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SILBURY HILL, WILTSHIRE
PALAEOHYDROLOGY OF THE KENNET, SWALLOWHEAD SPRINGS AND THE SITING OF SILBURY HILL

ENVIRONMENTAL STUDIES REPORT

Paul Whitehead and Mike Edmunds

INTERVENTION
AND ANALYSIS

ENGLISH HERITAGE

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PALAEOHYDROLOGY OF THE KENNET, SWALLOWHEAD SPRINGS AND THE SITING OF SILBURY HILL

Paul Whitehead and Mike Edmunds

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SUMMARY

The aim of the project has been to assess the palaeohydrology of the Silbury Hill area and determine the flow rates, groundwater levels and hydrological conditions in 4500BP. This has been undertaken using hydrogeological mapping techniques and hydrological modelling techniques, making use of outputs from the historical runs of a Global Circulation Model to recreate past flows and groundwater levels in the Upper Kennet at Silbury. The modelling results have recreated a palaeohydrology for the Avebury and Silbury area and indicate that there was a wetter climate in the area. This would have generated higher river flows and most importantly higher groundwater levels, which would have sustained the local populations through dry summers. Also, the raised water table would have ensured waterlogged ground in places, which when coupled with increased vegetation and tree cover would have provided a more sustainable environment and better soils for crops in the area. Thus the study indicates that there would have been wetter and warmer conditions in 4000-4500BP and this could have sustained a large population needed to construct Silbury Hill. In addition, the generally wetter nature of the area, compared to the current dry environment, could have given people the impression that the area was the source of the Kennet and a major source of the River Thames

Date of Research

September – December 2009

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1. INTRODUCTION

As a result of the field work and analysis of the recent conservation project at Silbury Hill (Grid reference: SU10024/68513) the palaeohydrology of Avebury and Upper Kennet River area has become of interest (Leary 2009, Campbell 2004). In particular, the idea that the monument may have been built at this location (Figure 1) in order to mark the source of the Kennet/Thames has been put forward along with the possibility that the ditch extension or reservoir at Silbury could present a monumentalised spring head (Leary 2009).

The aim of this report has been to assess the palaeohydrology of the Silbury Hill area and determine the flow rates, groundwater levels and hydrological conditions at ca. 4200BP. This has been undertaken using hydrogeological mapping linked to modelling techniques, making use of outputs from the historical runs of a Global Circulation Model coupled with models to recreate past flows and levels in the Upper Kennet River at Silbury.

Specifically the study has attempted to answer or shed light on the following questions:-

1. Why is the Swallowhead Springs thrown out at its current location?
2. Could it have moved since Silbury was built (ca 4,400 – 4,200BP)?
3. Could the Winterbourne coming down from Avebury have developed since 4,400 BP (in which case Swallowhead might have been the major visible source of the Kennet at the time of Silbury's construction)?
4. Could significant changes such as those outlined in 1 – 3 be brought about by human activities either at the time of construction (e.g. clearance of forest) or subsequently (e.g. water abstraction)?

The project is intended to provide information which will address several of the priorities identified in the Palaeo-Environmental Research Agenda for the Avebury World Heritage site (Allen 2001). In particular questions regarding the nature of hydrology in the area and the interactions between surface waters and groundwaters (Cleal and Allen 2001). Whittle (1997, 7) has stated that the 'hydrological history of the locality remains uncertain' and an assessment of the data from the Silbury Hill project identified the palaeohydrology as in need of urgent investigation. This project could also help in considering theories about the location of the Silbury monument (Leary *et al* 2009) and assist in commenting on whether the siting of the Hill is directly related to the source of the Kennet/Thames.

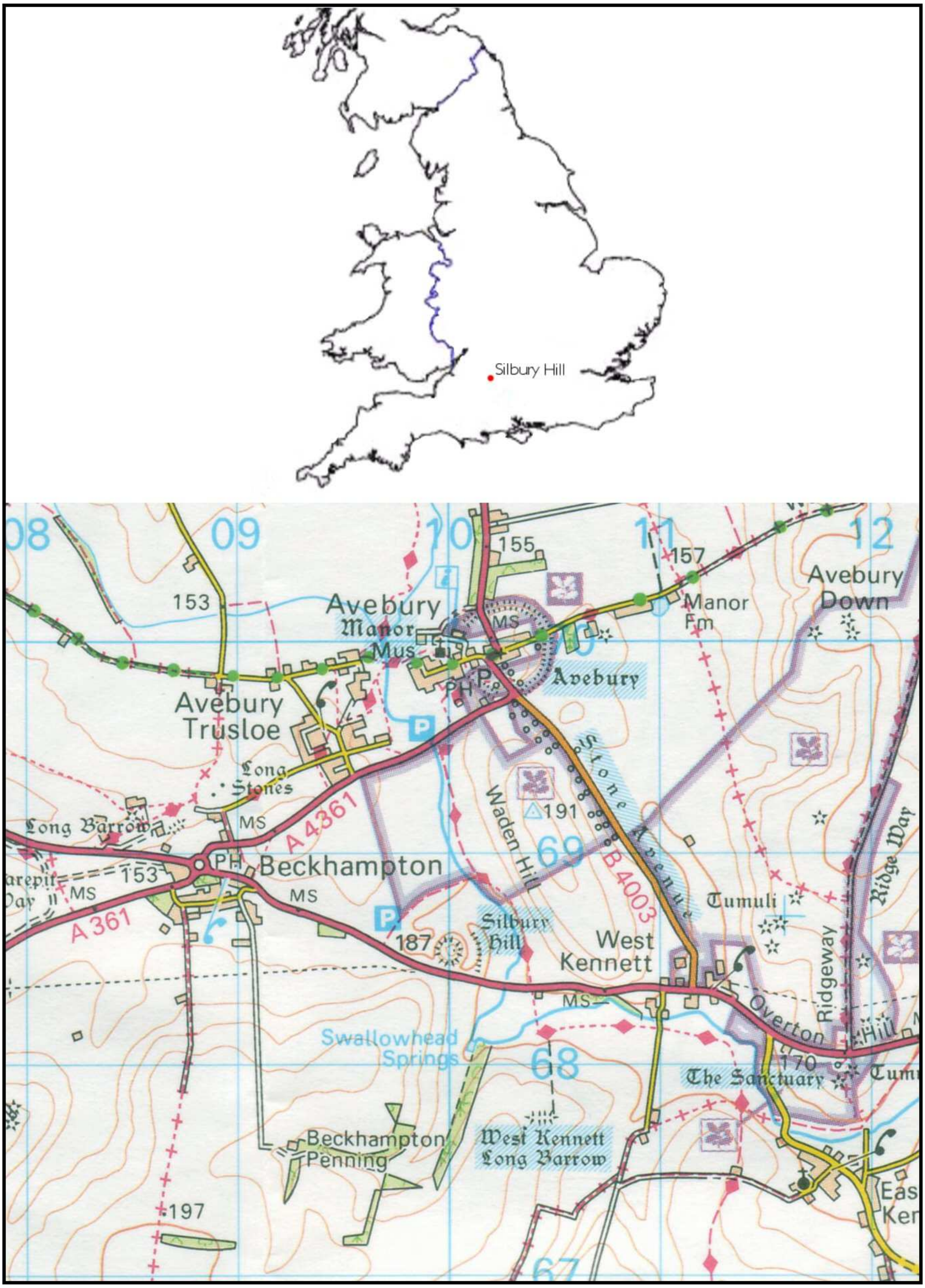


Figure 1: Maps showing the location of Silbury Hill, Avebury and Swallowhead Springs

2. BACKGROUND AND HISTORICAL INFORMATION ON THE UPPER KENNET: GEOLOGY, HYDROGEOLOGY AND HYDROLOGY.

The Kennet (Figure 2) is a major tributary of the River Thames, the principal river in the south east of England, and flows broadly west to east, with a catchment area of 1138 km^2 and a main river length of 86 km. Altitude varies across the catchment from 215 metres above sea level (m.a..s.l.) at the source of the Kennet near Avebury to 40 m.a.s.l. at the confluence of the Kennet with the Thames at Reading (Figure 3). This project focuses on the upper reaches of the Kennet above Marlborough, where Silbury and Avebury are located (Figure 1)

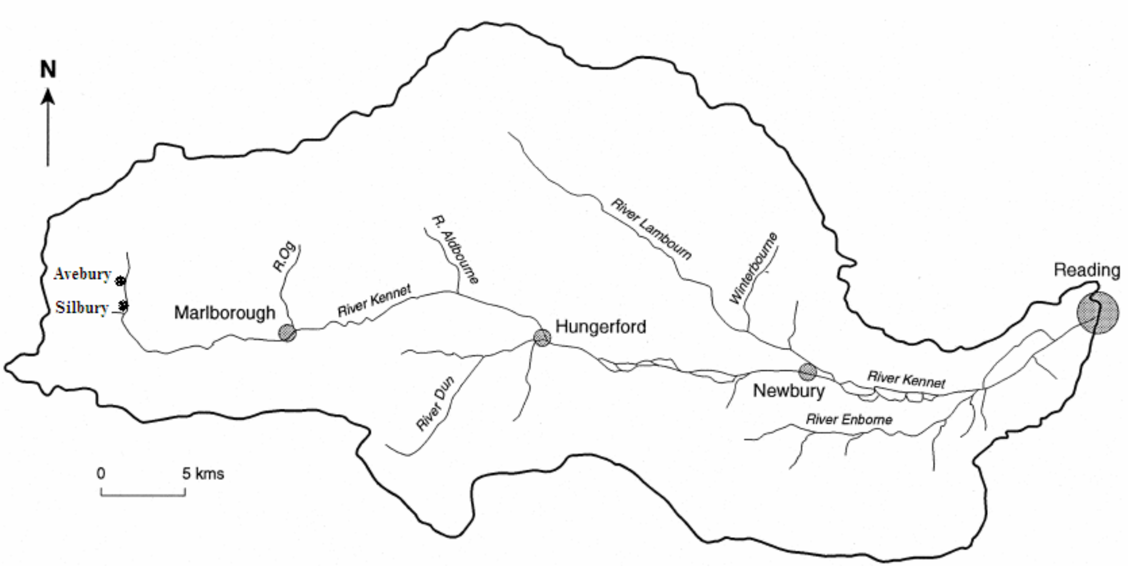


Figure 2: Map of the River Kennet catchment and major towns with Avebury and Silbury located in the uppermost reaches of the river system

Figure 3: Elevation map for the River Kennet catchment (Limbrick *et al* 2000)

2.1 Historical Geological Investigations of the Upper Kennet

Most of the information available on the geology and hydrogeology of the area (Wiltshire and the Marlborough Downs) comes from the 19th and mid 20th century publications of the British Geological Survey. An early account of the geology was published by Ramsay *et al* (1858) which provides good observations on the Sarsens and "Grey Wethers" which are noted to be particularly numerous on the Marlborough Downs and are used also around buildings on the "Turnpike Road" presumably the A4. These "Druid Stones" were recognised (as the quotation from the following passage in Ramsay *et al* indicates) as being relict deposits of overlying Tertiary strata and the contemporaneous description is still valid at the present day:

"In accordance with this view, he finds that wherever the stones are most numerous, there the nearest Tertiary strata, even though unconsolidated, are apt to assume a similar sandy or pebbly character. This helps to account for the patchy distribution of Grey Wethers around Tertiary areas, since where they do not occur we may suppose that although the Chalk was there also covered by Tertiary strata, yet these strata did not contain there the materials by the consolidation of which Grey Wethers were formed. It seems probable that the Grey Wethers belong to the more compact siliceous patches of the Lower Sandy Tertiary strata, and possibly they further hardened on exposure to external influences when the softer Tertiary material by which they were surrounded was denuded away."

The original field sheets (containing notes from the original and subsequent geological mapping, from 1857) have also been also consulted and are copied here (Figure 4). It was anticipated that observations relevant to the pre-development conditions of the region might have been included. However, little of importance was discovered. The comments seem to date from 1892 with later additions. The most recent memoir (Osborne-White 1925) provides some further comments on the Chalk of the area. He notes that the River Kennet follows an easterly pitching tectonic trough (in today's terms – an easterly plunging shallow anticline). He also notes that the river valleys are developed along weaker bands in the Chalk geological succession.

2.2 Hydrogeology

Information on the hydrogeology of the Marlborough Downs and specifically Avebury region has been obtained from the National Well record collection held at 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 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 reconstruction. Other historical data on wells and boreholes is contained in Whitaker and Edmunds (1925).

The field notes dating from 1892 contain observations on the geological boundaries as well as some information on wells. It was noted that the water level at a well at Beckhampton (SU 0876 6880) was 3ft below surface on 12/2/1892 and that the well was 38 feet deep. Also mentioned is that on 15/3/1893 there was water standing at the foot of Silbury Hill (immediately to the NNE of the hill). A water course is also described just to the east of

Beckhampton, immediately south of the Bath Road. The name Beckhampton may signify a greater significance of this small tributary in the past (Field 2002), but it is considered unlikely that this was more than an ephemeral stream in recent times. Information on the early hydrogeology may also be gained from wells or shafts. On the old Ordnance Survey map in the immediate area the site of a Roman well just south of Silbury is marked as well as another to the east of Silbury, both adjacent to the line of the Bath Road just south of the road. The former was fully excavated and had a depth of 7.9m (Brooke and Cunnington 1896). To the south of the area near Wilsford (on the Avon), a controversial shaft with a depth of 30.5m has been described (Ashbee *et al* 1989) which may either have been a water source or a site of ritual burial.

The most up-to-date summary of information is provided in the hydrogeological map of the area (IGS 1978). Recent information on ground and surface water management for the area is available from the Catchment Abstraction Management Plan for the Upper Kennet (EA 2006)

2.3 Hydrology and Climate

There have been relatively few studies addressing past hydrology of the upper Kennet although there have been studies of the impacts of changing land use from the 1930s (Whitehead *et al* 2002) and also estimations of groundwater resources in the area (Rushton *et al* 1989). Recent studies of the hydrology of the River Kennet have focused on the likely impacts of future climate change on the river system (Wilby *et al* 2006; Whitehead *et al* 2002, 2006; Limbrick *et al* 2000).

The reaches above Marlborough are traditionally thought of as ephemeral streams which dry up in the summer months. The perennial head tends to move up and down the river depending on the groundwater levels which are dependant on the recent rainfall and temperature patterns. Figure 5 shows the detailed topography around Avebury and Silbury and the sections of the stream that are generally dry in summer months. One factor that can affect stream flows which is not related to climate is that of groundwater abstractions, which can lower the water table and reduce flow in the upper Kennet. In recent decades there have been significant abstractions and local knowledge suggests that the flows in the upper Kennet have been reduced in the summer months, as illustrated here in a statement to the Action for the River Kennet group (www.riverkennet.org), by the owners of East Kennet Farm, about water flows in the past.

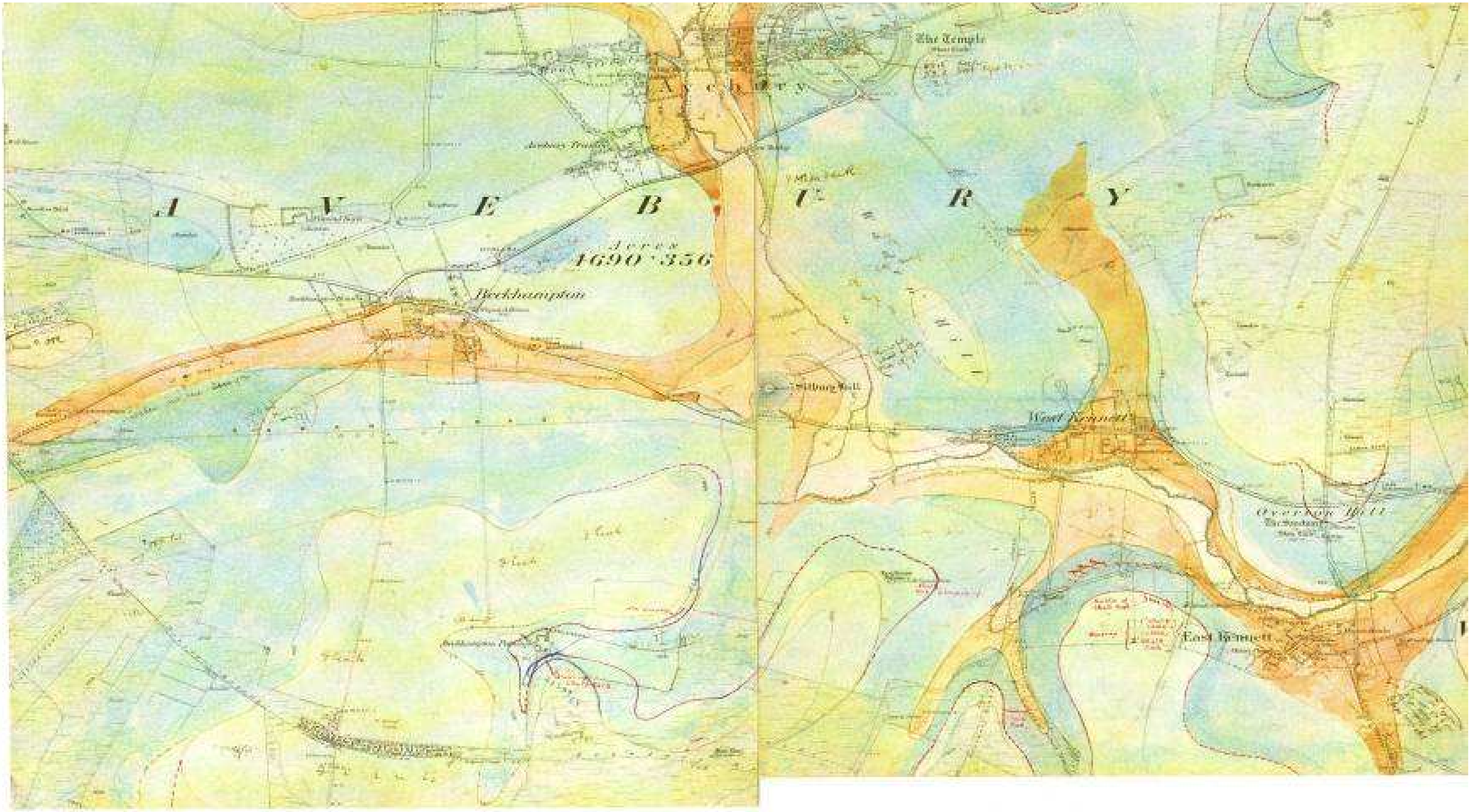
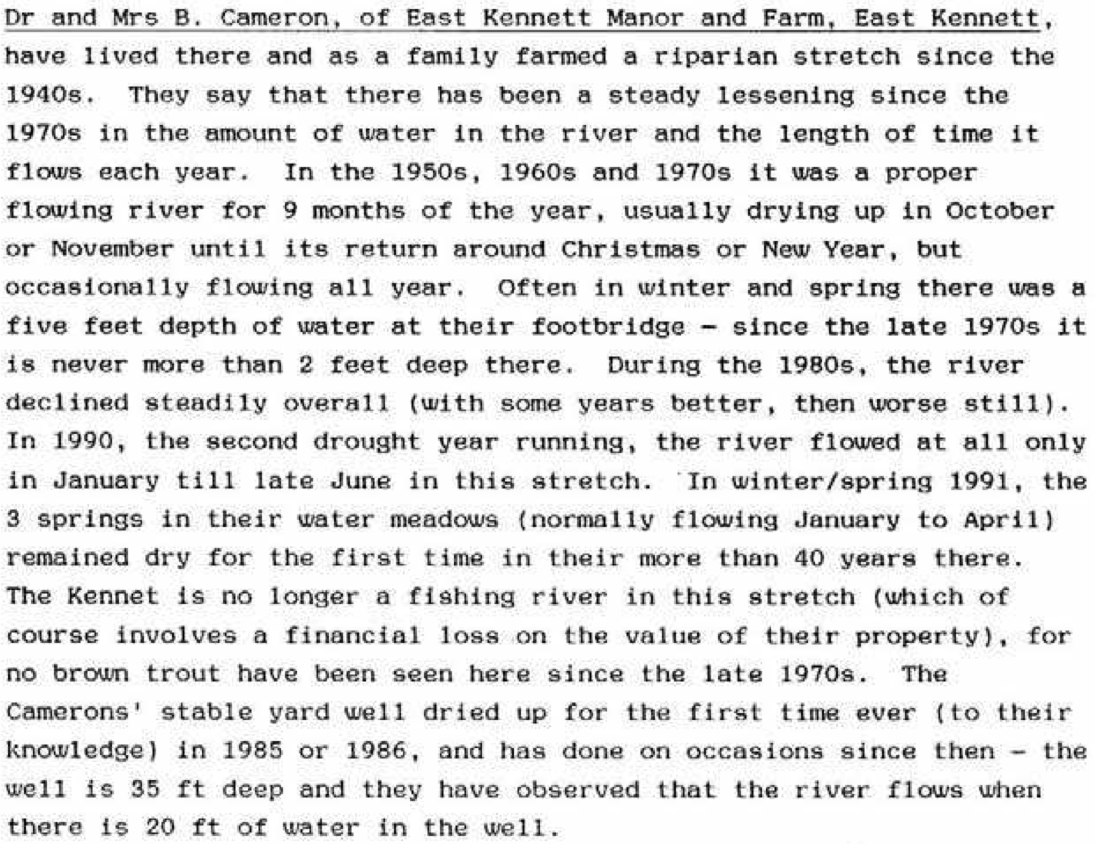


Figure 4: Original geological field sheets from 1857 (BGS archive)



Dr and Mrs B. Cameron, of East Kennett Manor and Farm, East Kennett, have lived there and as a family farmed a riparian stretch since the 1940s. They say that there has been a steady lessening since the 1970s in the amount of water in the river and the length of time it flows each year. In the 1950s, 1960s and 1970s it was a proper flowing river for 9 months of the year, usually drying up in October or November until its return around Christmas or New Year, but occasionally flowing all year. Often in winter and spring there was a five feet depth of water at their footbridge – since the late 1970s it is never more than 2 feet deep there. During the 1980s, the river declined steadily overall (with some years better, then worse still). In 1990, the second drought year running, the river flowed at all only in January till late June in this stretch. In winter/spring 1991, the 3 springs in their water meadows (normally flowing January to April) remained dry for the first time in their more than 40 years there. The Kennet is no longer a fishing river in this stretch (which of course involves a financial loss on the value of their property), for no brown trout have been seen here since the late 1970s. The Camerons' stable yard well dried up for the first time ever (to their knowledge) in 1985 or 1986, and has done on occasions since then – the well is 35 ft deep and they have observed that the river flows when there is 20 ft of water in the well.

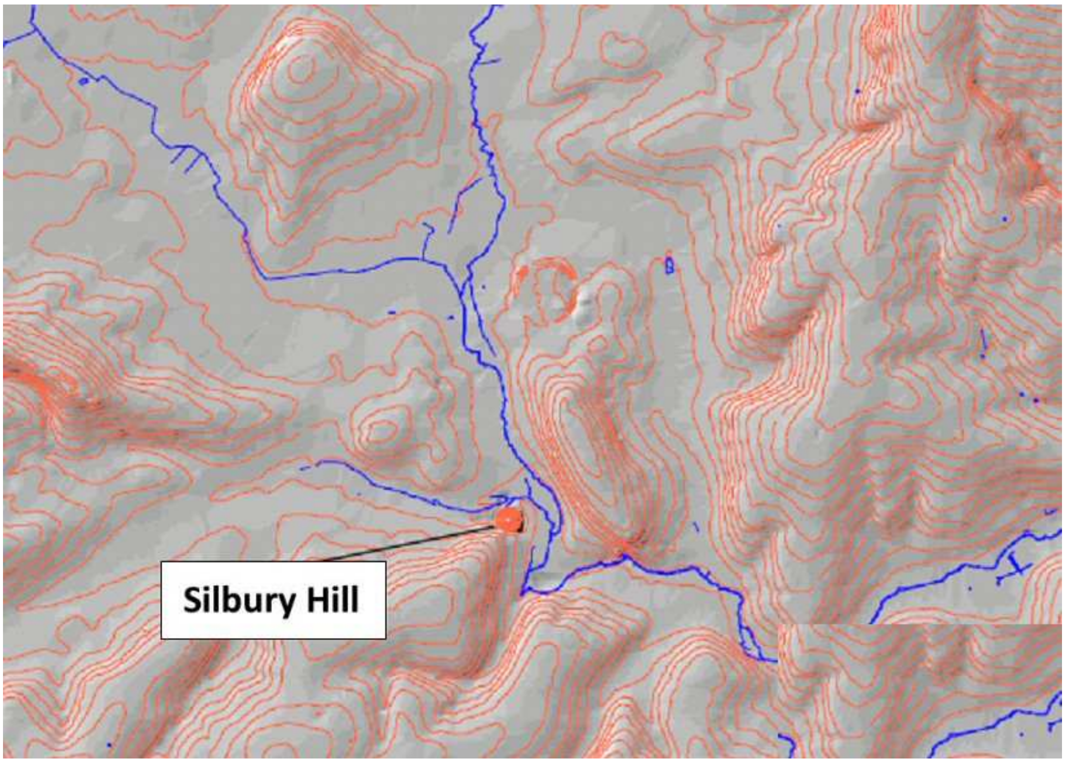


Figure 5: Terrain map of the Upper Kennet showing the main streams

3. DATA AVAILABILITY AND INTERPRETATION

3.1 Geology

The geology of the area is mapped on the Geological Survey Sheet 266 (BGS 1974) with descriptions given in Osborne-White (1925). The area of Silbury Hill contains a succession of Chalk, overlain by Quaternary and Recent alluvial and colluvial deposits. Here the Chalk is composed of three divisions – Upper Chalk (107m approx); Middle Chalk (45-60m) and Lower Chalk (55-90m). 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. In discussing the Lower Chalk, above the basal Chloritic Marl, Osborne-White notes that:

'the next 100 feet occupied by bluish-grey marly chalk contains distinct beds of varying hardness; firm marl, alternating with tough marlstone and occasionally with rocky argillaceous limestone which rings with the hammer…. The bulk of the marly chalk visible is jointed into blocks and flags.'

Thus it is important to note that the Lower Chalk is distinct from the younger overlying Chalk strata in containing no flints, having a distinct hard-ground marker horizon at the top and being composed of clay rich chalk horizons – also with lower overall permeability than the overlying rocks.

The region forms the extreme west of the structure known as the London Basin. This is an asymmetric syncline or trough with the northern limb being less steep than the southern limb. The valley of the Kennet follows the axis of this structure and as a result, in the vicinity of Silbury Hill the strata are almost horizontal. Borehole logs show the main aquifer to be the Lower Chalk (which is likely to show larger water table fluctuations than the overlying succession). One borehole (SU06/45) in Avebury showed a thick sequence (84m) of Lower Chalk.

The Chalk is a very fine grained (micron-sized) carbonate with high intergranular porosity yet with very low intergranular permeability (Figure 6); its properties have been summarised by Price (1993). It is a classic dual porosity aquifer having both fissure and intergranular flow. Most of the water is transmitted via fissures which tend to be most actively developed in the upper 15-20m of the rock. The Middle Chalk contains relatively small tabular flints but in the Lower Chalk flints are absent. Upper Chalk is characterised by large flints. The Lower Chalk is impure and may contain between 10-30% clays. In the area of the Marlborough Downs the base of the aquifer may also be in hydraulic continuity with the Upper Greensand (UGS); 20m of UGS was proven at a borehole (SU06/45) in Avebury. However, the hydraulic response may be restricted due to the rather thick clay (Plenus Marl) forming the base of the Lower Chalk.

3.2 Landscape and Quaternary geology

One very distinct feature of the region is the bend in the Kennet through about 110 ° and then striking north – south at right angles to the main channel downstream. It is considered that this must be geologically controlled although evidence cannot be found from the geological survey data to confirm this. In discussions with Andy Newell at BGS we conclude that the valleys probably follow a set of normal (90°) joints, and this is seen, for example, in some of the landscape to the south of Silbury Hill. No major faulting control is present or the Melbourn Rock would have shown displacement. The valley near Swallowhead springs is quite deeply incised at this point.

Early maps (Field 2002) seem to indicate that the course of the Kennet below Waden Hill may have been more meandering and have changed due to recent channel straightening. It may also be assumed that the extent of the mapped alluvium marks the probable extent of the river migrations in the Quaternary.

The landscape of the area is the product of physical and chemical weathering developed upon the Chalk topography and joint pattern over the whole of the Quaternary. The valleys (and dry valleys) have evolved as a result fluctuations in surface and groundwater flows and of successive periods of permafrost (Catt and Hodgson 1978). During glacial times permafrost would have led to cryoturbation and enhanced chemical dissolution (calcite has maximum solubility at 4°C) as a result of freeze-thaw action. Increased surface erosion and development of alluvial deposits would also have occurred at this time. The process was then enhanced due to the chemical weathering

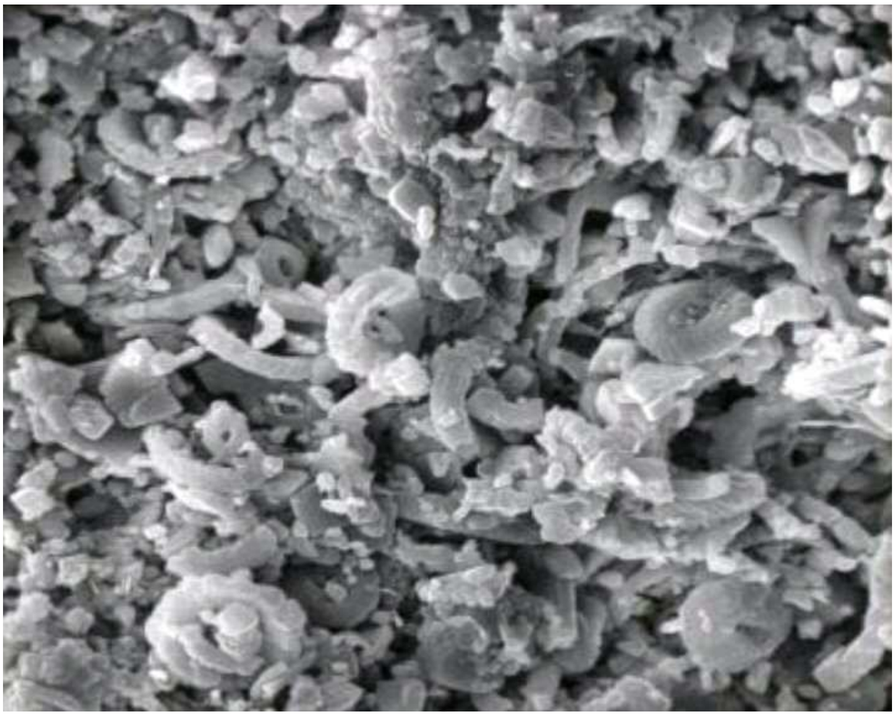


Figure 6: SEM photograph of the Chalk, which is composed of microfossil rings (up to 10μm in diameter).

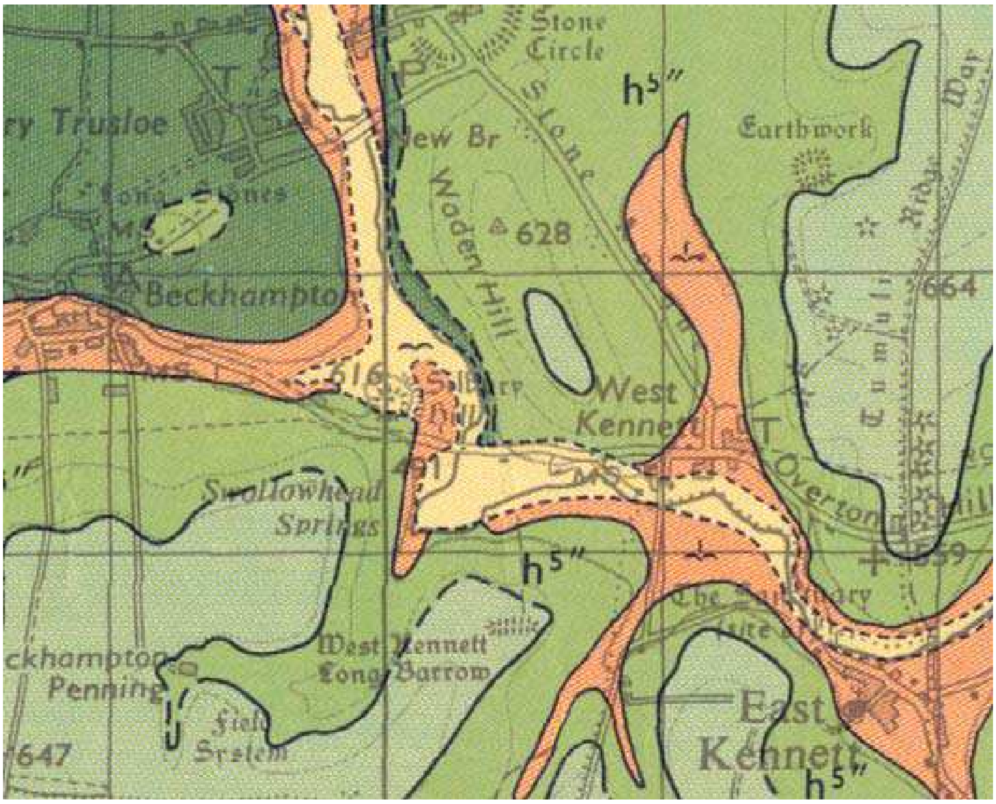


Figure 7: Geological map of the deposits at Silbury (Green is chalk; orange is valley gravel; yellow is alluvium). h5″ refers to Middle Chalk and the Lower Chalk is a darker green. It should be noted that the boundary of these two units passes beneath Silbury Hill (BGS 1974) leading to greater fissure permeability development in the valleys (Younger 1989). The development of alluvial deposits would also have affected the local valley flow hydrology, creating soils and raising groundwater levels.

3.3 Hydrogeology

The hydrogeological characteristics of the area are represented in the hydrogeological map (IGS 1978). The aquifer is unconfined in the area of the Upper Kennet and around Avebury; the water table roughly reflects the contours of the land surface, as shown in Figure 8. The water table fluctuates seasonally in response to rainfall recharge (see below). It is generally found that transmissivity is greatest in the aquifer beneath river valleys and significantly reduced by around an order of magnitude beneath interfluves (Owen 1981). The predominant groundwater flow direction towards Silbury Hill area is from the north with a hydraulic gradient of around 1 in 450.

The Chalk aquifer is recharged annually to a greater or lesser extent by rainfall which in this area has a long term (modern) average of 800mm. The exact mechanism of recharge is complex. Where there are fissures it is likely that rapid recharge is effective with a response in hours or days in the water table. More commonly, and in this area, the water movement will take place in response to pressure changes between the unsaturated chalk and the water table. During summer months water will be used by vegetation and lost by evapotranspiration, inhibiting recharge through the unsaturated zone and creating a soil moisture deficit. In winter months initial rains will be used up satisfying the soil moisture deficits. The water table will only start to rise once the pressures equalise between the soil and the aquifer beneath. There will therefore be a time lag of 2-3 months between the onset of rain and the commencement of water table rise.

It is important to note that, despite the "rapid" response of water tables, water only moves slowly through the unsaturated zone (unless widespread fissuring is present) at a rate of between 0.6 to 1m/yr. Thus water entering the aquifer by "piston displacement" may be up to several decades old. Once this recharge takes place then the rivers are able to respond as baseflow.

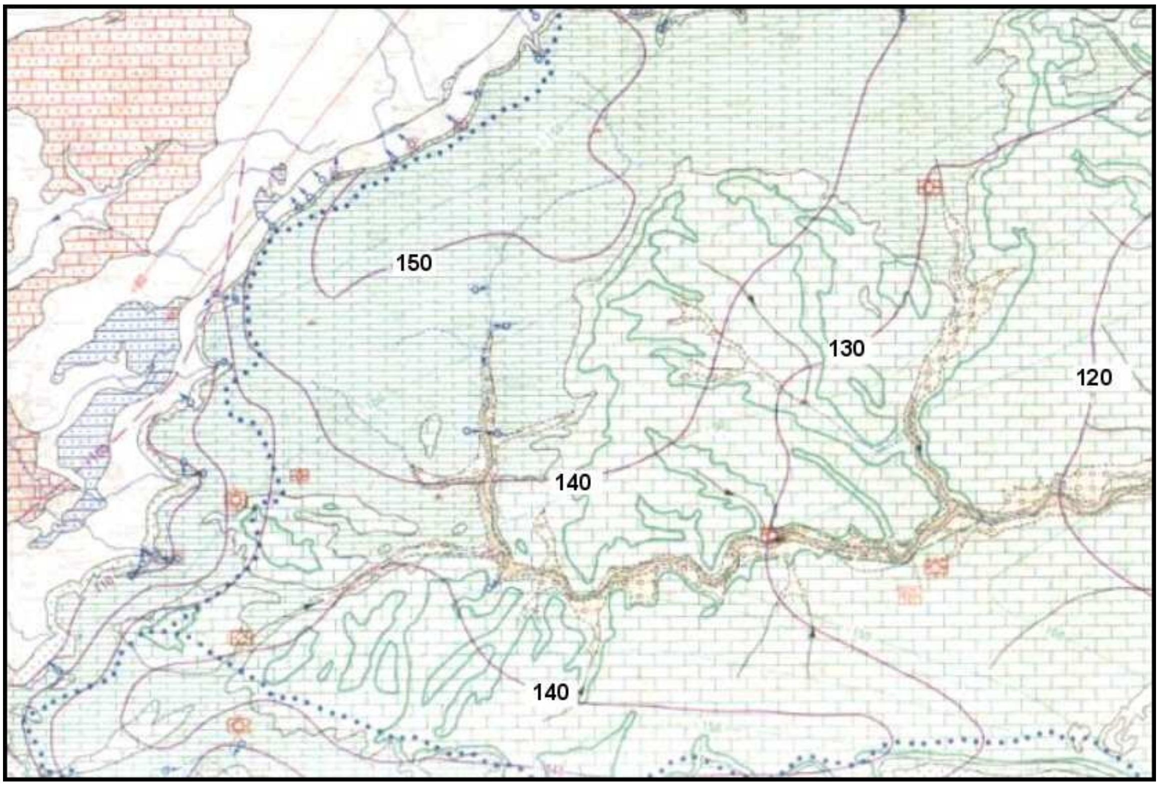


Figure 8: Hydrogeological map showing the modern groundwater depth contours

Whilst Roman wells have been discovered around Silbury Hill (see Field 2002; Corney 1997; Pollard and Reynolds 2002), there is little data from these as the wells have been largely filled in. The most complete record within 10km of Avebury is for Rockley borehole lying east of the area. Data from the National Well Record Collection shows this record from 1932 to the present day (Figure 9). The record shows the annual response in relation to the long term extremes and as deviations from the average expected hydrograph. It is noted that in one year (1976) no recharge occurred at all and that there have been several periods in which a succession of below-average years have given rise to groundwater droughts (eg 1995-1997 and 2003-2006). This latter interval is illustrated in more detail in Figure 10.

The extremes in fluctuation in water table at Rockley over the past 80-year period is 15.4m (Figure 9). However, in considering long term change and maintenance of perennial flows, more realistic would be the mean monthly range (7.3m). These ranges can then be used to check against the characteristics of the Winterbourne streams in the area. An additional point is that the water table for Rockley fluctuates within the Middle rather than the Lower Chalk. It is anticipated that the response characteristics for the Lower Chalk might differ to those of the Middle Chalk.

As well as data from Rockley, data are available (Table 1) for sites in and close to Avebury – at Galteemore Farm, Beckhampton (SU 06/7b) and in Avebury itself (SU 06/45). These three records are all available for the period encompassing the severe 1976 drought. The Galteemore Farm record is complex and would appear to be dominated by short term response. The Avebury record can be compared well with that from Rockley, although some individual measurements depart from the trend which is controlled by the regional aquifer. The noise in this record may be due to measurement or transcription errors (since they are either side of the mean – rather than local shallow water additions. A comparison of the three levels is shown in Figure 11 and the Avebury levels are on average 13.3m higher that those at Rockley. A full time series plot of the levels at Rockley are shown in Figure 12 and show periods of low water levels every decade or so, such as in the mid 1930s , the 1950s and in 1976 drought. It is interesting to note that the mean level for the period 1932-1960 was 134.27m and the mean level for 1970-2008 was 134.66m. In other words there was a slight increase in groundwater levels in recent years, despite water abstractions from the Kennet Chalk aquifer (Rushton *et al* 1989).

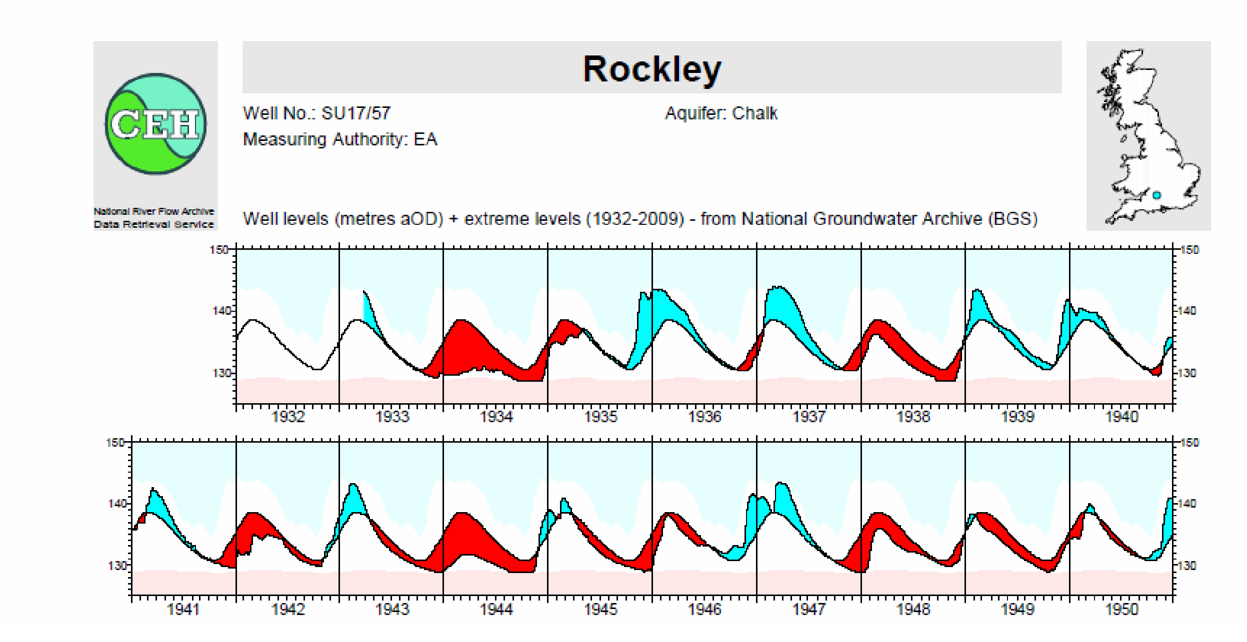


Figure 9: The Rockley Level record from 1932 – 1950 showing the well levels plus the mean level and the extremes. The blue shows the periods of recharge and the red represents periods where groundwater levels are not being replenished

Table 1 Records held in National Well Record collection, BGS, Avebury, Beckhampton and W Kennet area

Sheet No	Nat Grid Reference	Name	Record Details	OD	Depth (m)	Further data
SU/06/4	SU 0848 6923	Penning Barn	Borehole or shaft 1969		105	
SU/06/7b	SU 0908 6871	Galteemore Farm	Shaft dug c 1939. Drift over LCk ? Depth unknown	156.6		Thames Water Observation Well from 1972-75
SU/06/45	SU 0896 6891	Bray St. Avebury	L Ck 84m; UGS; 20m; Gault 6m	155	21.3	Geol Log, WL
SU/06/10	SU 0938 6988	Domestic well	Avebury		12.6	
SU/06/5	SU 0939 6989	Domestic well	Bray St Avebury		13.48	
SU/06/6	SU 0960 6995	Domestic well	Manor Farm 1969		12.2	
SU/06/69	SU 0991 6985	Mr Paradise owner	Shaft in Avebury Thames WA Obs well from 1972	152.32		More WL data 1915-1935 Thames WA
SU/06/31	SU 0952 6752	No records	Beckhampton Pennings			
SU/06/28	SU 0994 6764	No records				
SU/06/9	SU 0975 6610	Shaft	Tanhill Pennings, All cannings Down (pre 1939)		73.2	Thames WA Observation Well. 1970-
SU/16/8	SU 1019 6999	Red Lion Avebury	Disused pre 1959.OD. Water struck June 1948 @ 139.29.	159.1	24.38	Drilled for Stroud Brewery.
SU/16/72	SU 1005 6805	Swallowhead Spring				
SU/16/49	SU 1064 6832	Cottages W. Kennett	Sealed shaft. SWL 129.23		10.05	WL
SU/16/56	SU 1097 6833	Domestic well	Manor Farm		8.4	
SU/16/57	SU 1119 6830	Borehole	W Kennet Fm. RWL 10	143.1	18.2	
SU/16/71	SU 1130 6836	Domestic well	Disused. W Kennet House		9.45	
SU/16/5	SU 1084 6768	Shaft	E.Kennet 870m ENE of Christ Church.	151.18	32	
SU/16/9	SU 1084 6756	Domestic well	E Kennet			
SU/16/61	SU 1180 6742	Domestic well	E Kennet; Manor Farm			
SU/16/73	SU 1198 6739	Shaft	Orchard Fm. E Kennet.	146.5	10.67	Thames W Observation Well 1973-
N/A		Roman Well	Depth 7.92m Brooke and Cunnington (1895)			
	SU 0876 6880	Old Beckhampton Well	Date ca 1878		11.6	Details on BGS field slips
Observation	SU 1655 7075	Observation borehole	Rockley			Long term records

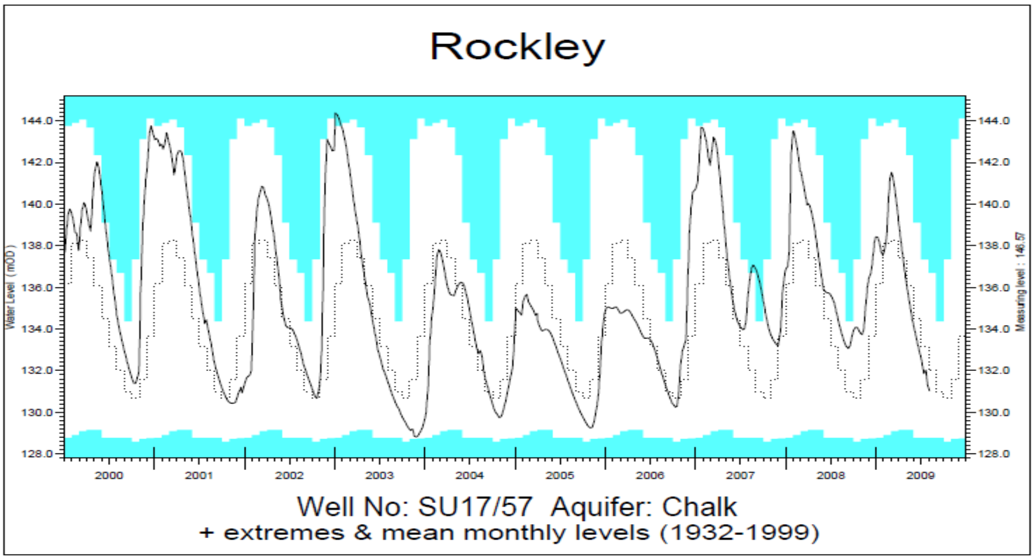
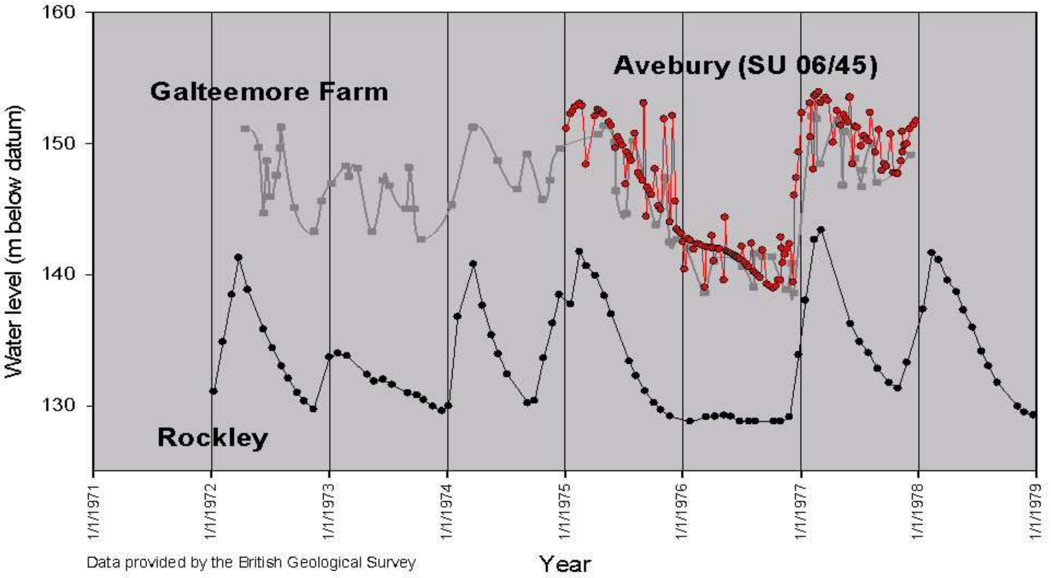


Figure 10: The Rockley Well record 2000-2009



Data provided by the British Geological Survey

Figure 11: The Levels at Rockley, Avebury and Galteemore Farm

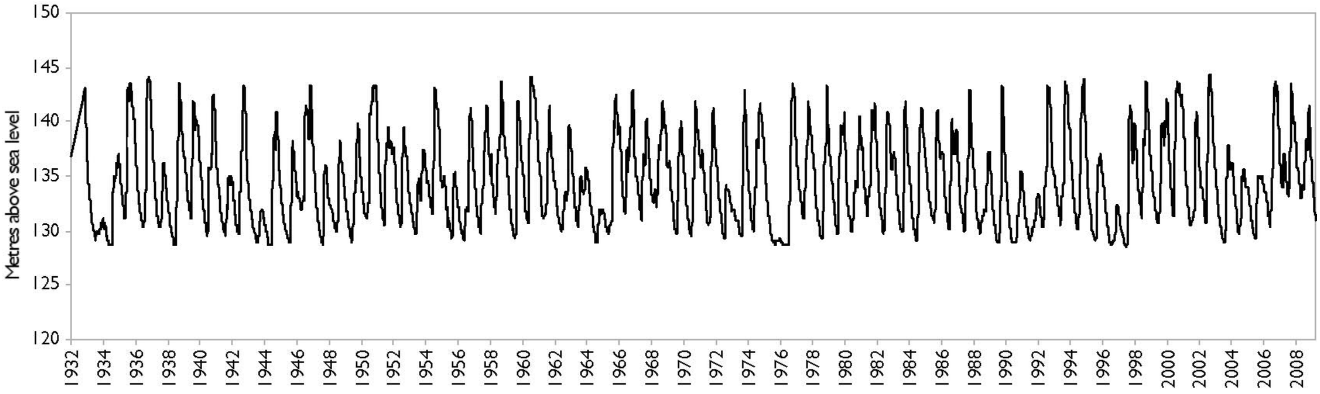


Figure 12: Monthly Mean Well Levels at Rockley during May from 1932 – 2008

3.4 Hydrological and Climate Data

The upper Kennet catchment is defined as the area draining into the Environment Agency gauging station at Knighton (just below Marlborough, Figure 2) and receives runoff from two tributaries, the Og and Aldbourne. At Knighton, 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 about 823 mm and runoff only 192 mm (CEH 2005) so that only about 23 % of the rainfall is converted to river flow. 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 0.95 for the upper Kennet (CEH 2005). This generally results in ephemeral flows (ie winter flows only) creating dry stream beds in summer and autumn months, as shown in Figure 13. However, as shown in Figures 14 and 15 the streams can be at bank full conditions in winter or during storm events. The flow gauge at Marlborough has an extensive record and Figure 16 shows the monthly data from 1973. The flow record shows periods of drought in 1975/76 are 1997/98 and at these times the streams are dry as far down as Marlborough. Climate records are also available for the Kennet area with extensive records of rainfall and temperature as shown in Figures 17 and 18. These data enable the development of models that can relate rainfall and temperature to stream flow.

Figure 13: Dry stream bed at Avebury

Figure 14: Upper Kennet Stream at East Kennet (March 2009)

Figure 15: Upper Kennet below Avebury (March 2009)

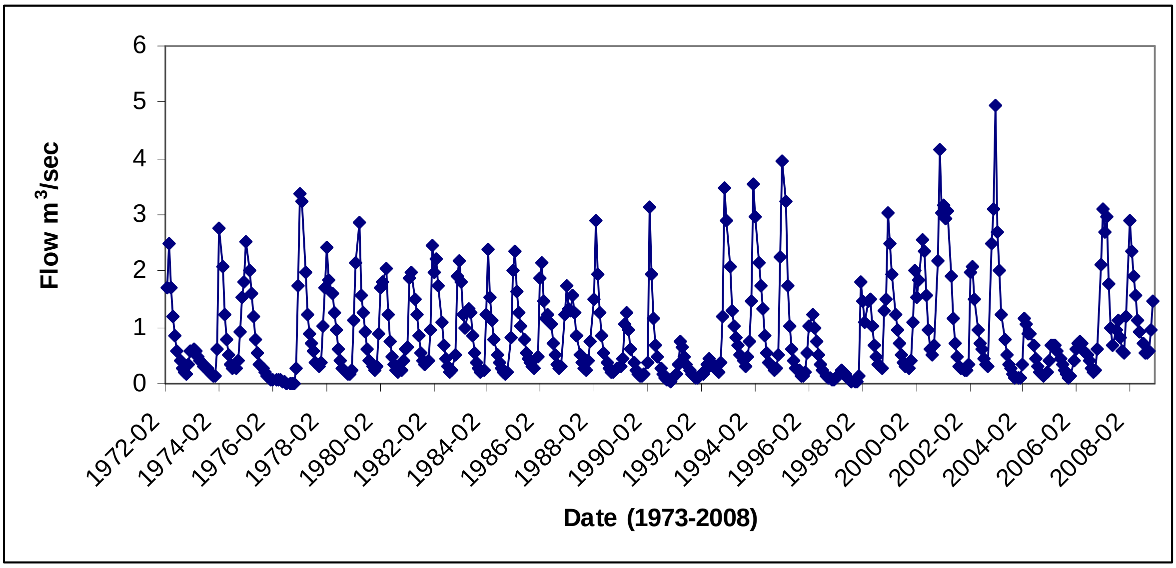


Figure 16: Monthly Flows at Marlborough 1972-2008

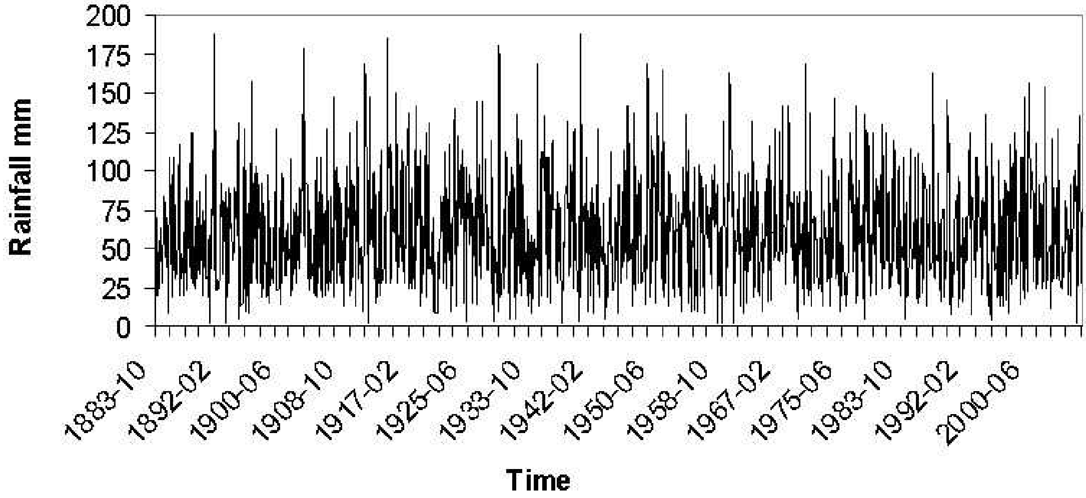


Figure 17: Monthly rainfall in the Kennet Catchment (1883-2000)

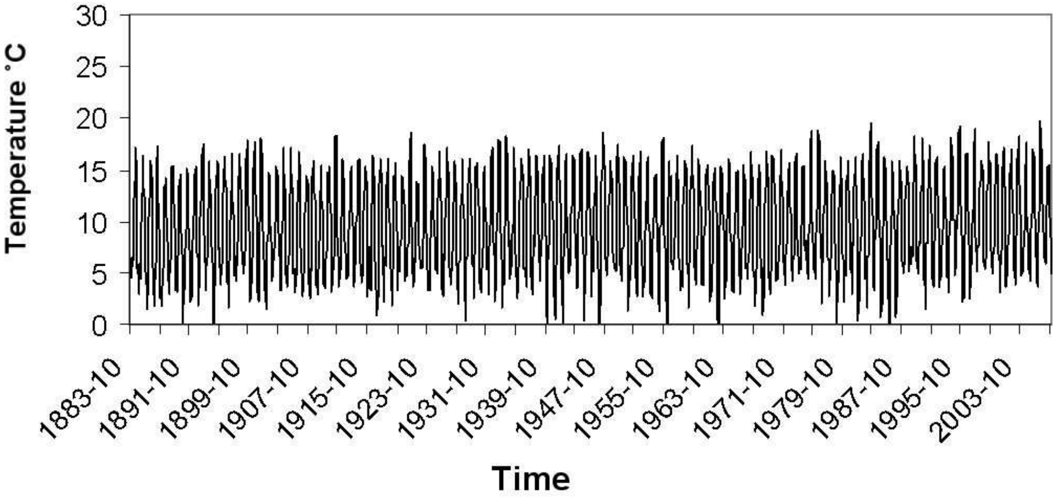


Figure 18: Mean monthly temperature (1883-2003)

4. MODELLING CLIMATE, HISTORICAL FLOW AND GROUNDWATER LEVELS IN THE UPPER KENNET

In order to understand the past hydrology, the strategy adopted in this project is to make use of modelling techniques to simulate the river flows and groundwater levels in the upper Kennet. These models are then used to simulate past behaviour using outputs from the GCMs to determine past climate. This combined modelling system provides the means to recreate past flows and levels in the Upper Kennet River. In this section of the report we describe the modelling processes, the GCM model results and the reconstruction of past groundwater levels and flows.

4.1 Reconstructing Past Climate in the Upper Kennet

A key requirement of this project is to assess in some manner the likely climate in the period 4000BP to 4500BP. There is considerable evidence from other palaeo-data and studies that the climate in 4500BP was wetter and slightly warmer than the current climate (eg Newson and Hanwell 1982). Figure 19 shows the likely changes in temperature and tree species over the past 13,000 years. A higher temperature, of between 0.5 and 1.5 degrees centigrade, is indicated. An alternative and independent source of information is also available from Global Circulation Models (GCMs) of climate. These models simulate the world's weather patterns and provide grid squares of information across the world. They are generally used for future prediction, as in the UK Climate Impacts Project (UKCIP09 www.ukcip.org.uk) . However, they have been used to estimate past climates (Valdes *et al* 1999). The model used in these studies has been developed at the Hadley Centre for Climate Prediction and Research, which is part of the UK Meteorological Office and the details of the model are described by Pope *et al* (2000). Historical model outputs for rainfall and temperature from these GCMs are available from the Bristol University web site (www.bridge.bristol.ac.uk). Such GCM model outputs have been used in a range of 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 and runoff changes generated using the HadCM3 version of the coupled atmosphere-ocean GCM for the Silbury Hill grid square. Figures 20 and 21 show the rainfall and runoff variations for the last 20,000 years and both rainfall and runoff show significantly higher levels in 4000-4500BP compared with the current values. The higher rainfall is equivalent to an 8% increase compared to current levels whilst the runoff change is higher because of the effects of evapotranspiration and hydrological flowpaths moderating the runoff.

There is, of course, considerably uncertainty about the exact numbers because of the inherent uncertainty in all GCMs and the question of the accuracy of GCM simulations is a highly active area of current research. For example, the ENSEMBLES project (www.ensembles-eu.org) has 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. All of these give rise to errors and will generate a range of behaviours within the models. Nevertheless the GCMs do provide a quantitative estimate of past rainfalls, runoff and temperatures.

Interestingly, the changes predicted for the 4000-4500BP period by the Bridge CGM 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 4000-4500BP climate in the UK. In fact, a recent comprehensive study of climate change on UK rivers by the UK Water Industry Research group (UKWIR) gives some very plausible estimates of changes to temperature and rainfall for the River Kennet (see Figures 22 and 23). In each graph a significant seasonal effect is predicted suggesting that rainfall will be higher in the winter and lower in the summer.

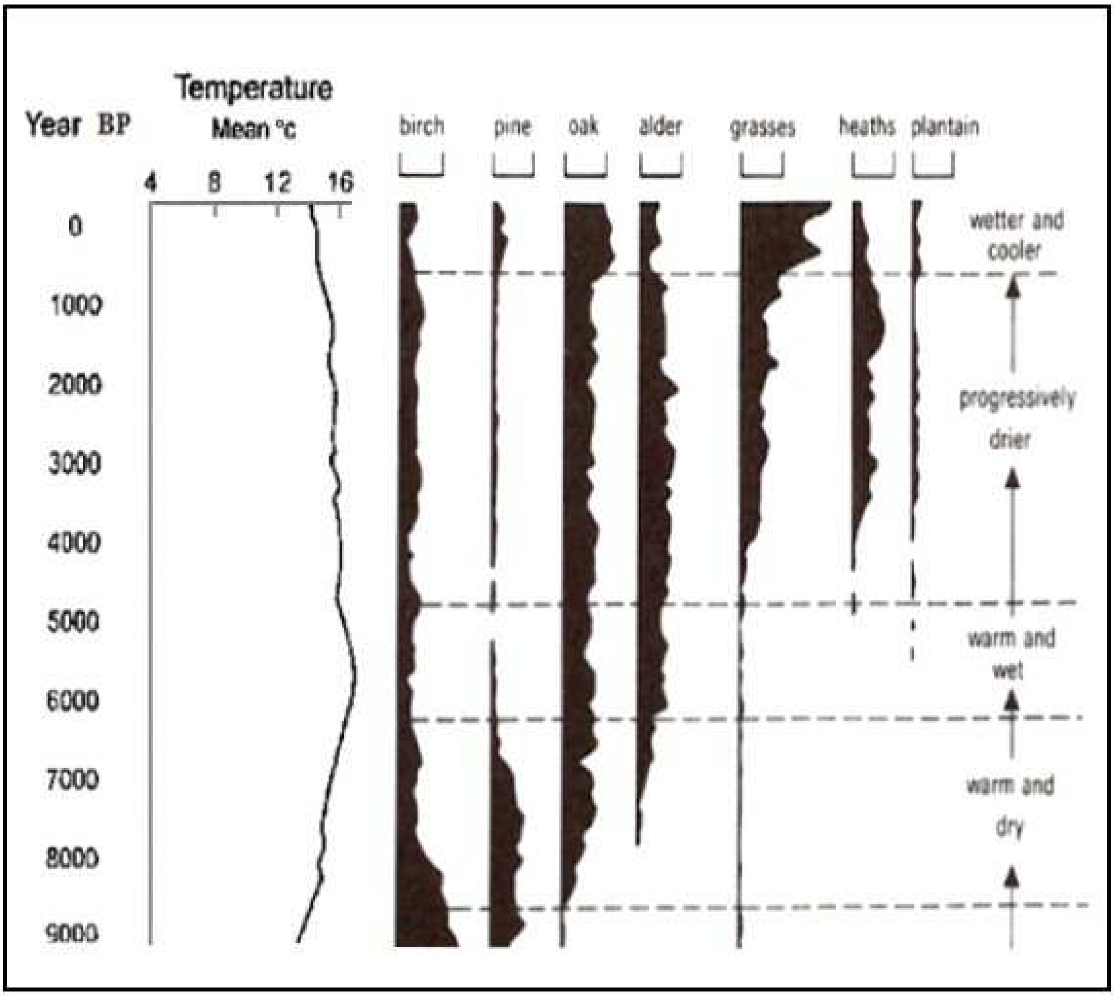


Figure 19: Temperature change and changing tree species over the past 9,000 years

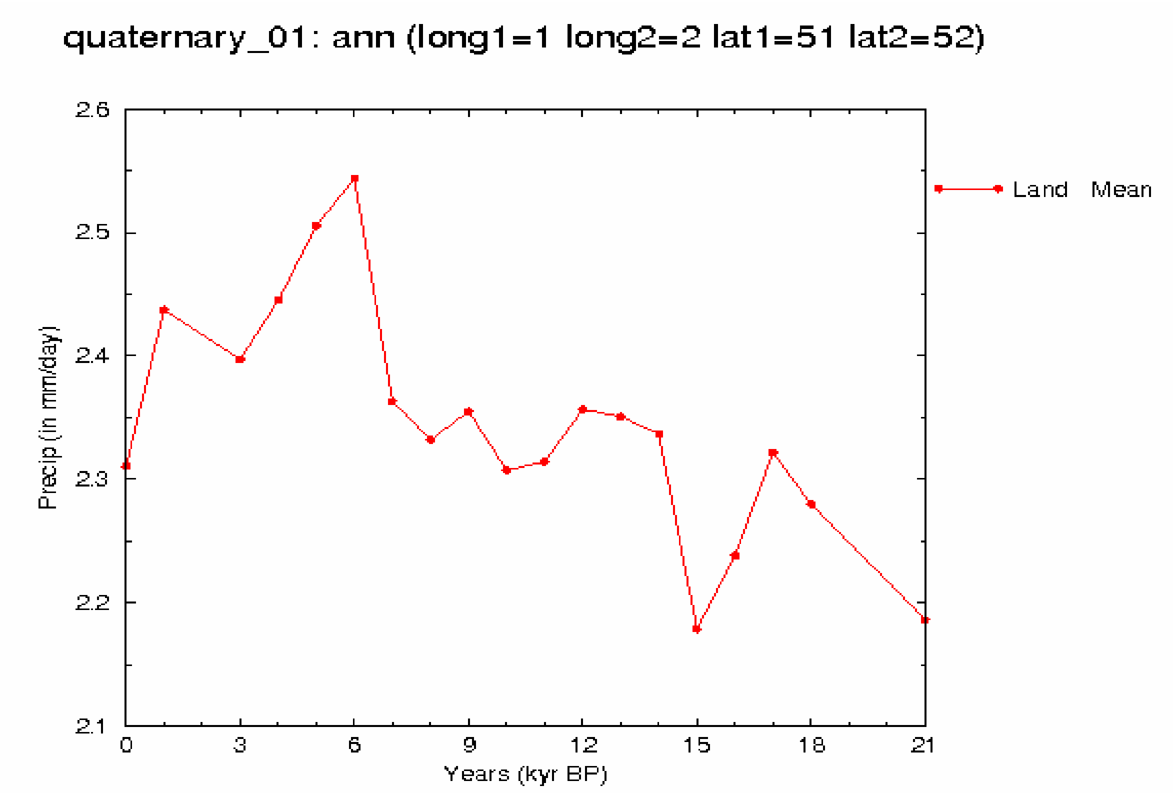


Figure 20: GCM Rainfall estimation for the Kennet Area for the past 20,000 years

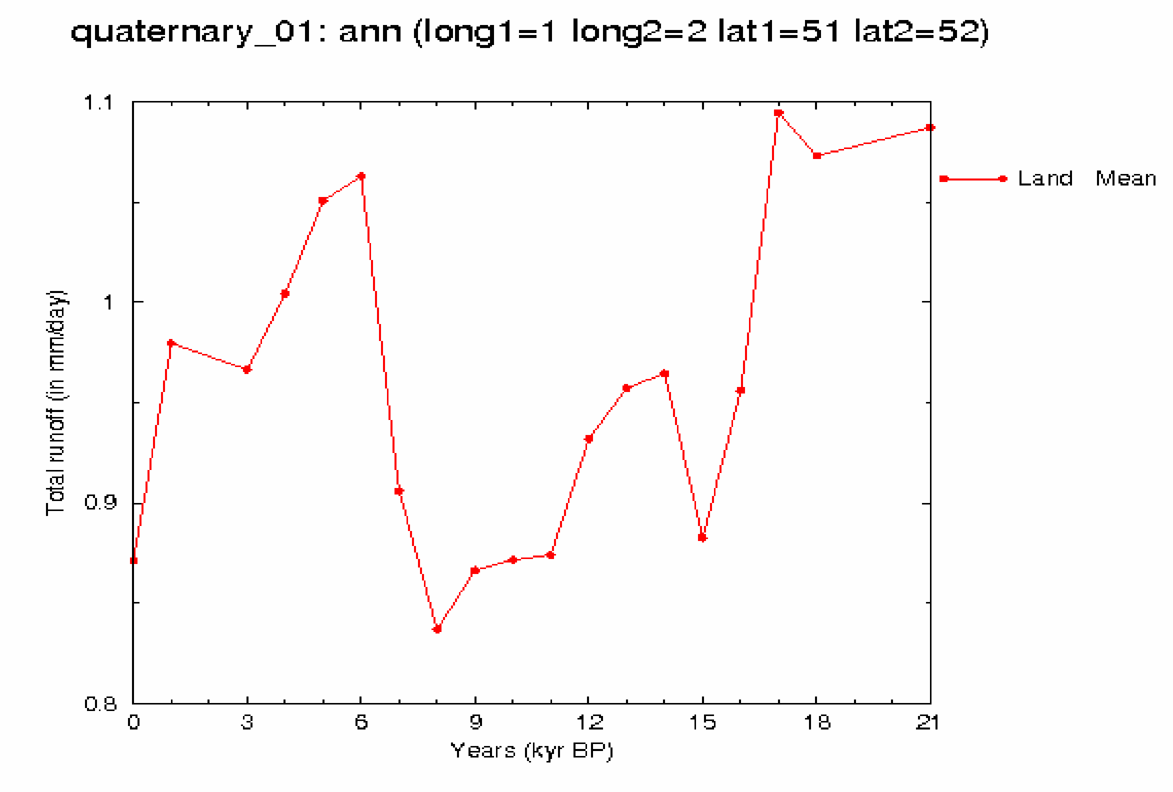


Figure 21: GCM Runoff estimation for the Kennet area the past 20,000 years

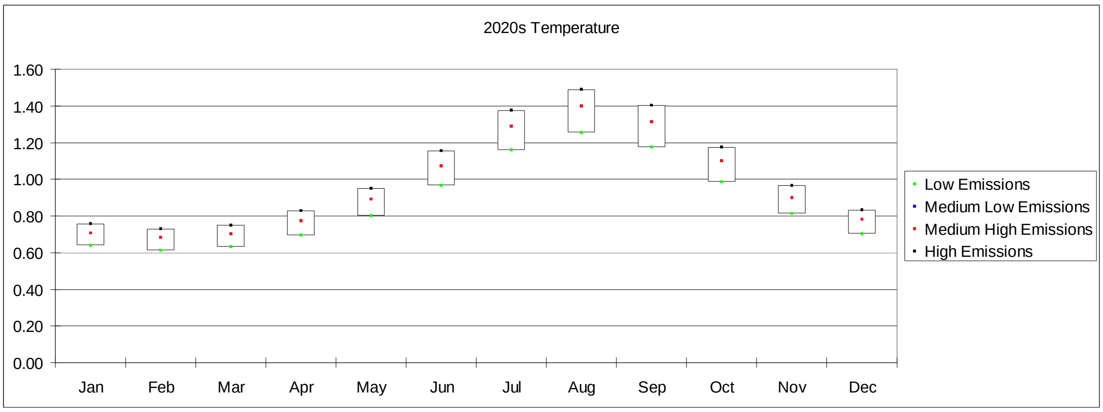


Figure 22: UKWIR seasonal temperature changes under a warmer climate in the Kennet area

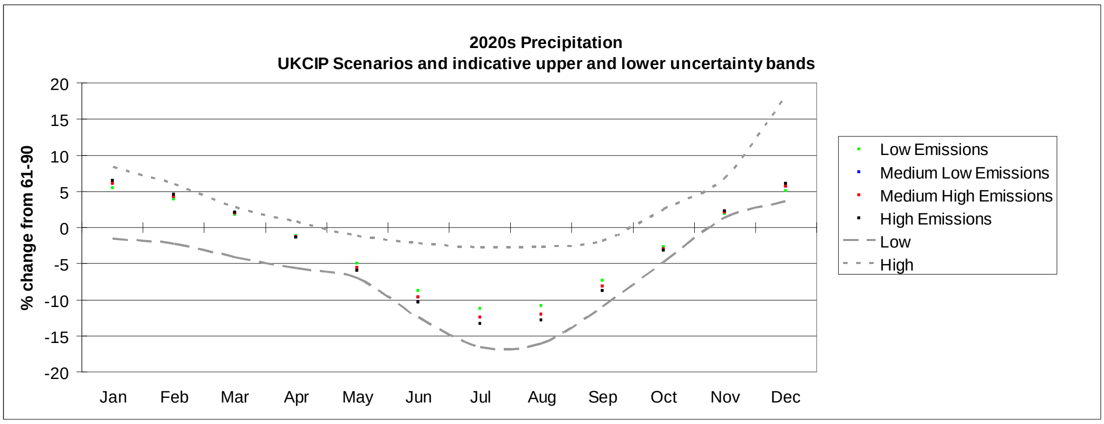


Figure 23: UKWIR seasonal rainfall changes under a warmer climate in the Kennet area

4.2 Modelling Surface Hydrology and Flows

The hydrology of the upper Kennet is complex as the flows are driven largely by groundwater from springs such as the Swallowhead Spring or springs farther up the valley above Avebury. However, there will be surface runoff in times of high rainfall. As previously discussed, the annual average rainfall for the upper Kennet is relatively low for the UK at about 823 mm and runoff only 192 mm (CEH 2005) 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 24 shows the monthly observed flows for the period 1972- 2008. The hydrograph shows high flows in winter months and 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 catchment area of 110 square km whereas at Silbury the catchment area is only 25 square km. Thus the *pro rata* flows at Silbury will be of the order of 27% those at Marlborough; Figure 24 shows the observed flows at Marlborough and the estimated flows at Silbury from 1972-2008. A conventional method of showing the statistical behaviour of such flow estimates is to plot a flow duration curve

(FDC) and Figure 25 shows the FDC for the Silbury estimated flows. This gives a baseline FDC with which to compare historical climate behaviours. The GCM Bridge historical predictions for changes in runoff can now be applied to the estimated Silbury flow record. Applying the seasonal patterns of runoff estimated for 4000-4500BP gives a changed flow estimate and Figure 26 shows a typical 5 year set of data for the Silbury baseline flow and the estimated 4500BP flow. The estimated 4500BP flows are quite similar in summer but are higher in winter.

A second approach to this is to use the UKWIR estimates of changes in runoff and these percentage changes in flow for Marlborough are given in Figure 27. Taking the mean percentage changes for the UKWIR analysis and applying these to the Silbury data gives us a new time series of data and also a new flow duration curve, as shown in Figure 25. The results of the flow duration analysis indicate that higher flows of the order of 20% could have been obtained in winter.

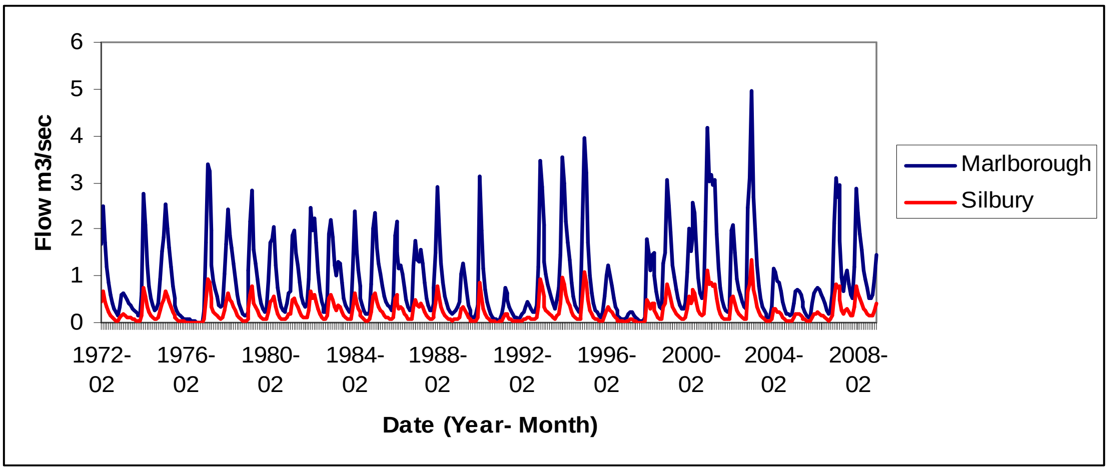


Figure 24: Observed flow on the Kennet at Marlborough and estimated flows at Silbury 1972-2008

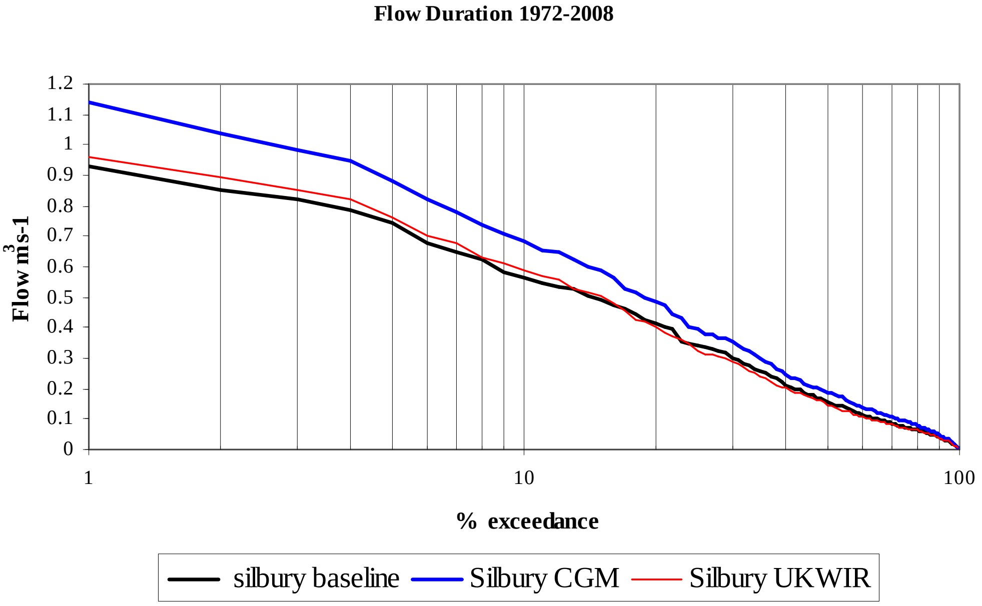


Figure 25: Flow duration curves estimated for Silbury for the baseline data set and two

warmer climate scenarios.

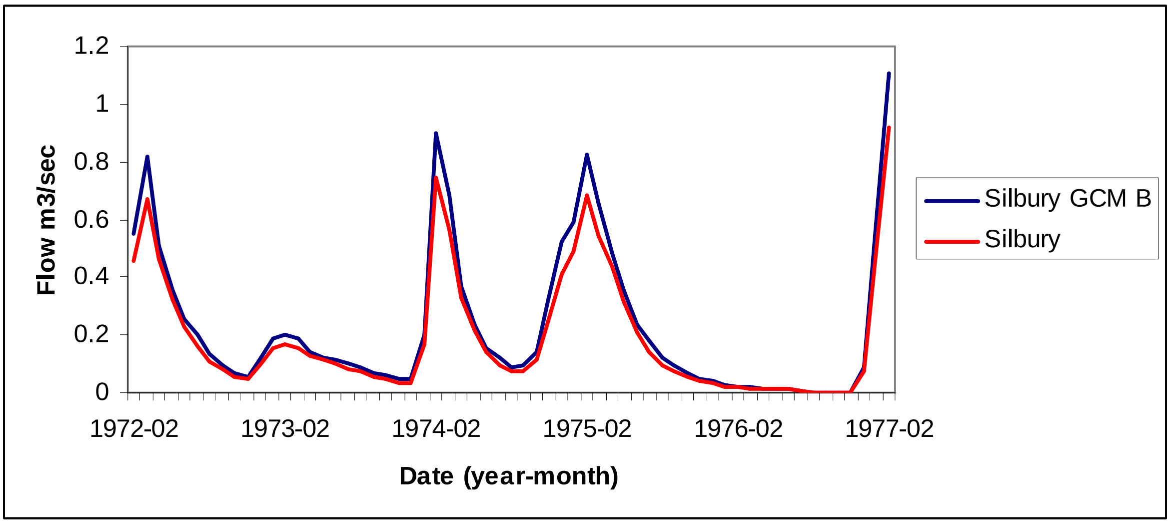


Figure 26: Estimated flow at Silbury together with a GCM climate change estimate of the Silbury flow

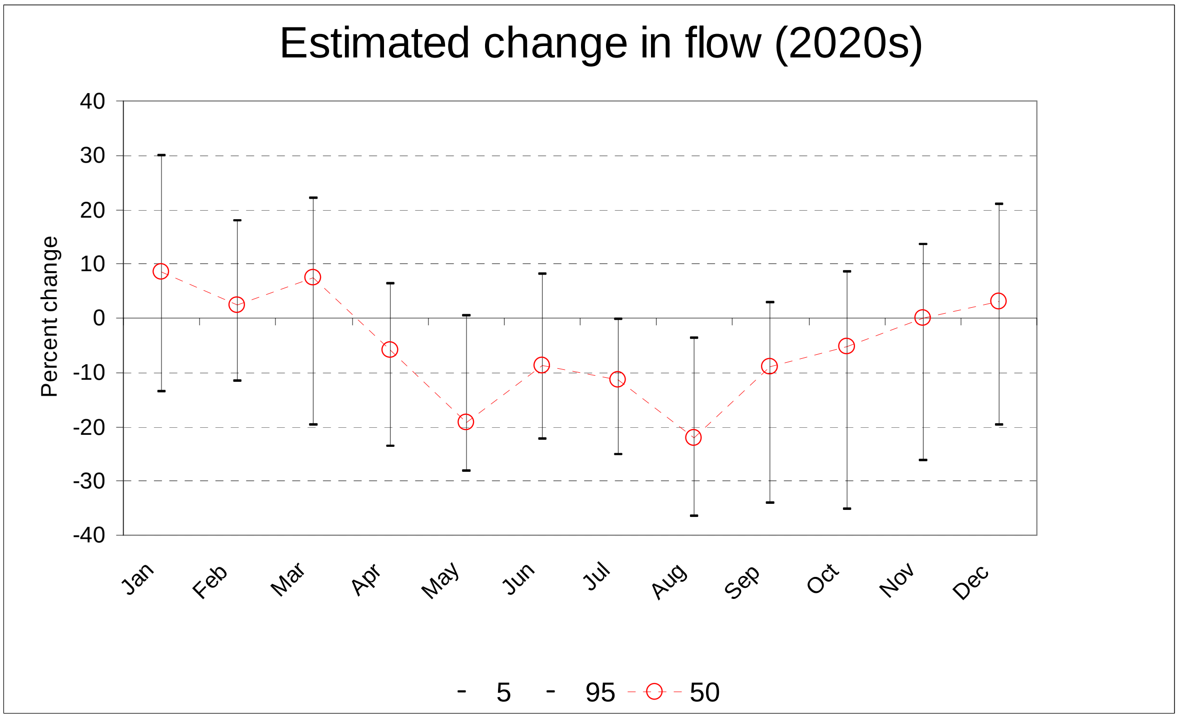


Figure 27: Changes in the upper Kennet flow under a warmer climate (UKWIR study)

4.3 Modelling Groundwater and Impacts of Past Climates on Well 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 study. 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). Figure 28 illustrates the basic idea behind IHACRES. The model is driven by input rainfall (blue plot) and a loss model is used to remove the effects of evaporation and transpiration to create an effective rainfall time series (green plot). A time series model is then established between the effective rainfall and the observed stream flow or well level and this model can then be used to predict well levels under a range of scenarios (purple plot). A detailed explanation of the IHACRES model is given in Appendix 1 as well as the papers by Jakeman *et al* (1990) and Littlewood *et al* (2003). The IHACRES model has been applied to the model the Rockley Well Levels using the monthly rainfall and temperature for the area. The parameters developed for the rainfall loss model and the linear part of the model (Figure 28) are described in Appendix 1. The simulated and observed well levels for Rockley are shown in Figure 29, indicating that a very good time series model has been obtained.

Having established the model for Rockley we can convert this to a simulation for the Avebury- Silbury area. From section 3 it was established that there is, on average, a 13.33 m difference between the Rockley level and the Avebury well level. Applying this factor and also applying the model to the full rainfall dataset from 1883-2008 produces a simulation of the Avebury levels, as shown in Figure 30. 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 4500BP. We have run the models with the two climate change scenarios used above, i.e. the GCM Bridge simulations for 4500BP and the UKWIR scenario for the warmer climate. Figure 31 shows the effects of these two climate scenarios compared to the baseline or current conditions. 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 percentage exceedance curves for the Avebury levels, shown in Figure 32. The results from this analysis indicate that the levels could have been about 2 m higher on average in the past compared to current values.

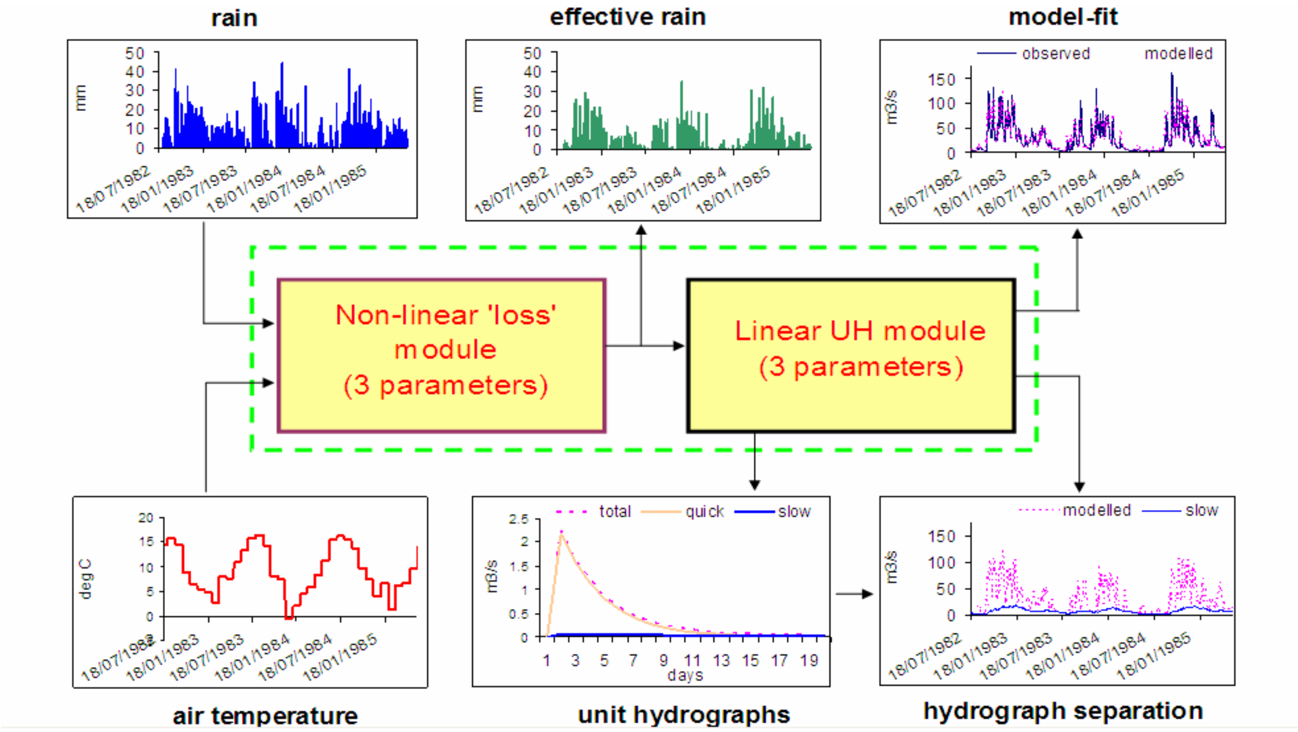


Figure 28: Schematic of the time series analysis IHACRES model

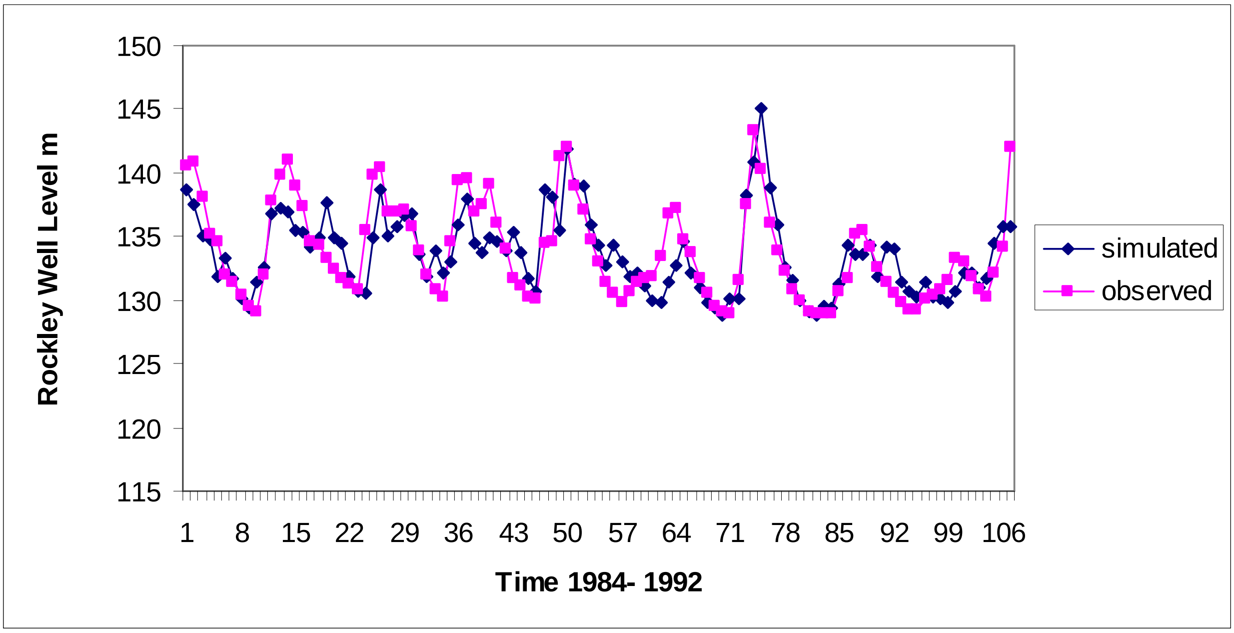


Figure 29: Simulated and observed Rockley well levels (m = metres above sea level)

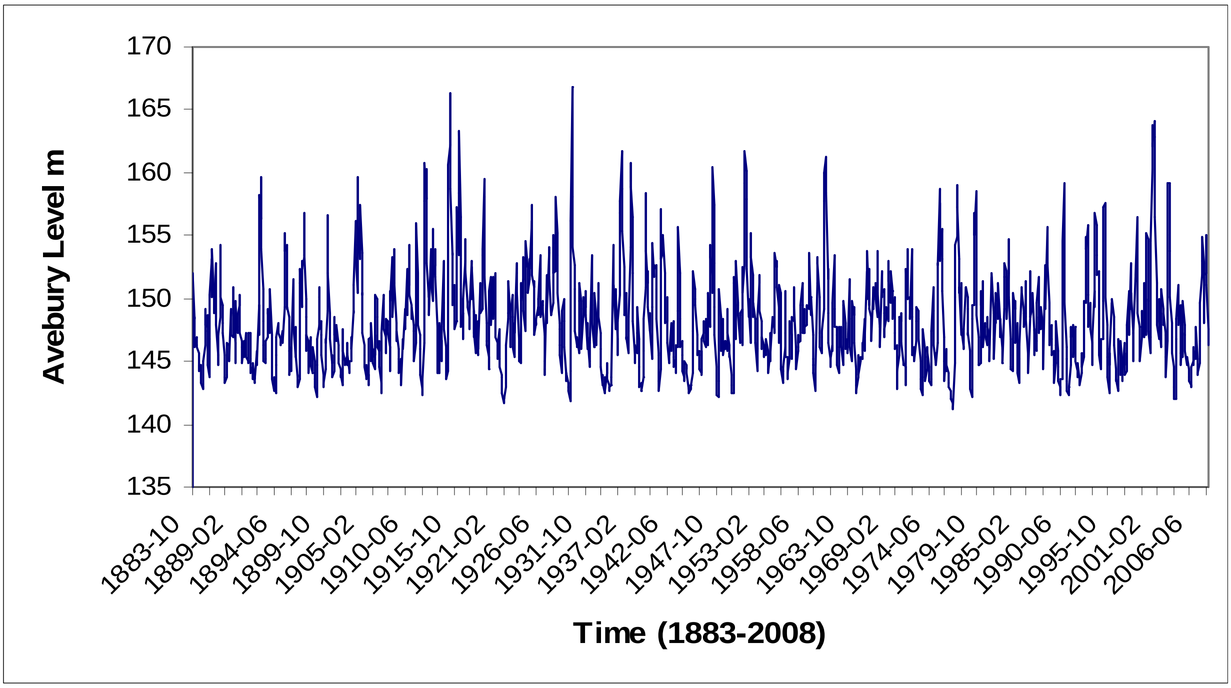


Figure 30: Simulated levels at Avebury for 1883-2008

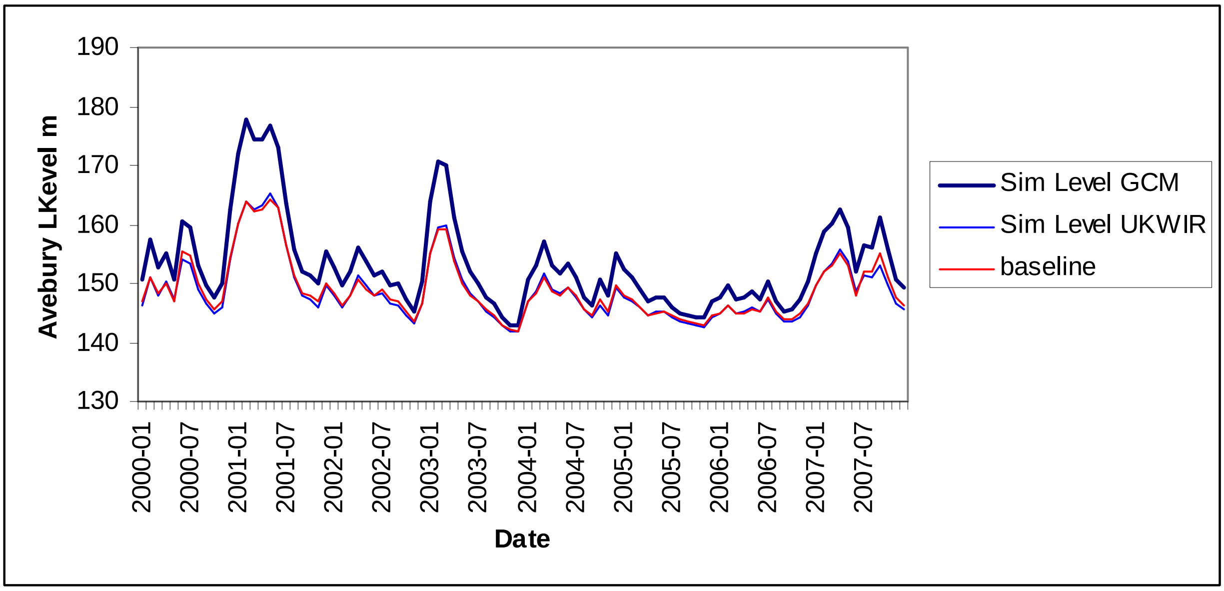


Figure 31: Simulated Avebury baseline levels and the levels based on the GCM Bridge model and the UKWIR scenario

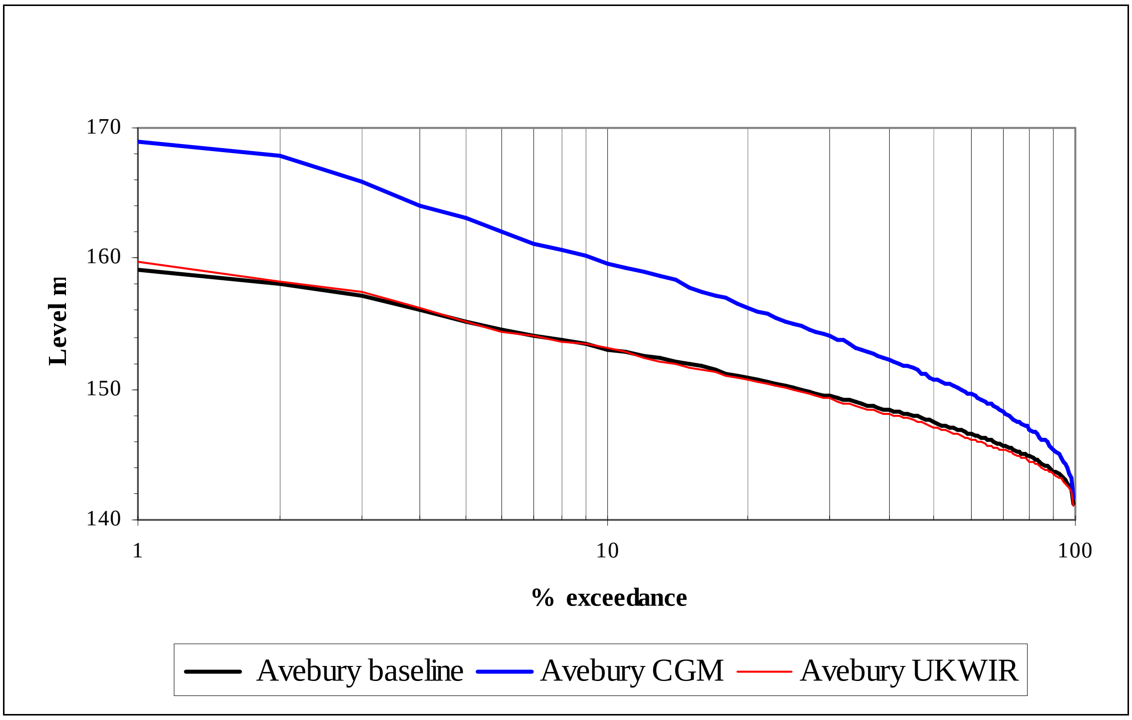


Figure 32: The Level Duration Curve for Avebury for the baseline conditions and the GCM Bridge and the UKWIR climate scenarios

5. DISCUSSION AND CONCLUSIONS

The results from the study suggest that there was a significantly warmer and wetter climate at the time of the construction of Silbury Hill and that this would have generated higher stream flow as well as higher groundwater, and hence, well levels.

Specifically the study has sought to answer the following questions:-

1. Why is the Swallowhead Springs thrown out at its current location?
2. Could it have moved since Silbury was built (ca 4,400 – 4,200BP)?
3. Could the Winterbourne coming down from Avebury have developed since 4,400 BP (in which case Swallowhead might have been the major visible source of the Kennet at the time of Silbury's construction)?
4. Could significant changes such as those outlined in 1 – 3 be brought about by human activities either at the time of construction (e.g. clearance of forest) or subsequently (e.g. water abstraction)?

From our study of the hydrology and hydrogeology we conclude that the Swallowhead spring would most likely have been perennial at around 4500BP. In addition it is likely that the source of the Kennet (and the Thames) would have been in the main river channel very close to the point at which Silbury Hill was constructed. It is not considered that the drainage pattern would have been different from today at this time. Also because of the wetter climate and hence higher flows in the streams, it is very unlikely that the winterbourne would have developed since 4400BP; the topography of the Winterbourne would have been established over the whole Quaternary era.

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; 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 33 shows a map of the height contours for the area and shown on the map are the 145, 150 and 150m contours, where they cross the riverbed. From the Avebury level duration curve (Figure 32), the levels for the 50 percentile probability (ie the mean condition) are 147m under the current condition and 152m under the condition estimated by the models for 4500BP. This suggests that on average the mean groundwater levels were 5m higher than at present.

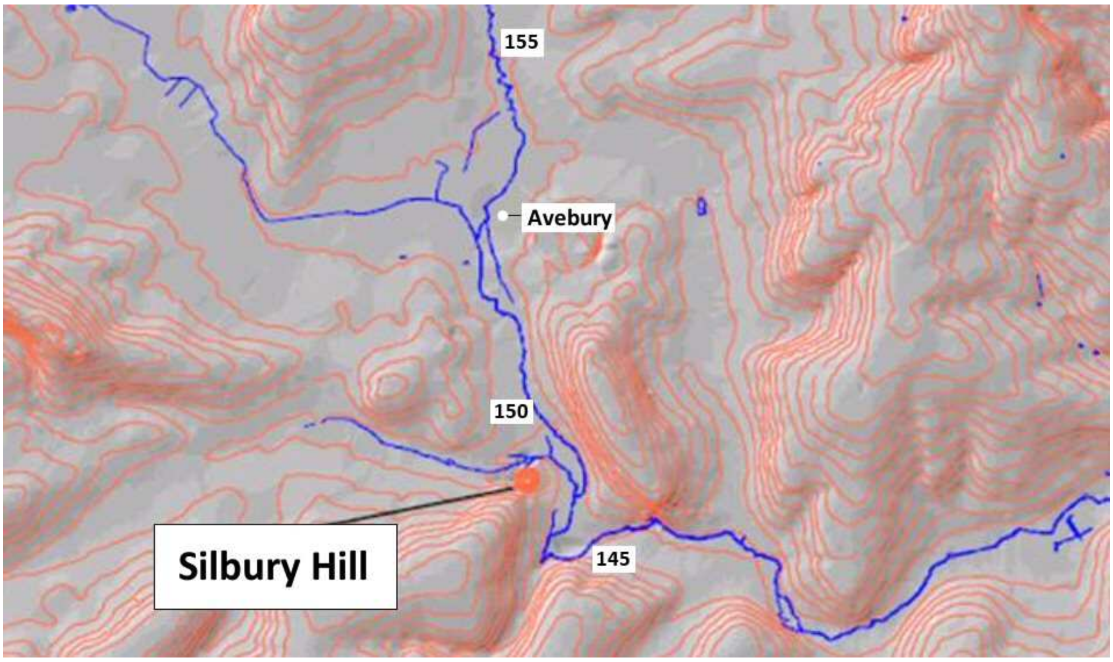


Figure 33: Map showing height contours at points that cross the upper Kennet streambed

Thus, according to Figure 33 the mean stream head would move upstream from exactly the location of the Swallowhead Spring to the centre of Avebury. This is an important result as it suggests that there would have been a good flow of water into the stream for a longer proportion of the year and that the flatter land in the area would have been saturated. Therefore, from a water perspective we conclude that in the past Avebury and Silbury Hill would have been a more sustaining environment than it is now, enabling a large population to live in the area.

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APPENDIX 1

An Overview of the IHACRES Model Structure and Calibration to the Upper Kennet

IHACRES is a time series approach to modelling that has been developed from the early times series algorithms developed by Young (1974) and originally applied to model rainfall river flow relationships by Whitehead (1979). The modelling approach was improved by Jakeman *et al* (1990) and published (http://www.ceh.ac.uk/products/software/water.html) as a stand alone package which has been widely used by researchers and hydrologists in the water industry (Littlewood *et al* 1997; Littlewood *et al* 2003; Littlewood 2008). Croke *et al* (2005) later released a more powerful IHACRES package which is now available from http://www.toolkit.net.au/ihacres. There are variants of the IHACRES model structure. 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 1, which also gives brief descriptions of the six key catchment characteristics that are obtained from an IHACRES analysis.

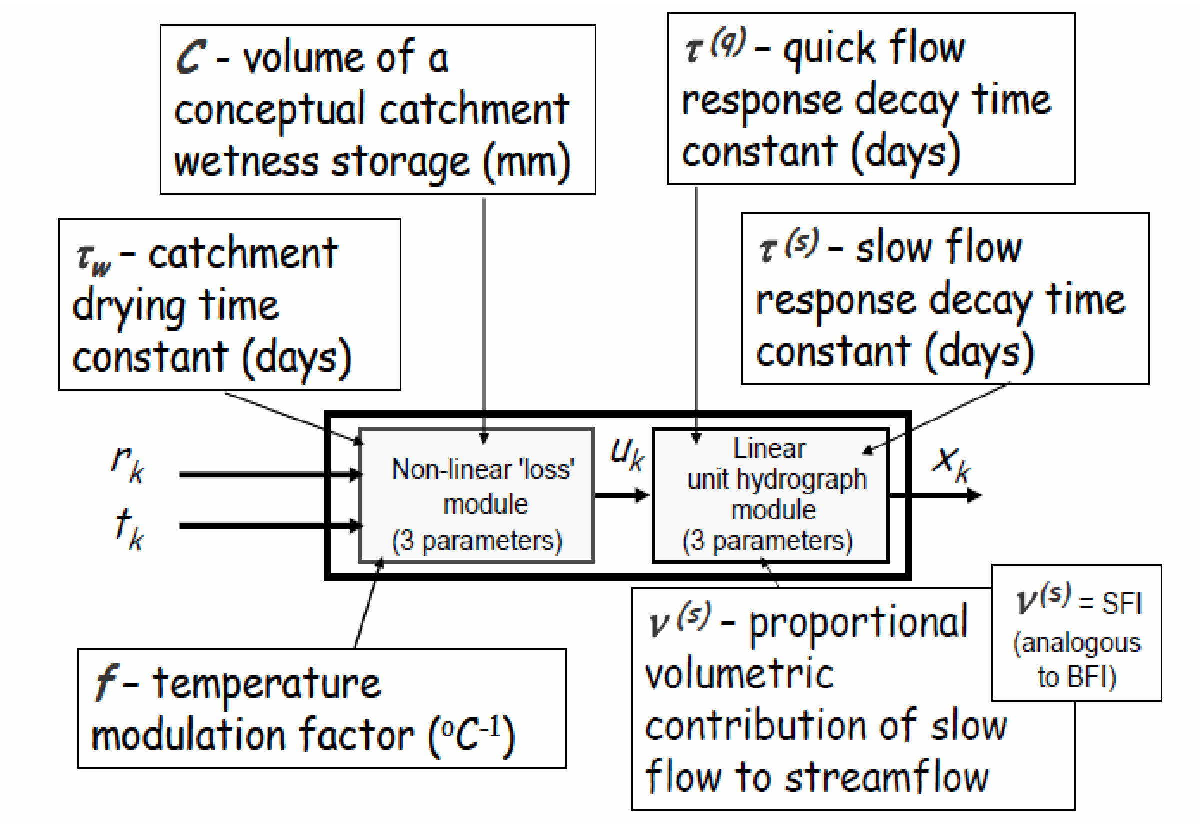


Figure 1: Basic Structure of IHACRES and the key catchment characteristics

The non-linear loss module is the first component of the IHACRES approach and this effective rainfall module was first developed by Whitehead (1979) and then modified by Jakeman and Hornberger (1993). The equations in IHACRES are as follows:-

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

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

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

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 1.

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 now that portion of rainfall (r_k) that eventually becomes stream flow. The a and b parameters define first-order transfer functions ($-1 < a^{(\cdot)} < 0$, $b^{(\cdot)} > 0$), 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 $u^{(s)}$ 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.

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

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

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

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

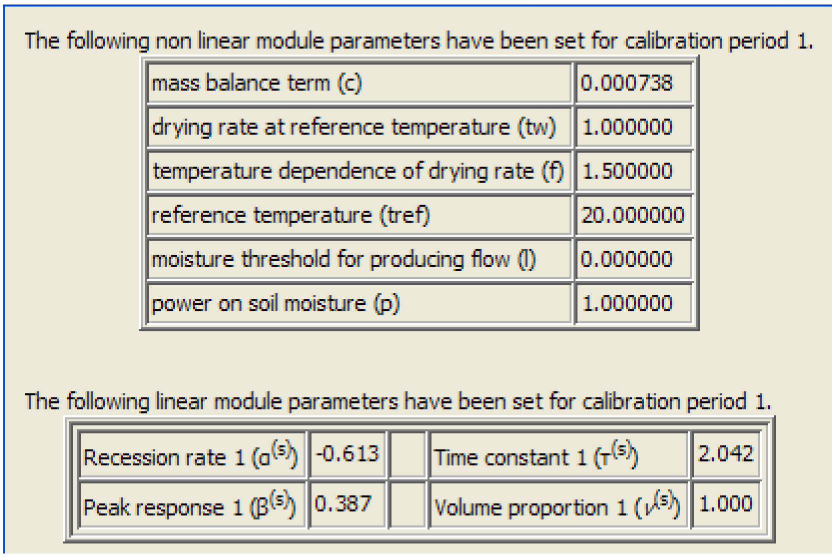
From Equation 4 it follows that modelled quick- and slow-response hydrographs, i.e. $Q^{(q)}{}_k$ and $Q^{(s)}{}_k$ for k = 1, m where m is the number of time-steps in the length of record being used for model calibration, are calculated by recursive application of Equations 9 and 10 respectively, where $Q_k = Q^{(q)}{}_k + Q^{(s)}{}_k$. 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.

$$Q^{(q)}{}_k = b^{(q)} u_k - a^{(q)} Q^{(q)}{}_{k-1} \tag{9}$$

$$Q^{(s)}{}_k = b^{(s)} u_k - a^{(s)} Q^{(s)}{}_{k-1} \tag{10}$$

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. The IHACRES model is first calibrated using the available data and the best estimated parameters obtained are shown in Figure 2. The model simulated levels compared to the observed levels are shown in Figure 3.



The following non linear module parameters have been set for calibration period 1.

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

The following linear module parameters have been set for calibration period 1.

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

Figure 2: The parameters for the non-linear loss model and the linear transfer function model

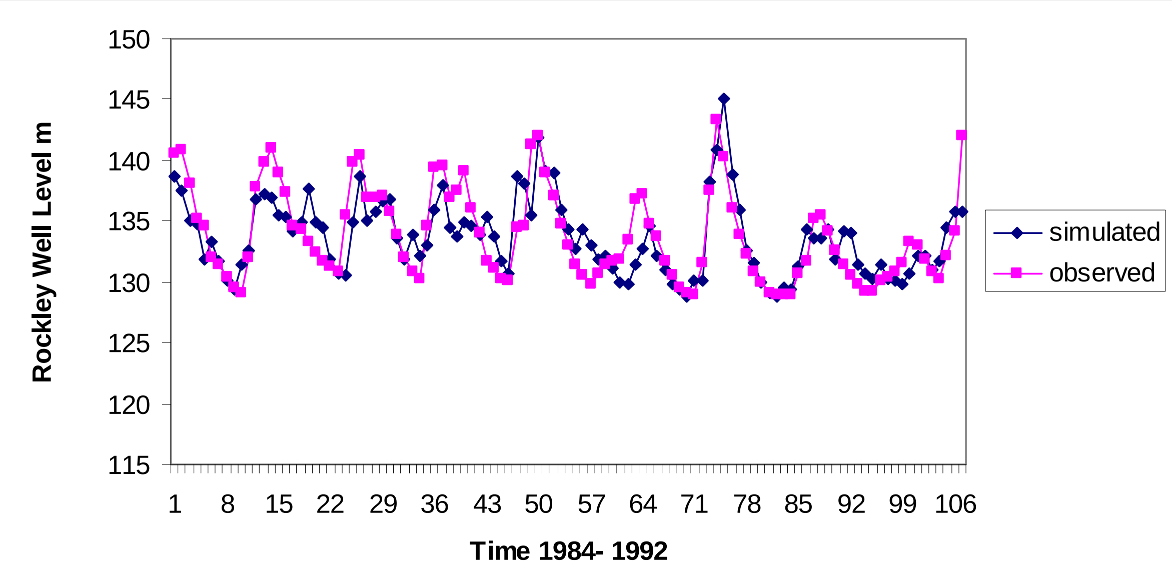


Figure 3: Simulated and observed Rockley well levels using the IHACRES model

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