Modelling and reconstruction of the River Kennet palaeohydrology and hydrogeology: Silbury Hill and Avebury in 4,400 BP

P. G. Whitehead and W. M. Edmunds

ABSTRACT

With the availability of Global Circulation Models (GCMs) it is now possible to apply hydrological and hydrogeological models and knowledge to assess environmental conditions in past climates. In the upper Kennet there is considerable interest in the development of the construction of the man-made hill at Silbury. Silbury was built in several stages over a period of time and the question arises as to the availability of water for the people who built Silbury. The current Kennet flows at Silbury are low and the current stream tends to be dry for on average 5 months of the year. The aim of the research has been to assess the palaeohydrology of the Silbury Hill and Avebury area and determine the flow rates, groundwater levels and hydrological conditions in 4,400 BP. This has been undertaken using hydrogeological mapping and modelling techniques, making use of outputs from a GCM to recreate past flows and groundwater levels in the upper Kennet at Avebury and Silbury. The modelling results indicate a past wetter climate in the area, with higher river flows and higher groundwater levels, which would have sustained the local populations through dryer summer months.

Key words | climate change, hydrogeology, Kennet, modelling, palaeohydrology, Silbury

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INTRODUCTION

Silbury Hill (UK Grid reference: SU110685 or 51°24′56″ N 1°51′27″ W) is an ancient mound due west of Marlborough in the upper reaches of the River Kennet and close to the large stone circle at Avebury, as shown in Figures 1 and 2. There have been extensive archaeological examinations of Silbury Hill in recent years (Canti *et al*. 2004; Leary & Field 2010) and the palaeohydrology of Avebury and the upper Kennet River area has become of particular interest (Leary 2010). According to Leary & Field (2010), the hill's position could be explained by a number of theories, which are all open to speculation and debate. However, one potential reason for its development could be the association with local springs, ditches and the Swallowhead Spring (Figure 1). These form the collective source of the River Kennet and Leary & Field (2010) suggest that the Kennet and the Thames were sacred rivers by virtue of the ritual deposits found in them. Whatever the reason for the extended construction, there has been considerable uncertainty over the population levels required to build such a monument, where they lived and where their water supplies would have come from (Leary & Field 2010). At present, under the current climate conditions, the upper Kennet at Silbury and Avebury is dry for several months of the year, often from June through to November and so the question arises as to how the large numbers of people required to build Silbury Hill survived in dry summer months, assuming the present climate conditions.

The aim of this paper is to assess the palaeohydrology of the Silbury Hill and Avebury area and determine the flow rates, groundwater levels and hydrological conditions in ca. 2400 BC (i.e. 4,400 BP-Before Present) when it is thought the mound was constructed. This assessment has been undertaken using hydrogeological data analysis and mapping linked to modelling techniques, making use of

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Figure 1 | The Silbury Hill in the upper Kennet River System.

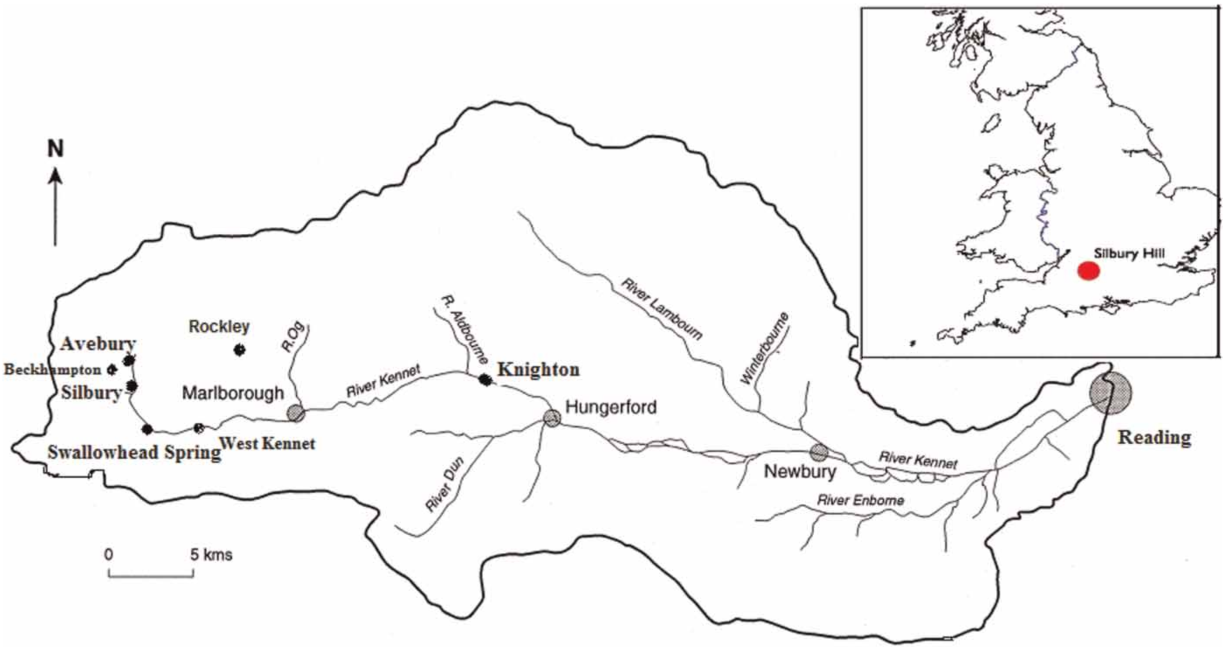

Figure 2 | Maps showing the location of Silbury Hill, Avebury and the Swallowhead Spring in the upper Kennet.

outputs from the historical runs of a Global Circulation Model (GCM) coupled to hydrological and hydrogeological models to recreate past flows and groundwater levels in the upper Kennet.

THE UPPER KENNET RIVER SYSTEM

The River Kennet is a major tributary of the River Thames, the principal river in the south east of England and, as shown in Figure 2, flows broadly west to east, with a catchment area of about 1,200 km^2 and a main river length of about 40 km. Altitude varies across the catchment from 215 metres above sea level (m.a.s.l), the source of the Kennet near Avebury, to 40 m.a.s.l at the confluence of the Kennet with the Thames at Reading. The catchment is approximately 80 km from the south coast at the English Channel and about 100 km from London and the Thames estuary and the southern North Sea. Land-use within the Kennet catchment is predominantly rural, with an underlying geology predominantly of Cretaceous Chalk.

This study focuses on the upper reaches of the Kennet, above the market town of Marlborough (Figure 2). The upper Kennet catchment is defined as the area draining into the Environment Agency gauging station at Knighton (Figure 2), at which point the catchment area is 295 km^2, equating to approximately 25% of the total catchment area of the Kennet. The annual average rainfall for the upper Kennet is relatively low for the UK at 828 mm and, with high evaporation giving a mean runoff of 195 mm, so only about 23% of the rainfall is converted to river flow (Marsh & Hannaford 2008). Owing to the highly permeable nature of the bedrock, the Kennet is primarily groundwater fed. Thus, the hydrograph response to rainfall is highly damped with a base-flow index of 0.94 for the upper Kennet (Marsh & Hannaford 2008).

Geology and hydrogeology of the upper Kennet

The geology of the area is given in the Geological Survey Sheet 266 (BGS 1974) with descriptions given in Osborne-White (1925). The area of Silbury Hill and Avebury contains a succession of Chalk, overlain by Quaternary and recent alluvial deposits. Here the Chalk is composed of three divisions – Upper Chalk (107 m.a.s.l); Middle Chalk (45–60 m.a.s.l) and Lower Chalk (55–90 m.a.s.l). The nearest classified sites show Silbury Hill sits on the boundary between the Middle and Lower Chalk, whilst Avebury lies wholly on Lower Chalk. The Upper Chalk is only found on higher ground commencing just south of West Kennet long barrow. The boundary of Middle and Lower Chalk is marked by a significant 'hard ground' – the Melbourn Rock – a band of yellowish nodular hard Chalk, formed in Cretaceous times by the sub-aerial emergence of the chalk sea. This horizon may be of archaeological significance since it is mapped as passing beneath Silbury Hill and may have been encountered in excavations.

Information on the hydrogeology of the Marlborough Downs and specifically Avebury region has been obtained from the National Well record collection held by the British Geological Survey. These records for the Avebury area contain historical information on the location of boreholes, wells and shafts; well depths are recorded together with a classification of the geology. Some historical water level data are also available back as far as 1915 for a well (Galteemore Farm) at Beckhampton. The BGS also hold long term records for water levels in several parts of the Chalk aquifer. One of these, Rockley (SU 1610 7190), contains a continuous record from 1932 and is used in the current study. A full time series plot of the levels at Rockley is shown in Figure 3 and shows periods of low water levels every decade or so, such as in 1934, in 1964 and in 1976. It is interesting to note that the mean level for the period 1932–1960 was 134.3 m and the mean level for 1970–2008 was 134.7 m. In other words, there has been a slight increase in groundwater levels in recent years, despite water abstractions from the Kennet Chalk aquifer (Rushton *et al.* 1989). However, Rockley is some distance from Avebury and an analysis of the well data at Avebury indicates that there is a 13.3 m difference between Rockley and Avebury, with the Avebury water levels higher than Rockley (Whitehead & Edmunds 2008).

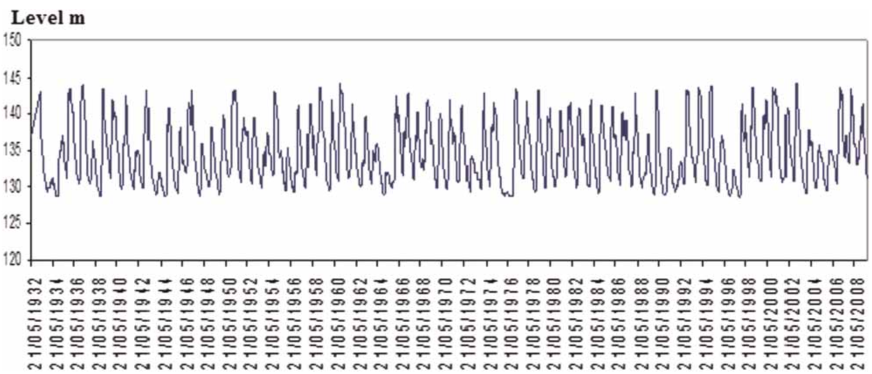

Figure 3 | Observed monthly Rockley well levels (m above sea level) from 1932 to 2008.

Hydrology of the upper Kennet

The hydrology of the upper Kennet is complex as the flows are driven largely by ephemeral groundwater from springs such as the Swallowhead Spring (Figure 2) or groundwater seepage farther up the valley above Avebury. However, there is surface runoff in times of high rainfall. As previously discussed, the annual average rainfall for the upper Kennet is relatively low so that only about 23% of the rainfall is converted into river flow in the upper Kennet. The uppermost flow gauge on the Kennet is at Marlborough and Figure 4 shows the monthly observed flows for the period 1972–2008. The hydrograph shows high flows in winter and also periods of drought, such as over the years 1975–1976 and more recently the years 2003–2005. The flows at Marlborough are fed by a surface catchment area of 110 km^2 whereas at Silbury the surface catchment area is only 25 km^2. Based on the ratio of catchment areas, the flows at Silbury will be of the order of 27% those at Marlborough and Figure 4 also shows the observed flows at Marlborough and the estimated flows at Silbury from 1972–2008.

PAST CLIMATES AND GCM RECONSTRUCTIONS

A key objective of this research is to assess in some manner the likely climate in 4,400 BP. There is considerable evidence from other palaeo data and pollen studies that the climate in 4,400 BP was wetter and slightly warmer than the current climate (Newson *et al.* 1982), with temperatures of between 0.5 and 1.5 °C higher. An alternative and independent source of information is also available from GCMs as described by Valdes *et al.* (1999). The model used in this study is from the Hadley Centre (UK Meteorological Office) and the details of the model are described by Pope *et al.* (2000). Historical model outputs for rainfall and temperature from this GCM are available from the Bristol University Bridge Project (www.bridge.bristol.ac.uk). Such GCM model outputs have been used in other palaeoclimate studies by Haywood *et al.* (2002) and by Whitehead *et al.* (2008) in a palaeohydrology study of the Bronze Age settlement of Jawa in Jordan.

The GCM results presented here show rainfall changes generated using the HadCM3 version of the coupled atmosphere-ocean GCM for the central Southern England area. Figure 5 show the rainfall variations for the last 20,000 years. The figure indicates higher rainfall levels in the 4,000–4,500 BP period. The higher rainfall is equivalent to an 8% increase compared to current rainfalls. There is considerable uncertainty about the rainfall because of the inherent complexity of the GCMs. The question of the accuracy of GCM simulations is a highly active area of current research. For example, the ENSEMBLES project has had a large team of modellers across the EU evaluating a number of GCMs and investigating model uncertainties due to forcing inputs, boundary conditions, process parameters, process understanding and numerical solution techniques (see www.ensembles-eu.org). All of these give rise to errors and will generate a range of behaviours within the models. Figure 5 does indicate the magnitude of

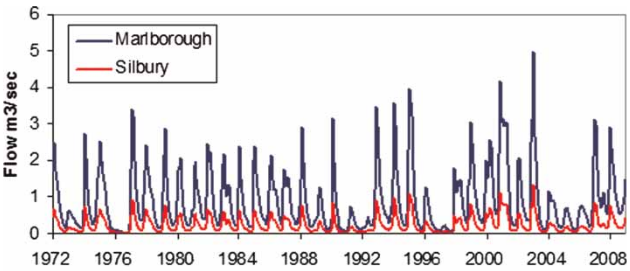

Figure 4 | Observed monthly flow at Marlborough (blue) and estimated flows at Silbury (red) over 1972–2008. The full colour version of this figure is available online at www.iwaponline.com/nh/toc.

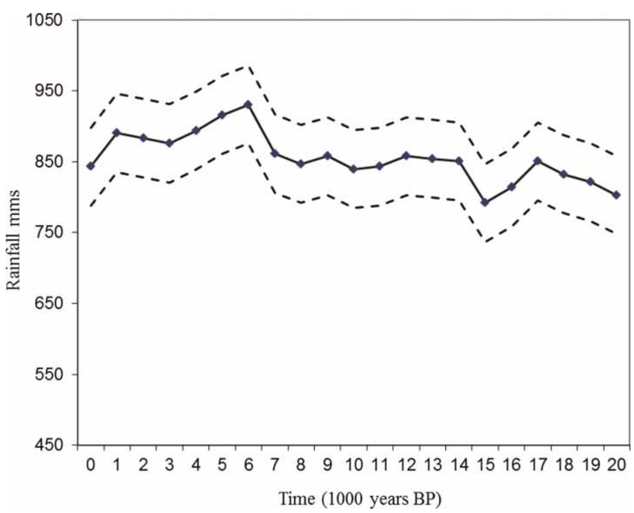

Figure 5 | GCM modelled past rainfall estimation for the Kennet area for the past 20,000 years plus confidence bounds (dashed lines representing the plus and minus one standard deviation).

model variability, which is illustrated as standard deviation bounds. Despite this uncertainty, the GCMs do provide a quantitative estimate of past rainfalls, runoff and temperatures.

Interestingly, the changes predicted for the 4,400 BP period by the Bridge Project CGM simulations are actually quite similar to the predictions of future climate change in the UK (Wilby *et al.* 2006), which implies that we are moving back to a 4,400 BP type climate in the UK. In fact, a recent comprehensive study of climate change on UK rivers by the UK Water Industry Research group (UKWIR 2006) gives estimates of changes to temperature and rainfall for the River Kennet and suggests that flows in the Kennet will be higher in the winter and lower in the summer, as shown in Figure 6. Whilst these changes are plausible, observational evidence from Marlborough (Figure 4) does not show any decline in mean flows and the main feature of the last 30 years has been an increase in year-on-year variability, in relation to both low and high flows.

MODELLING GROUNDWATER LEVELS

In order to model groundwaters and well levels in catchments, a number of different approaches have been established. The most complex of these is to set up a fully distributed flow model of the groundwater zone over a wide area and solve the set of partial differential equations describing water movements (Rushton *et al.* 1989). This is a time consuming exercise and beyond the scope of this work. An alternative approach is to investigate the dynamics of wells in the area and to relate level variations to rainfall. If a suitable dynamic model can be established, then the model can be used to investigate impacts of future or past changes in rainfall patterns. Time series analysis models have been extensively used in hydrological studies to undertake such analysis (Whitehead 1979) and one modelling technique that can be used to model well levels is that of IHACRES (Jakeman *et al.* 1990; Croke *et al.* 2006; Littlewood 2008). The IHACRES model has been applied to the model of the Rockley well levels using the monthly rainfall and temperature for the area.

IHACRES is a time series approach to modelling that has developed from the recursive analysis algorithms of Young (1974) and applied to model rainfall river flow relationships by Whitehead (1979). The modelling approach was later improved by Jakeman *et al.* (1990) and made available (http://www.ceh.ac.uk/products/software/water.html) as a standalone package which has been widely used by researchers and hydrologists in the water industry (Littlewood *et al.* 1997, 2003; Littlewood 2008). Croke *et al.* (2006) later released a more powerful IHACRES package which is now available (http://www.toolkit.net.au/ihacres). The overall model structure used for this study, as shown in Figure 1, consists of a rainfall loss model reflecting the losses during evapotranspiration and uptake by the soils, followed by a unit hydrograph module. This is shown at the core of Figure 7, which also gives brief descriptions of the six key catchment characteristics that are obtained from an IHACRES analysis.

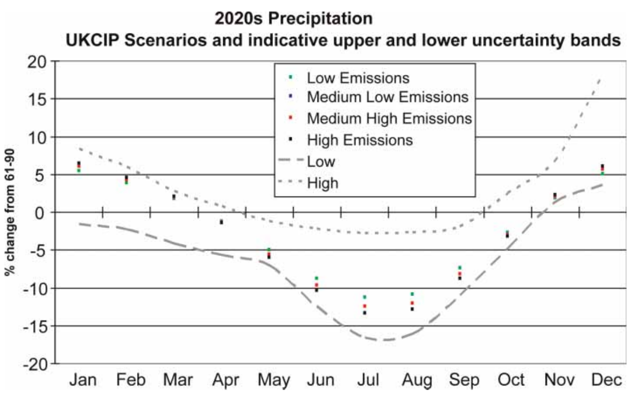

Figure 6 | Water industry estimated seasonal rainfall changes under a warmer climate in the Kennet area. The full colour version of this figure is available online at www.iwaponline.com/nh/toc.

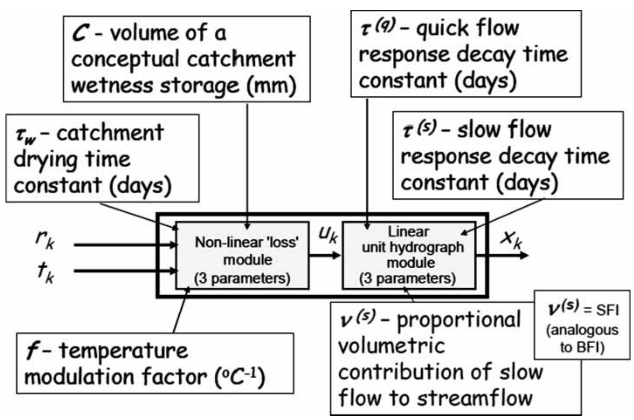

Figure 7 | Basic structure of IHACRES and the key catchment characteristics.

The non-linear loss module was first developed by Whitehead (1979) and then modified by Jakeman & Hornberger (1993). The equations in the loss module are as follows:-

$$u_k = r_k \frac{(s_k + s_{k-1})}{2}, \; s_0 = 0 \tag{1}$$

$$s_k = \frac{r_k}{c} + \left(1 - \frac{1}{\tau_w(t_k)}\right) s_{k-1} \tag{2}$$

$$\tau_w(t_k) = \tau_w \exp(0.062 f (R - t_k)) \tag{3}$$

where, s_k is a dimensionless catchment wetness index ($0 < s_k < 1$); t_k is air temperature (°C); τ_w is a catchment drying time constant (e.g. days) given by the value of $\tau_w(t_k)$ at a reference temperature, R (°C); f is a temperature modulation factor (°C^{-1}); and c is the depth of a catchment wetness store (e.g. mm) such that the volumes of effective rainfall and observed streamflow are the same over the model calibration period. The three catchment characteristics are derived from this model are c, τ_w and f, as shown in Figure 7.

For dominant quick- and slow-response flows acting in parallel, streamflow at time-step k (Q_k) is estimated from effective rainfall (u_k) by Equation (4). Superscripts q and s in Equation (4) denote dominant quick and slow response flows, respectively. It is important to note that effective rainfall is the portion of rainfall (r_k) that eventually becomes stream flow. The a and b parameters define first-order transfer functions ($-1 < a^{(.)} < 0$, $b^{(.)} > 0$), and z^{-1} is the backward-shift operator (i.e. $z^{-1}x_k = x_{k-1}$). Pure time delay, δ (i.e. $u_{k-\delta}$ instead of u_k in Equation (4)) is important as the context of the Kennet groundwater response because of the lag between rainfall and the response of the well levels.

$$Q_k = \left(\frac{b^{(q)}}{1 + a^{(q)} z^{-1}} + \frac{b^{(s)}}{1 + a^{(s)} z^{-1}}\right) u_k \tag{4}$$

The three catchment characteristics, $\tau^{(q)}$, $\tau^{(s)}$ and $v^{(s)}$ define the linear module, shown in Figure 1, and are given by Equations (5) to (7), where Δ is the data time-step (e.g. 1 day) and V is given by Equation (8).

$$\tau^{(q)} = \frac{-\Delta}{\ln(-a_1^{(q)})} \tag{5}$$

$$\tau^{(s)} = \frac{-\Delta}{\ln(-a^{(s)})} \tag{6}$$

$$v^{(s)} = \left(\frac{b^{(s)}}{1 + a^{(s)}}\right)\left(\frac{1}{V}\right) \tag{7}$$

$$V = \frac{b^{(s)}}{1 + a^{(s)}} + \frac{b^{(q)}}{1 + a^{(q)}} \tag{8}$$

From Equation (4), it follows that modelled quick- and slow-response hydrographs, i.e. $Q_k^{(q)}$ and $Q_k^{(s)}$ for $k = 1$, m where m is the number of time-steps in the length of record being used for model calibration, are calculated by recursive application of Equations (9) and (10), respectively, where $Q_k = Q_k^{(q)} + Q_k^{(s)}$. The quick-response hydrograph is given by recursive application of Equation (9) with $Q_0 = 0$, $u_1 = 1$ and $u_k = 0$ at all other k. Similarly for the slow-response, using Equation (10).

$$Q_k^{(q)} = b^{(q)} u_k - a^{(q)} Q_{k-1}^{(q)} \tag{9}$$

$$Q_k^{(s)} = b^{(s)} u_k - a^{(s)} Q_{k-1}^{(s)} \tag{10}$$

Application of IHACRES to predict Rockley well levels

The IHACRES modelling system has been applied to predict the Rockley level data using temperature and rainfall data from the catchment and the observed well level data at Rockley. The IHACRES model is first calibrated using the available data and the best estimated parameters obtained are shown in Figure 8. It was found that IHACRES performed best with a baseline level of 127 m removed from the Rockley time series. This is because time series recursive estimation algorithms utilise the dynamic characteristics of the data to optimise on parameters values. The model

mass balance term (c)	0.000738
drying rate at reference temperature (tw)	1.000000
temperature dependence of drying rate (f)	1.500000
reference temperature (tref)	20.000000
moisture threshold for producing flow (l)	0.000000
power on soil moisture (p)	1.000000

Recession rate 1 ($\alpha^{(s)}$)	-0.613		Time constant 1 ($\tau^{(s)}$)	2.042
Peak response 1 ($\beta^{(s)}$)	0.387		Volume proportion 1 ($\nu^{(s)}$)	1.000

Figure 8 | The IHACRES parameters for the non-linear loss model (top) and the linear transfer function model (bottom).

simulated and observed well levels for Rockley are shown in Figure 9 and a reasonable fit to the observed time series is obtained with an r^2 of 0.62 and with a good match to the peaks in winter and the low levels in summer.

Having established the model for Rockley we can convert this to a simulation for the Avebury-Silbury area, making use of the knowledge that there is an average 13.3 m difference between the Rockley levels and the Avebury well levels. Applying this factor and, also applying the model to the full rainfall dataset from 1883 to 2008 (Marsh & Hannaford 2008), produces a simulation of the Avebury levels, as shown in Figure 10. The simulated levels indicate considerable variability since 1883 and this reflects the changing rainfall patterns and sequences of wet and dry periods.

The key question in this study, however, is to ask how the levels at Silbury or Avebury would have differed in 4,400 BP. The well level model has been run with two climate change scenarios used above, namely the GCM Bridge Project simulations for 4,400 BP and the UKWIR scenario for the warmer climate. Figure 11 shows the effects of these two climate scenarios compared to the baseline or current conditions. The new climate scenarios are obtained by simply scaling the Kennet rainfall record to reflect the percentage change in the GCM and the UKWIR rainfalls compared to current average Kennet rainfall. It can be seen that the GCM Bridge scenario generates much higher well levels than the UKWIR scenario, but this might be expected as the GCM Bridge scenario is considerably wetter and does not simulate the much dryer summers of the UKWIR scenario. This is also reflected in the probability duration curves for the Avebury levels, shown in Figure 12. The results from this analysis indicate that the levels could have been about 5 m higher at the 50 percentile point in the past compared to current values.

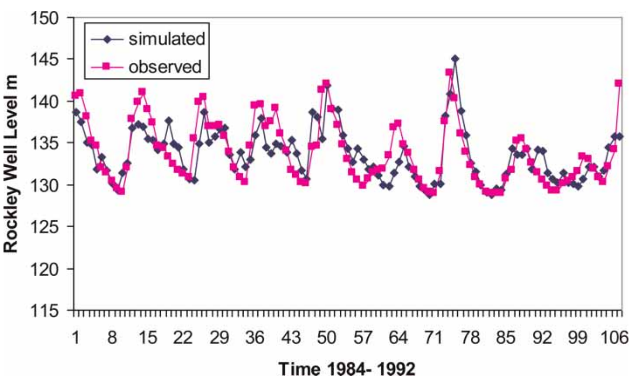

Figure 9 | Simulated and observed Rockley water levels (m.a.s.l).

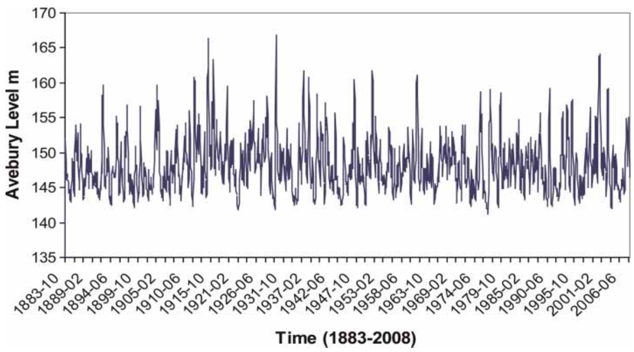

Figure 10 | Simulated water levels at Avebury for 1883–2008. The full colour version of this figure is available online at www.iwaponline.com/nh/toc.

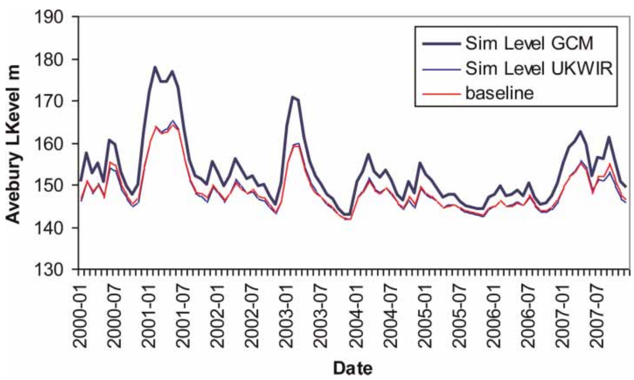

Figure 11 | Simulated Avebury well baseline water levels and the levels based on the GCM Bridge Project model and the UKWIR scenario. The full colour version of this figure is available online at www.iwaponline.com/nh/toc.

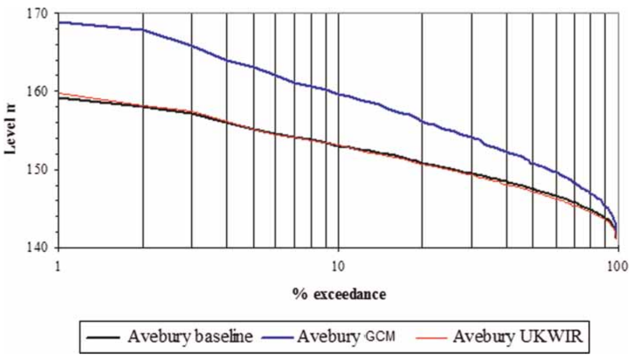

Figure 12 | The water level duration curve for Avebury for the baseline conditions and the GCM Bridge and the UKWIR climate scenarios. The full colour version of this figure is available online at www.iwaponline.com/nh/toc.

The same type of analysis has been undertaken for the river flows. The GCM Bridge historical predictions and the UKWIR warmer climate changes in runoff have been applied to the estimated Silbury flow record. Applying the seasonal patterns of runoff estimated for 4,400 BP gives a changed flow time series which when converted to a flow duration curve (Figure 13) suggests that higher flows would have been obtained in winter.

DISCUSSION AND CONCLUSIONS

The results from the study support the idea that a wetter climate prevailed at the time of the construction of Silbury Hill and Avebury and that this would have generated higher stream flow as well as higher water tables and, hence, well levels. From our analysis of the hydrology and hydrogeology we conclude that the Swallowhead Spring would most likely have been perennial at around 4,400 BP. Prior to human settlement, this area would have been wooded (although the extent may not have been significant) and, depending on tree density, the vegetation could have had the effect of increasing evapotranspiration. Whilst trees tend to lower the water table, by increasing evapotranspiration, they also reduce sunlight reaching the surface soils and hence reduce near surface evaporation, thereby creating wetter soils. Further research into the extent of vegetation of the later Holocene in the area might help refine the hydrological and hydrogeological conditions. The higher rainfall would have led to greater flows than today due to the higher overall water table. Also, the impact of human settlement and clearance of vegetation would have led to a net increase of recharge. The overall higher rainfall conditions and the saturated riparian zones would have led to the creation of groundwater-fed wetlands in the area near the perennial headwaters. Figure 14 shows a contour map for the area and shown on the map are the 145, 150 and 155 m contours where they cross the riverbed. From the Avebury water level duration curve (Figure 12), the levels for the 50 percentile probability are 147 m under the current condition and 152 m under the condition estimated by the models for 4,400 BP. This suggests that on average the groundwater levels were 5 m higher than at present. Thus, according to Figure 14, the stream head would move upstream from the location of the Swallowhead Spring at 147 m to the centre of Avebury at 152 m. This is an important result as it suggests that there would have been a good flow of water

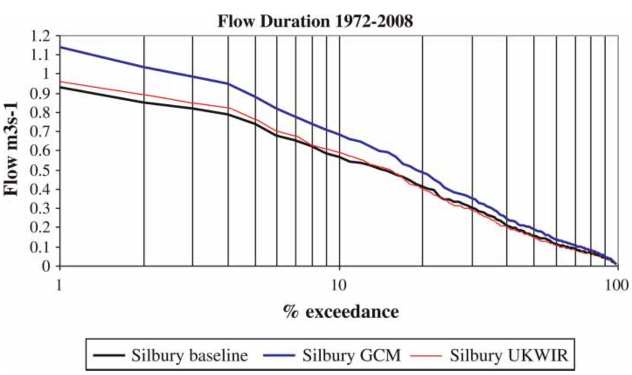

Figure 13 | The flow duration curves estimated for Silbury for the baseline data set and two warmer climate scenarios. The full colour version of this figure is available online at www.iwaponline.com/nh/toc.

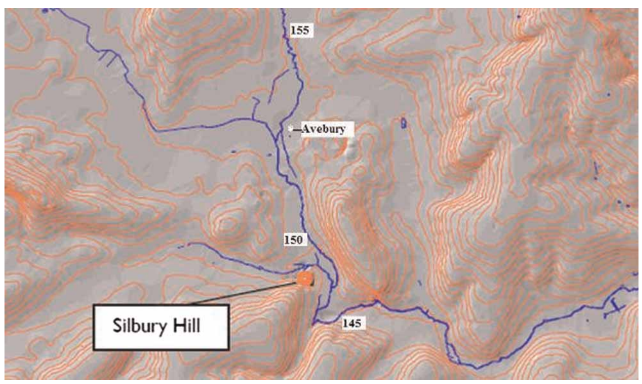

Figure 14 | Map showing height contours at points that cross the upper Kennet streambed. The full colour version of this figure is available online at www.iwaponline.com/nh/toc.

into the stream for a longer proportion of the year and that the flatter land in the area would have been wetter. Also, it suggests the Swallowhead Spring would have been perennial. Therefore, from a water perspective, we conclude that in the past Avebury and Silbury Hill would have been a more sustaining environment that it is now, enabling a large population to live in the area.

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