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VALUING NATURE PROGRAMME

The Natural Capital of Temporary Rivers:

Characterising the value of dynamic aquatic–terrestrial habitats.

Valuing Nature | Natural Capital Synthesis Report

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Summary

Temporary rivers naturally transition between flowing, pool and dry states, creating aquatic–terrestrial habitat mosaics that change in space and time. These dynamic habitats are common in the UK's cool, wet climate. Here, they take many forms, from headwater streams that may dominate networks in remote uplands, to winterbourne rivers crossing the chalk of south England. We examine published and unpublished sources to provide an evidence-informed characterisation of the natural assets in temporary rivers.

Their physical assets include water, and the geodiversity of sediments and landforms. In combination, these assets allow temporary rivers to support dynamic communities in which aquatic and terrestrial species including rare specialists enhance biodiversity. Natural assets provide ecosystem services, and we identify services that may be enhanced during or unique to both wet and dry phases. However, natural assets are at risk from interacting water resource, land use and climate change pressures. In addition, our understanding of temporary rivers is limited and biased, and notable knowledge gaps include small headwater streams and the terrestrial species that inhabit dry channels. These knowledge gaps hinder development of metrics to track progress towards ecosystem service goals, and we call for research to comprehensively explore these important but undervalued ecosystems.

Key Messages

- **Drying is a natural part of many river flow regimes but can also reflect human impacts.**
- **Aquatic and terrestrial species enhance the total biodiversity of temporary rivers.**
- **Physical and biological assets deliver different ecosystem services during wet and dry phases.**
- **A focus on chalk streams in southern England obscures the diversity of UK temporary rivers.**
- **We need to better characterise the full range of temporary river types found in the UK, with research priorities including small headwater streams and dry-phase communities.**

Introduction: the natural capital of temporary rivers

What are temporary rivers?

Perennial rivers flow all the time, whereas temporary rivers are defined as those in which surface water sometimes stops flowing [1]. Many temporary rivers also lose water, becoming a series of isolated pools or drying completely at the surface, after which sediments remain moist or saturated, and water may still flow within the bed sediments [2,3]. Temporary reaches account for a substantial proportion of the global river length, and can dominate arid, semi-arid and mediterranean-climate river networks [4]. Here, they are particularly well-studied and can be highly valued by people [5].

Temporary rivers in the UK

Temporary rivers are common in places with cool, wet climates, including the UK **(Fig. 1)** [3]. Here, as in many regions, flow intermittence is increasing in space and time, as demands for water resources increase in our changing climate [6,7].

Many UK temporary rivers are small headwaters or larger groundwater-dominated systems, but these dynamic ecosystems take many forms:

- Any UK river reach can have temporary flow during extreme droughts – even the Thames ceased to flow and experienced partial sediment drying at Teddington in West London in 1976. Some groundwater-dominated rivers are near-perennial, drying naturally during droughts, in particular events in which a dry winter provides limited recharge of the aquifer [13,14].

Figure 1: The diversity of UK temporary rivers

UK temporary rivers are widespread and diverse, including: (A) the limestone Allt nan Uamh, Inchnadamph; (B) Clunie Water, a near-icebound mountain stream, the Cairngorms; (C) the disappearing River Wharfe, North Yorkshire; (D) a ponded peatland stream; (E) the karst River Manifold, Staffordshire; (F) the winterbourne headwaters of the chalk River Till, Wiltshire

Box 1: Temporary reaches, not temporary rivers, are typical in the UK

Whole rivers dry in arid regions, but in the UK, reaches can shift between temporary and perennial flow over short distances. This moorland stream in the north Pennines has temporary upper headwaters Ⓐ, flow increases downstream Ⓑ due to surface runoff and groundwater inputs, then decreases downstream of sinkholes in the limestone bedrock Ⓒ.

- The winterbourne reaches of chalk rivers in England **(Fig. 1F)** experience predictable, seasonal shifts between flowing and dry states. Those in south England are well-known [8-11] and their characteristic communities are part of the reason that some sites are legally protected [12].
- Like winterbournes, some groundwater-fed rivers crossing karst limestone, for example in the Peak District, have an 'intermittent' water regime [sensu 2] characterised by seasonal loss of flow and surface drying. Certain rivers have been well-researched in recent years, including the Lathkill in Derbyshire [15-17] and the Manifold in Staffordshire **(Fig. 1E)** [18].
- Temporary streams are extensive in headwaters [19] and may dominate the network length in peatland **(Fig. 1D)** and mountain landscapes **(Fig. 1B).** Poorly studied [20-22] and highly variable, the extent and distribution of temporary headwaters are unknown, due to difficulties in defining where a stream begins [23] and their inconsistent representation on maps [24].

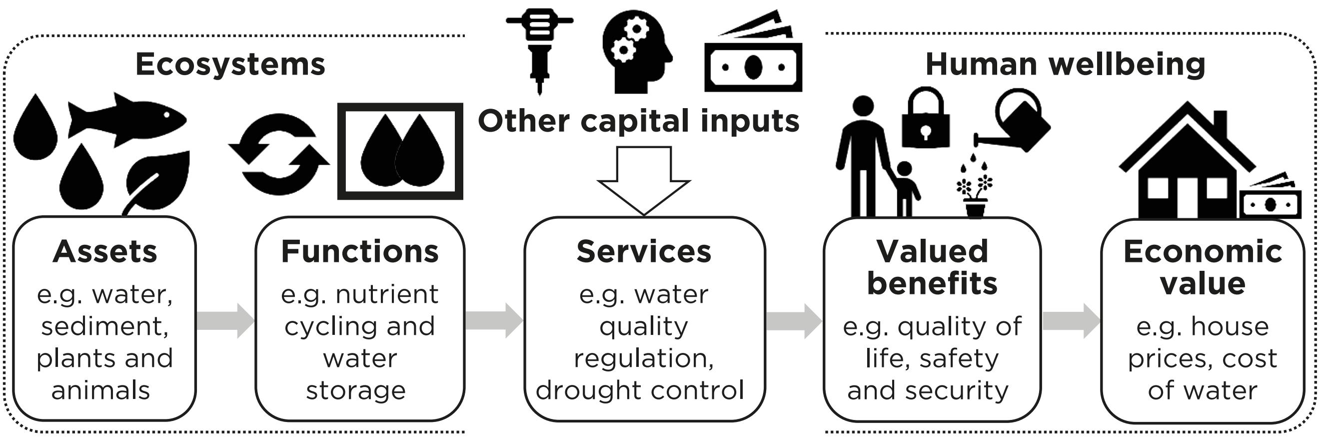
Although we refer to 'temporary rivers' and 'temporary streams' throughout this report, in most UK systems, temporary reaches occur within systems that have both perennial and non-perennial stretches **(Box 1).** Flow intermittence often increases with progression upstream, but sometimes local variation in the water table results in alternating sections with contrasting flow permanence **(Box 1).** Elsewhere, human activity, and in particular water abstraction, has created rivers that are artificially temporary [7]; although we recognise the profound ecological changes caused by a shift in flow permanence, our report focuses on rivers that dry naturally. We also limit our characterisation of near-perennial rivers, which normally flow year-round and are therefore likely to support natural assets comparable to those in perennial rivers.

The natural capital approach to ecosystem protection

Natural capital comprises assets encompassing all physical and biological elements of the natural environment. The natural assets of river ecosystems include landforms, sediments, freshwater, living organisms, and non-living organic material. Assets including freshwater can directly provide goods such as drinking water [25], and assets also interact to perform the natural ecological functions that provide ecosystem services from which people benefit and which have value **(Fig. 2)** [26]. For example, the grasses and herbs that colonise river channels during dry phases may provide habitat for pollinating insects, enhancing the productivity of nearby arable land [27].

Reflecting growing recognition of the socio-economic importance of natural assets by policymakers, a natural capital approach is increasingly being used as a tool in environmental decision making, and the approach underpins the UK government's 25-year plan to improve our environment [26,28]. This approach builds on the Millennium Ecosystem Assessment [29], which demonstrated the global importance of ecosystems in providing services that support human wellbeing, and the subsequent UK National Ecosystem Assessment [30], which highlighted the national importance of ecosystems including freshwaters and grasslands for goods and service provision [25,27].

Figure 2: The natural capital approach: linking ecosystem assets and functions to benefits valued by people



Relationships are described in the text. Adapted from [31] and [32].

Using a natural capital approach to explore the value of temporary rivers

Many natural assets in UK ecosystems are declining in extent and condition, putting the services they provide at risk, and national-scale assessments identify the capacity of some freshwater assets to provide benefits including clean water, recreation and wildlife as "at high risk" [33]. Temporary rivers remain excluded from such attempts to quantify national service provision, and as poorly known ecosystems, may be at particular risk. In addition, some temporary rivers are highly modified and managed, for example chalk rivers (including their winterbourne reaches) have been dredged, straightened and deepened for land drainage and flood control, and remain subject to regular weed cutting and considerable water resource use. Although such activities can reduce natural ecosystem functions, cultural services such as recreation and aesthetic value may be enhanced. Where such opposing service demands arise, a balanced consideration of environmental, economic and social goals should inform management decisions [34].

Recent global characterisation of the ecosystem services that temporary rivers provide has compared their flowing-phase services to those of perennial rivers, and how this provision changes during pool and dry phases [35,36]. In some cases, a lack of evidence or limited exploration of available evidence may have led to underestimation of service provision in temporary rivers. Dry-phase services are also described by global reviews [6,37], and one study compared service provision in UK-climate systems with other regions [3]. However, the ecosystem services that temporary rivers may share with terrestrial ecosystems such as grasslands remain unexplored, as do unique services that differ from those provided by fully aquatic or terrestrial habitats.

We address this knowledge gap by uniting efforts to describe the benefits that people derive from the UK's natural capital with the conceptualisation of temporary rivers as aquatic–terrestrial ecosystems [38]. We use a systematic, evidence-informed approach **(Appendix 1)** to characterise the natural assets of temporary rivers during both wet and dry phases, then attempt to link these assets to services provided by, enhanced in, and unique to these dynamic environments.

The environmental assets of temporary rivers

Below, we examine the environmental assets of temporary rivers, including physical components – waters, landforms and sediments, as well as non-living biological assets – leaves and wood.

Geomorphology and bed sediments

Geomorphology refers to the landforms that influence landscape character and their associated sediments, with geodiversity encompassing the variety of our geomorphological assets. Geodiversity is a noted feature of limestone landscapes in some UK Natural Character Areas [43,44]. Landforms and sediments interact with water and vegetation to provide habitat for wildlife, the nature of which varies among systems with substrates from peat to bedrock. Sediments can also retain free water or remain humid during dry phases, providing a refuge for many aquatic organisms.

What do we know about the geomorphology of the UK's temporary rivers?

Accounts of geomorphological variability among and within temporary river types are limited, especially beyond chalk and karst limestone. Across river types, most information is observational.

- Chalk rivers occur in undulating landscapes in south and east England [43,44]. The channels of these iconic, sometimes legally protected systems may be unnatural [45], having been extensively modified for land drainage and flood control [10]. Winterbourne sediments are diverse during flowing phases and may be dominated by fine grains including gravels [46,47].
- Temporary rivers flowing over karst limestone can occur in gorge-like valleys as well as wide, open landscapes, and are sometimes noted for their geological significance [48]. Sediments vary from silt to bedrock but are typically coarse, and boulders and cobbles can dominate **(Box 2).**
- The geomorphology of small headwater streams varies greatly [24], but we know little about how temporary streams underlain by substrates as contrasting as peat and granite differ.
- Sediment composition is dynamic, changing in response to surface flow. During flowing phases, water transports sediment downstream, allowing temporary headwaters to supply lower reaches [49,50]. In winterbourne reaches, flowing-phase transport of fine sediment leaves behind clean gravels that can provide spawning areas for fish including brown trout [10].
- As flow declines, the proportion of fine grains on the bed increases due to deposition, and temporary rivers store these sediments after flow ceases. When flow resumes, sediment is washed downstream, the size of mobilised grains varying in response to flow characteristics.

Box 2: The geodiversity of UK temporary rivers

Distinctive landforms enhance temporary river geodiversity, such as the River Manifold's limestone cliffs (A). Within such karst (A) (B) and chalk (C) (D) channels, sediments include bedrock, boulders (B), gravels (D) and silt (C).

Water regimes

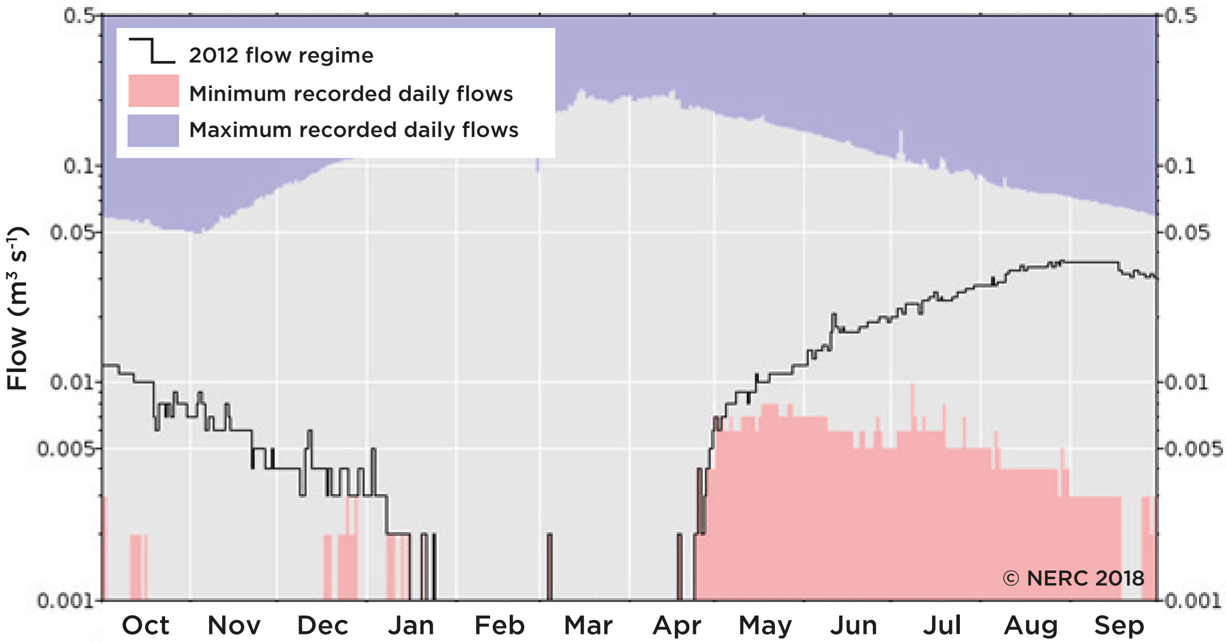
The water regime of a temporary river describes the frequency, magnitude, duration, seasonality and predictability of flowing, pool and dry phases, and the rates at which transitions between these phases occur. Relative surface and groundwater contributions are key drivers of the water regime, which, in turn, is a key influence on the diversity of habitats available to ecological communities.

What do we know about the water regimes of the UK's temporary rivers?

UK research exploring temporary river water regimes is limited by their poor representation in flow monitoring networks, and small, remote, upland streams remain particularly poorly characterised.

- At least one day of zero flow has been recorded at 11.7% of (175) UK National River Flow Archive monitoring stations [39]. Of these, 36 have on average at least 15 zero flow (ponded or dry) days per year, mostly in summer, but zero flow can occur in any month [40]. Most monitored locations are small lowland rivers draining limestone in south and east England. For example, in Ewelme Brook in 2011–12, a gradual decline in flow occurred in September, flow ceased in January and then resumed in April due to an increase in groundwater levels **(Fig. 3).**
- Except for chalk streams, temporary rivers are poorly represented in the flow monitoring network operated by regulatory bodies to inform the UK National River Flow Archive.
- Observations distinguishing flowing, ponded and dry phases complement zero-flow data at a few monitored locations to reveal how temporary rivers change in space and time. Reports publishing such data are restricted to chalk rivers in south England [41].
- Year-round UK precipitation means that rain-fed temporary rivers experience long dry periods when rainfall is limited, and short, unpredictable, rain-driven flowing phases. Such flow regimes are defined as 'ephemeral' [2] and are common in small headwater streams in upland regions.
- Compared to rain-fed systems, groundwater-dominated rivers are more likely to dry seasonally, often in summer, in response to a gradual decrease in groundwater levels. These rivers can experience considerable variability in flow between years, sometimes drying or remaining wet for several consecutive years [41].
- UK temporary rivers are projected to have higher winter and autumn flows and lower spring flows in future, but recent analyses have not identified significant changes to date [42].

Figure 3: Daily flow on Ewelme Brook, a chalk river in south England



Water chemistry and organic matter

Biologically important compounds in freshwater include the inorganic nutrients nitrogen (N), and phosphorus (P), and organic matter (OM) in dissolved and particulate forms. Coarse particulate OM is important in naturally functioning habitats, and includes leaves and woody material. N and P influence plant growth, and these producers and OM underpin food webs and ecosystem functions [51]. Other ecologically important aspects of freshwater include its temperature and dissolved oxygen concentrations, which influence species health and survival during flowing and pool phases.

What do we know about water chemistry and organic matter in temporary rivers?

Few recent studies focus on water chemistry or organic matter in any UK temporary rivers, and research exploring subsurface water is particularly limited both here and in other regions (but see [52]). However, studies focusing on ecological communities [53] and from comparable climate regions also report relevant data. Global evidence describes temporary river OM and nutrient dynamics as "pulsed", with transitions between flowing, pool and dry phases acting as major determinants of nutrient concentrations, OM accumulation, processing, transformation and transport [38].

- As flow declines, P concentrations can increase due to reduced dilution [54,55] or be constant [56], whereas N concentrations consistently decreased with flow in one winterbourne chalk river [54,56]. Temperatures may rise as solar radiation increases in influence, causing oxygen levels to fall; such changes are tempered in rivers fed by groundwater or shaded by trees [57].
- OM concentrations may increase as flow declines [58], and slower flows result in particulate OM being deposited and accumulating in pools and on the bed [55]. Evidence from temperate regions shows that OM decomposition is minimal on the bed and low in pools, due to low abundance of 'shredder' invertebrates [59-61]. Oxygen concentrations fluctuate in response to production and respiration by aquatic wildlife and can become limited, especially in pools [62].
- The return of water to a dry channel is a "hot moment": a period of rapid change and activity [63]. Nutrient concentrations can peak as an advancing wetted front mobilises ions in the channel sediments and surrounding land [54], but patterns are very variable [51,55]. Accumulated OM is inundated and microbial activity rapidly increases [51,64], leading to decomposition as material moves downstream **(Box 3)** [65]. The contribution of surface water and groundwater strongly influence both temperatures and oxygen concentrations [62].
- Flow variability alters the effects of surface runoff and point source pollution inputs. If inputs remain stable as flow declines, pollutant concentrations increase due to reduced dilution.

Box 3: Flow reumption moves leaves and woody material downstream

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Large amounts of leaves and woods can accumulate in pools and on the bed during dry phases (A). When flow resumes, material moves downstream as its decomposition by microorganisms starts in a period of intense biological activity (B) (C).

Panes (B) (C) are from video footage capturing advancing wetted fronts on the River Albarine in France:

(B) **https://www.youtube.com/watch?v=RhU0o-tziK0**
(C) **https://www.youtube.com/watch?v=3kAhY1fzafA**

The biological assets of temporary rivers

The environmental assets described above combine to provide dynamic habitats that shift between wet and dry states, supporting wildlife – living natural assets – from across a spectrum from fully aquatic, to semi-aquatic, to terrestrial species. Some communities that represent the biological natural assets of UK temporary rivers are relatively well-documented, but existing evidence shows several biases:

Bias: chalk and karst limestone

Many studies examine winterbourne reaches in the chalk rivers of south England and karst rivers in the Peak District, whereas smaller headwater streams, particularly in the uplands, remain unknown [66-67].

Bias: aquatic invertebrates and plants

Representation of biological groups is unbalanced. Most studies explore aquatic invertebrates and aquatic plants during flowing phases, whereas all terrestrial assemblages are very poorly described.

Bias: impacts and droughts

Research tends to consider ‘impacts’, in particular impacts of severe droughts in rivers that rarely dry [14,28,55,68]. This focus may have contributed to the common public perception of drying as ‘bad’.

Bias: comparison with perennial rivers

Researchers have tended to compare temporary rivers with other habitats, in particular perennial rivers, rather than focusing on spatial and temporal variability within temporary rivers [13,16,53].

Bias: the reach scale

Most research examines communities at a few sites within a few kilometres of one another, whereas few studies investigate patterns at catchment or larger scales [17,18,53].

Below, we summarise what is known about the ecological communities that inhabit temporary rivers: aquatic, semi-aquatic and terrestrial vertebrate and invertebrate animals; plants including larger algae; and microorganisms including microscopic algae. We focus on studies of peak diversity and natural variability in community composition, and supplement published work with unpublished data and expert observations **(Appendix 1).**

Aquatic vertebrates: fish communities

Fish: the aquatic vertebrates of temporary rivers and their ecological functions

Among the most valued assets in freshwaters because of their recreational use, fish play important ecological roles in temporary rivers. They transfer energy through food webs as both predator and prey, their migrations can transfer energy between perennial and temporary reaches, and their consumption by birds and mammals can supply energy to terrestrial environments.

What do we know about fish in UK temporary rivers?

Few published studies explore the communities that use temporary rivers in cool, wet temperate regions, with a recent global review excluding temperate regions except for those with mediterranean climates [69]. In the UK, almost all research has been descriptive, with published observations supported by those of researchers, stakeholders and river users. As for many assets, information is most comprehensive for the winterbourne reaches of chalk rivers in south England.

- Only a few species occur in winterbourne reaches: brown trout *(Salmo trutta)*, Atlantic salmon *(Salmo salar)*, bullhead *(Cottus gobio)*, minnows *(Phoxinus phoxinus)* and three-spined sticklebacks *(Gasterosteus aculeatus*, 10].
- In the UK, only brown trout are adapted to a temporary flow regime **(Box 4).** Adults actively swim upstream in winter to use clean, gravel-dominated, competition-free sediments as spawning and nursery habitat. The stable environments of groundwater-fed winterbournes [8] allow spawning, egg development and hatching to occur within one flowing phase [70]. Adults and newly recruited juveniles then head downstream in synchrony as flow declines [70,71].
- One study of a near-perennial small mountain stream in North Wales reported only brown trout after a long flowing phase, with fish being eliminated by a rare dry phase [20].
- Opportunist taxa move upstream when flow resumes, for example bullhead become abundant as flowing phases increase in duration [72]. Later, these fish decline in abundance as predation increases and oxygen concentrations decline in diminishing pools, and they die en masse when the bed dries [20].
- Their economic value can lead regulatory agencies to rescue brown trout, other salmonids and coarse fish species that become stranded in contracting pools [70,71].

Box 4: Temporary reaches promote recruitment in trout populations

Brown trout (D) are adapted to the predictable flow regime of chalk winterbournes. Adults move upstream in winter (A) to spawn in competition-free gravels (see **Box 2**, (E)), before adults and newly recruited juveniles head back downstream in summer (B) before flow is lost in autumn (C).

Terrestrial and semi-aquatic vertebrates

The terrestrial and semi-aquatic vertebrates of temporary rivers and their ecological functions

The terrestrial and semi-aquatic vertebrates associated with temporary rivers are diverse, including amphibians, reptiles, birds and both wild and domestic mammals. It is difficult to summarise the range of natural ecosystem functions that such a large, diverse group supports, although energy transfer between aquatic and terrestrial habitats is a common role.

What do we know about how terrestrial and semi-aquatic vertebrates use temporary rivers?

Most research exploring the use of temporary rivers by terrestrial and semi-aquatic vertebrates considers arid and mediterranean systems with long-lasting dry phases [73], but comparable use is proposed for cooler, wetter regions [3]. Across climate types, quantitative studies are minimal, but are supported both by the observations of local people and expert researchers, and inference based on other aquatic-terrestrial ecosystems such as temporary ponds [73].

- During flowing phases, foraging bats and birds may target adult insects emerging at the water surface, as reported in floodplains [74]. Bat activity can be higher in temporary rivers than in surrounding upland areas, as documented in a forested region of California [75].
- During flowing and pool phases, accessible drinking water attracts wild animals and livestock to temporary rivers, with some bat species only able to drink from standing water [75]. During dry phases, herbivores may enter the channel to graze on colonising terrestrial grasses and herbs [5,76] and small, active mammals such as shrews forage for invertebrates.
- As flowing phases increase in duration in winterbourne reaches, high bullhead abundance [72] may create rich feeding grounds for otters *(Lutra lutra)* [77]. As aquatic habitats contract, predatory birds including grey herons *(Ardea cinerea)* and little egrets *(Egretta garzetta)* have also been seen preying on fish trapped in contracting pools [72].
- Amphibians use ponded reaches, isolated pools and stream-fed ponds for reproduction **(Box 5)** [78], as also observed in temporary ponds [79]. Expert observations indicate that tadpole masses can attract opportunistic predators including grass snakes *(Natrix natrix)*.
- Channel networks aid navigation by animals moving across landscapes [5,75], and evidence from multiple regions shows that wet and dry river corridors guide bat migrations [73,80].

Box 5: Temporary river pools provide seasonal amphibian habitat

Observations suggest that frogs, toads and newts (including the protected great crested newt *Triturus cristatus* in the UK) make seasonal use of in-channel pools and river-fed ponds. In (B), common toads *(Bufo bufo)* mate in a river-fed pond on a chalk winterbourne (A). Their tadpoles provide rich pickings for opportunistic predators such as grass snakes *(Natrix natrix).*

Aquatic invertebrate communities

The aquatic invertebrates of temporary rivers and their ecological functions

Aquatic invertebrate communities in temporary rivers comprise many crustacean, flatworm, insect, leech, mollusc, mite and worm taxa, and include common generalists and endemic temporary-river specialists [81]. Often diverse and abundant, these animals play important ecological roles by processing leaf material, transferring energy through food webs and across aquatic-terrestrial boundaries, and acting as prey for animals including fish and birds. As surface water is lost, those stranded on the bed also provide food for opportunistic terrestrial predators including beetles.

What do we know about aquatic invertebrates in UK temporary rivers?

Many studies explore aquatic invertebrates in UK temporary rivers, including descriptive accounts and quantitative evidence. Most focus on larger macroinvertebrates in surface sediments during flowing phases, in particular in chalk and karst limestone rivers in England. Fewer studies examine assemblages in pools and subsurface sediments or consider smaller meiofauna or groundwater specialists. As for other assets, assemblages beyond English limestone rivers are poorly documented.

- After long flowing phases, surface sediments support diverse assemblages, with 79 taxa found across four seasonally dry and near-perennial sites on one karst river in Derbyshire [16,82].
- When reaches are compared, there are typically fewer species in temporary than in perennial rivers [83], but differences decline as flowing-phase durations increase. In contrast, global evidence suggests that biodiversity can be higher in temporary rivers when differences among reaches are recognised, due to both greater habitat diversity [84] and random differences in the species colonising isolated temporary stretches [85].
- Different species occur during flowing and pool phases, enhancing aquatic biodiversity [18,20]. One study of two karst limestone rivers recorded 78 taxa in standing water, including 28 not found in flowing water, and dominated by beetles, true bugs and snails **(Box 6)** [18].
- Temporary river communities can be distinct from those in perennial rivers, and include specialist insects [9,18,86,87] and microcrustaceans [88] with adaptations such as desiccation tolerance [17,89], although some evidence of such adaptations is inferred [20,53].
- Subsurface sediments support surface water species and groundwater specialists. UK studies of flowing-phase assemblages in seasonally dry [16] and near-perennial [90] reaches note that low flows and high temperatures can trigger migrations into deeper sediments, and global evidence suggests that many species use these sediments as a refuge after surface water is lost [91,92].

Box 6: Beetles and bugs colonise pools to enhance biodiversity

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One study of the karst River Manifold in England's Peak District found 28 txa exclusively in pools (A) including many beetles, such as *Helophorus grandis* (B), and true bugs, including the water boatman *Sigara nigrolineata* (C).

Rare specialist species

Which UK species are rare temporary river specialists?

Below, we describe species that are encountered infrequently – they are rare – and that are known only from temporary rivers. All such species – one mayfly, one stonefly, and one blackfly – are insects with aquatic juvenile and terrestrial adult life stages, and two are of conservation interest.

What do we know about the UK's rare temporary river species?

We know most about the mayfly *Paraleptophlebia werneri*, which is relatively easy to identify; the stonefly *Nemoura lacustris* and blackfly *Metacnephia amphora* are less well-known. All species are associated with chalk winterbournes – the best-known temporary rivers; further research in temporary upland headwaters may reveal more rarities. It is likely that rare specialists also occur within more obscure groups, such as meiofauna and diatoms.

- The mayfly *Paraleptophlebia werneri* is listed as Nationally Scarce [93]. Its known distribution is expanding, but records remain restricted to chalk winterbournes and other temporary rivers **(Box 7)** [53,87].
- First recorded in the UK in 2009 [94], the stonefly *Nemoura lacustris* is now known from 16 winterbourne reaches in south England [95]. It is listed as Nationally Rare [96], but its distribution requires confirmation, as it may previously have been misidentified as another temporary river specialist, *Nemoura cinerea* [94].
- The blackfly *Metacnephia amphora* was first described in a winterbourne in Dorset in 1975 [97] and records remain restricted to this county [53], Hampshire [11], and West Sussex [98].
- A study of just four winterbourne sites on one river [53] recorded: three Red Data Book species – *Nemoura lacustris, Paraleptophlebia werneri* and the soldier fly *Oxycera terminata,* which is Nationally Scarce and internationally Near Threatened [99]; the Nationally Scarce beetle *Agabus biguttatus* [100]; and *Metacnephia amphora,* which is too poorly studied to confirm its rarity.
- Several studies note that aquatic macroinvertebrate communities in winterbournes have "very high" conservation value [11,53,87] as characterised by the Community Conservation Index, an index based on species richness and rarity [101]. Although "very high" value is of potential national significance and warranting legal protection [101], the index needs careful interpretation as the occurrence of a single rare species can inflate scores.

Box 7: A mayfly that lives only in temporary river reaches

The mayfly *Paraleptophlebia werneri* is a temporary river specialist. Its aquatic juveniles (A) are know largely from winterbourne reaches of chalk streams in south England, and it also occurs in other temporary rivers (B). Emerging terrestrial adults (C) colonise the riparian zone.

Terrestrial invertebrate communities

The terrestrial invertebrates of temporary rivers and their ecological functions

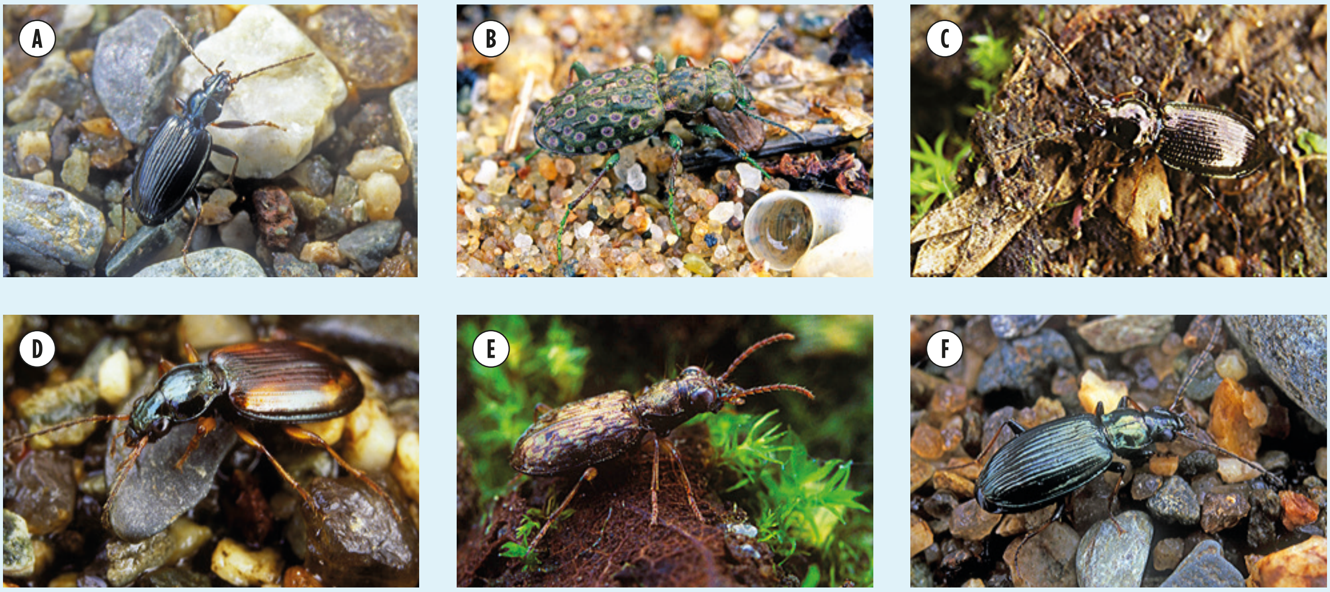
The few details we have indicate that a diverse terrestrial invertebrate assemblage may begin to establish as soon as flow starts to recede. Such colonists could promote natural ecological functioning at landscape scales by transferring energy across aquatic-terrestrial boundaries.

What do we know about terrestrial invertebrates in temporary rivers?

Almost no published work describes the terrestrial invertebrates within dry UK river channels [102], with relevant research coming from comparable and wider climate zones, other UK habitats, and unpublished data collected in dry chalk and karst channels. Based on these sources:

- Diverse beetle assemblages colonise dry channels, with 33 species in the ground beetle, rove beetle, click beetle and leaf beetle families collected by hand searching in one small study of two karst limestone channels **(Box 8)** [103].
- A study of two winterbournes sampled ground beetles, rove beetles, slugs, spiders, flies and woodlice using pitfall traps [104]. These groups overlap with those in another chalk stream, in which mud beetles also occurred on rotting algal masses [102], and with those found in cool, wet temperate Australasia [65,105]. The non-native invasive landhopper *Arcitalitrus dorrieni* was also recorded, sometimes at high abundance [104], and a humid microclimate could promote its spread along dry river channels [106].
- Communities including many beetle, spider and true fly species are well-known in other UK riverine habitats that shift between wet and dry states, such as the exposed riverine sediments that occur in some dynamic channels [107-109] and floodplain habitats [110].
- Quantitative sampling of the dry channel of the River Albarine in temperate France found 113 taxa in a 10-km section [64,111]. Ground beetles, rove beetles, ants and spiders were most diverse, and springtails were most abundant [111].
- A study of Australian and Italian channels noted that assemblages are dominated by riparian taxa, and may include "unique" dry-channel specialists with adaptations such as inundation tolerance [112].

Box 8: Many beetle species inhabit dry UK river channels



A small study of the karst Rivers Manifold and Hamps, Staffordshire, found 23 species in the ground beetle family, including: (A) *Bembidion atrocaeruleum;* (B) *Elaphrus riparius;* (C) *B. lampros;* (D) *B. tetracolum;* (E) *Asaphidion curtum;* and (F) *B. tibiale.*

Aquatic plants

The aquatic plants of temporary rivers and their ecological functions

All plant species are on a spectrum spanning fully aquatic to terrestrial habitat preferences, as reflected in the zonation of temporary river vegetation. Aquatic species contribute to ecosystem functioning by maintaining water levels, providing structure and modifying flow to increase habitat diversity, and acting as moist dry-phase refuges for aquatic invertebrates and microbes [113].

What do we know about aquatic plants in UK temporary rivers?

Relatively few studies examine aquatic plant communities in UK temporary rivers, and existing literature has a considerable bias towards chalk rivers [76,114,115]. In other temporary rivers, aquatic plants remain largely uncharacterised; we found just one review of headwater streams noting mosses as dominant in Scotland's "impermanent burns" [21]. The following observations come, with one exception, from studies of chalk rivers in south England:

- When individual sites are considered, aquatic plant richness is higher in perennial compared with temporary reaches [76]. However, the presence of aquatic, semi-aquatic and terrestrial taxa enhances diversity in temporary rivers when longer sections are compared **(Box 9)** [76].
- Characteristic winterbourne plant communities are associated with gradual changes in flow permanence. Multiple community sub-types occur in winterbourne and intermittent reaches, each with different proportions of aquatic, semi-aquatic and terrestrial species [76].
- Where flow velocity is sufficient, fast-growing annuals dominate winterbournes, and some water speedwells *(Veronica anagallis-aquatica)*, water-crowfoots *(Ranunculus peltatus; R. pencillatus)* and watercress *(Rorippa nasturtium-aquaticum)* are "classic" species [10,56].
- Communities change in response to flow. Given sufficient flow, water-crowfoots often dominate during spring and early summer. As flow declines, watercress and fool's watercress *(Apium nodiflorum)* typically become more abundant [56] and filamentous algae accumulate. Algal mats rot during dry phases [56,102], contributing to nutrient peaks after flow resumes.
- A decline in flow can expose extensive, gently sloping, aquatic–terrestrial sediments at the water's edge – a dynamic habitat that promotes plant diversity in winterbourne reaches [115].
- In a near-perennial Welsh mountain stream, a moss *(Fontinalis squamosa)* and a water starwort *(Callitriche intermedia)* dominated during wet phases, and both survived a rare dry phase [20].

Box 9: A temporary flow regime enhances plant diversity

In the winterbourne reaches of chalk streams, the typical length of a dry phase can gradually increase from downstream to upstream. In response, characteristic plant communities with different proportions of aquatic Ⓐ Ⓑ, semi-aquatic Ⓐ Ⓑ and terrestrial Ⓒ taxa occur at sites within a few kilometres of one another.

Terrestrial plants

What do we know about terrestrial plants in UK temporary rivers?

Plant surveys of temporary river channels focus on aquatic, wet-phase assemblages. Even where UK dry channels have been surveyed (typically in chalk rivers in south England), reports focus on persisting aquatic vegetation, and identify encroaching terrestrial plant taxa to a much coarser level. The ecological roles of terrestrial plants in dry channels are therefore uncertain, but they are likely to provide habitat for animals including pollinator insects, to store sediments through binding to their roots, and to alter water chemistry through nutrient uptake from the sediments.

- Studies of chalk stream flora in south England note "non-aquatic" herbs and grasses as increasing in extent as flow declines, and as dominating dry-channel vegetation in winterbourne reaches and at sites experiencing longer, less predictable dry periods [76,114,115]. Terrestrial mosses may also occur [56], their long life cycles indicating inundation tolerance.
- Only the grasses creeping bent *(Agrostis stolonifera)* [116] and marsh foxtail *(Alopecurus geniculatus)* [76] are species documented as occurring in dry chalk river channels, but expert observations note several additional species as present, including great willowherb *(Epilobium hirsutum)*. Such species prefer damp conditions and also occur in other aquatic–terrestrial habitats, such as perennial river margins [117]. Competitive generalists such as stinging nettles *(Urtica dioica)* are also common colonists of dry channels.
- Competitive tree saplings can encroach into dry channels [118], and expert observations note willows including *Salix alba* as colonising dry winterbournes. If such saplings establish, binding with their inundation-tolerant roots can stabilise sediments to create features such as mid-channel islands, thus altering channel geomorphology **(Box 10).**

Box 10: The terrestrial plants of temporary rivers are poorly known

Terrestrial plants soon colonise dry channels, but the species present are barely described in published literature. Our own observations show that, even within the (relatively well-known) temporary chalk rivers of south England, colonising assemblages are very variable and may be dominted by terrestrial (A) or semi-aquatic (B) grasses. Tree saplings can also colonise and, where they establish, can create islands that enhance in-channel habitat diversity (C).

Microorganisms

The microorganisms of temporary rivers and their ecological functions

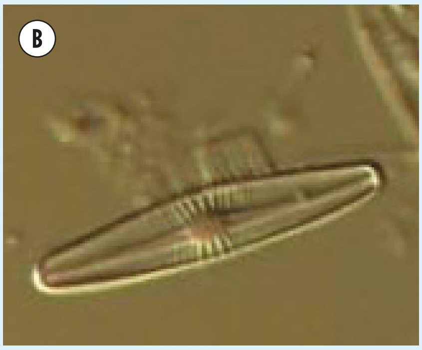
Evidence from other temporary streams and from perennial UK systems suggests that microbial communities may be diverse in our temporary rivers, including archaea, bacteria, cyanobacteria, diatoms, fungi, green algae and protozoa. These microbes make major contributions to natural ecosystem functioning by performing biogeochemical processes such as nutrient uptake and transformation. Microorganisms include many primary producers and are a crucial source of energy at the base of food webs.

What do we know about microbial communities in temporary rivers?

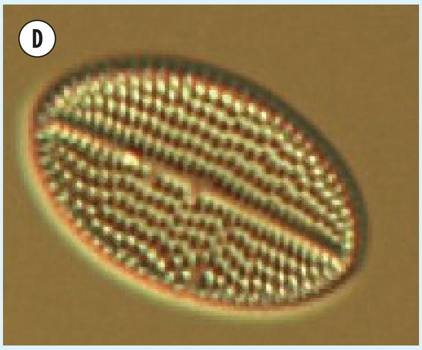
Few temporary-river studies from the UK or other cool, wet temperate-climate regions explore the microbial communities that occur in surface or subsurface water, or in the biofilms that cover bed surfaces.

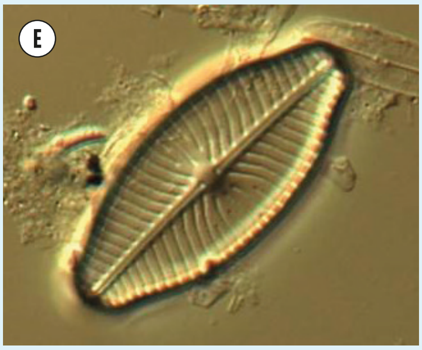
- Evidence from mediterranean regions shows that biofilm communities respond to transitions between flowing, pool and dry states, and differ from those in perennial rivers due to the absence of desiccation-sensitive taxa and the occurrence of temporary river specialists [119,120].
- A major UK study, conducted in chalk-river-fed experimental channels representing stony headwater streams, showed repeated shifts between wet and dry states to limit the dominance of a green alga, which allowed a diverse diatom assemblage to develop **(Box 11)** [121].
- Subsurface sediments may retain free water during a 'dry' phase, or may remain moist compared with the sediment surface, in particular when sustained by rainfall [122]. These sediments support different communities in free water and in the biofilms coating sediment grains [123,124]. Although pore-water richness may decline during dry phases [123], sediment-associated assemblages are relatively stable [124] and can remain metabolically active after free water is lost.

Box 11: The 'scum' on bed surfaces is a diverse algal community



'Scum' to the untrained eye (A), the biofilms coating temporary river bed surfaces include 'microalgae': diatom species such as *Achnanthes minutissima* (B), *Amphora fogediana* (C), *Cocconeis placentula* (D) and *Placoneis gastrum* (E). Each one is typically just 20–200 µm long; images not to scale.





Images B–E © P. J. Meadows

Linking assets to ecosystem services

The physical and biological natural assets described above interact to perform natural ecological processes that deliver provisioning, regulating and/or cultural ecosystem services that benefit people. Flowing-phase services that overlap with those in perennial freshwaters are well-documented and include tangible services such as provision of drinking water as well as valued recreational opportunities such as angling. In contrast, dry-phase services may be hidden from view [35] and remain poorly understood; as a result, people may not value dry-phase services.

To redress the flowing-phase bias of service provision in temporary rivers, we identify services that evidence suggests may enhanced or different during, or unique to, dry phases:

- **Table 1** links the physical and biological assets of temporary rivers to a range of ecosystem services delivered during wet and/or dry phases;
- Based on the overview in **Table 1, evidence boxes** describe selected services which we propose may be enhanced or different during, or unique to, dry phases;
- To illustrate service provision proposed in evidence boxes, **benefits wheels** summarise the relative provision of the selected services during wet and dry phases;
- A **logic chain** is then used to link the specific attributes of a set of natural assets to the delivery of valued services.

We use colour codes to distinguish **provisioning, regulating** and **cultural** ecosystem services.

Table 1 lists services identified by the UK National Ecosystem Assessment (NEA) as provided primarily by freshwaters, and also by woodland, farmland and/or urban habitat types. All terms are as stated in either the *NEA Introduction* [30] or the *Freshwaters* chapter [25], with one exception: within the broad *hazard* regulation service, we consider *fire regulation*, as well as both *flood* and *drought* control, the latter supplementing services described to date [25,30]. We exclude services not provided by temporary rivers, and exclude species diversity and genetic resources [30], which we view as multiple assets, each of which provides many ecosystem services [125]. The final column of **Table 1** proposes services that may be enhanced *during* dry compared to wet phases and those that may be enhanced *by* a flow intermittence (i.e. by differences between wet and dry phases), with justification provided in the subsequent **evidence boxes.**

Key to Table 1 asset symbols

Wet-phase/dry-phase contribution to service provision

Major/primary

Minor/secondary

Absence of asset enhances service

Physical

Landforms

Sediment

Surface water

Subsurface water

Riparian inputs

Leaves

Woody material

Organisims:

Aquatic

Biofilms

Plants

Invertebrates

Fish

Terrestrial

Plants

Invertebrates

Birds

Table 1: Services provided by wet and dry-phase assets in temporary rivers

	Ecosystem service	Natural assets associated with provision in: Wet phases	Dry phases	Dry phase enhanced[1]
Provisioning	Fish			
	Livestock			✓
	Fuelwood			✓
	Drinking water supply			
	Health products			✓*
Regulating	Local climate regulation			
	Erosion control			✓
	Hazard regulation: fire			
	Hazard regulation: flood and drought control			✓
	Flow regulation			
	Pollination			✓
	Water quality regulation			✓
Cultural	Aesthetics			
	Education			✓*
	Recreation			✓*
	Sense of place			✓*

[1] ✓ provision is enhanced during or unique to a dry phase compared to a wet phase;
✓* provision is enhanced by differences between wet and dry phases.

The evidence that temporary rivers deliver provisioning, regulating and cultural services during dry phases.

Suggestions of service provision in the evidence boxes below are based on sound science, informed both by our own observations and by a wide range of literature. However, research is needed to examine the extent to which the suggested patterns accurately reflect service provision across different UK temporary river types.

Provisioning services

Livestock. Dry-phase channel use by livestock has been quantified in arid regions and in UK perennial, but not temporary, rivers [126-127]. This and observations from temporary chalk streams indicates that grazing in adjacent fields provides livestock with variable access to drinking water. Access to and movement in the channel may be enhanced or reduced compared with flowing phases [126], and resources become increasingly scarce but valuable as water levels decline below the surface. Subsequent encroachment by terrestrial plants enhances food resources [76] that could support livestock production.

Fuelwood. Woody material is deposited as flow declines [128], and accumulations on dry channels may provide fuelwood for local residents in some global regions. In the UK, wood may be sporadically distributed and removed for flood control, limiting its potential use.

Health products. All taxa provide genetic resources, and the different taxa present during flowing, pool and dry phases increase genetic diversity in temporary rivers. In particular, specialist species with adaptations such as desiccation tolerance represent genetic resources that could benefit people, due to potential medical applications [129].

Regulating services

Erosion control. Whereas flowing phases reduce erosion control by transporting sediment downstream, sediments are retained during pool and dry phases. During dry phases, the roots of persisting aquatic plants and colonising terrestrial plants bind the sediment, which continues to limit sediment transport after flow resumes.

Flood and drought control. During dry phases, the sediments of surface-water-fed temporary rivers may represent a water storage area. Rain infiltrates the bed to recharge groundwater [130], and this stored water may enhance water resource availability. If water levels continue to rise above the bed surface and overtop the banks, the timing of peak flows could differ in temporary and perennial tributaries, staggering water delivery to reduce flood peaks downstream [131]. The attributes of these and other assets influencing this service provision are explored in **Figure 5.**

Pollination. As a dry phase proceeds, grasses and herbs colonise and can become extensive [76], and dry channels may therefore represent unmanaged linear habitats dissecting agricultural landscapes [132]. Dry phases often occur in summer, allowing pollinating insects to use these plants as habitat, and sediments may also support ground-dwelling insects. These pollinators may enhance productivity in nearby cropland.

Water quality regulation. Flowing phases transport pollutants including inorganic nutrients downstream, whereas biofilm microorganisms have longer to metabolise nutrients during pool and dry phases, in particular in subsurface sediments that remain saturated [133]. Regular drying can also increase diatom diversity [121], and uptake by these microalgae could reduce concentrations of inorganic nutrients including phosphate [54] to mitigate nutrient pollution.

Cultural services

Education. Distinct educational opportunities are provided by wet and dry temporary rivers. Field trips may target dry channels, which allow close examination of landforms and sediments. In addition, temporary rivers remain particularly poorly studied during dry phases, representing a wealth of research opportunities [37].

Recreation. Temporary rivers can be features of interest for tourists, for example a Peak District leaflet tells visitors: "watch out for the rivers… as they disappear beneath porous limestone" [134]. Other specific recreational opportunities include:

- **Fishing.** Loss of fish stops recreational angling during dry phases, but brown trout spawning in the clean gravels of chalk winterbournes helps to maintain fisheries in catchments in which such habitats are absent from perennial downstream reaches [135].
- **Caving.** If water levels decline sufficiently during dry phases, recreational access to subsurface parts of karst river corridors is enhanced [136]. Visited features include caves and sites of historic interest, such the Lathkill Dale and Mandale Mines Scheduled Ancient Monument in the Peak District [137].
- **Walking and cycling.** Dry channels can provide routes across hard-to-navigate landscapes, especially in uplands. In summer-dry systems such as limestone reaches, dry phases typically coincide with peak visitor numbers, promoting recreational use [138].

Sense of place. UK Natural Character Area (NCA) profiles and opinions voiced in the media show that flowing water can be crucial in promoting a sense of belonging to a place. However, terms such as bourne, combe and slad indicate that temporary rivers are important to local people [43,139,140]. Some NCA profiles also use winterbourne reaches to justify selection of landscape attributes [43,139].

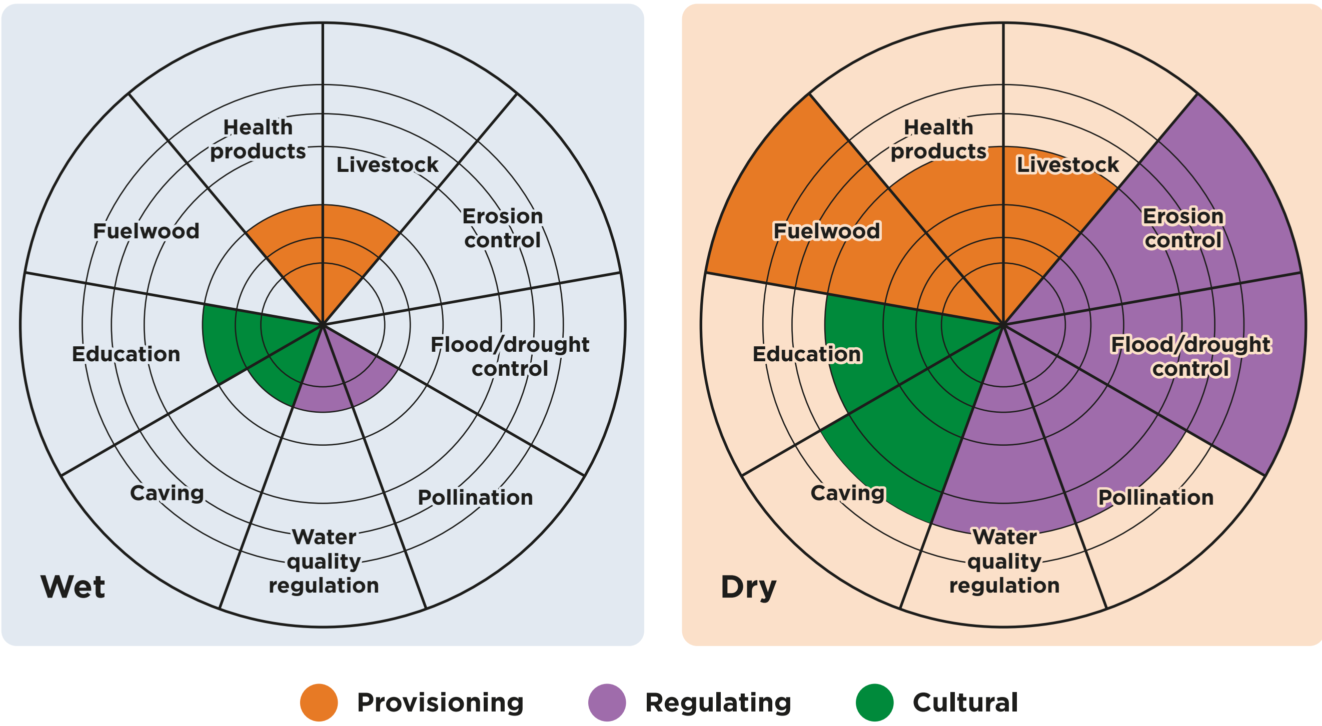
Landforms interact with historic structures to create distinctive landscapes, such as those reflecting mining activity in Lathkill Dale, Derbyshire **(Box 12)** [48,141].

Box 12: Natural and historic features contribute to the distinctive character of some temporary river valleys

In Lathkill Dale, natural features of the karst limestone bedrock (A) interact with the remains of historic buildings and structures (B) to create a distinctive and valued landscape. The dale is designated for its natural geological significance as part of Derbyshire Dales National Nature Reserve. In addition, above and below-ground mine workings are features of the Lathkill Dale and Mandle Mines Scheduled Ancient Monument.

Benefits wheels summarise the relative provision of selected **provisioning, regulating** and **cultural** ecosystem services. The wheels above compare wet-phase and dry-phase provision for services which, based on evidence in the above boxes, may be enhanced or distinct during, or unique to, dry phases **(Fig. 4).** Wedge sizes are proportional to our assessment of each service's relative provision during the two phases; in each case, wet-phase provision + dry-phase provision = 1. Although sound scientific principles inform these relative proportions, the numeric weightings assigned to each phase are subjective and should be refined in light of future research.

Figure 4: The multiple benefits of wet and dry phases in temporary rivers



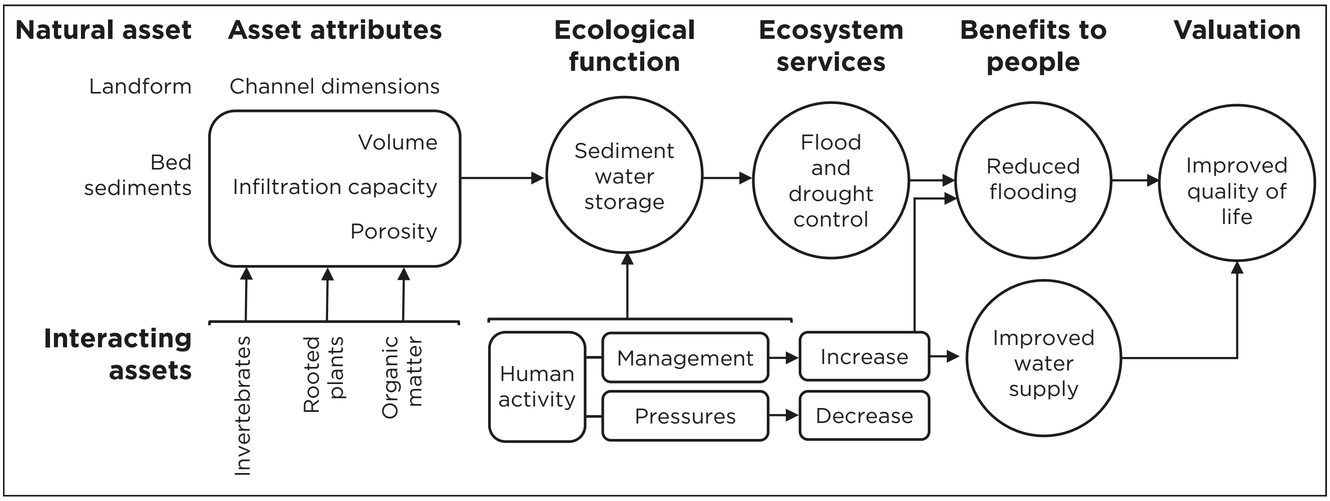
Logic chains show how assets with specific attributes perform ecological functions that deliver services from which people benefit. The logic chain in **Fig. 5** links attributes of landforms and bed sediments to one service set which we suggest may be enhanced during dry phases, flood and drought control, in this case in a surface-fed temporary river. Here, the size and shape of the landform determines the channel surface area onto which rain can fall. Several attributes then influence the capacity of the bed sediments to receive and store water, including their total volume (with subsurface dimensions differing from those at the surface); their capacity to be infiltrated by water; and their porosity (the volume of the pore spaces between sediment grains; **Fig. 5**).

Other assets interact with sediments to influence their capacity to accept and store water during dry phases **(Fig. 5).** Terrestrial, semi-aquatic and persisting aquatic invertebrates that move within the bed alter sediment characteristics to influence their infiltration capacity. The below-ground biomass of all rooted plants binds to sediments, altering their capacity to be infiltrated, and can intercept water moving through the root zone, leading to its loss through evapotranspiration.

The above-ground biomass of these plants, as well as dry-phase accumulations of organic matter including leaves and woody material, can create moist microhabitats that reduce evaporation from the sediment surface.

The benefits of and risks to the ecosystem services delivered to people will depend on land use in the adjacent riparian zone and surrounding catchment, and the location of the dry channel within a landscape, specifically the direction and distance to places requiring service provision. Opportunities to enhance service provision in temporary rivers using catchment-scale management strategies that seek to promote natural ecosystem functioning are explored in the *Summary* on pages 46–47.

Figure 5: Asset attributes influencing flood and drought control during dry phases

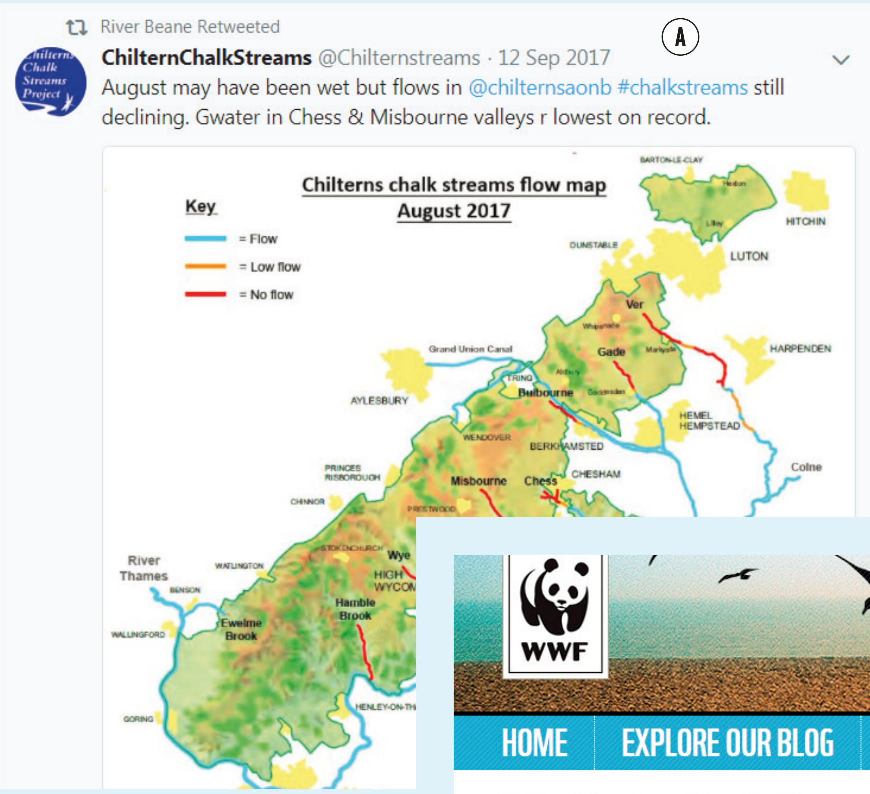


Perceptions of temporary rivers

We emphasise the ecosystem services provided by temporary rivers – services from which people may benefit. However, valuation of potential benefits will vary depending on the perspective of an individual, and media reports of unusual drying during droughts and unnatural drying caused by over-abstraction may influence how people view temporary rivers during dry phases **(Box 13)** [142].

The concerns of local people also encompass pool phases, with ponded water seen as a potential breeding ground for mosquitoes, insects which are increasingly perceived as carriers of disease in the context of global warming. Attempts to balance negative views with recognition of drying as natural and ecologically valuable are limited **(Box 13)** [143].

Box 13: Public perceptions of temporary rivers



Public perceptions of temporary rivers, in particular dry phases, may be negatively affected by valid concerns voiced by conservation groups about water resource use (A) (B). Such views are rarely balanced by positive portrayals in online media (C).

Metrics to measure the natural assets of temporary rivers

A range of different measures, or metrics, can be used to describe natural assets both individually and in combination, and therefore to investigate the services that assets provide. The challenge is to identify a manageable subset of metrics for which enough data exist to effectively characterise the extent, distribution and condition of assets, and therefore to track progress towards service provision goals and to identify risks to provision. However, our evidence-based review of temporary river assets has revealed that, in most cases, there are insufficient data to document assets adequately, and therefore to determine their provision of different services.

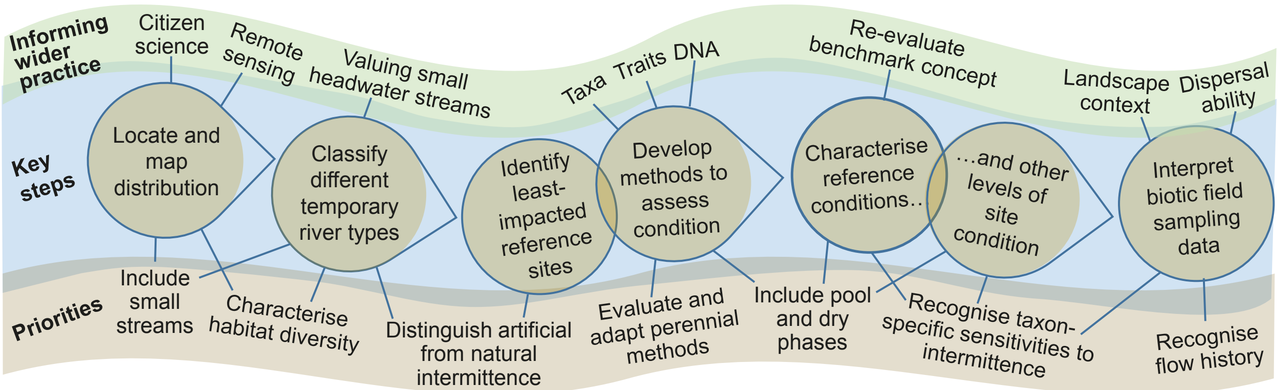
Key challenges in temporary river characterisation

A more fundamental challenge compromising the characterisation of temporary rivers is that many, notably the small headwater streams that dominate network lengths, remain unmapped. Citizen science initiatives exploiting local knowledge as well as remote sensing technologies involving aerial photography may be useful tools to enable efficient, widespread mapping **(Fig. 6)** [144,145].

Once mapped, a temporary river typology requires development, alongside identification of least impacted sites in each type, at which assets can be characterised **(Fig. 6).** The unmapped headwaters require particular attention, to document differences between streams in contrasting landscapes and subject to different levels of human modification. However, subsequent assessment of river condition by comparison with least impacted sites may be difficult in dynamic ecosystems such as temporary rivers, because community composition is highly variable in both space and time [146]. Developing multi-site networks that enable effective characterisation of these variable communities remains an ambitious goal.

Once sites or site networks are defined, methods to characterise assets are needed, and those developed for other ecosystems (including perennial rivers) may or may not be suitable, for example, flow metrics do not readily distinguish ponded from dry zero-flow states. Equally, indices developed to summarise aquatic invertebrate community condition in perennial rivers can sometimes be used effectively in temporary rivers, in particular those which have long, predictable flowing phases [147]. However, these indices may also underestimate condition, due to the absence of taxa sensitive to both natural flow intermittence and human impacts [148]. In such cases, new indices require development [149], and approaches exploring the functional traits of biological communities [150] as well as DNA-based technologies [151] may prove informative, alongside traditional taxonomic methods **(Fig. 6).**

Figure 6: Steps towards ecological condition assessment in temporary rivers



Adapted from Stubbington et al. (2018) [146].

What data are available to characterise assets?

Extensive regulatory agency data are available for a few assets. In all cases, data are from few sites, and coverage of the UK's temporary river network is biased towards chalk rivers, whereas other river types remain largely unexplored. Regulatory data are complemented by those from individual research projects, but again, this information is limited in extent. Exploring existing data could establish baseline conditions including patterns of change in space and time, and could therefore allow future investigation of responses to management interventions done to improve asset condition. For example, available data could be used in the following ways:

- National River Flow Archive data from monitoring stations in temporary reaches could be used to establish the **extent** of **freshwater**, including temporal changes in extent. In addition, one quantitative exploration of flow cessation and drying in 10 temporary chalk rivers [41] has developed metrics (such as mean dry-phase duration) which have wider potential for use in assessments of the **extent** and **distribution** of **freshwater.**
- Monitoring data held by regulatory agencies for water chemistry variables including nitrate, phosphate and dissolved oxygen could be used to explore changes in **freshwater condition.**
- Survey data held by regulatory agencies, water companies [71] and angling clubs could be examined to document **fish** community composition and population sizes. Spawning site count data from these sources could also be used to estimate the number of spawning fish and to describe the **extent, distribution** and **condition** of **sediments.**
- Survey and sampling data collected by regulatory agencies at temporary sites could be used to establish the **extent, condition** and **distribution** of **aquatic plant** and **aquatic invertebrate** communities.

What data are needed?

Despite the few highlights above, available data do not adequately describe the extent, condition or distribution of any asset at regional or national scales. In particular, we need data to characterise:

- all physical and biological assets in temporary rivers beyond the chalk and karst limestone;
- all living biological assets associated with dry phases in all temporary river types, including colonising terrestrial assemblages and persisting aquatic assemblages;
- non-living biological assets including leaves and woody material, in all temporary river types;
- temporal change in all assets in relation to transitions between flowing, pool and dry states.

We may need to adapt and add to current survey and sampling methods to link characterised assets to service provision. For example, to link assets to flood and drought control, we would need to:

- quantify attributes listed in **Figure 5,** including variability at multiple spatial and temporal scales;
- investigate functional characteristics of aquatic, semi-aquatic and terrestrial invertebrates, including their body size, use of subsurface sediments and burrowing ability [92];
- document variability in the extent and distribution of organic material, and determine the capacity of natural, dynamic accumulations of woody material to obstruct flow;
- describe in-channel plant communities during wet and dry phases, including their above and below-ground biomass and its influence on water infiltration of the bed sediments.

The considerable challenges of collecting such comprehensive multi-asset data should not undermine the usefulness of quick wins: using available data to inform initial assessments, the result of which can be refined as further data become available.

Moving towards metrics

As data characterising the attributes of an asset or set of assets linked to provision of an ecosystem service of interest become available, metrics will be needed to summarise each asset. Metrics must effectively reflect variability in asset characteristics, allowing comparison within and between temporary river types and recognising change over time, for example before and after a management intervention. We also need to consider when and where each metric can be used: during flowing, pool and/or dry phases, and in all or just some temporary river types.

Many metrics used both in research contexts and by regulatory agencies are of potential use, and we have compiled a considerable (but not exhaustive) list of measures that could be used to document the natural assets considered above **(Appendix 2).** Below, we use invertebrates as an example asset to outline a range of potential metrics, with flowing-phase aquatic and terrestrial communities being particularly well-known and poorly described, respectively.

Aquatic invertebrate communities

- Simple measures including total abundance, taxa richness, and presence of a functional group **(Appendix 2)** can be calculated, based on the presence or abundance of taxa within assemblages sampled during flowing phases using a standard method and identified to a sufficient taxonomic resolution. Such assemblage characterisations are typically site-specific, but metrics can be used to investigate local to regional scale patterns of diversity.

- The suitability of summary indices for use in temporary rivers has rarely been determined (but see [148]), but in the UK, the Community Conservation Index (CCI) has been assessed as robust in "all ... aquatic habitats: (flowing or ponded) water, permanent or temporary" [101]. Based on species richness and rarity, the CCI could be used to indicate the conservation value of aquatic invertebrate communities in temporary rivers during flowing and pool phases. It may also be able to characterise aquatic assemblages persisting in the 'seedbank' during dry phases [89,152], with research examining these assemblages entailing sediment rehydration experiments to trigger development of dormant life stages [89].

- Standard biological indices that summarise an aquatic invertebrate community and reflect general degradation could be adapted for temporary rivers. For example, Munné and Prat (2009 [194]) developed a new index specifically for Spanish temporary rivers with seasonal flow, and found that it outperformed the standard index.

Terrestrial invertebrate communities

- Globally, we know of only one (Australian) study comparing terrestrial invertebrate assemblages at impacted and unimpacted sites. Differences were identified using simple measures such as taxa richness and total abundance, indicating that the simple metrics proposed for aquatic invertebrates may also be suitable for terrestrial assemblages [127].

- Pantheon is an online tool that analyses lists of terrestrial invertebrates to identify, for example, an assemblage's association with sites of contrasting ecological condition [153]. Information within this database could be used to create a new index, equivalent to the CCI [101], to summarise the conservation value of assemblages in temporary river channels. First, however, research is needed to adequately characterise these dry-phase assets.

There is considerable, clear potential to ultimately develop a broad suite of natural capital metrics that effectively track progress toward ecosystem service provision goals. However, considerable work precedes metric development, as summarised in **Figure 6** and explored in more detail below.

Research priorities

Several knowledge gaps compromise our characterisation of the extent, distribution and condition of the natural assets in temporary rivers. At the same time, these assets – and therefore the ecosystem services they provide – face risks, notably increasing water resource pressures, which operate within catchments altered by human activity and against a backdrop of ongoing climate change. Addressing knowledge gaps is crucial to underpin effective strategies that seek to manage these risks by maintaining, and where necessary enhancing, asset condition to achieve service provision goals [33].

Key priorities to enable progress towards adequate characterisation of asset extent, condition and distribution are outlined below. A complementary step is to develop metrics that track progress towards ecosystem provision goals, informed by best practice examples [71] and online data [39].

Find out where temporary rivers are

As noted by national conservation organisations [154] and European research networks [155], mapping the distribution of freshwaters – including small streams – and sharing collated data is fundamental to effective asset characterisation and wider ecosystem protection.

Tools: citizen scientists [144]; remote sensing [145].

Head upstream and upslope

Beyond England's chalk rivers, many believe that "we don't have temporary rivers here". We back recent [156] and previous calls [19,21,67] to recognise, study and monitor small headwater streams, which may dominate the network length. Those in remote uplands may be priority habitats due to their naturalness [45].

Head north, and west

UK temporary river research has focused on limestone catchments in England. Beyond England, we found one review briefly describing Scottish 'impermanent burns' [21], one 1958 study of a near-perennial Welsh stream [20], and no studies from Northern Ireland. In addition, most flow monitoring stations on UK temporary rivers are in England (A). Future research should seek to represent all UK countries.

Map data © 2018 GeoBasis-DE/BKG (© 2009) Google

Don't go with the flow

Europe-wide biomonitoring is restricted to wet phases and aquatic organisms [146]. Dry-phase communities including colonising terrestrial and persistent aquatic taxa need characterisation, first at least impacted sites, and then to explore the effects of human activity [127].

Potential tools: beetles; plants; DNA; Pantheon [153].

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Summary: managing risks and opportunities in temporary rivers

Temporary river assets are at risk from human activity

In characterising the natural assets of temporary rivers, we identified risks to their distribution, extent and condition. For example:

- The extent of freshwater is at risk [33] from over-abstraction. Although evidence of climate-change impacts has not been confirmed, an increase in droughts may exacerbate this risk [157].
- Sediment condition is at risk from fine sediment pollution associated with agricultural land uses, and this risk may be exacerbated by water abstraction if flow velocities are reduced [158].
- A change to a natural water regime has complex, interacting effects on biological assets.
    - Increases in the occurrence of dry phases may reduce the richness of aquatic communities; comparable increases in terrestrial communities may occur but have yet to be described.
    - Loss of natural flow intermittence puts temporary river specialist species at risk.

Wider strategies provide opportunities to enhance temporary rivers

Interventions that balance trade-offs and interdependencies between environmental, economic and social goals may be needed to manage risk and enhance the capacity of assets to deliver services. For example, revegetating riparian zones can intercept fine sediment from farmland and reducing abstraction rates can increase flow velocities, both improving sediment condition. However, by reducing the land and water allocated to farming, both actions have economic consequences that may or may not be deemed acceptable. Given such complexities, service goals require careful development in consultation with a broad range of stakeholders [159]. Interventions should also be informed by wider strategies that recognise the importance of natural functioning in supporting resilient ecosystems that operate at large spatial scales with human-influenced landscapes [45].

Build ecological resilience

Promoting natural ecosystem functioning builds resilience to allow adaptation to pressures [28,160]. For example, management that allows natural, dynamic growth and accumulation of plant material to slow flow in headwaters [161] may offset human-caused increases in dry phases, with local inundation of land reducing flood risk downstream [162].

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Take a landscape perspective

Recognising local communities as linked across landscapes [85, 163] may characterise assets most robustly [160,162,164], and catchment-based approaches also promotes service provision [165]. For example, integrating natural flood management projects across perennial and temporary tributaries can stagger movement of water downstream to mitigate urban floods [161].

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Place people at the heart of ecosystem services

Placing people at the heart of a service provision strategy can also benefit ecosystems [28,160]. It is crucial to connect with farmers as countryside stewards responsible for many streams, and with the public, to promote recognition of temporary rivers as ecosystems that support natural capital to deliver a broad suite of services across wet and dry phases.

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Glossary

Temporary river terms

Drought. A sustained period of below average natural water availability. Hydrological drought entails a deficit in surface water and is caused by limited precipitation [166].

Dry. Defined here as lacking in free water. In cool, wet temperate climates, "dry" bed sediments typically retain some moisture.

Dry phase. A period in which surface water is absent or largely absent from a channel. Isolated pools may persist during an otherwise dry phase, and subsurface sediments may retain free water.

Ecological resilience. The capacity of a species, population, community or ecosystem to persist in a naturally functioning state during a period of environmental change. (Note that this definition is less specific that that used in the international temporary rivers literature.)

Near-perennial. A river or stream that has continuous surface flow during most years but ceases to flow or dries during drought events.

Perennial. A river or stream that has continuous surface flow during all years.

Ephemeral river or stream. A temporary river or stream characterised by unpredictable and often short flowing phases that occur in response to precipitation; typically smaller streams [2].

Intermittence (flow). The state of having any temporary flow regime, including a near-perennial, intermittent or ephemeral flow regime.

Headwaters, headwater streams. Used here as a general term to describe the smallest streams, which occur in the upper reaches of a river network, close to the source.

Intermittent river or stream. A temporary river or stream characterised by predictable, seasonal and typically long flowing periods; includes larger rivers [2].

Reach. Used here as a general term to describe a river or stream length of roughly 10-100 metres and including a range of habitat types [167].

Taxon (plural **taxa**). A group of organisms in any one taxonomic unit within the hierarchy of biological classification, from species (and subspecies) through to domain.

Temporary river or stream. A general term used to describe any river or stream that sometimes stops flowing and may dry; includes near-perennial, intermittent and ephemeral systems.

Wet phase. A period in which flowing and/or standing surface water dominates a temporary river channel.

Winterbourne. Reaches of chalk rivers and streams that experience a natural, seasonal and typically annual period of streambed drying, often in summer.

Zero flow. A condition in which upstream-to-downstream water movement within a channel is not perceptible or detectable. Also termed *no-flow*.

Natural capital terms

Asset. See *natural asset.*

Benefit. A positive or negative change in the welfare or wellbeing of people resulting from the use or consumption of goods, or from the knowledge that something exists [26].

Cultural services. Non-material benefits that people obtain from ecosystems and landscapes, including educational and recreational opportunities, and aesthetic experiences [168].

Ecosystem services. Natural functions and products that ecosystems provide and that can result in benefits for people [26]. Includes cultural, provisioning and regulating services.

Goods. Natural assets, the consumption or use of which provides people with benefits that can be valued [33].

Metric. A means of measuring change in an asset, good or benefit [26].

Natural asset. A particular aspect of natural capital defined by the processes and functions it performs. Includes species, freshwater, sediments and organic materials [26].

Natural capital. Components of nature that produce value to people, including ecosystems, ecological communities, species, freshwater, landforms, sediments and air, and the natural processes and functions they perform [26]

Provisioning services. Ecosystem services that relate to the provision of materials such as drinking water [31].

Regulating services. Ecosystem services relating to the regulation of environmental processes such as river flow [31].

Value. A measure of the change in the welfare or wellbeing of people resulting from the use or consumption of goods [26].

References and other online resources

The resources below are available via the Freshwater Biological Association website, at: **http://www.fba.org.uk/temporary-rivers** and include a Reference list of all cited sources, a Temporary rivers research spreadsheet will share details of new publications that characterise the natural assets of UK temporary rivers. Users can add resources themselves or can send suggested additions to **rachel.stubbington@ntu.ac.uk**

Appendices

Appendix 1. Temporary Rivers Natural Capital Report – information searching methods

Appendix 2. Temporary Rivers Natural Capital Report – longlist of potential natural capital metrics

Unpublished data

Carling, B., Doyle, P., Bates, A.J., England, J. and Stubbington, R. Hand search data characterising terrestrial invertebrate communities during a dry phase in the Rivers Hamps and Manifold, Staffordshire, UK. Nottingham Trent University, Nottingham, UK.

Durkota, J. Pitfall trap data characterising terrestrial invertebrate communities during a dry phase in the Lewes Winterbourne and the River Lavant, East Sussex, UK. Environment Agency, UK.

Stubbington, R. Surber sample data characterising aquatic invertebrate communities during a flowing phase in the River Lathkill, Derbyshire, UK. Loughborough University, Loughborough, UK.

Key resources

Datry, T., Bonada, N. and Boulton, A.J., eds. Intermittent Rivers and Ephemeral Streams: Ecology and Management. Academic Press, London. 597 pp. Available at: **https://doi.org/10.1016/B978-0-12-803835-2.09997-6**

National River Flow Archive **https://nrfa.ceh.ac.uk**

Stubbington, R., England, J., Wood, P.J. and Sefton, C.E., 2017. Temporary streams in temperate zones: recognizing, monitoring and restoring transitional aquatic-terrestrial ecosystems. Wiley Interdisciplinary Reviews: Water, 4, e1223. doi. 10.1002/wat2.1223. Available at: **http://onlinelibrary.wiley.com/doi/10.1002/wat2.1223/full**

UK National Ecosystem Assessment website: **http://uknea.unep-wcmc.org/** and resources page including cited Technical reports: **http://uknea.unep-wcmc.org/Resources/tabid/82/Default.aspx**

Valuing Nature Programme website: **http://valuing-nature.net** including information on the Natural Capital Synthesis Report call **http://valuing-nature.net/natural-capital-synthesis-reports-0**

Notes

Notes

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Further information visit:
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