Article

Petrifying Springs in Wales

Jonathan Graham and Gareth Farr report on the first systematic survey of 'tufa' springs in Wales

△Above. Tufa associated with the Carboniferous Limestone forms on a vertical coastal rock face at Fedw Fawr, Anglesey. In the background Jonathan Graham can be seen hard at work. G. Farr

Most bryologists are familiar with petrifying or 'tufa' springs as they are a habitat where bryophytes often predominate. In Britain, these springs and seepages are often associated with the pleurocarpous moss *Palustriella commutata*. The importance of petrifying springs in Europe is further highlighted by their inclusion within the EC Habitats Directive (92/43/EEC) as the Annex 1 habitat: H7220 Petrifying springs with tufa formation (*Cratoneurion*). The authors were commissioned by Natural Resources Wales (NRW) to survey a range of Welsh sites; the aim was to provide a baseline dataset for the habitat, whilst also fulfilling the EC Habitat Directive's requirement to record the condition of this Annex 1 habitat (see Farr *et al.,* 2014).

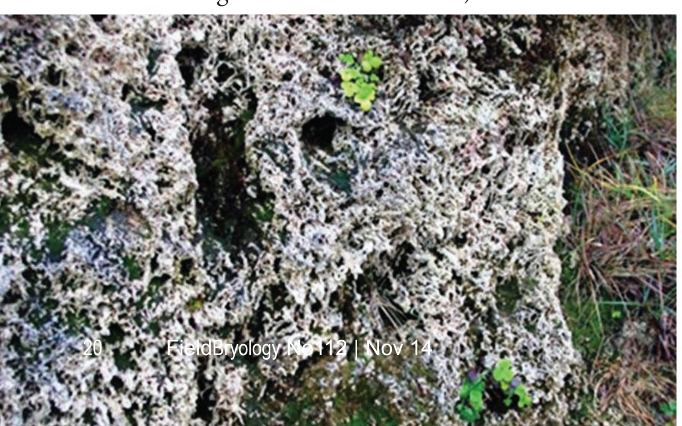
Twenty seven sites at fifteen locations were surveyed during November 2013 and January 2014, a wet but not exceptionally cold Welsh winter. The sites ranged from natural locations such as the vertical cliff seepage faces on the Anglesey coastline (Fig. 1) to those highly influenced by historic anthropogenic activities. An example of the later was a site associated with highly calcareous, hyperalkaline (>pH 12) waters leaching from the base of spoil heaps at Herbert's Quarry, Mynydd Du (The Black Mountain) (Fig. 2).

From the outset, the project aimed to combine both botanical and hydrogeological investigations of the sites including: species-richness, water chemistry, water supply mechanisms, geological setting and identification of land use pressures.

△Figure 1, left. Natural vertical coastal cliff seepage with *Palustriella commutata*, *Eucladium verticillatum*, *Didymodon tophaceus* and tufa, Fedw Fawr, Anglesey. J. Graham. △Figure 2, right. Water leaching from ancient lime spoil heaps forms large areas of tufa supporting marginal stands of *Palustriella falcata* dominated vegetation with *Carex flacca*, *Carex demissa*, *Fissidens adianthoides*, *Scorpidium revolvens*, Herbert's Quarry, Mynydd Du. J. Graham

The study sites were selected by Natural Resources Wales based upon existing knowledge of the habitats. Most were designated SSSI, SAC and NNRs although some exist outside of the designated site series. The study sites aim to represent the diversity of environments in which this habitat occurs in Wales, although the list is by no means comprehensive and it is expected that there are many more unknown sites still to be identified. The ecological boundary of each site was delimited by focusing on homogenous vegetation dominated by *Palustriella commutata* and *P. falcata*, and at selected sites transects across runnels were sampled for variations in both pH and electrical conductivity. The conjectural hydrological boundary (surface water catchment and groundwater catchment) of each site was then considered, as were any existing or potential pressures including, grazing, agriculture (e.g. application of fertilizers) and changes to the water supply such as abstractions and drainage.

The term 'petrifying' means to replace with stone, and in the context of the springs it refers to the habitats' close association with the hydrochemical process of calcium carbonate precipitation. Tufa deposits are associated with geological sources rich in calcium carbonate including: the Carboniferous Limestone, some Jurassic Liassic limestones, and calcrete units within the Devonian Old Red Sandstone. The calcium carbonate deposits are commonly known as 'travertine' or 'tufa', both terms that are used in the literature (see Pentecost, 2005 for full discussion), and the latter term will be used throughout this article. Tufa forms when calcareous water reacts with the atmosphere, releasing carbon dioxide and thus becoming supersaturated with calcium bicarbonate. The calcium carbonate or tufa can be deposited in



◁Figure 3. Complex tufa block, with *Eucladium verticillatum*, associated with a calcrete in the Devonian Old Red Sandstone, Hen- Allt Common. J. Graham

▷Figure 4. Tufa deposition on the lower stems of *Scorpidium cossonii*, Cors Eddreiniog, Anglesey. J. Graham

various morphological forms (Pentecost & Viles, 1994). It is likely that the upper leafy shoots of bryophytes offer a large surface area for water to be in contact with air, and thus encourage the deposition of tufa. In addition to well cited "tufa forming" mosses such as *Palustriella commutata*, *Eucladium verticillatum* (Fig.3) and *Didymodon tophaceus,* the survey found a broad range of other species actively associated with tufa formation including *Palustriella falcata*, *Bryum dichotomum, Bryum pseudotriquetrum, Campylium stellatum, Gymnostomum aeruginosum, Hymenostylium recurvirostrum, Philonotis calcarea, Scorpidium cossonii* (Fig. 4), *Scorpidium revolvens* and *Jungermannia atrovirens* as well as charophytes and the distinctive alga *Rivularia haematites.*

At many sites where tufa formation was recorded (importantly it was not recorded at six of the sites in this study), it formed without the involvement of living plant material (Fig. 5). This confirms that bryophyte-dominated vegetation is not a prerequisite for tufa formation, rather that the two are often associated, and that the tufa is an easily recognisable geological feature that indicates the occurrence of high calcium carbonate waters. The authors observed active tufa formation on twigs, stones and even an old ten pence coin. There are well known 'petrifying wells' such as Mother Shipton's Cave, North Yorkshire and Knaresborough, Buxton, both of which have long historical use, where disparate objects, including even soft toys, have been left in the waters until they become petrified. At several sites there was evidence of cyclic tufa deposition, as formerly large stands of *Palustriella* or *Bryum pseudotriquetrum* were observed fully stratified (and killed) alongside newer living patches associated with active tufa deposition.

The survey sites can broadly be separated into two groups – Group 1 and Group 2 – the key defining features are listed in Table 1. The contrasting altitude preferences of *Palustriella falcata* and *Palustriella commutata* are the most

▽Figure 5. Tufa deposition associated with historic lime spoil at Herbert's Quarry, Mynydd Du/The Black Mountain. J. Graham

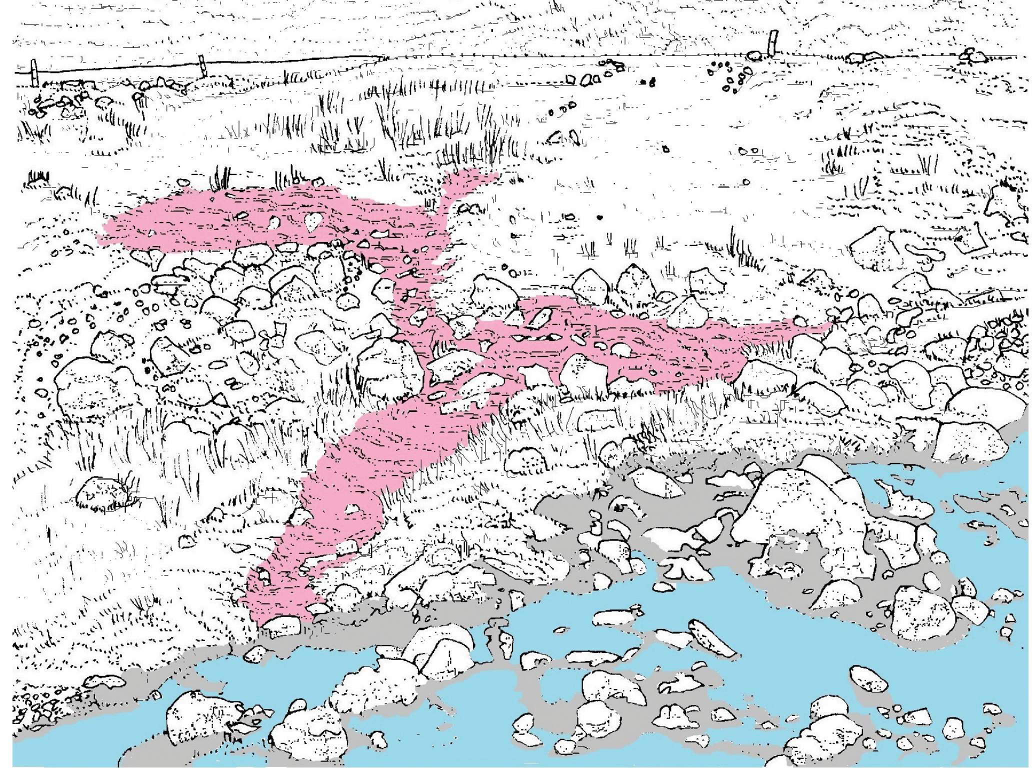
Table 1. Key defining features of Group 1 and Group 2 survey sites

	Group 1	Group 2
Key species	Dominantly *Palustriella falcata*	Only *Palustriella commutata*
NVC Community	M38	M37
Elevation	Upland (275-690maOD)[1]	Lowland (5-402maOD)
Vegetation: Total species Vascular Plants[2] Small *Carex* species	Often with *Festuca ovina* 21-52 11-27 2-3	Often with *Festuca rubra* 5-20 1-10 0-2
Flow	Smaller flows (<0.1-0.51/s)	'Larger' flows (<0.1-11/s)
Occurrence of tufa	Less tufa - some sites with no tufa	More tufa - often deposited in significant quantities under natural conditions
Water chemistry	Less base rich (as bicarbonate)?	More base rich (as bicarbonate)?
Water quality	Low nutrient levels	Higher nutrient levels
Openness of site	Open	Typically not open (incl. woodland, cliffs and gorges)
Land use	Upland/common land	Lowland agricultural
Grazing pressure	Significant	Low or none (incl. many vertical sites)

[1] *meters above Ordnance Datum i.e sea level*
[2] *Including clubmosses, horsetails and true ferns*

obvious difference between the two groups and appear to be an important ecological distinction in Wales. The groups correspond well with the National Vegetation Classification (NVC) communities M37 and M38, although floristic tables for NVC communities do not separate the two *Palustriella* species.

In addition, existing bryophyte literature highlights the different ecology of these two species in terms of altitude as well as other parameters such as "openness" of habitat and degree of base enrichment of the habitat. During the late nineteenth century, Dixon (1896) noted that *P. falcata* (*Hypnum falcatum*) occurs on bogs, principally at higher elevations than *H. commutatum*. Watson (1968) reported that *P. falcata* "would appear to be less exacting in requirements" (than *P. commutata*) "occurring more generally in moorland flushes and mountain springs". These "less exacting requirements" were again reported by Bosanquet *et al.* (2005) who suggested *P. falcata* " is more common" (than *P. commutata*) "in open habitats and shuns the gorges and woodlands where *P. commutata* sometimes grows". The use of altitude to separate Group 1 and 2 also ties in with observations made by Pedrotti (2006) who noted that *P. falcata* occurs in 'weakly acidic habitats' that are, at least in Wales, more common in upland settings, compared with *P. commutata* which occurs 'in basic habitats' such as the lowland sites within this study. Atherton *et al.* (2010) also noted that *P. falcata* "may occur in slightly less calcareous habitats than *P. commutata*".



△Figure 6. A field sketch of a typical Group 1 site discharging into an upland stream (Pont Clydach, Black Mountains). Pink - *Palustriella* dominated vegetation, Grey - Bryophyte dominated riparian vegetation without *Palustriella*, Blue - open water of stream. J. Graham

Group 1

Group 1 sites are typically upland spring sites on open hills (Fig. 6) almost exclusively dominated by *Palustriella falcata* (Fig. 7 & 8). *Palustriella commutata* may also be present alongside *P. falcata* at these sites but typically occurs as smaller patches, often associated with spring heads, especially where these are rocky. Where many individual spring heads are present, complex branching patterns of flushed vegetation can develop across wide areas. These flushes are species-rich with a significant flowering plant component (including *Juncus acutiflorus, Juncus effusus, Carex flacca, Carex demissa, Anagallis tenella, Cardamine pratensis, Ranunculus flammula, Ficaria verna, Galium palustre*) as well as a broad suite of associated bryophytes (including *Fissidens adianthoides, Ctenidium molluscum, Scorpidium cossonii, Leiocolea bantriensis, Campylium stellatum, Jungermannia exsertifolia* ssp. *cordifolia, Bryum pseudotriquetrum).* Spring heads often have a slightly modified flora, characterized by a greater proliferation of *Palustriella commutata* and lawns dominated by *Cratoneuron filicinum* and *Philonotis fontana*. Elsewhere smaller hollows or runnels are characterised by a greater domination of *Campylium stellatum* (Fig. 8), stands of *Scorpidium revolvens* and occasional

◁Figure 7. Llyn-y-Fan Fach: a typical upland Group 1 site. J. Graham

△Figure 8, left. Llyn-y-Fan Fach: *Palustriella falcata* dominated vegetation at margin of runnel with *Campylium stellatum*, *Scorpidium revolvens*, *Carex flacca* and *Anagallis tenella*. J. Graham. △Figure 9, right. An unusual dome formed of *Palustriella falcata*, located in an upland, acidic setting dominated by silicate rich bedrock. Nant Peris, Snowdonia. J. Graham

stands of *Scorpidium scorpioides*. Deeper central runnels (especially those with a permanent flow of water) regularly support emergent flowering plants (including *Apium nodiflorum*, *Nasturtium officinale s.l.*, *Potamogeton polygonifolius*, *Veronica beccabunga*, *Mentha aquatica*, *Glyceria fluitans* and occasionally *Hypericum elodes*). The cushion forming moss *Hymenostylium recurvirostrum*, the liverworts *Jungermannia atrovirens*, *Preissia quadrata* and the alga *Rivularia haematites* are often associated with tufa occurring at these sites. A number of interesting plants were recorded

▽Figure 10. *Scorpidium scorpioides* within runnel, Nant Peris, Snowdonia. J. Graham.

△Figure 11. A typical Group 2 site in a wooded gorge. Gareth Farr is shown collecting water samples and recording field readings of water dripping from the base of the tufa block. McWalter's Dingle, North Wales. S. Campbell

from these sample sites including *Amblyodon dealbatus*, *Pinguicula vulgaris*, *Moerckia flotoviana*, *Wahlenbergia hederacea*, *Philonotis calcarea*, *Equisetum variegatum*, *Eriophorum latifolium* and *Carex lepidocarpa*.

A subset of three Group 1 sites at Nant Peris, Snowdonia, occurred at a high altitude, 681-689 mAOD (meters above Ordnance Datum i.e sea level) and stood out as having an unusual mix of species, absence of tufa deposition and unusual morphology. They are dominated by *Palustriella falcata* but have a number of additional northern (and more upland) vascular plant species including *Montia fontana*, *Saxifraga hypnoides* and the invasive alien *Epilobium brunnescens*. These sites are also unique within this survey because they comprise dome-shaped floating mats of *Palustriella falcata*-dominated vegetation, associated with small runnels, springs and seepage areas (Fig. 9). A number of typical *Palustriella*-associated bryophytes occur (i.e. those typically associated with base-rich water) including *Cratoneuron filicinum*, *Campylium stellatum*, *Scorpidium revolvens*, *Fissidens adianthoides*, *Bryum pseudotriquetrum*, *Scorpidium scorpioides* (Fig. 10) and *Philonotis fontana* despite the water quality having a very low base status. In contrast, a number of less markedly calcicole species (*Rhizomnium punctatum*, *Brachythecium rivulare*, *Plagiomnium undulatum*) were also recorded. While these latter species are not unusual within upland flushes, the presence of *Straminergon stramineum* (a moderate calcifuge) in good quantity mixed with *Palustriella falcata* and *Brachythecium rivulare* at two of these sites was exceptional. The floating vegetation mat present at these sites was estimated to be at least 25 cm thick, however the evolution of and hydrological controls at these unusual sites remain poorly understood.

Group 2

Group 2 sites are typically not species rich and comprise *Palustriella commutata*-dominated

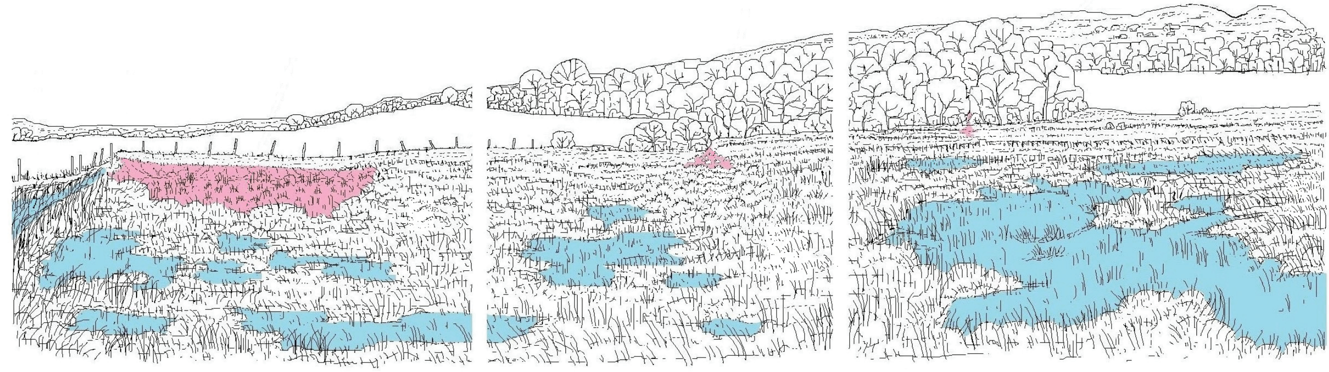
△Figure 12. Mixtures of calcifuge (*Diplophyllum albicans*, *Succisa*, *Pteridium* left) and calcicole (*Palustriella commutata* right) in close proximity, vertical rock face, Fedw Fawr, Anglesey. J. Graham

vegetation on rocky and shaded sites, including rock outcrops in woodland, wooded river gorges (Fig. 11) and coastal cliffs (Fig. 12). Other common mosses associated with Group 2 sites include: *Pellia endiviifolia*, *Cratoneuron filicinum*, *Conocephalum* species and *Chrysosplenium oppositifolium*. The shaded and rocky nature of these sites favour woodland species that occur in small quantities, such as ferns (*Asplenium scolopendrium*, *Asplenium trichomanes*) as well as *Hedera helix, Rubus fruticosus, Geranium robertianum* and at one site each *Carex sylvatica* and *Hypericum androsaemum*.

All of the Group 2 sites have tufa formations (Fig. 13), however, they have more of a lowland bryophyte assemblage with tufa supporting extensive fruiting cushions of *Eucladium verticillatum, Didymodon tophaceus, Fissidens taxifolius* var. *taxifolius, Leiocolea turbinata*, occasional *Bryoerythrophyllum recurvirostrum* (contrasting with the *Hymenostylium, Gymnostomum aeruginosum, Rivularia haematites* communities on upland tufa). In addition, the only *Jungermannia* species recorded from these sites was *J. atrovirens* which usually (again in contrast to upland springs) occurred only in small quantity.

An interesting lowland site was Cors Erddreiniog, Anglesey (Figs. 14 & 15) where a large seepage face, comprising numerous springs issuing from the Carboniferous Limestone,

▽Figure 13. Tufa face dominated by *Didymodon tophaceus* with *Pellia endiviifolia*, *Eucladium verticillatum*, Anglesey cliff. J. Graham



△Figure 14. Lower limit of *Palustriella commutata* dominated vegetation (Group 2) between *Schoenus nigricans* hummocks, transitioning into tall fen community, Cors Erddreiniog, Anglesey. Pink - *Palustriella* dominated vegetation, Blue - open water pools within fen. J. Graham

discharges down a gentle slope, partially via a wooded area, into a calcareous fen. The discreet spring heads have dominant patches of *Palustriella commutata* with *Conocephalum* (especially where rocky or wooded) and the *Palustriella* vegetation then continues along the margins of the spring runnels before quickly being replaced by *Campylium stellatum* and *Bryum pseudotriquetrum* followed by a rapid transition into tall fen vegetation (dominated by *Juncus* species) or open water communities. The *Palustriella commutata*-dominated vegetation is associated with *Campylium stellatum, Fissidens adianthoides, Cratoneuron filicinum, Ctenidium molluscum, Scorpidium cossonii* and locally *Scorpidium scorpioides. Palustriella-* or *Campylium stellatum*-dominated vegetation often grows at ground level between tussocks of *Schoenus nigricans* within the zone of flushing by calcareous spring water. In contrast, the upper tussocks of *Molinia* (and occasionally *Schoenus*), which receive a greater proportion of rain water than calcareous spring water are without *Palustriella* and support a small number of calcifuge species including *Erica tetralix, Succisa* and *Potentilla erecta*.

At a micro level (individual vegetation patch or runnel), slope can vary greatly and this 'microtopography' is also reflected by subtle changes in the 'microhydrology', such as the range and duration of base flushing of vegetation. These small changes result in variation of the vegetation across very small distances. Based on individual transect measurements (Fig. 16), it was common to record vegetation with *Sphagnum* (pH 5-6, occasionally 4-5), *Palustriella*-dominated vegetation (pH 6-7) and open runnels with *Scorpidium revolvens* (pH 7-8, occasionally 9) within less than 0.5 m distance. At a number of sites, we observed dramatic vegetation transitions over very short distances. These include Waun Ddu (Craig-y-Cilau) where stands of *Sphagnum cuspidatum* (at the margins of a bog) directly adjoin *Palustriella*-dominated vegetation at the break of a small slope (pH transition 4.9 to 7.4 and electrical conductivity 51 to 272µs/cm) and Moel Gornach, where acid grassland and bog vegetation closely adjoin *Palustriella*-dominated vegetation at the break of slope (pH transition 4.7 to 6.3). In summary, the observed dramatic changes in vegetation type, water quality and supply emphasise microtopography as an important factor influencing the character and structure of *Palustriella*-dominated springs.

In total, thirty two water samples were collected from Group 1 and 2 sites for chemical analysis.

△Figure 15. Collecting field water quality parameters (pH, temperature, electrical conductivity, dissolved oxygen) from water flowing between *Palustriella commutata* dominated vegetation and *Schoenus nigricans* hummocks, Cors Erddreiniog, Anglesey. G.Farr

△Figure 16. Transect across an open runnel providing a range of pH values over a short distance - pH 5.31 with *Sphagnum subnitens* (left) pH 6.74 (central runnel with *Scorpidium revolvens*), pH 6.06 with *Sphagnum subnitens* (right), Pont Clydach, Black Mountain. J. Graham

This showed that the majority were calcium-bicarbonate type waters, with the exception of the upland sites at Nant Peris where sodium and chloride also contributed significantly to the total ions, reflecting the influence of localised rainfall rather than groundwater. The diversity of the sites is reflected in the range of pH values associated with *Palustriella*-dominated vegetation ranging from 6.4 (Pont Clydach) to 12.2 (Herbert's Quarry) with an overall average of pH 8.0. The majority of sites were low in nutrients (nitrate <2 mg/l N, phosphate and orthophosphate <0.04 mg/l), reflecting their low intensity land use. Where higher levels of nutrients occurred, e.g. Cors Erddreiniog (nitrate 1.93 – 7.35mg/l N), the site was still considered to be in favourable condition, suggesting that factors such as the hydrology of the site may be just as important if not more so than water chemistry for the favourable condition of these sites.

An interesting observation from the project was that six of the sites surveyed in Wales had *Palustriella*-dominated vegetation in the absence of tufa. A single locality, Nant Peris, Snowdonia (Fig. 9 -10) had *Palustriella*-dominated vegetation in the absence of both calcium carbonate rich water and tufa. These anomalies are likely to add to the ongoing debate on the classification of calcareous spring vegetation and the use of terms such as "tufa" or "petrifying" springs.

In terms of conservation, *Palustriella*-dominated spring vegetation is an interesting habitat because it requires specific geological and hydrogeological settings and is therefore more restricted than many other vegetation types. In addition, it occurs in small, intricate and often difficult to map stands and has a number of species (including invertebrates) that are specially associated with it. All but one of the sites surveyed in Wales were assessed as being in favourable conservation status.

The authors acknowledge that the study surveyed only a small subset of the total known sites in Wales with, no doubt, more remaining undiscovered. The ecological and hydrogeological dataset collected during this project forms an excellent baseline from which to monitor change, however seasonal and long term monitoring of sites would also improve our hydroecological conceptual understanding of how these diverse sites function. Future surveys should consider the inclusion of both invertebrate and algal data collection.

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