance event. However, the Tham can be considered a temporary stream (drying occurs every summer) and the low flow event was not short-term in nature, the lentic phase lasting for between 6 – 10 weeks.

3.2 Fish

As per the case of macroinvertebrates, it was clear from speaking to national experts within the regulatory agencies that quantitative or semi-quantitative data on the effects of manmade short-term extreme low flow events on fish are rare. It is possible that such events are themselves rare, owing to effective regulation of water resources in the UK (Dominic Longley, pers com), and/ or standard regulation and monitoring does not record such events (which are likely to be limited in spatial scale) (Graeme Peirson, pers com). Some anecdotal evidence was available, but was in relation to responding to fish-kill events; a single example supported by quantitative data was given relating to a dewatering event on Bradshaw Brook in 2004 (Mark Warren, pers com).

The Bradshaw Brook, located in North West England, normally receives a compensation release from the upstream Jumbles Reservoir. In December 2004 a short-term low flow event occurred, where no flow was released from the reservoir for approximately six hours. The exact magnitude of impact was unclear, however it was reported that the brook drained to standing water with no flow. Concern was raised over the impact this may have had on the resident brown trout population and subsequent quantitative analysis of brown trout densities was made for five impact locations (situated between c. 2 and 7 km downstream of the reservoir) and 10 control locations. Cohorts of year groups were analysed for two years subsequent to the event.

No significant results were observed across this period barring for 1+ brown trout of spring 2005. A reduction in 1+ brown trout densities was established in the spring following the event however by autumn 2005 the same cohort was found to be no different to those of the control locations. It was hypothesised that fish were displaced downstream or that fish in pools, or sufficiently close to pools, were able to take refuge, however juveniles in the preferred, shallow, mixed riffle/run habitats most likely did not move in response to the reduced flow and therefore most likely were stranded. It was noted that downstream connectivity in this water body is not considered to be affected by morphological alteration and therefore fish migration was not thought to have been limited by this potential pressure. Although connectivity was not considered to be limiting, the morphology of the water body is considered to be quite unnatural and it was therefore considered somewhat surprising that a greater effect was not observed.

Regarding timing/ seasonal sensitivity, it was hypothesised that egg exposure might have resulted in impacts regarding recruitment. However there was no evidence for such an effect as no difference was observed the following year for the 0+ cohort relative to control locations. It was thought this might reflect the natural history of brown trout and density dependent effects; normal brown trout life-strategy involves production of large numbers of eggs with proportionately low numbers surviving to the fry stage. Furthermore post-survey data showed that redds appeared to have survived, ascribed to innate site selection and the short-term nature of the event.

A more anecdotal example was given for the Solent and South Downs region where an irrigation abstraction was made in late summer to save a soft fruit crop. The abstraction of a small river resulted in extreme low flows and resulted in a fish kill of adult sea trout in the lower reaches (Dominic Longley, pers com). Whilst the example is not supported by quantitative or semi-quantitative data it highlights a number of important factors regarding short-term extreme low flow events and impacts on fish; namely the importance of existing conditions (the context of late summer low flows), timing (coincident with migration of sea trout); fish species traits (salmonids have a particularly high oxygen demand and are sensitive to increased temperatures) and stream size (relatively small agricultural abstractions are more likely to result in extreme low flows in streams with lower discharge).

Further anecdotal examples were given relating to the temporary damming of rivers, resulting in major impacts on fish populations (Judy England, pers com). Owing to the limited spatial nature of such disturbance events, recolonisation from upstream and downstream following the removal of temporary dams was rapid.

Although examples of the impacts of abstraction induced short-term extreme low flow events were largely unavailable, an analogous scenario was given for natural extreme low-flows.

The complete ceasing of flow occurs naturally in some New Forest streams (Dominic Longley, pers com). During flow recession in these streams a critical point is reached where continuous channel becomes a series of disconnected pools. Once this occurs it was reported that a short space of time elapses before resident fish die from asphyxiation. Data for this example was not available.

Low flow event characteristics that were highlighted as being of particular relevance to fish were:

- The rate of change of flow was noted as being important regarding possible stranding of fish. Although no evidence based mechanism to link the rate of change to impact was available, it was believed that the thousands of fish that died during the flow cessation in the River Glen (See macroinvertebrate section above) likely related to the speed at which flow was lost.
- The importance of morphological alteration in determining resilience of fish populations to low flow events was stated. Although not pertaining to short-term low flow events, an example was given for two brown trout chalk rivers in southern England (Dominic Longley, pers com). Long term monitoring data has established that juvenile brown trout respond to seasonal variation in flow in these rivers with similar patterns observed between the two rivers. The two rivers are similar barring their degree of morphological alteration and the amplitude of reduction in abundance is consistently greater in the heavily modified river relative to the more natural river.
- The importance of timing of low flow events in combination with possible water quality effects of low flows was noted; oxygen levels being crucial for fish egg survival.

In relation to the challenges presented in measuring the impacts of short-term low flow events on fish, it was noted that the common and widespread practice of fish stocking results in difficulties in interpreting fish population data, potentially masking impacts.

3.3 Pytobenthos and macrophytes

It was clear from the interviews that less is known regarding the impacts of short-term low flow events on phytobenthos and macrophytes. Indeed, no examples, even anecdotal, were provided.

It was thought that phytobenthos is likely to be responsive to short-term low flow events, i.e. lack resistance. However it was also thought that phytobenthos would rapidly respond to restored flows and therefore be a highly resilient group.

Macrophytes were thought to display the opposite relationship and were considered a relatively resistant group. Little impact was expected on macrophytes owing to the short-term nature of the kinds of disturbance event of interest. It was thought, however, that this would depend on whether drying of the substrate (sub-surface drying) occurred following extreme low flows that resulted in channel dewatering. Whilst it was considered unlikely that macrophytes would be impacted, where this were to occur they were thought to be a relatively non resilient group, and would require a relatively long time to recover.

3.4 Environmental flow standards

To better understand the regulatory/ licencing challenges associated with short duration effects of abstraction on rivers and the strengths/ weakness of current flow standards in regulating short duration abstraction effects telephone interviews included discussion of environmental flow standards.

Particular challenges were highlighted as follows:

- Defining appropriate and relevant standards in the first instance.
- Subsequent management of the defined standard. The primary challenge identified in this regard was the limitations associated with gauging station data, which in most cases are unlikely to be concurrent with locations suffering short-term extreme low flows (especially considering that the events of primary interest are likely to be limited spatially)
- How to build a temporal element into a licencing system. Particularly given the imperfect information on flows (lack of concurrent gauging stations)

Although the consensus was that the current system is effective, it was discussed that perhaps it is more effective spatially (catchments are well represented) but weaker temporally. Flow varies around a given average and the high level of resolution required to respond to very short-term events is missing. The current licencing system is risk based but allows for the possibility that short-term events are not detected (gauging station issue) or are responded to late.

It was stressed that the original WFD 48 project work did not make any pronouncements on whether flow standards should be implemented on a Flow Duration Curve (FDC). It is possible to have a standard defined on a percentile, for example at Q95, 75, etc., however this does not mean that a standard has to be implemented through use of a long-term FDC framework (as per the current system). Enforcement of a standard could be implemented through measurement of flow on a given day.

A problem was highlighted that the current WFD hydrological classification system was designed to fit in with a pre-existing licencing system. It might be considered over-precautionary, but is the way it is because of constraints imposed by what was/ is the current system for water resources licencing; i.e. not because of considerations for ecology or for scientific evidence. The issue regarding any potential alternative would be how to licence it.

As already documented the telephone interviews highlighted the fact that the types of event of primary interest are apparently rare. A recurrent interpretation made regarding this point is that the current licencing/ flow standards system is generally working well. However it might also be considered that the system is overprotective. The problem is that there is insufficient evidence to say whether the system is overprotective or not, owing to the rarity of the events.

Regarding possible alternatives where extreme low-flows might be measured directly to inform flow standard implementation, there would clearly be a need for getting ground information fed upwards to water resource managers. This represents a possible resourcing

challenge, as enforcement might require, for example, site visits, stream walkovers and spot-flow gauging. It was noted that current enforcement of licencing regarding site visits to ensure compliance, such as visually inspecting infrastructure, checking instantaneous pumping rate limits, etc., has reduced in frequency in more recent years (Mark Warren, pers com).

A further point was raised that the current system does not work on the basis of a risk-based approach regarding where low flow stress is most likely to occur. An alternative would be for national resources to be assigned proportionately to regions considered to be more susceptible to flow stress, for example the south east. This is linked to understanding of catchment sensitivity, conservation interest, etc. and applies to short-term events as well as longer-term regulation.

Licensing challenges pertaining to fish

Current licencing regulation can be insufficient to protect rivers from short-term low flow events, as compliance is measured using a long term average derived FDC. Short-term events are likely to go undetected using this approach. Examples given to demonstrate this point arose from Special Area of Conservation (SAC) sites which are protected by Habitats Directive legislation. In the review of SAC consents NRW looked at daily and sub daily impacts to assess short-term effects of abstraction. Through this process NRW identified potential low flow impacts upon SAC features (shad, salmon and lamprey) of rapid dewatering within daily licenced limits , but further data collection has been initiated to try to find evidence to confirm or allay this risk.