Chalk streams of the future:

The effects of climate change on biodiversity in England's iconic river ecosystems

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Building on insights from expert reviews considering a range of English rivers, this summary report presents scientific evidence exploring the effects of climate change on biodiversity in chalk streams, and is informed by a detailed literature review. Our aim is to guide evidence-based decision making that enables effective management actions to support biodiversity in these celebrated ecosystems.

A note on terminology. We use the term *stream* to refer to all rivers and streams, and to refer to small streams, including all winterbourne and ephemeral reaches as well as some with perennial flow. We sometimes use *river* to describe larger downstream reaches and networks. We use *climate change* to refer to a wide range of interacting factors including temperature, precipitation and their effects on river flow.

Contents

Title page photo: The River Itchen (© Tim Sykes)

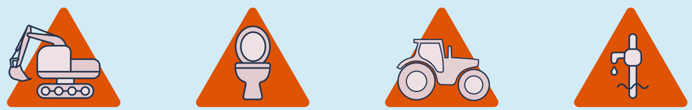
Headline messages

Chalk streams are changing—but future change is uncertain

Temperatures are increasing, including hotter summers and milder winters. Extreme events including floods, droughts and heatwaves may also be increasing. Despite the stabilising influence of groundwater on water temperatures and flows, chalk streams are changing in response to these climatic shifts. Effects vary from the ephemeral headwaters to seasonal winterbournes and to larger downstream perennial reaches. Extreme drought could cause perennial reaches to dry for the first time.

Climate change is interacting with other pressures

Chalk streams are changing in response to multiple interacting pressures, including aspects of climate change; physical modification; pollutants including sewage, inorganic nutrients and fine sediment; over-abstraction, in particular of groundwater; and invasive species, not least signal crayfish. These additional pressures threaten biodiversity and ecosystem functions, but—through management and restoration—also offer opportunities to act to increase ecological resilience to climate change. For example, improvements to water quality can offset the negative impacts of rising temperatures.



Aquatic communities are changing

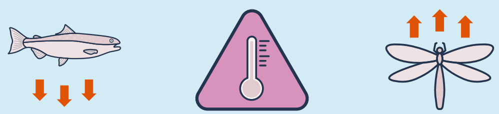
Communities of fish, invertebrates, plants, algae and microorganisms are changing. Declines in biodiversity are expected, in particular due to the loss of coldwater and other sensitive species, and due to shifts in the timing of lifecycle events that affect survival and the recruitment of future generations. New invasive non-native species (INNS) are expected to arrive, and the distribution of existing INNS is likely to change.

Climate change puts chalk stream species at risk

Increasing temperatures and changing flow regimes put chalk stream species at risk of population declines and local extinction. These species include migratory salmonids, eel and lamprey, remaining populations of native white-clawed crayfish, and nationally rare specialist insects whose lifecycles are timed to coincide with the wet and dry phases of winterbourne flow regimes.

Coldwater species are at particular risk as temperatures rise

Coldwater salmonids including Atlantic salmon and grayling, and invertebrates including mayfly, stonefly and caddisfly species, are among those whose populations are expected to decline as temperatures rise. Equally, the ranges of many dragonflies and damselflies are extending northwards, and range contractions are expected for some invasive species.



An introduction to England's chalk streams

Both renowned for their gin-clear water quality and lamented for their exposure to sewage and other pollutants, England's chalk streams are national icons, due to their biodiversity, fisheries and international rarity. Most of the world's chalk streams occur in south and east England, where they span southern counties from Dorset to Kent and extend north to Yorkshire. Fed by the chalk aquifer, these streams are characterised by stable temperatures and flows.

Although primarily celebrated for the ecological and cultural value of their perennial reaches, profound changes in chalk streams as they flow from source to sea enhance river-scale habitat diversity. In their uppermost reaches, ephemeral flow occasionally inundates dry valleys. Moving downstream, winterbourne reaches experience gradual, seasonal shifts from winter wet phases to low flows, flow cessation and summer dry phases. Next, near-perennial reaches are transition zones that dry only during extreme droughts. Finally, in perennial reaches, reliable groundwater inputs and surface runoff sustain year-round flow.

The winterbourne stonefly, *Nemoura lacustris*

These longitudinal shifts in flow permanence allow chalk streams to support high catchment-scale biodiversity, including aquatic and terrestrial species. Some of these species are national rarities, including specialist insects (such as the winterbourne stonefly *Nemoura lacustris*, pictured) whose lifecycles are timed to coincide with winterbourne wet and dry phases, and plants such as water crowfoot (*Ranunculus*, pictured). Chalk streams also support biodiverse fish communities including salmonid fisheries of economic and cultural importance.

Water crowfoot, *Ranunculus*

We direct readers to the **CaBA Chalk Stream Restoration Strategy** for a detailed account of chalk streams, the pressures they face, and priorities for their management and restoration.

An overview: how climate change is altering chalk stream environments

Confidence in the statements made in this overview is provided on pages 5 and 6.

Extreme events are increasing

Floods and droughts may become more frequent, severe, and longer. The blue boxes describe their expected effects from the uppermost reaches to the aquifer.

Temperature

- Hot spells and heatwaves are increasing
- Temperatures are rising most in south England
- Summers are getting hotter
- Winters are getting milder
- Solar radiation is increasing surface water temperatures
- Groundwater temperatures will rise more slowly

In the uppermost reaches

- Dry phases continue for years, with channels becoming increasingly like adjacent terrestrial land
- Usually dry valleys and wider floodplains are inundated, with ephemeral flow in the channel

In winterbourne reaches

- Dry phases become unusually long in space and time, and moisture declines in subsurface sediments
- Short-term flow pulses cause rapid dry-to-wet shifts that interrupt or end seasonal dry phases

In near-perennial reaches

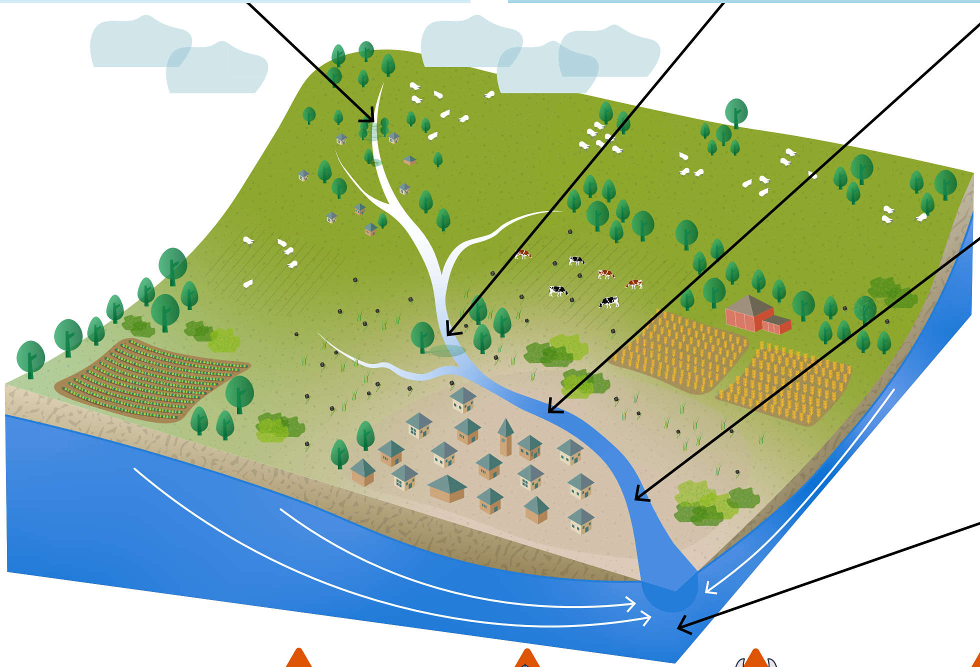
- Rare drying events occur, including in reaches previously considered perennial
- Floods have comparable effects to those in perennial reaches

In perennial reaches

- Water depths and flow velocities decline, with the loss of fast-flowing riffles and inundated marginal habitats
- Water depths and flow velocities increase, and sediments may be mobilised, creating clean gravel habitat

In the aquifer

There is insufficient evidence to know if or how groundwater levels are changing



Interacting pressures: Farmland runoff | Urban runoff | Invasive non-native species | Water abstraction | Sewage inputs | Physical modification

Temperature, rainfall and sea levels are changing

Confidence levels of ***high*** *H,* ***medium*** *M and* ***low*** *L were assigned by climate experts on the basis of evidence from analytical models, published scientific studies and grey literature.*

Temperatures are increasing

- Mean and maximum air temperatures will increase, as will surface water temperatures, due to increased net solar radiation H.
- Temperature increases will be greatest in southern England H.
- Although increases in surface water temperatures are expected to vary considerably among chalk streams M, all increases will be limited by the moderating influence of groundwater, and some by riparian shading H.
- Groundwater temperatures will increase slowly, and upwelling groundwater will create patches of thermally stable surface water that remain relatively cool in summer H.

Extreme events are increasing

- Summer droughts may become longer, more frequent and more severe H. Projections for longer droughts are uncertain, but long multi-season events may still occur. Droughts are likely to result in more frequent and extreme low flows (and potentially unprecedented drying) in perennial reaches, drying of near-perennial reaches, and longer, more intense dry phases in winterbourne and ephemeral reaches M.
- Intense precipitation events may occur more often H, leading to increased flooding, especially in winter M. In summer, such rainfall may cause unpredictable, short-duration flow events in dry channels and flow peaks in perennial reaches M, particularly in urban areas H.
- If heavy rainfall events become more common summer M, more water may enter channels as runoff H, and associated inputs of fine sediment may also increase M.
- Rising maximum temperatures are expected to increase the occurrence of hot spells and heatwaves during summer H.

The climate is changing across seasons

- On average, winters are projected to be wetter M and milder H, with fewer very cold days H, but cold, dry winters may also occur H.
- Summers are expected to be hotter, with more frequent hot spells and heatwaves H.
- Summers may be drier on average, especially in southern England M, but high-intensity rainfall events may become more common H and wet summers may still occur L. Any changes to total summer rainfall volumes remain uncertain.

Sea levels are rising

- Sea level rise may change the salinity and temperature conditions within estuaries L.

Changing temperature and precipitation are altering aquifer recharge and stream discharge

High H, *medium* M and *low* L *confidence levels are explained on* *page 5**.*

Aquifer recharge and stream discharge

- The temporal pattern of groundwater recharge is expected to change H, but we don't know *how* patterns will change or *if* overall recharge magnitudes will change.
- Groundwater recharge may, on average, occur within a shorter annual period, due to:
  - hotter summers, in which evapotranspiration is greater H;
  - drier summers, in which the annual period of reduced summer recharge (associated with drier soils) persists into autumn—in other words, effective rainfall is expected to start later M;
  - shorter, more intense winter rainfall periods that end earlier in late winter M.
- Changes in rainfall patterns will alter how the relative contributions of groundwater and runoff influence discharge H.

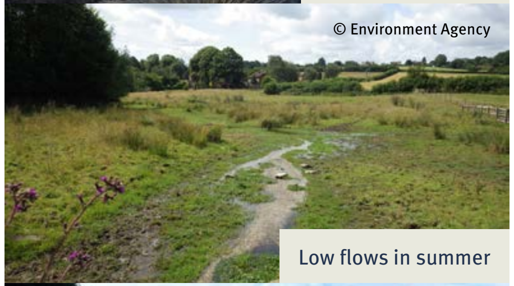
Changes in flow permanence

- If extreme droughts cause perennial reaches to shift to near-perennial flow, perennial heads will move downstream L.
- Discharge may start to decline earlier in the year M, and greater evapotranspiration at higher temperatures may accelerate transitions from wet to dry conditions M.
- Winterbourne reaches may extend further upstream and/or downstream, and may vary more over time M. In years with exceptionally high or low groundwater recharge, their seasonal dry or wet phases could be lost L.
- Inundation of headwater reaches may extend further upstream more often, during unpredictable flow events L.
- Heavy rainfall events may increase the rate at which discharge rises during transitions from dry to wet conditions, and 'false starts' (i.e. short-duration flow events that occur prior to a 'true' flow resumption) may become more common H.
- During hot, dry summers, the subsurface sediments beneath the bed of dry reaches are likely to become less humid H.

A site on the River Gade, showing within-season flow variability:

A winter wet phase

A winter dry phase



Low flows in summer

A summer dry phase

Climate change is altering aquatic microbial communities

Microorganisms have important functional roles, including nutrient cycling, organic matter decomposition and, in particular, primary production by the biofilms that coat sediments and plants, which are an important energy source for riverine food webs. Changes to microbial communities may therefore alter those at higher trophic levels (including invertebrates and fish) and ecosystem functioning.

Increasing temperatures may alter biofilm communities

Temperature and light are among the key influences on biofilm communities, and increasing temperatures are thus likely to cause shifts in the composition of groups including diatoms, green algae and cyanobacteria (i.e. blue-green algae).

Phytoplankton growth may increase in warm, perennial reaches

Rising temperatures may extend the phytoplankton growing season both earlier into spring and later into autumn, increasing its biomass. In particular, such increases are likely to become more common if hot spells or heatwaves coincide with summer droughts, and may be most pronounced in perennial reaches downstream of sources of polluting nutrients, such as sewage treatment works.

Blue-green algal blooms may increase in warm, slow-flowing reaches

Warm, nutrient-rich, slow-flowing and still waters can promote cyanobacteria growth, resulting in potentially toxic blooms. Such increases will be greatest in the conditions that also promote overall phytoplankton growth.

Drought alters biofilm communities

Drying can alter biofilm composition, with encrusting green algae being lost and replaced by mat-forming diatoms, while overall algal densities decline. Such shifts may occur during drought in near-perennial and previously perennial reaches. In perennial reaches, low flows could increase light levels, favouring the growth and dominance of competitive species.

Floods alter biofilm communities

Floods scour algae from surfaces, and any increase in flood events may promote the dominance of ‘pioneer’ taxa with strong dispersal abilities, which can quickly colonise after a flood ends. However, community recovery may be delayed if summer floods increase suspended fine sediment, reducing light levels.


© Environment Agency

Climate change is altering aquatic plant and algal communities

Increasing temperatures may change community composition

Higher temperatures are expected to increase the length of the plant growing season, causing temporal changes in the occurrence of individual species and in community composition. Plants influence flow velocities and sediment composition, and habitats may thus change, altering other communities including aquatic invertebrates.

Changing flow patterns are causing shifts in community composition

Any changes to the flow regime during the growing season are likely to affect plant community composition. Terrestrial and aquatic plants typically decline then are lost during wet and dry phases, respectively.

The effects of increases in drought will vary among perennial, near-perennial and winterbourne reaches:

In **perennial** reaches, declining water depths and flow velocities and increasing silt deposition will change community composition, as marginal plants encroach and fast-flow-loving species such as brook water crowfoot *Ranunculus penicillatus* subsp. *pseudofluitans* are lost. Subsequent high flows are then required to mobilise deposited silt and restore clean gravels.

In **near-perennial** reaches, drying will allow marginal and terrestrial species to increase at the expense of aquatic species such as brook water crowfoot—but once flow returns, aquatic communities can typically recover within two years. As such, any increase in drought frequencies exacerbates the risk of interrupting recovery trajectories, which could cause long-lasting shifts in community composition.

In **winterbourne** reaches, communities are adapted to seasonal drying and characteristic species such as pond water crowfoot *Ranunculus peltatus* (pictured) can tolerate long dry periods and recover quickly as flow returns. However, any increase in dry-phase durations could compromise their populations.

Channel shape affects responses to drought, with 'classic' chalk streams—channels with gently sloping banks and extensive margins—being more resistant to the effects of drought.

Filamentous algal growth may increase in warm, slow-flowing waters

Both stable low flows and warm water promote the growth of filamentous algae (in particular, *Cladophora*), especially where inorganic nutrient concentrations are high. Such growth can thus be extensive in perennial, nutrient-rich reaches during summer droughts.

© Environment Agency

Ranunculus peltatus

Climate change is altering aquatic invertebrate communities

Increasing temperatures may alter community composition

Temperature increases favour some species while eliminating others, including sensitive mayflies, stoneflies and caddisflies. Despite changes in community composition, overall species diversity may remain stable.

The effects of drought will vary among perennial, near-perennial and winterbourne reaches within river networks:

In **perennial** reaches, drought can reduce species diversity, in particular if silt accumulation reduces the growth of water crowfoot, due to the loss of taxa (including mayflies and blackflies) associated with this habitat. Drought effects vary among functional feeding groups, and predators, shredders, filterers and collector-gatherers may all decline.

In **near-perennial** reaches, drying has particularly severe effects on invertebrate communities, eliminating some taxa and thus creating habitat space for more tolerant species—and causing overall declines in species diversity.

Winterbourne communities are adapted to seasonal drying, but any increase in dry-phase duration or severity could reduce community diversity.

At the **river network** scale, aquatic habitat availability can remain sufficient during drought to prevent regional-scale species extinctions.

© Judy England

The yellow may mayfly *Heptagenia sulphurea*

An increase in high-flow events could limit community recovery

Even in low-energy chalk streams, high flows routinely mobilise sediments, displacing invertebrates, but community recovery is typically rapid. Any increase in flood duration or magnitude could exacerbate losses of both individuals and species, and an increase in flood frequency could interrupt, or even prevent, community recovery. Floods can also flush groundwater organisms into the surface stream, reducing their subsurface population densities.

Increasing temperatures put subsurface biodiversity at risk

The communities of invertebrate 'stygobites' within the subsurface sediments and the underlying aquifer are dominated by crustaceans such as *Niphargus aquilex* (pictured) and include several species of conservation interest. These communities are expected to be particularly sensitive to thermal change, and their diversity could decline with even modest increases in groundwater temperatures.

© Chris Proctor

Niphargus aquilex

Hot, dry summers may reduce survival of non-aquatic life stages

After surface water is lost, desiccation-tolerant life stages such as the eggs of winterbourne specialist insects can persist within the bed sediments, with their survival depending on moisture availability—and diversity may thus decline during hot, dry summers. In addition, the terrestrial adults of insects that have aquatic juveniles may be adversely affected by increasing air temperatures.

Aquatic invertebrate species are at risk from climate change


© John Mason
The white-clawed crayfish *Austropotamobius pallipes*

Rising temperatures threaten species of conservation concern

As temperatures increase, the distributions of species that prefer cool waters, for example the Nationally Scarce depressed river mussel (*Pseudanodonta complanata*), are contracting. The range of the globally Endangered white-clawed crayfish *Austropotamobius pallipes* (pictured) is also likely to decline.

Coldwater species could face local extinction

Species already at their thermal tolerance limits are at particular risk from increasing temperatures, especially when summer low flows and heatwaves coincide. Several such temperature-sensitive chalk stream species, including stoneflies, caddisflies and flatworms, have been identified as vulnerable to local (and potentially national) extinction. In contrast, the UK distributions of groups including damselflies and dragonflies are extending northwards.

Winterbourne specialists of conservation concern may be at risk

Winterbourne specialist insects such as the Nationally Rare winterbourne stonefly and the Nationally Scarce scarce purple dun mayfly *Paraleptophlebia werneri* (pictured) are among those at potential risk from rising temperatures and changing flow regimes—in particular, changes in the timing and duration of wet and dry phases—but we don't know if or how their ability to complete their lifecycles will be affected.


© Adrian Chalkley
The scarce purple dun *Paraleptophlebia werneri*

Increasing temperatures are changing insect lifecycles and recruitment

Rising temperatures are altering insect lifecycles, for example accelerating egg and juvenile development and thus bringing forward the timing of egg hatching and adult emergence. For species including the green drake mayfly *Ephemera danica* (pictured), these changes are expected to reduce recruitment. Equally, rising temperatures could enable completion of additional generations, increasing annual recruitment, as observed for species including the large dark olive mayfly *Baetis rhodani*.

Summer pulses of fine sediment could eliminate sensitive species

If runoff generated by heavy summer rainfall carries fine sediment into streams, this may reduce streambed habitat diversity, reduce growth of water crowfoot (an important invertebrate habitat) and clog sediments, reducing or eliminating sediment-sensitive invertebrate species.


© Cyril Bennett
The green drake mayfly *Ephemera danica*

Climate change is altering fish communities

Fish responses to both the hydrological and thermal aspects of climate change vary among species, within species and over space and time. This variability is most evident for migratory fish with complex lifecycles, for which responses also vary among life stages.

Distributions are changing, for both warmwater winners and coldwater losers

The ranges of warmwater species, which include cyprinids and other coarse fish, are expected to increase; in contrast, the ranges of coldwater species that need well-oxygenated waters, including salmonids, are contracting. These concurrent shifts, contractions and expansions of species' ranges will cause overall shifts in community composition, with local changes to diversity depending on the relative numbers of species lost and gained.

Invasive species are likely to increase

Climate change is expected to facilitate both the spread of existing non-native fish species and invasion by new species, negatively impacting on native communities already stressed by climate change and other pressures.

Stressors interact as habitats contract

Regardless of whether they occur in winterbournes during seasonal flow declines or in previously perennial reaches during extreme droughts, fish trapped in isolated pools and shallow, contracting aquatic habitats are exposed to multiple stressors, potentially including poor water quality and intense predation. Then, if surface water is lost completely, fish almost inevitably die.

Changing flow regimes put even adapted winterbourne species to the test

Brown trout *Salmo trutta* and bullhead *Cottus gobio* have lifecycle adaptations that enable them to inhabit winterbournes: they swim downstream to escape drying, then head upstream as water returns. However, any increase in the rate at which streams transition from wet to dry could reduce the time that fish have to move to wet refuges.


© N. Howard-Jones

A dead brown trout *Salmo trutta* in a shallow, isolated pool

Migratory fish species are at risk from climate change

Migratory fish are at risk

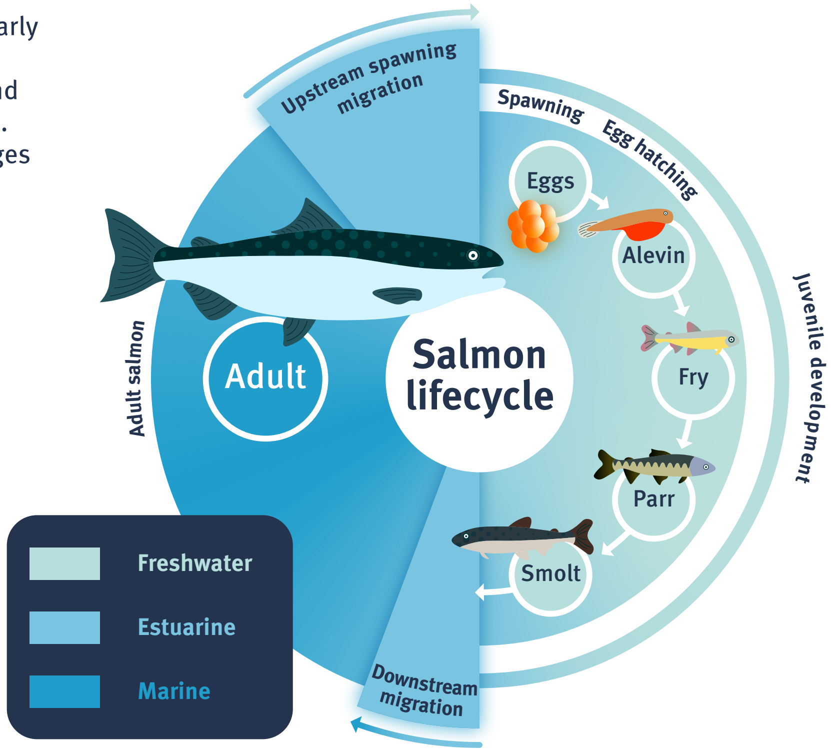
Species which migrate between rivers and the sea, i.e. Atlantic salmon *Salmo salar*, sea trout *Salmo trutta*—and, in particular, the globally Critically Endangered eel *Anguilla anguilla*—may be highly vulnerable to multiple aspects of climate change, due to their exposure to cumulative stressors during complex lifecycles in which seasonal events are spread across multiple habitats in marine, estuarine and freshwater ecosystems.

Coldwater species are on the edge

Atlantic salmon and grayling *Thymallus thymallus*, both of which are legally protected, are already at their thermal tolerance limits and are thus particularly vulnerable to rising temperatures. Ranges of other protected coldwater species, including bullhead and brook lamprey *Lampetra planeri*, may also contract. Groundwater-fed habitat patches could act as refuges that promote their survival.

The lifecycles of migratory fish are changing

Increasing water temperatures in both summer and winter are interacting with changing flows to influence the timing of events including migration, spawning and egg hatching. For salmonids, rising temperatures can accelerate juvenile development, shorten the time spent in rivers before downstream migration and delay spawning migrations. These changes can reduce feeding by juveniles, adult body size, reproductive potential and recruitment. It is unclear how rising temperatures are altering eel lifecycles, or if sea lamprey *Petromyzon marinus* are responding to temperature change in chalk streams.



Drought-driven low flows affect multiple life stages

Autumn low flows can preclude the flow peaks needed to trigger spawning migrations, and for fish that do start to migrate, water depths may fall too low for them to swim upstream. As a result, fewer fish return to spawn, and seaward spawning migrations of eels may also be delayed. In summer, low flows can promote silt deposition, degrading the gravel beds that species including Atlantic salmon, grayling and brook lamprey need for spawning, reducing oxygen supply to eggs and juveniles, and thus reducing their growth. If drought frequencies increase, the cumulative impacts of successive events could cause long-term population declines.

High flows may displace eggs and young fish

Even in low-energy chalk streams, fast-flowing water can mobilise sediments, and any increase in high flows in winter and early spring could increase displacement of the eggs and juveniles of autumn and winter-spawning salmonids, reducing recruitment. Summer floods are also a major cause of death in young-of-the-year coarse fish and any increase in flood frequency could thus threaten their populations.

Climate change is altering terrestrial biodiversity in winterbournes

During dry phases, winterbournes and ephemeral headwater reaches support terrestrial as well as some semi-aquatic species. Terrestrial communities are dominated by generalists, but include some species of conservation concern, such as Nationally Rare ground beetles (e.g. *Badister peltatus*, pictured), which also inhabit adjacent riparian zones.

Greater drying may not increase use of dry channels by terrestrial animals

If dry phases become increasingly frequent, long and severe in winterbourne reaches, the terrestrial invertebrate biodiversity within dry channels may not increase—because many colonists arrive soon after a dry phase starts, to exploit resources such as water and stranded aquatic invertebrates and fish. Once such resources are gone, dry channels become increasingly harsh, in particular during hot, dry summers. Plants also colonise quickly, and long dry phases may give sufficient time for trees to establish.

Droughts may promote the transfer of aquatic energy into terrestrial food webs

Transitions from wet to dry conditions may become faster, reducing the period in which terrestrial animals, including beetles, herons and otters, can feed on the aquatic invertebrates and fish stranded within contracting pools and on drying sediments. Equally, an increase in the frequency of drought (and thus wet–dry transitions) and drying of near-perennial reaches could increase the availability of aquatic prey in contracting wet habitats. Such resources could provide important energy inputs into terrestrial food webs.

Unpredictable flow resumptions may introduce terrestrial energy into aquatic food webs

Unpredictable, sudden-onset, short-duration flow resumptions may increase in frequency in ephemeral headwater channels. Such events may catch in-channel terrestrial invertebrates unawares, washing them downstream and thus reducing their populations while transferring energy to aquatic ecosystems. Terrestrial plants may be sufficiently inundation-tolerant to survive such fleeting flowing phases.

© Environment Agency

Terrestrial plants fill the dry channel of the River Gade

© Roy Anderson

Badister peltatus

Climate change is altering the effects of invasive non-native species

INNS include climate change winners and losers

Invasive non-native species (INNS) include species which are experiencing climate-driven increases or decreases in their distribution and/or densities. Of our current INNS, signal crayfish *Pacifastacus leniusculus* (pictured) thrives in stable low flows and moderate temperatures, and could thus increase in perennial streams during drought. In contrast, drought-driven reductions in soil moisture may eliminate riparian plant INNS such as Himalayan balsam *Impatiens glandulifera* (pictured) from southern streams. Increasing temperatures are expected to enable invasion by new warmwater INNS.

INNS can bounce back quickly after extreme events

Droughts, floods and heatwaves can all cause catastrophic declines in both native species and INNS, but the latter are typically opportunistic generalists with high dispersal potential, rapid population growth and wide environmental tolerances, and they may therefore recover more quickly and become dominant in post-disturbance communities.

Changing INNS distributions and densities will have knock-on effects on natives

The composition of riverine communities is likely to change due to climate-driven shifts in INNS distributions, including range expansions of current INNS and introductions of new invaders. The nature of these changes is difficult to predict, but native species diversity is likely to decline.

Rising temperatures are exacerbating impacts of current INNS

Increasing temperatures promote feeding activity of some INNS, including signal crayfish and the demon shrimp *Dikerogammarus haemobaphes*, exacerbating their impacts on native fish and aquatic invertebrates.

New INNS may arrive in new ways

Climate change and other aspects of global change are expected to alter how new INNS are introduced and their subsequent likelihood of population establishment, spread and ecological impacts. Aquaculture of warmwater species is a particular risk, with shipping also increasing risk in river catchments near ports.

© Tim Flood

Signal crayfish *Pacifastacus leniusculus*

© Tim Flood

Himalayan balsam *Impatiens glandulifera*

An overview: how climate change is altering biodiversity

This infographic summarises key messages on pages 7–14, with information organised by network position, trophic level, stressor and species.

Effects from upstream to downstream… and below

In the headwaters

Coldwater species, including rare invertebrates, will first become confined to cool headwaters, and may then be lost

In winterbournes

Changing flow regimes may affect insects, plants and fish whose lifecycles coincide with wet and dry phases

In near-perennial reaches

Drying during drought has severe impacts, because communities in these reaches lack adaptations to such rare, unpredictable events

In perennial downstream reaches

Decreasing water depth during drought may impede salmonid spawning migrations

In the aquifer

Groundwater species can be particularly sensitive to increasing temperatures, so their biodiversity may decline

Effects through food webs, from predators to microorganisms

At higher trophic levels **salmonids** are decreasing and **cyprinids** are increasing, partly in response to rising temperatures

Changes to aquatic **invertebrate communities** include the loss of sensitive species during drought, but no change in diversity or densities has been linked to climate change—yet

During droughts, growth of **water crowfoot** can be poor due to slow flow, while filamentous algae thrive in warm, slow-flowing water

At the base of food webs, shifts in **microbial communities** include increases in blue-green algal blooms in warm, slow-flowing water during drought

Changes that cascade through food webs will alter how river ecosystems function

Effects of specific climate change stressors

Increasing temperatures are changing the timing of lifecycle events for migratory salmonids and eels. Recruitment is likely to decrease.

Rising temperatures are altering species ranges, and those of coldwater fishes and invertebrates including native crayfish may decline

Drought can cause warm water to flow slowly over silty beds, eliminating sensitive fish, insects and plants. Water may become too shallow for salmonids to migrate.

Increases in **flood magnitude** could cause severe declines in densities and diversity across biotic groups. An increase in **flood frequency** could prevent community recovery.

Biodiversity is responding to climate change alongside a breadth of other **pressures**

Effects on selected species

Salmonids

Atlantic salmon and grayling are at particular risk from increasing temperatures

Winterbourne specialists

Rising temperatures and changing flow may alter the complex lifecycles of nationally rare insects in winterbournes

White-clawed crayfish

Rising temperatures may reduce the range of our native crayfish—but may also decrease overlap with the range of invasive signal crayfish

Water crowfoot

Drought-driven low flows increase silt deposition, reducing growth of sensitive aquatic plants such as water crowfoot

Invasive non-native species

New species are expected to be introduced, spread and have ecological impacts—but their identities are a mystery

Changes to communities are altering ecosystem functions and services

Changes to the species and communities of aquatic and terrestrial microorganisms, plants, invertebrates and fish that occur in chalk streams will have consequences for ecological processes such as primary production, leaf litter decomposition and wider energy transfer through food webs, thus altering ecosystem functions and services.

Replacement of salmonids by cyprinids could have effects that extend through food webs

Due to differences in feeding modes and diets, a decline in salmonids and concurrent increase in cyprinids within fish communities may have effects that extend through food webs. In addition, cyprinids such as carp *Cyprinus carpio* disturb sediments while feeding, and the expected increases in their occurrence could thus modify streambed habitats, reducing their suitability for some invertebrate and other species.

Drought could reduce transfer of energy through food webs

Experimental evidence indicates that increasing drought frequency and intensity, including partial streambed drying, can change the primary producers in biofilms from green algae to diatoms, and can cause reductions in the diversity of top invertebrate predators, overall invertebrate community diversity, trophic interactions, total biomass and secondary production. Consequences at higher trophic levels include reductions in food for fish, and energy transfer to riparian consumers may also decline.

Drying reduces 'shredding' of leaf litter, a key energy source

Decomposition of organic matter including leaf litter depends on the densities of aquatic invertebrate 'shredders' such as *Gammarus* shrimps, which can dominate invertebrate communities. During low flows, shredder densities can be high, but drying temporarily eliminates *Gammarus*, and any decline in flow permanence could therefore reduce transfer of energy from organic matter through food webs.

Reductions in groundwater biodiversity could reduce water quality

Groundwater species, including the microorganisms that biodegrade contaminants and pathogens in polluted water, may be particularly sensitive to increasing temperatures. As such, climate change may reduce groundwater quality, with potential consequences for public water supply.


© Tim Sykes

Climate change is interacting with other pressures to influence ecological responses

Climate change encompasses a range of factors relating to temperature, precipitation, aquifer recharge and stream discharge. These factors interact with each other and many other sources of natural and anthropogenic variability to determine ecological responses.
In particular:

Modified rivers are more vulnerable to climate change

Physically modified (e.g. straightened, widened, deepened or impounded) channels are more susceptible to the effects of droughts and floods. In addition, where riparian trees have been removed more sunlight hits the channel, and increases in surface water temperatures will thus be greater in artificially unshaded than naturally shaded reaches.

Silt deposition can reduce habitat quality and thus biodiversity

If heavy rain hits dry soil, inputs of sediment-laden runoff may increase in summer, depositing silt on the bed. Until its clearance—likely by winter high flows—this silt reduces habitat quality, with consequences for sensitive juvenile insects that develop in autumn, and for spawning salmonids in early winter.

Groundwater levels in the chalk aquifer are an increasing ecological and societal concern

Although we don't know if climate change will reduce aquifer recharge, demand for water is rising, peaks during hot summers, and is increasingly expected to coincide with low flows. Associated water abstraction may compound the effects of drought-driven flow reductions.

Increasing heavy rainfall events will exacerbate the release of polluting effluent

If intense rainfall events become more frequent, this will increase both the release of untreated sewage from storm overflows and inputs of pollutant-laden runoff from urban and agricultural land. Resultant declines in water quality have consequences for both ecosystem health and human societies.

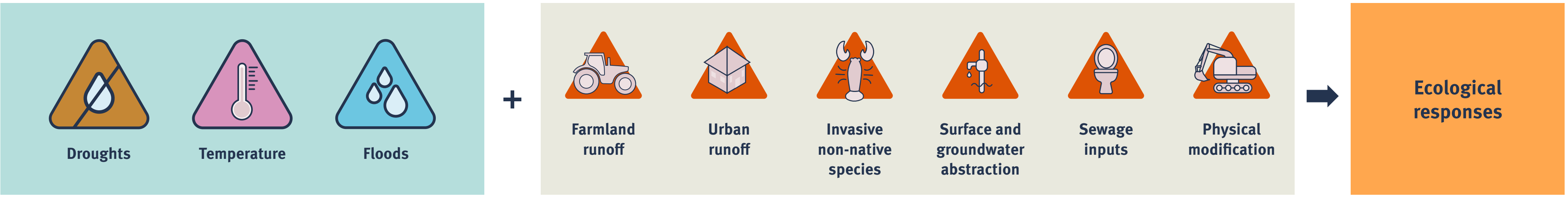
Instream barriers reduce recovery after extreme events end

Impoundments such as weirs interrupt longitudinal connectivity and thus limit instream dispersal by aquatic animals, reducing recolonisation of impacted reaches after extreme events end.

Drought can mean warm, slow-flowing, polluted water

Species that need cool water, high oxygen concentrations, fast flows and clean gravels are at risk on hot days during summer droughts, when shallow waters are warmed by solar radiation, limited dilution of organic pollution can reduce oxygen availability, flow velocities may be slow, and deposited silt smothers gravel.

Due to the interacting effects of multiple pressures, confirming responses to individual stressors and stressor combinations is challenging and typically requires complex experimental approaches. As such, expected responses to climate change (and, in particular, increasing temperatures) have yet to be confirmed, not least due to concurrent responses to variation in water quality.



Research is needed to better understand ecosystem responses to climate change

Knowledge gaps introduce uncertainty into the prediction of ecological responses to climate change. Addressing these gaps will enable the development of effective management strategies that promote the ecological resilience of chalk streams to climate change. We need to better understand:

- **The thresholds at which ecosystems change.** Climate change may be gradual—but ecological responses can be stepped, as the capacity of populations or communities to remain unaltered is surpassed, potentially causing dramatic changes to ecosystem structure and function. Identifying where these ecological thresholds are could inform strategies that protect ecosystems at risk from catastrophic change.

- **Responses to interacting extreme events.** We know little about responses to floods, hot spells and heatwaves, and about how multiple concurrent events (such as a heatwave and a drought) or sequential events (such as multiple dry winters) interact to influence responses, and potentially to cause permanent changes in ecosystem structure and function.

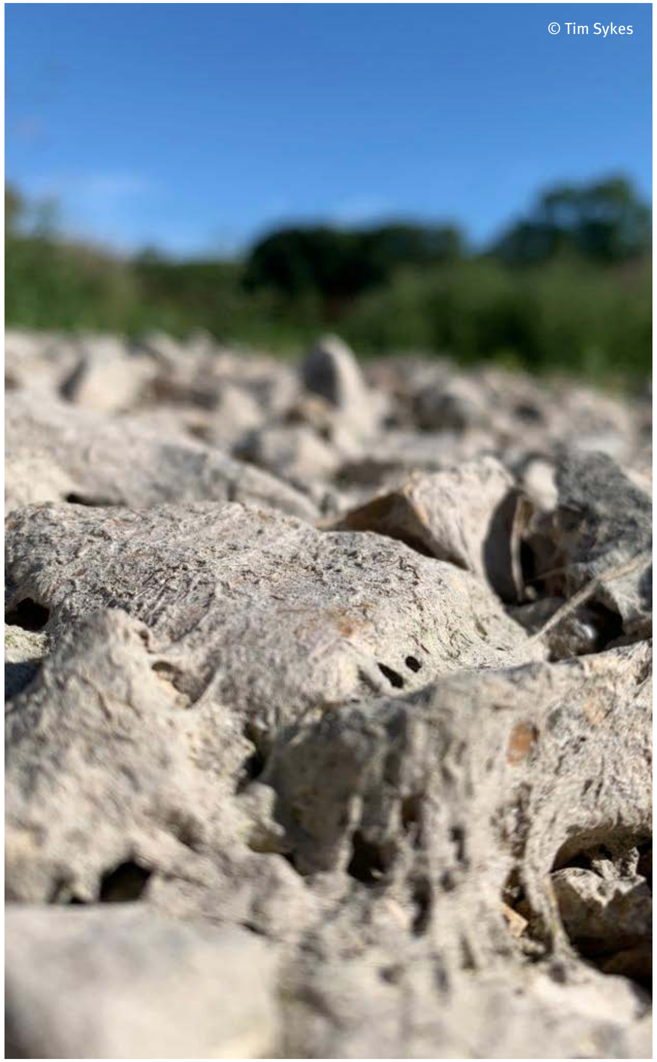
- **How climate change and other pressures interact.** Climate change operates over longer timescales than the other pressures to which ecosystems are exposed. We need to better understand how multiple pressures interact to determine ecological responses, and how adaptation measures including nature-based solutions such as riparian revegetation and/or rewilding could reduce climate change impacts.

- **Network-scale and long-term responses.** We know most about how single communities respond to environmental drivers at local scales over short time periods, and little about both network-scale responses of connected 'metacommunities' and long-term ecological change.

- **The effects of climate change in transitional reaches.** Winterbourne, ephemeral and near-perennial reaches relatively remain poorly known, despite the potential for ecological change in such reaches to cascade downstream, altering network-scale ecosystem functioning.

- **The responses of individual species**. Except for fish and a few insects, we know little about species-specific responses to climate change, including alteration of behaviours such as feeding, refuge seeking and predation, and the timing of lifecycle events such as egg laying and egg hatching—or how within-species genetic variability influences these responses. Research is most urgent for species of conservation concern.

- **The responses of poorly known biotic groups.** Aquatic meiofauna (microscopic animals), stygofauna (groundwater animals) and microorganisms are poorly studied, as are all the terrestrial groups which inhabit winterbourne and ephemeral reaches during dry phases. Such groups require characterisation to improve our understanding of chalk streams as biodiverse aquatic–terrestrial ecosystems.



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Details of the supporting literature review will be available at: **https://dynamicstreams.wixsite.com/website/publications**

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