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Research Article

Dating springlines from hydrogeological and archaeological evidence

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Abstract

The relationship between prehistoric populations and water is often poorly understood, partly as a function of historical reliance on qualitative and fragmentary datasets in many regions. Here, we adopt a quantitative approach to analyze a specific aspect of the relationship between prehistoric populations and water for the Cotswold Hills, southwest UK; an area of documented hydrogeological change and extensive Neolithic (ca. 5.5 ka) activity. Using a database of all known Neolithic monuments, we interrogate the significance of water to their habitation. By marshaling a large dataset of recent (ca. 100 years) changes in the discharge and elevation of 259 springs, we establish a striking negative relationship between present-day spring discharge and annual elevation change. We then formulate an inverse problem to predict spring elevations in Neolithic times. Spring elevations are predicted to be closer to, and higher than, Neolithic-dated sites relative to the location of modern springs. These results emphasize a utilitarian and/or reverential link between water and prehistoric populations. Our approach of reconciling markedly different datasets and timescales can easily be adapted to other regions. While groundwater had behaved reasonably predictably since Neolithic times, recent human activity is (and will continue to be) far more significant in influencing groundwater behavior.

Keywords: Cotswolds, UK, Limestone aquifer, Neolithic, Springs, Worldview

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INTRODUCTION

Rationale: relationships between human and hydrological activity

Although "human engagements with water permeate every aspect of culture" (Strang, 2008, p. 38), the nature of this relationship and ways in which it has changed over time are often poorly understood. In many regions across the world, the links between hydrology and archaeology have yet to be extensively explored owing to the scarcity of compatible data in space and time. O'Donoughue (2017, p. 22) noted the importance of archaeological techniques as a "bridge between past and present" that might unlock "the social and historical importance" of springs and rivers. North America has seen recent focused work on the social and cosmological relationships between people and water; for instance, the role of the Mississippi River in the growth and decline of the pre-Columbian urban center of Cahokia (Pauketat et al., 2017).

In many cases, rich archaeological resources that yield intriguing insights into people's former livelihoods contrast against the paucity of knowledge about the main elements of the sites they occupied. As a result of this situation, much of our understanding of prehistoric monuments and sites is dictated by landscape-oriented and morphological approaches that are the most common and informative (Darvill et al., 2011). We seek to obtain a degree of insight into the relationship between ancient peoples and water, and focus on drawing a tangible link between springs and the positioning of ancient sites that include funerary monuments.

Hydrogeology

The Jurassic bedrock strata of the Cotswold Hills in the southwest UK (Fig. 1) form an alternating succession of permeable oolitic limestones and impermeable mudstones and clays, reflecting relatively modest sea-level fluctuations in a shallow marine environment (Sumbler et al., 2000; Barron et al., 1997). Described as "classic cuesta terrain," the landscape has a steep, west-facing escarpment and a gentler southeastern dip slope (Goudie and Parker, 1996, p. 34). As a result, the few "obsequent" rivers that flow west from the main Thames/Severn (and also North Sea/Atlantic Ocean) drainage divide tend to have steeper channel gradients and greater discharge relative to the more languid "consequent" dip-slope rivers (Paul et al., 2018).

Lying to the south of the effects of the most recent direct Northern European glaciation (75–12 ka), the Cotswolds nevertheless experienced intense periglacial activity that sculpted the present landscape, governing many regional and local hydrogeological phenomena (e.g., Goudie and Parker, 1996; Neumann et al., 2003). Combined with striking differences in rock permeability over short lengths (tens to hundreds of meters), and two

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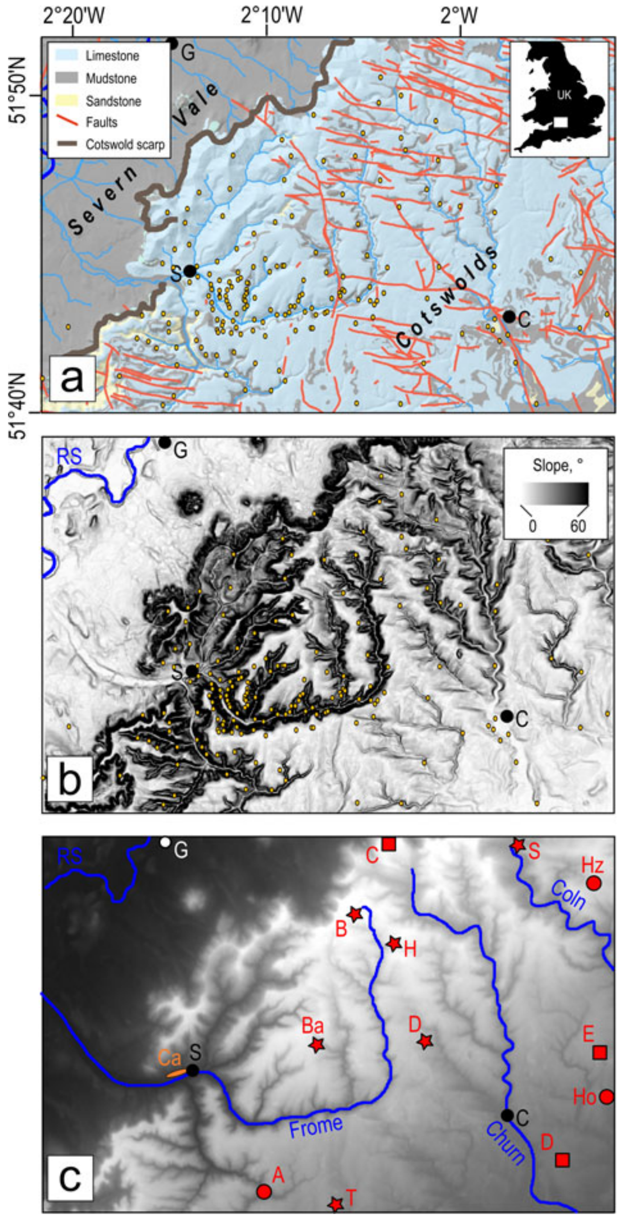

Figure 1. Top right inset: map of UK with location of study area, Cotswold Hills, SW UK, indicated by white rectangle; other maps are close-ups of study area showing: (a) simplified geology and structure based on the 25-km UK geological data map of the British Geological Survey (DiGiMapGB-25: https://digimap.edina.ac.uk/). RS: River Severn; C: Cirencester; G: Gloucester; S: Stroud. Yellow circles indicate springs (N = 195). (b) Slope in degrees derived from OS Terrain-50 topography (https://www.ordnancesurvey.co.uk/business-government/products/terrain-50); note steep slopes of the Cotswold scarp and irregularly indented and deeply incised western valleys radiating from Stroud. (c) Location of key archaeological sites and rivers mentioned in the text. Background: topography. Stars: lithic scatters and flint assemblages; circles: long barrows; squares: hilltop causewayed enclosures; orange lozenge labelled Ca: Cainscross Terrace of River Frome. A: Avening (see also Figs. 2, 5); B: Brimpsfield; Ba: Battlecombe; C: Crickley Hill; D: Duntisbourne Rouse; E: Eastleach; H: Harcombe; Ho: Horcott; Hz: Hazleton North; S: Syreford; T: Troublehouse Covert.

fractured and highly porous limestone aquifers (Inferior Oolite and Great Oolite), the region has attracted much interest from the perspectives of distributed groundwater modeling to extensive groundwater-quality monitoring campaigns (e.g., Hart, 1976; Rushton et al., 1992; Allen et al., 1997; Bricker et al., 2014). While groundwater flow patterns reflect gentle regional SE dips, the solutional enhancement of fractures and intense high-angle faulting in the northern and eastern Cotswolds generate highly transmissive flow pathways: the effect is concentrated along valley floors where periglacial activity was most intense (Hancock, 1969; Morgan-Jones and Eggboro, 1981). Indeed, the high regional concentration of solutional karstic features leads to discontinuous drainage, underground river courses, and discharge diminution over permeable limestone (Dury, 1953; Goudie, 1967; Self and Boycott, 2004). Both aquifers exhibit large and variable seasonal variations in groundwater levels and a rapid or "flashy" response to rainfall (Rushton et al., 1992). Despite localized connectivity via faults or eastward stratigraphic thinning of the separating Fuller's Earth aquiclude, both aquifer units are hydraulically independent, with different water table elevations (Maurice et al., 2008; Bricker et al., 2014). Also, despite manifold preferential flow pathways, the strength of correlations between spring discharge and limestone porosity, and discharge and water hardness, together with widespread water seepages known locally as "lissens," suggest that pores may also contribute to aquifer transmissivity (Paul, 2017).

The distribution of springs in the mid-Cotswolds is governed by the local clay–limestone impermeable–permeable lithological succession. Large springs with a mean annual discharge $> 1\ m^3s^{-1}$ are common, and tend to be concentrated on valley floors and on the western side of valleys, reflecting high densities of solutionally enhanced fracture swarms (Allen et al., 1997; Paul, 2017; Fig. 1). Smaller springs cluster around two well-defined stratigraphic interfaces—the contacts between the Great Oolite and Fuller's Earth, and the Inferior Oolite or Bridport Sand and Lias clay—and are particularly well-exposed where west-flowing scarp streams and periglacial erosion have carved deep (~150 m) valleys through the stratigraphy (Richardson, 1930; Paul, 2014; 2017; Fig. 1). Bricker et al. (2014) compared the ground elevation of several Cotswold springs to groundwater level from nearby boreholes for both aquifers. They found in general, there was a good agreement, although the existence of a perched spring adjacent to a fault zone implied preferential groundwater flow within a localized area of higher fracture density. A qualitative association between stream-head migration (between a higher elevation winter maximum and a lower elevation summer minimum) and groundwater levels has also been observed, as well as a groundwater level threshold that is controlled by the discharge elevation of a springline (James, 2011; Bricker et al., 2014).

During periglacial conditions, groundwater levels, spring elevations, and river discharges were all probably much higher than present; however, evidence for this is fragmentary and largely qualitative. The gradient of the Cainscross Terrace (dated to ca. 13 ka) of the River Frome (Fig. 1c) is steeper than present valley gradient, suggesting that the paleo-Frome was able to transport a greater load for a given discharge (Large and Sparks, 1961). Moreover, "dry valleys" are widespread: their formation involves discharge reduction, groundwater level decrease, and increased limestone porosity (e.g., joint enlargement) since end-Pleistocene times.

As far as changes in recharge are concerned, there is little evidence that precipitation in Neolithic times was substantially higher than modern patterns observed across northern Europe (e.g., Arbogast et al., 2006; Sánchez Goñi et al., 2016). Betti et al. (2020) suggested that temporal changes in Neolithic (8–4 ka) climate were relatively modest across much of northern Europe, but more pronounced in the Near East and South Asia, thus leading to the rapid dispersal of farmers from these regions. Sánchez Goñi et al. (2016) suggested that annual changes in temperature, precipitation, and humidity are comparable from Neolithic times and the present day across the UK and northern France. Assuming surface recharge as the only variable governing changes in groundwater levels, several studies have applied sophisticated climate models to make predictions older than Pleistocene times (e.g., Wilkinson, 1993; Whitehead and Edmunds, 2012). However, these predictions often suffer from low spatial resolution and are relatively poorly constrained in time.

Archaeology

The Mesolithic and Neolithic Cotswolds

Understanding the prehistoric occupation of the Cotswolds has long been problematic due to overreliance on lithic implements that constitute much of the available evidence. While a great corpus of archaeological sites and monuments exist, much of our understanding relies on inadequately recorded historical investigations, and those dedicated to other functions such as burial, waymarking, etc. Although efforts to rectify this situation have begun, these have been largely explored through genetic and isotopic analysis of human remains recovered from these sites (Saville, 1984).

The beginning of the Mesolithic Period in Britain was roughly contemporaneous with the ending of the Younger Dryas and the return to more a boreal climate at ~11.7 ka. As the climate continued to improve, evidence of annual occupation of the Cotswolds becomes greater, particularly in the latter half of the period, which is predominantly informed by lithic scatters, the largest assemblage of which comes from the alluvial gravels alongside the River Coln at Syreford (Saville, 1984). This location, together with all other sites mentioned in this section, is shown on Figure 1c. A paucity of studies means that this particular period is difficult to explore using site data, although it clear that springs and rivers played a key role in prescribing areas of activity (Brett and Hart, 2015). One notable site that attests to an Early Mesolithic presence in the Cotswolds occurs at Bourton-on-the-Water, where a pit or post alignment was discovered on a small gravel island in the braided channels of the River Eye (Brett and Hart, 2015). One of the primary fills of one of the pits was dated to 8892 ± 0.03 cal yr BP (before present is considered prior to 1950), while two samples from another pit returned dates of 9771 ± 0.029 and 9180 ± 0.032 cal yr BP, not only attesting to a local early presence here, but also one that was recurrent and long-term as reflected by the lack of overlap present between the two pits' dates (Brett and Hart, 2015).

Evidence of Mesolithic settlement is often inferred from evidence such as large flint assemblages of diagnostic microlithic forms, such as those found at Harcombe and Troublehouse Covert, both of which are focused around or above the current springline; and at Hazleton North long barrow and Tog Hill, which occupy hilltop positions (Sykes and Whittle, 1965; Saville, 1984). In more recent years, sites such as Winchcombe, Ascott-under-Wychwood, and Horcott have yielded evidence for structures in a variety of locales but further study is required to explore these sites fully (Benson and Whittle, 2007).

The Neolithic period witnessed substantial changes in prehistoric lifeways, with a movement away from hunter-gatherer subsistence strategies towards arable and pastoral-agrarian regimes alongside more permanent housing; fueled by a burgeoning population, social change of great proportions ensued (Darvill, 2004). In the Early Neolithic, extensive monumentality began to be constructed, i.e., long barrows and causewayed enclosures, which fundamentally changed the way the landscape was characterized and used. These sites have been considered recurrently in numerous syntheses, often focusing upon the typology and physical form of these sites, with little detail paid to the broader landscape and settings of the sites (e.g., Witts, 1883; Crawford, 1925; O'Neil and Grinsell, 1960; Corcoran, 1969; Darvill, 2010).

Long barrows, broadly defined as Neolithic elongated- or oval-shaped burial mounds (e.g., Chesterman, 1977), represent the first widespread monument type constructed in Britain. Due to their robust construction and imposing size, they represent one of the richest sources of evidence from the period (Darvill, 2010). Sometimes referred to as long mounds, they are elongated, trapezoidal earth-and-stone funerary structures in which the disarticulated remains of the dead were placed in a several chambers contained therein. Over 80 examples are known within the Cotswolds, varying quite considerably in dimensions (e.g., Darvill, 2010, p. 72). As early as 1925, researchers noted that long barrows were observed to conform to some locational traits, namely the occupation of high ground just off the crest of hills, with proximity to valleys and expansive viewsheds (Crawford, 1925; Darvill, 2010). While such observations hold true for the Cotswolds, elsewhere, such as to the west of the River Severn, and at the Medway group in Kent, a preference for river valley locations was shown, demonstrating a degree of regional individualism (Darvill, 2010).

Occupational evidence is sparse, yet is evidenced at several hilltop causewayed enclosures such as Crickley Hill, Eastleach, and Down Ampney (Dixon, 1994; Darvill et al., 2011). Much like earlier Mesolithic sites, causewayed enclosures seem to occur at junctions of distinct environments, nominally between lowland and upland, often close to topographical positions, facilitating easier negotiation of the valley or scarp edges (Darvill et al., 2011). These sites were subsequently sealed and abandoned, and the Middle and Late Neolithic in the Cotswolds display a marked paucity of evidence, often only flint scatters and modest deposits of pottery. Understanding the later Neolithic is challenging because of a lack of direct evidence, and preservation and discovery bias.

Humans, water, and monumentality

Water is literally essential to human existence and to all human-environmental engagements (Strang, 2008), but its significance clearly resonated in other facets of life. While post-Iron Age periods were characterized by increasing human agency over controlling and managing water, in earlier prehistory, water (and, more broadly, nature), was symbiotic to worldviews and prehistoric lifeways. Aside from such utilitarian use, water also possessed additional ceremonial or divine qualities, with purposeful deposition of artefacts occurring within aqueous locales since Early Mesolithic times (Bradley, 2017; Milner et al., 2018). Indeed, Van de Noort (2004) notes that the wetlands of the Humber region were exploited far more than were upland areas during the Mesolithic.

It has been argued recurrently that rivers were interwoven with prehistoric mobility, with the Thames perhaps serving as an arterial route from eastern England, and this claim has been invoked to explain the high number of Thames headwaters possessing archaeological complexes (Sherratt, 1996). Monuments equally seem to share affinities with water: their positioning and planforms are influenced by water and the natural landscape, the most apparent of which are henges. Even those monuments positioned on hilltops often intentionally had their ditches lined with clay in order to capture rain and groundwater (Harding, 2003). Seasonal wetness was also exploited at other Neolithic sites, with the massive artificial mound of Silbury Hill likely having moated the site (Leary et al., 2013).

Within the Cotswolds, prehistoric archaeology is well-attested to but greatly understudied as a consequence of both intense interest from antiquarians and a paucity of modern research-led projects. Perhaps the most widespread and widely studied monuments are the Early Neolithic long barrows, of which there are over 80 known examples across the landscape. These barrows are part of a regional group called the Cotswold-Severn, which is concentrated along the southern coast of Wales, the Cotswolds, and North Wiltshire, and has been the focus of several typological studies and syntheses (e.g., Witts, 1883; Corcoran, 1969; Darvill et al., 2011). Locational traits seemingly possessed by these monuments and ancient settlements have been noted for nearly a century: for instance, Crawford (1925) noted a preference for valley side locations, proximal to water sources such as springs.

Some of the earliest long barrows were constructed on virgin ground (Darvill et al., 2011). So-called "springhead supermounds," tentatively suggested to share affinities with the likes of Silbury Hill, have been noted at several places across the Cotswolds, potentially indicating a desire to draw significance or imbue these places with agency (Darvill et al., 2011). In exploring the megalithic architecture of several British landscapes, Tilley (1994) noted ancient monuments being aligned or placed carefully and deliberately proximal to water and watercourses. This was ascribed to a recognition among ancient populations of the persistence of watercourses, valleys, and related landforms (Tilley, 1994). In recent work undertaken on the Avening long barrow by Moore (2021), attention to the geomorphological position and proximity to springs was made, which together likely influenced its positioning and would have had a profound effect on its Neolithic setting. In the Mesolithic, occupational evidence is almost entirely derived from flint scatters in the Cotswolds, with notable exceptions existing in the north of the Cotswolds that possess more substantial evidence of settlement and monumentality (Brett and Hart, 2015). Locational traits of the Early Neolithic in the Cotswolds, predominantly formed by funerary monumentality, equally share this trend, likely attesting to some degree of shared worldview (e.g., |Darvill, 2004, 2010).

Objectives

The purpose of this paper is to marshal hydrogeological and archaeological evidence to place quantitative constraints on spring position, discharge, and groundwater level. The Cotswolds are an excellent natural laboratory for this approach due to the widely documented proliferation of both springs and Neolithic settlements and monuments. However, the relationship between people and water is poorly understood in the Neolithic of the Cotswolds. We use these Cotswolds Neolithic sites as an independent dataset to test our hypothesis that water was significant in their habitation. Fundamentally, we seek to: 1) interrogate data related to local hydrogeological change from the past 100–150 years; and 2) explore whether spring elevation may be extrapolated to Neolithic times to test the hypothesis that the positioning of ancient settlements was governed by proximity to water.

These questions have been addressed elsewhere, using various modeling techniques. For instance, Rushton et al. (1989) solved a set of partial differential equations describing current groundwater flow to "cycle backward" and make predictions about changes in flow speeds and directions over the last 1000 years. Jakeman et al. (1990) modeled well levels using the IHACRES (identification of unit hydrographs and component flows from rainfall, evaporation and streamflow data) rainfall-runoff model, with predictions of rainfall derived from a global circulation model (GCM) as the driver. Whitehead and Edmunds (2012), using a similar technique but different GCM, predicted elevated groundwater levels and river discharge at Silbury Hill, Wiltshire, 4.5 ka, arguing that these conditions could have sustained a sufficiently large local population to construct the Neolithic monument. Our approach is data-driven: we seek to reconcile hydrogeological and archaeological evidence directly.

METHODS

We began by assembling a database of all documented springs in the Cotswolds including coordinates, maximum (winter) discharge, and, if groundwater level fluctuates annually, the apparent maximum (winter) and minimum (summer) spring elevations in meters above ordnance datum (mAOD) (see Appendix). For our own measurement campaigns, we used a differential GPS with a vertical resolution of ± 0.5 cm (Garmin DGPS-53) to measure spring position and elevations. Because spring locations and productivity were important for various historic fulling, dyeing, and cloth industries, they were well-documented by Richardson (1930), who marshaled data from a series of interviews, direct measurements, and water-board reports from the mid-nineteenth century until 1928. This information was carefully scrutinized; records were only selected for inclusion if spring coordinates could be verified (e.g., using Google Earth), and minimum and maximum elevations were reported, together with discharge (often averaged, e.g., gallons per day). Other more recently reported spring data were then included from Morgan-Jones and Eggboro (1981), Rushton et al. (1992), Neumann et al. (2003), and Paul (2014, 2017). Finally, guided by the spring locations of Paul (2014) and seeking to revisit as many of the springs noted in Richardson (1930) as could be currently accessed, 51 measurements of spring positions and discharge were made in triplicate in January and August 2020. Potential springs were selected for inclusion only if: 1) water egress took the form of a single flow from solid rock; 2) at least 200 mL of water could be collected and measured in one minute (i.e., $0.012\,m^3s^{-1}$; a threshold value used elsewhere, e.g., Morgan-Jones and Eggboro, 1981; Neumann et al., 2003); and 3) there was evidence of ephemeral or winterbourne streamflow if the spring's minimum and maximum elevations varied seasonally.

This process yielded 259 data points, of which 195 are unique in space (i.e., repeated measurements at 64 springs). Figure 2 shows seasonal spring migration together with the position of Neolithic sites for a small portion of the mid-Cotswolds. In winter, valleys are often drained by ephemeral streams (winterbournes) due to higher groundwater levels. Figure 2b illustrates the relationship between annual changes in spring elevation (i.e., groundwater level) and lateral changes in the position of the spring as it appears to "migrate" up- and down-valley as a function of groundwater level. Richardson (1930) reported that the along-slope distance between a given "full" (i.e., winter; highest groundwater levels) and "empty" (i.e., summer) spring may exceed 10 m. Equation (1) was used to obtain change in spring

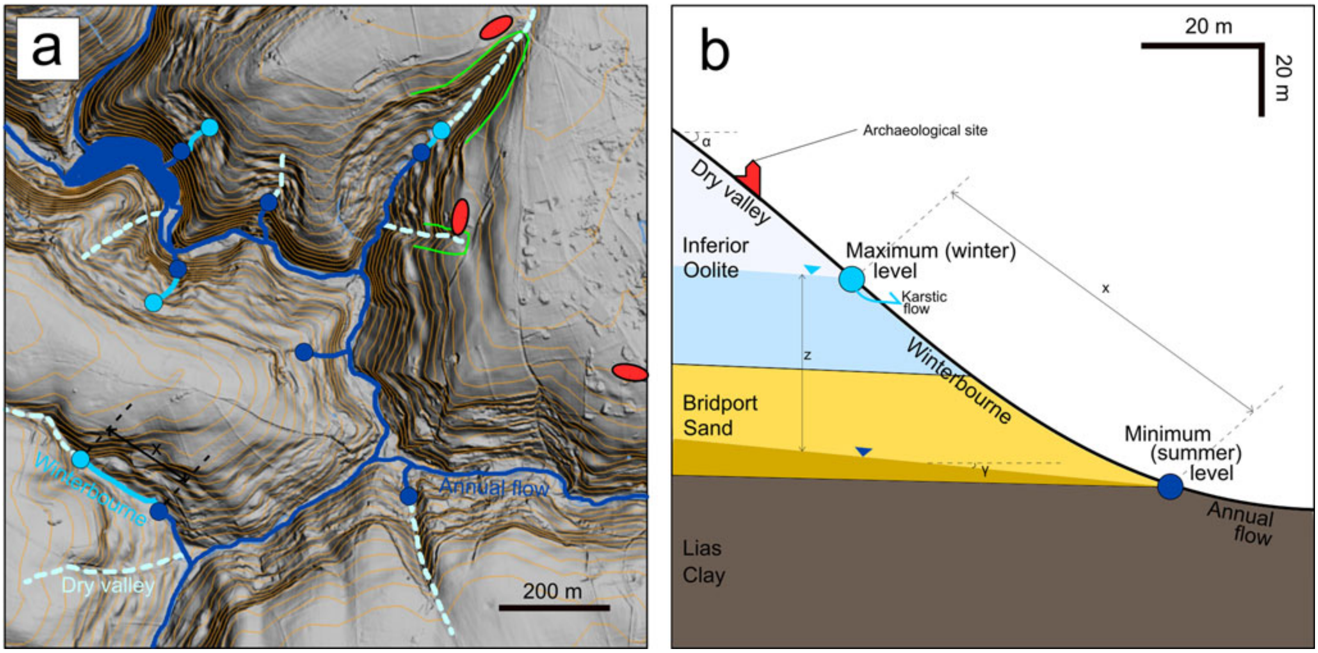

Figure 2. (a) 1 m-resolution LIDAR digital terrain model (DTM) from UK Defra (https://environment.data.gov.uk/DefraDataDownload) illustrating the relationship between permanent (dark blue lines) and ephemeral (winterbourne; lighter blue solid lines) streams and dry valleys (dashed lightest blue lines), spring positions (dark blue and light blue circles: respectively minimum/summer and maximum/winter levels), and archaeological sites (red lozenges). Green lines: prominent valley heads. Thin orange lines: 10 m elevation contours. α, x, γ, and z: parameters used in Equation (1). (b) Schematic cross-section through hillslope, showing idealized annual variation in spring level.

elevation if only a downslope migration distance was provided:

$$z = x(\sin\alpha - \cos\alpha\tan\gamma) \qquad \text{(Eq. 1)}$$

where z = change in spring elevation; x = apparent along-valley spring migration distance; α = mean hillslope angle; and γ = groundwater gradient, which is typically assumed to reflect regional strata dips of ∼4° (Neumann et al., 2003). Using satellite imagery, only those springs for which evidence of apparent migration along-slope could be found, such as watercress beds or localized depressions, were included. Nine records where spring position was coincident to within 100 m of mapped faults (Fig. 1a) were excised because these springs may be perched, so the idealized relationship between spring and groundwater level position shown in Figure 2b breaks down (Bricker et al., 2014).

Next, archaeological records were scrutinized to compile an exhaustive database of all Neolithic sites and monuments across the Cotswolds, largely informed by those assembled by O'Neil and Grinsell (1960) and, more recently, Oswald et al. (2001) and Darvill (2010); only sites that included an accurate geographic position were included. Where possible, we used the centroid of each known site. Stray finds are included for completeness but have not been plotted or further analyzed because they cannot be fairly attributed to settlement or occupation (Saville, 1984). All radiocarbon dates mentioned in text were calibrated using the IntCal20 curve in Oxcal 4.4 from original laboratory-based results (Reimer et al., 2020).

We then sought the simplest continuous relationship between spring elevation and time that would account for recent (early 1900s to present) changes in documented spring elevations for all 64 spring records for which temporal variation data exist (see Appendix). To do this, we formulated a joint inverse problem (e.g., Sambridge, 1999) to minimize the misfit H between predicted and actual (i.e., early 1900s) spring elevation. A conjugate gradient method was used to minimize H; large drops in data misfit correspond to a rotation of coordinate system space (Press et al., 1992). We assumed that any synthetically produced spring may migrate only along a line of minimum hillslope gradient (i.e., valley floors), calculated using standard flow-routing functions in ArcGIS v.10.8.1 software. We tested this relationship on a different timescale by generating crude estimates for spring elevations in Neolithic times (ca. 5.5 ka), when long barrow construction and ancient settlement activity were respectively largely completed and most intense (e.g., Crawford, 1925). The proximity between present and predicted spring position and the centroid of the nearest Neolithic site was calculated as the minimum difference in elevation between the two.

RESULTS

In agreement with findings reported elsewhere, higher discharge present-day springs are concentrated towards the western scarp edge of the Cotswolds, close to valley floors, and on west-facing valley flanks, suggesting that solutional enhancement of localized fracture swarms dominates primary aquifer transmissivity (e.g., Hancock, 1969; Morgan-Jones and Eggboro, 1981; Paul, 2014). Figure 3 demonstrates a striking negative exponential relationship ($R^2 = 0.89$) between annual changes in spring position and peak discharge: many of the larger springs (typically with peak winter discharges of >1 m^3s^{-1}) maintain both a constant discharge and elevation throughout the year. By contrast, springs where peak discharge does not exceed 0.05 m^3s^{-1} may migrate along-slope up to 35 m annually (Paul et al., 2018; Appendix).

By interrogating all known data for Cotswold Neolithic monuments and evidence for settlement, we discovered a marked preservation and study bias toward funerary monuments, such as long

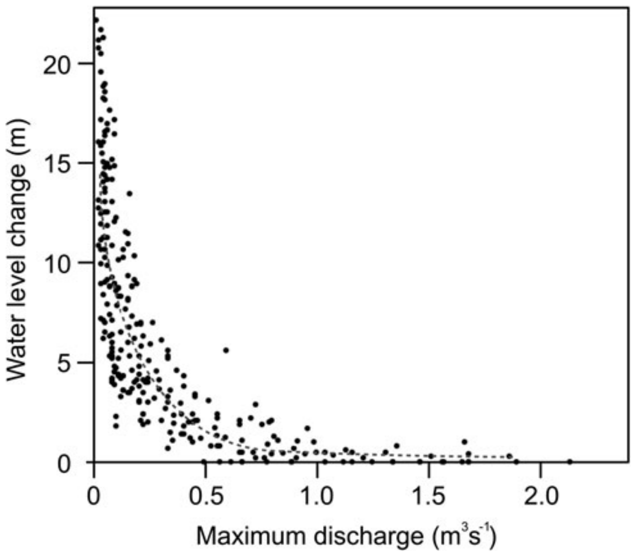

Figure 3. Relationship between change in annual spring elevation and peak (winter) spring discharge; N = 259 (see Appendix). Dashed red line = best-fitting exponential relationship: $y = 9.64 \times 10^{-3.20x}$; $R^2 = 0.89$.

barrows. Other workers have noted this bias, which has led to an overreliance on funerary monuments as evidence or geographical indicators of other facets of life despite likely having a limited social and economic influence or local presence (e.g., Crawford, 1925; Saville, 1984). Also, because much evidence was only uncovered during excavations or other engineering work, discovery bias is another factor that complicates the establishment of a clear link between occupation and proximity to water (e.g., Mudd et al., 1999; Brett and Hart, 2015; Marshall, 2020).

There exists a correlation between modern spring discharge and proportional discharge diminution over the last ~100 years (Fig. 4a). For instance, the powerful "Black Gutter" spring (spring 15 in Appendix) has suffered a decrease in discharge of 0.62 m^3s^{-1} (15%) in the 85 years between 1928 and 2013. Over the same period, there has been a regional decrease in spring elevation (i.e., groundwater level) that is most pronounced across the SE Cotswold dip slope and at lower elevations (greatest decrease in elevation: 12 m; Fig. 4b). Figure 4c shows that the range of annual variability in spring position has increased; this effect is often most pronounced at higher elevation springs (e.g., spring 142 in Appendix: an increase of 15 m in annual variability from 7 m in 1922 to 22 m in 2006).

Our inverse procedure sought an objective function that would minimize the misfit in elevation, H, between an actual spring in the early 1900s, and a spring whose elevation was predicted based on its present position. We sought a balance between data misfit and model smoothness, i.e., the simplest relationship that would fit all 64 springs reasonably well (e.g., Parker, 1994). This process yielded the following simple objective function (final root-mean-square misfit = 0.64)

$$z_t = z_0 + \frac{1}{3}\ln\left(\frac{t}{z_0}\right) \tag{Eq. 2}$$

where z_t = spring elevation (in m) at time t (in years before present), and z_0 = present-day elevation (in m). Equation (2) assumes that springs can only move in one dimension along a line described by minimum descent. The position of each synthetic spring was checked carefully against Google Earth imagery to verify that it lay in a dry valley. The results of this inverse procedure demonstrated that a single relationship (Eq. 2) can simultaneously describe the change in elevation and discharge of a group of springs over ca. 100–150 yr. Table 1 contains summary statistics of the elevation difference between springs and archaeological sites for modern and early 1900s datasets as well as the two sets of predictions using Equation (2).

DISCUSSION

The statistics presented in Table 1 demonstrate that the vast majority (97%) of modern springs are located at lower elevations than Neolithic sites, with a mean difference in elevation of ~45 m. In contrast, data recorded in the early 1900s revealed that fewer springs (67%) were below the same sites, and the standard deviation of the elevation differences decreased from 15 m to 10 m, suggesting lower seasonality. Statistics for the synthetic springs calculated using Equation (2) are very similar. Next, if Equation (2) is used for a cursory prediction of possible spring elevations in Neolithic times (ca. 5.5 ka), the spring/archaeological site elevation difference decreases dramatically (mean: 9 m; two springs exactly coincident), with more springs (72%) now located marginally above the sites. These results could imply some form of link between these sites, monumentality, and water, either for purely functional purposes (Crawford, 1925), or reflective of forms of reverence or undocumented significance to ancient populations (e.g., Tilley, 1994; Darvill et al., 2011). Figure 5 shows a typical Neolithic Cotswold-Severn long barrow, together with the (much closer) predicted Neolithic position of a nearby spring, which apparently migrated down the now-dry valley over time to its present location.

Moreover, the results shown in Table 1 could imply that the groundwater level and spring discharges have behaved reasonably predictably back through ancient times as governed by stratigraphy and geological structure when compared to the immediate past, which has been complicated by anthropogenic factors including groundwater abstraction, artificial recharge, and acidification. Processes that govern long-term hydrological change must therefore operate at far longer (>10 kyr) timescales; e.g., significant Quaternary climate change and periglacial erosion. Indeed, one corollary is that current anthropogenically driven climate change will have an even greater effect on spring and river discharges (Bovolo et al., 2009; Earman and Dettinger, 2011).

On the other hand, we acknowledge that our primary purpose was to seek a smooth and simple solution to a joint inverse problem, which necessarily involves eliding some significant and complex hydrogeological detail. For instance, the migration of spring locations does not occur at a uniform rate as implied by Equation 2: spring position is determined by geological inception horizons that enable solutional development of fissures. Moreover, the processes that governed recent (last ca. 100 yr) diminutions in discharge and spring elevation drops were likely anthropologically dominated, unlike those over longer timescales. Nevertheless, a simple logarithmic objective function can honor the more recent data while also providing coherent and self-consistent predictions back to Neolithic times; these predictions require ground validation, e.g., using ground-penetrating radar or tracer tests to elucidate groundwater flow pathways in the immediate subsurface proximal to a spring.

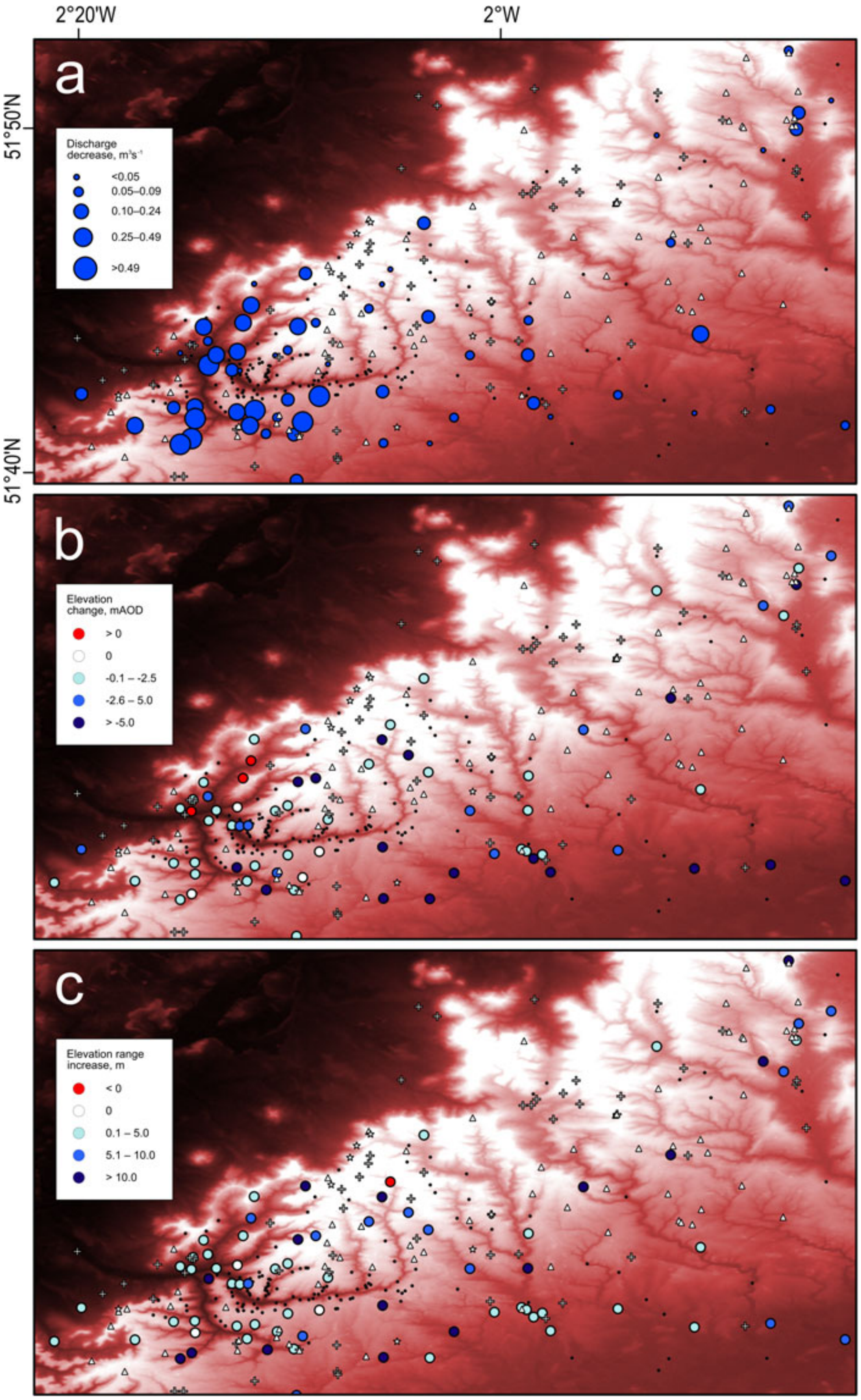

Figure 4. Recent (early 1900s to 2010s) changes in springs: (a) discharge diminution; (b) mean elevation (meters above ordnance datum; mAOD); (c) annual change in observed elevation. Black dots: springs for which no temporal data exist (see Appendix). Archaeological evidence: crosses: Mesolithic sites; triangles: long barrows; stars: other Neolithic sites. Background: topography (darker shades correspond to lower elevations).

We also explicitly acknowledge the potential muddying role of measurement or study bias in drawing firm interpretations about hydrogeological change and its effect on ancient populations. From a hydrogeological perspective, the trend towards springs with greater discharge towards the west of the study area could reflect higher rates of river incision and periglacial erosive activity leading to solutionally enhanced fracture swarms (e.g., Hancock, 1969; Self and Boycott, 2004; Paul, 2014), or it could represent a bias in discovery and documentation because population density (and historical water demand) is greater in the west.

It is clear that the most productive springs in the west of the study area and focused along valley floors have had enormous decreases in discharge over a relatively short time (early 1900s to present). Richardson (1930, p. 48) noted that “since the end of the 18th Century, [the number] of boreholes has increased tenfold, pushing water levels down regionally, as capacious water sources that can satisfy both man and beast are sought.” Such exploitation of groundwater by humans not only results in water level decline and flow reductions on short timescales, but also likely explains why springs may be at lower elevations now

Table 1. Summary statistics of elevation difference in m between 64 springs for which temporal data exist, and nearest Neolithic site.

	Present-day (data)	Early 1900s (data)	Early 1900s (predicted)	Neolithic (5.5 ka; predicted)
Mean	45	18	20	9
Minimum	16	9	11	0
Maximum	84	55	55	19
Standard deviation	15	10	11	4
Number of springs below site	62 (97%)	43 (67%)	45 (70%)	18 (28%)
Number of springs above site	2 (3%)	21 (33%)	19 (30%)	46 (72%)

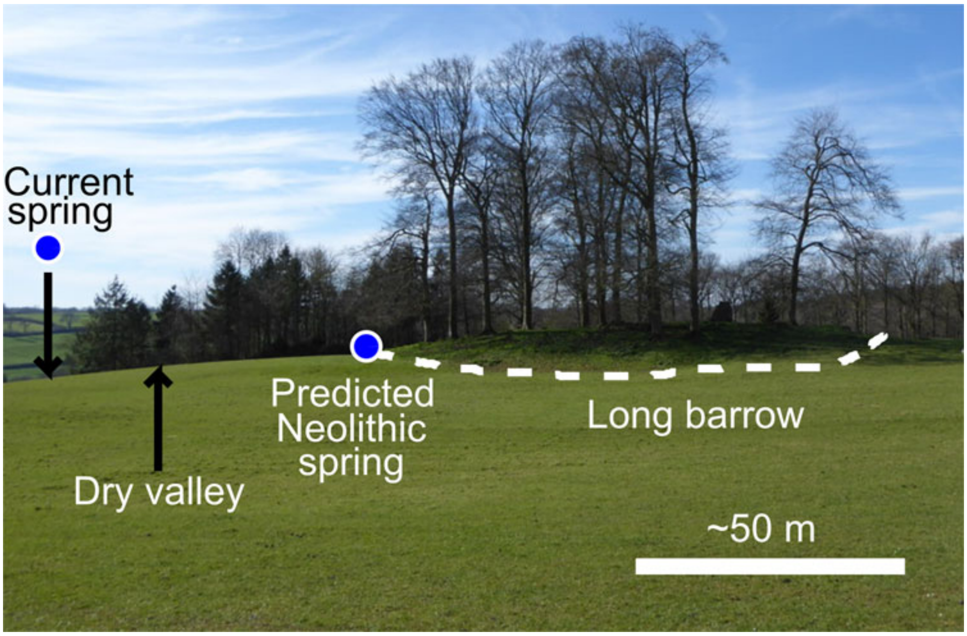

Figure 5. Photograph of Tingle Stone (Avening) long barrow (ca. 5.5 ka). Difference in elevation between long barrow (delineated by white dashed line) and predicted Neolithic spring position, and current mean summer spring position = 6 m and 37 m, respectively.

than they would have been a few thousand years ago (Fig. 4). Over longer geological timescales, considering that groundwater flow throughout the Cotswolds Jurassic limestone aquifers is controlled by karst processes, progressive dissolution could likely result in lower elevation springs as well as increasing seasonality of originally higher elevation springs, i.e., only discharging when the capacity of the conduits and fissures discharging at the lower spring is exceeded (e.g., Self and Boycott, 2004; Waltham, 2005). Over longer time periods (>10 kyr), seasonal springs may become relict, so springs may migrate down valleys, leaving upstream sections that are ephemeral, and, even further upstream, sections that are completely dry (Waltham, 2005).

Figure 3 shows a striking relationship between annual spring level change and associated discharge that could be used as a predictive tool; it suggests the importance of groundwater flow through the rock matrix (resulting in seepages or lissens) in feeding fractures and fissures (Bricker et al., 2014; Paul, 2017). One limitation of our approach is that the spring discharge and level data (Appendix) may inevitably contain some noise due to seasonal extremes (i.e., floods and droughts) in any measurement year. This is unavoidable, yet the fact that our inverse model was able to capture a coherent signal across the entire study region suggests that seasonal extremes (noise) do not significantly affect our approach. Indeed, Bricker et al. (2014) reported a surprisingly small year-on-year variation in seasonality in well levels: for 18 mid-Cotswold boreholes, mean maximum (winter) water level varied by only 0.65 m over an 11-year period.

Turning to the archaeological evidence, Neolithic remains are widespread across the Cotswold Plateau, with a few clusters in promontories of the western Cotswold scarp (Fig. 4). Many sites are situated on the flank of modern dry or winterbourne valleys, generally close to, but at higher elevation than, present spring positions. Darvill et al. (2011, p. 9) noted that in the Cotswolds, Mesolithic settlements almost always occupy "sheltered spots, often near a permanent water supply and on the junction between different types of environment." In this respect, a "junction … of environment" occurs with altitude, and therefore valley sides, near the top of which generally occurs a springline.

While we suggest that these Neolithic sites were much more immediately positioned to natural springs, caution in accepting these conclusions must be stressed. Archaeology has long been affected by the preservation bias of funerary structures, quantities of which often greatly exceed those directly attributable to settlement. As a consequence, extrapolating themes directly concerning social aspects of Neolithic life is challenging.

Validation of our predictions could be facilitated by expansive geophysical surveys, and paleochannels and geomorphological deposits could also provide a degree of corroboration. Archaeological investigation into Neolithic sites rarely extends beyond the confines of the site itself, thereby neglecting the understanding of the surrounding landscape (Darvill, 2010). Recent broad-scale work, such as at the Early Mesolithic site of Star Carr, was undertaken using vast coring strategies enabled for the extent of an old lake to be elucidated, as well as to track the hydrological and vegetational change that the landscape experienced (Milner et al., 2018). Expansive landscape biographies of important Neolithic landscapes such as Avebury and Stonehenge clearly demonstrate the benefit and feasibility of undertaking such work, yet even in these well-studied locations, an understanding of the links between the natural world and prehistoric lifeways is lacking.

The methodology documented herein can easily be adapted to other regions where a link between ancient occupation and water is implicit: this reproducibility is one of the main objectives of the work. The Cotswolds served as a useful case study because of the two different hydrogeological (ca. 100 yr) and archaeological (ca. 5,000 yr) timescales: we have demonstrated how they can be reconciled, and that Quaternary hydrological changes are likely long-term and reflective of subsurface stratigraphy and structure rather than anthropologically driven change.

CONCLUSIONS

We exploited a large, independent dataset of Neolithic monuments to test the hypothesis that water played a role in their siting. While the precise nature of the relationship between people and these monuments remains elusive, we use quantitative techniques (i.e., inverse modeling) to attempt to delimit the possible range of human experiences with water in Neolithic times.

We also compiled a comprehensive database that documents recent (ca. 100 yr) changes in the discharge and position of 259 springs across the Cotswold Hills, UK. There exists a striking negative exponential relationship between modern spring discharge and the change in maximum and minimum (i.e., winter and summer) spring elevation, suggesting that the most productive springs, which are generally located along valley bottoms, are fed by extensive and well-developed fissure swarms. In contrast, smaller springs are likely to be fed by more poorly developed and/or smaller solutional networks.

Over the past ca. 100 yr, the larger springs have suffered pronounced diminutions in discharge that can be attributed both to human activity, such as increased groundwater pumping for industry, and short-term hydrogeological change, such as major flow pathways becoming blocked due to increasing rates of secondary precipitation. At the same time, the lengths of winterbourne valley portions, where springs appear to migrate between summer and winter, have increased.

Based on these observations of recent changes in discharge and position, we constructed a joint inverse problem that effectively extrapolated spring elevations back to Neolithic time (5.5 ka), allowing us indirectly to interrogate a theorized link between ancient settlement patterns, monumentality, and water. Across the Cotswolds, we predict that spring elevations were much closer to (and higher than) the ancient settlements as compared to modern springs. These results could emphasize the importance of water to the ancient populations of southwest Britain, either for utilitarian or more symbolic and reverential purposes. Mesolithic occupation is well-attested to at many Neolithic sites in the Cotswolds, a situation often considered to imply existing importance, therefore imbuing or enhancing the siting of later Neolithic monuments. However, it is difficult to discern the role of entirely unaltered features of the landscape such as springs; proximity alone might not account for an interwoven bond. Yet, as a replicated act, it can be fairly argued to be the case.

Our methodology can easily be adapted to analyze the relationship between water and pre-Roman settlements elsewhere. We have demonstrated that markedly different datasets (hydrogeological and archaeological) and timescales (ca. 100 yr vs. ca. 5,000 yr) can be reconciled via extensive data collection campaigns and a relatively simple inverse procedure. This suggests that groundwater levels and spring discharges have behaved reasonably predictably from Neolithic times to the present, while recent human activity has had, and will continue to have, an impact of far greater magnitude.

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