The Study of an Anthropogenic Tufa Deposit at Harpur Hill, Buxton, Derbyshire.

Stephen Frazer Rhodes

A Dissertation Submitted in Partial Fulfilment of the Requirements for the Degree of BSc (Hons) Geography.

April/1999.

Department of Geographical and Environmental Sciences,
The University of Huddersfield

Abstract

Anthropogenic tufa is a soft, porous calcareous rock that has been deposited by natural processes following human activity. The anthropogenic tufa observed at Brook Bottom, Nr. Harpur Hill, Buxton, Derbyshire, is believed to be the only landform of this type in existence. The human activity that has lead to the deposition of the tufa, is the extensive dumping of lime ash, the waste product from lime burning, onto a series of natural springs. Spring waters become saturated with calcium hydroxide from the lime ash waste and through a chemical process deposits this as tufa within the Brook Bottom stream.

The two central aims of the study were firstly, to determine the rate of tufa deposition and distribution in time and space, and secondly, to determine the development of the Brook Bottom site since 1883, and the possible future of the site.

Primary data collection was undertaken over an eleven-week period (18/08/98-27/10/98). This involved the placement of three microscope slides at fifteen equidistant sites within the Brook Bottom stream. These were replaced, each week with a set of previously weighed slides. The tufa-encrusted slides were taken to a laboratory at the University of Huddersfield to be re-weighed. At each of the fifteen sites, the water pH, conductivity and temperature and the stream velocity were measured each week over the eleven-week period. Discharge was also measured at sites eleven and fifteen using two 90° V-notch weirs, again this was recorded each week over the eleven-week period. Finally, a survey of the stream/tufa deposit was undertaken using a theodolite/total station in order to produce an accurate map of the brook Bottom site.

In terms of secondary data, both rainfall and air temperature data (recorded at Buxton) were obtained. Previous Ordnance Survey maps of the Brook Bottom site were also consulted, as were aerial photographs which were used in conjunction with local literature to assess the history of the Brook Bottom site.

The data were analysed to determine whether any relationship existed between the rate of deposition and four environmental parameters: conductivity of water at the time of slide removal, pH, air temperature, and total rainfall at Buxton over seven days prior to slide removal. Long-term deposition rates were also extrapolated over one year, and for one hundred years. The depth of deposition and the rate of deposition were used in conjunction with the local literature in determining the history of the site and the probable age of the tufa deposit.

The data show that the rate of tufa deposition at the Brook Bottom site ranges from 0.0048 – 0.411 g/cm^2/week, notably greater than rates recorded in studies of natural tufa- depositing streams, springs and lakes in the UK. The pH and conductivity levels recorded at the site are also greater than those recorded in studies of natural tufa-depositing streams, both in the UK and abroad. The rate of tufa deposition at the Brook Bottom site varies in both time and space. At both the micro and meso-scale, large variations in the rate of deposition are apparent. At the macro-scale, or over longer periods of time broad trends within the deposition data can be recognised. Analysis of the data set showed that no clear relationship exists between the rate of deposition and the selected environmental parameters, pH, conductivity, total rainfall and air temperature. Finally, the anthropogenic tufa at Brook Bottom originated or began to form circa. 1890, when the construction of the wagon repair works at Harpur Hill allowed the transportation of lime ash from the Hoffman Kiln works to the Brook Bottom site. The tufa has therefore developed to its present state in a surprising short period of approximately 110 years.

'I, Stephen Frazer Rhodes certify that all the research described in this dissertation, except where clearly acknowledged, is my own work. Except where shown by quotation marks and appropriate referencing, the language in this dissertation is my own. I understand that "where a MAAB is advised that a student has submitted a project that has been plagiarised, it will normally decide that the student has failed the module.." (University of Huddersfield Students Handbook of Regulations, 1997 edition, p. 13)'

Stephen Frazer Rhodes.

Acknowledgements

Foremost, I acknowledge the continual guidance of Professor John Gunn throughout the completion of the study. I acknowledge the help received from Dr Paul Hardwick, Katie Kirk and Nicholas Spicer, who all assisted with fieldwork. I acknowledge the assistance of Neil Webber, who undertook the water chemistry analysis, Dr Jill Labadz who assisted with the reproduction of the theodolite/total station data, and Richard Hughes who provided much of the necessary equipment required for the study. I Acknowledge the Peak District National Park Centre, Buxton Library, Matlock Public Records Office and the High Peak Borough Council for providing the secondary data necessary for the study.

Finally, but by no means least, I acknowledge the continual support from my parents (including financial!) without whom it would not have been possible to undertake the investigation, and acknowledge the support I received from Alison Sykes during the final, and stressful! stages of the study.

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1. Introduction

The following study is an investigation of a tufa-depositing stream that has resulted from human (anthropogenic) activity. The phenomena is situated approximately 2 km south of Buxton, Derbyshire, and less than one km east of Harpur Hill, Derbyshire, within a small valley known locally as Brook Bottom, Grid Reference SK 055710 (see Figure 1.1).

The human activity that has resulted in the deposition of calcium carbonate to create the tufa, is the extensive dumping of lime ash, which is the waste product from lime burning. Spring waters become saturated with calcium hydroxide from the lime ash waste and through chemical process deposit this "load" within the Brook Bottom stream.

1.1 Aims of the Study

The study had essentially two central aims:

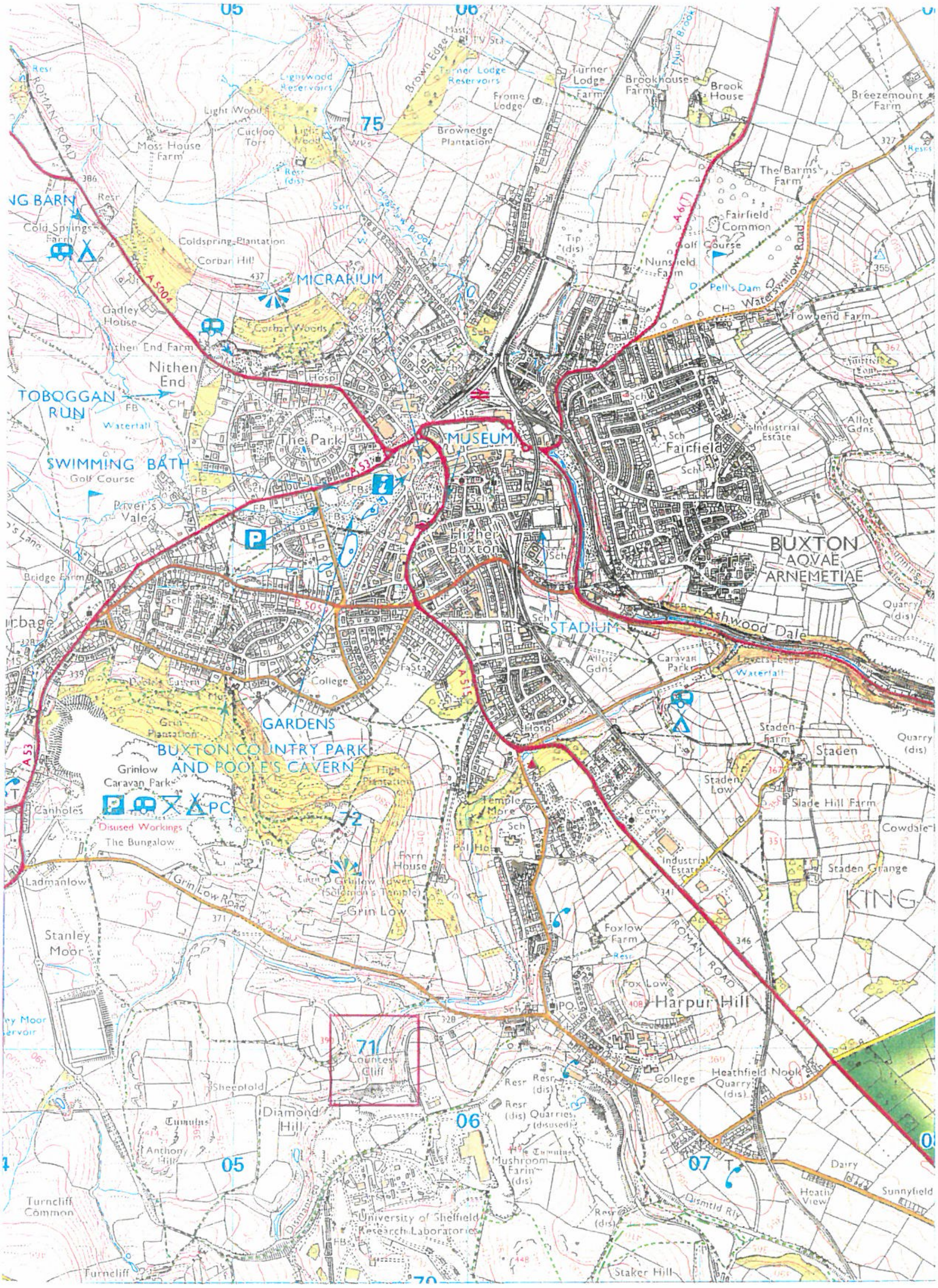
1. **To determine the rate of tufa deposition and distribution in time and space.**

2. **To determine the development of Brook Bottom since 1883, and the possible future of the site.**

The first aim of the study was achieved by the collection of primary data, i.e. data recorded in the field. The primary data consisted of stream velocity, stream discharge, water pH, water conductivity, and measurements of deposition. This primary data was then examined using a number of statistical/analytical methods in order to draw conclusions from the data and thus ascertain the first aim of the study.

The second aim primarily involved the use of secondary data. This secondary data consisted of aerial photographs and previous maps of the site. Overlays were then produced from the maps to

Figure 1.1: The location of the study site in relation to Buxton, O.S. Grid Reference SK 055710



Source: 1:25000, Ordnance Survey, Outdoor Leisure 24, The Peak District, White Peak Area.

examine the history of the site, and the results were combined with the conclusions from the first aim of the investigation in order to complete the second aim of the study.

1.2 Objectives of the Study

In order to successfully achieve the two defined central aims; a number of objectives were defined:

1. To undertake a pilot study to determine the feasibility of the study and/or most suitable and effective methods of data collection.

2. To measure deposition at a number of pre-defined sites, within the stream, over an eleven-week period, with regular data collection.

3. To measure stream velocity and discharge at a number of pre-defined sites, within the stream, undertaken over an eleven-week period, with regular data collection.

4. To measure water pH at a number of pre-defined sites, within the stream, undertaken over an eleven-week period, with regular data collection.

5. To measure water conductivity at a number of pre-defined sites, within the stream, undertaken over an eleven-week period, with regular data collection.

6. To survey the tufa/stream using a total station/theodolite, and to produce an accurate map of the site using a computer aided design package.

7. To analyse and evaluate both primary and secondary data using appropriate techniques.

1.3 Terminology

It can be observed within the literature that there are a variety of terms for freshwater carbonate deposits, that many are similar in meaning and that the two common terms tufa, and travertine, are often used interchangeably. However, some authors perceive the two terms as relating to characteristically different forms of carbonate deposit. Ford and Williams (1991, p. 20) describe travertines as:

"*...crystalline, quite dense calcite that is usually well layered, lustrous and lacks visible plant content*".

However, they describe tufa as:

"*...granular deposits accreting to algal filaments, plant stems and roots at springs, along river banks, lake edges etc. Tufa is often a sort of framestone. It is typically dull and earthy in texture, and is highly porous once the vegetal frame rots out.*" (Ford and Williams, p.20).

In contrast, Ford and Pedley (1997) suggest that tufa is regarded as a freshwater limestone deposited from spring systems at ambient temperatures, whereas the term travertine is reserved for deposits formed from thermal waters. From the literature, associated definitions and classifications of tufa, it is clear that the phenomena observed at Harpur Hill, Buxton, is a tufa formation. However, the attributes associated with freshwater tufas may not apply to an anthropogenic form of this type.

1.4 Geological Background to the Peak District.

The Dinantian Rocks present in the Peak District can be classified as a marine sequence, mainly composed of limestones with small areas of shales and sandstones. In the early Dinantian it is probable that carbonates were deposited throughout the region although they are only exposed in the Dovedale-Ecton-Caldon Low area, in the South West of the region (Harrison and Adlam, 1985). In the later Dinantian, select areas of the Peak would have been characterised by shallow, well oxygenated seas, particularly in northern, central, and south-west areas (the Derbyshire and Staffordshire shelf respectively), while an area of deeper water covered the intervening "off-shelf" area (Aitkenhead *et al* 1985).

Uniform pale-coloured limestones were deposited on the "shelfs" over a wide area, although, the off-shelf areas allowed a much greater variation in sequences. During the closing stages of the Dinantian, both on-shelf and off-shelf areas experienced localised volcanic eruptions, this lead to intrusion of lavas into the limestones. Finally at the close of the Dinantian period, Carbonate deposition ceased and was replaced with the deposition of muds and sands during the Namurian. During this deposition period earth movements were relatively minor, although, relatively large-scale movements took place at the end of the Carboniferous. These larger movements did not affect the shelf limestones to any great degree, although, the rocks between shelfs were folded and deformed into a series of north and north-westerly trending folds.

Following this "folding period", erosion and alteration of the rocks took place. This included the change of some limestone to dolomite, possibly during the Permian, and the mineralisation of limestone from the Carboniferous through to Jurassic times, when some of the fissures in the limestones were in places infilled with calcite, baryte and fluorite, locally containing lead, zinc and copper ores (Harrison and Adlam, 1985).

During the Tertiary period uplift of the land resulted in the removal of the post-Dinantian rocks and the subsequent deposition of fluvial and lacustrine sands and clays onto the limestone. Finally, the most recent deposits within the Peak District are essentially surface drift – boulderclay and head deposits, which date from the Quaternary period.

2. Description of the Study Area

2.1 The Field Study Site

As stated previously, the study focuses on a small stream near Harpur Hill, approximately two kilometres south of Buxton, (Grid Reference SK 057711). The site in question is known locally as "Brook Bottom" or "Countess Cliff" and essentially encompasses a tufa depositing stream within a small, relatively steep sided valley. On initial inspection the stream appears to originate from an adit situated below an area of extensive lime ash tips, the waste product from lime burning (Appendix 1, Plate A2.11, A2.12). The entrance to this adit is located approximately five hundred metres south-west from it's exit. The water source that enters this adit and subsequently exits to continue as a small stream, rises from a number of springs which are located south-west of the adit entrance (Appendix 1, Plate A2.13, Plate A2.14).

The stream, which originates from the adit at the foot of the spoil tips, is the main focus of the study. Within this stream, terraces of tufa produce a step-like topography from the exit of the adit to a confluence with an adjoining stream. The main body of tufa occurs at the foot of the lime ash tips and continues for approximately 150 metres before the first major terrace can be observed (Appendix 1, Plate A2.15). From the first terrace, a second large mass of tufa can be recognised and this continues for approximately 200 metres before a second main terrace occurs. However, this second main terrace is characterised by a number of smaller terraces that have produced a distinctive step-like topography (Appendix 1, Plate A2.16). The majority of the stream water flows down these smaller terraces and forms a main stream channel. Within this stream, smaller terraces are present at regular intervals as the stream flows towards a confluence with an adjoining tributary stream, approximately 200 metres downstream of the second main body of tufa.

It is clear from field observations that the formation of the terraces and thus, the deposition of tufa, are occurring at an astonishing rate. The study therefore focuses upon determining the rate of deposition, the possible spatial variances in deposition, and probable future trends. However, the study does not attempt to fully quantify the cause of deposition and/or the mechanisms of this deposition.

3. Historical Background

3.1 Historical overview of Lime Burning.

The use of lime, and the burning of lime within Britain, can be traced to the Roman period when buildings were constructed with limestone and cemented with lime morter. There is a wealth of evidence to suggest that lime was used in the smelting of metals, particularly lead, in the county of Derbyshire up until the 16th and 17th centuries. During the early seventeenth Century coal replaced wood as a fuel source, it is suggested by Jackson (1950, p.9) "*...that the use of local coal marks the birth of the Buxton Lime Trade*".

The eighteenth century saw improvements in road networks, tramways and canals and thus an increase in production. The opening of the High Peak Railway in 1826 allowed the exploitation of areas south of Buxton. "*The ancient works at Grin now had connection with the canal system and the works near Parkes House (Harpur Hill) was now able to send its lime along the new railway. Consequently the works at Grin and Harpur Hill grew and assumed a greater importance in the trade.*" (Jackson, 1950, p. 12).

In 1872 a large Hoffman Kiln was opened at Harpur Hill. This was a change from more traditional kilns in the district, although the Hoffman type kiln did produce a very high quality lime. However, the high costs of production associated with this type of kiln eventually put the Hoffman kiln at Harpur Hill out of production in 1944 (Jackson, 1950).

Following the First World War, coal mining in the Buxton area ceased and this was accompanied by the mechanisation of the lime and quarry industry. In 1924, the Safety in Mines Research Board purchased a site at Harpur Hill, five hundred metres south-east of the lime ash tips. The Safety in Mines research establishment was opened in June 1927 with a 213 metre explosion gallery, completed in 1928.

Historical Background

From the historical literature available it is possible to estimate a period when the dumping of lime ash commenced, and ceased, at the Harpur Hill site. It would be logical to suggest that the regular deposition of lime ash would have been greatly influenced by the opening of the High Peak railway in 1826. However, perhaps further influenced by the construction in 1890 of wagon repair works immediately south of the lime ash tips, which was connected by rail to the Hoffman kiln works. As lime production declined, and production costs increased for Hoffman style kilns, it was inevitable that the Hoffman works at Harpur Hill closed (c. 1944). It is therefore probable that the dumping of the lime ash waste ceased around this period.

It can therefore be concluded that lime ash waste was deposited at the Harpur Hill site for approximately 60 years, considering a "start date" of 1883 and a "finish date" of 1944. The relevance of this time period will be apparent in consideration of the rate of tufa deposition and terrace growth rates.

4. Literature Review

None of the sources consulted specifically refer to anthropogenic tufa or to the Harpur Hill/Brook Bottom site and Gunn (pers. comm.) has stated that he is unaware of any previous research at the site. The literature which has been consulted is essentially of two types: firstly, articles which essentially provide an introduction or overview of tufa phenomena, and secondly articles which specialise on particular aspects of tufa and travertine studies.

The diversity of studies of tufa and travertines is noticeable; for example, studies have been undertaken concerning the climatic controls on the morphological fabric of tufa (Pedley *et al*, 1996), the hydrodynamic control of inorganic calcite precipitation (Zaihua *et al*, 1995), the late-Holocene tufa decline in Europe (Goudie *et al*, 1993), and reconnaissance studies of the tufa deposits of the Napier Range, N.W. Australia (Viles and Goudie, 1990).

Classifications of tufa are also prevalent within the literature. For example, Pedley (1990) attempts to classify and define environmental models of cool freshwater tufas. Within the article tufa deposits are subdivided into groups such as "Intraclast tufa", "Microdetrital tufa" and “Peloidal tufa". The Pedley classification essentially integrates a diverse range of classification approaches. For example, Pentecost and Lord (1988) adopted a botanical approach, Geurts (1976) attempted a classification based on physichemical and biochemical parameters, Symoens *et al* (1951) chose a geomorphological approach, and Buccino *et al* (1978) employed a petrographical approach. The article, however, does not contain a classification for anthropogenic tufa or a suggested equivalent. Therefore, whilst this article was useful in providing a framework for classifying and/or identifying natural tufa, in terms of the phenomena at Harpur Hill, further research is needed to create a separate individual classification, or to place the tufa under investigation within a pre-defined category.

There are a number of articles which seek to provide an overview of the nature and origins of tufa. For example, the aptly titled "Tufa, the Whole Dam Story" (Ford, 1989), and "Tufas, travertines and allied carbonate depositts" (Viles and Goudie, 1990) These articles outline the origins of the word "Tufa" and aim to provide succinct descriptions of the various proposed mechanisms of deposition. The outlined mechanisms of deposition can be associated with the amount of $CaCO_3$ dissolved in water, in relation to the CO_2 content of the water, the amount of rainfall, the duration of contact with the limestone, the residence time within the limestone, the degree of supersaturation, the degree of "contamination" with humic acids, fulvic acids, and organo-phosphates, the metabolic activity of micro-organisms, the degree of biochemical processes, and the alkalinity of the waters. This is by no means an exhaustive list and it is clear that a large number of variables control the deposition processes and the morphology of tufa. As stated previously, the present study does not attempt to identify the exact depositional processes which are forming the tufa at Brook Bottom, but, it is still important to understand the different mechanisms of deposition as this is a much debated field of karst, and one which is often the basis of tufa and travertine studies.

Ford (1989) provides an account, in relation to published literature, of significant British and foreign tufa. For example, in terms of British tufa deposits, the article highlights the tufa cascades at Gordale Scar, Malham (Pitty, 1971, Pentecost and Lord, 1988) and the tufa deposits at Lathkill Dale, Derbyshire (Burek, 1977, and Towler, 1977). In terms of foreign tufa deposits, the "general" articles consider the classic "travertine marbles" such as the tufa deposits of Bagni Di Tivoli east of Rome (Chafetz and Folk, 1984), the extensively studied tufa of Plitvice, Yugoslavia (Anon, 1965; Sweeting, 1972; Stoffers, 1975; Srdoc *et al*, 1985), the tufa of Falling Spring Creek, Virginia, U.S.A. (Lorah and Herman, 1988), and the thermal tufa terraces at Pamukkale, Turkey (Ekmekci *et al*, 1995).

Many of the studies highlighted within such articles, on further inspection, display methodologies, results and conclusions which are relevant to the present study. For example, Pentecost (1981), provides an account of growth rates and the geomorphology of a previously studied tufa stream, Howgill, and states (p. 379) that "*The growth rates of the tufa deposits in Howgill are 0.2 - 0.34 mm* a^{-1} *(Pentecost, 1978) and detailed studies of* Rivularia *incrustations in the area gave rates of 0.2 - 1.6 mm* a^{-1}".

Towler (1977, p. 89) states "*It was assumed that the Alport spring in its present condition deposits one gram of tufa per day, and it has been ascertained that one cubic centimetre of tufa weighs approximately two grams, then a rough calculation shows that the spring would deposit 183 cubic centimetres of tufa in one year*".

Viles and Goudie (1990, p. 31) state "*Rates are highly variable, ranging from < 1 mm per year to circa 0.5 m per year, depending on environmental factors and also the method of measurement/estimation used*".

Although the deposition or growth rates defined by these articles apply to natural tufa, the deposition rate values obtained from the study of the Harpur Hill tufa can be compared with these "natural values" to determine whether the deposition rates for the anthropogenic tufa are higher or lower than the "norm".

L. Zaihua *et al* (1995, p. 3089) provide an account of the methodology employed by Dreybrodt *et al* (1992) to measure calcite deposition rates in a small spring-fed stream, the Westerhofbach, and state that " *Precipitation rates were measured by immersing specimens of Carrara marble or local natural limestone of 3 x 3 x 0.4* cm^3 *into the stream. After a period of only three days the weight increase due to deposited calcite on the specimens amounted to several tens of milligrams and could be easily measured*".

A similar method was employed by Towler (1977, p. 89) whereby: " *...a quantitative estimation of the rate of tufa accumulation was attempted, using the method developed by S.T. Trudgill, by placing weighed limestone tablets at predetermined sites, changes in the flow of the River Lathkill rendered it physically impossible to ensure that the tablets remained in a constant flow of water where they would be subject to the deposition of calcium carbonate*".

This method of immersing objects with a fixed area into a tufa stream to record the precipitation rate, is the procedure which was employed at the Brook Bottom site.

The importance of water chemistry was briefly mentioned earlier in terms of the mechanisms of tufa deposition, and it appears from the literature that most research into tufa phenomena involves the sampling of water chemistry in terms of water pH, water conductivity and the dissolved oxygen content, as these chemical characteristics are possibly key factors in determining the type of tufa formation, the rate of deposition and the mechanism of deposition.

It was therefore essential that a programme of water sampling was undertaken at the Brook Bottom site firstly, to examine how the water chemistry changes over time, and secondly to determine any relationship between water chemistry and deposition rates.

In general the literature consulted does not relate to the study of the anthropogenic tufa at Harpur Hill. However, there are a select number of articles which were relevant in terms of the methodologies for data collection and data analysis which were evaluated and taken into consideration when drafting the research design.

The articles consulted that related in some way to the study in question have been identified above. However, it is quite clear that there is a significant gap within the literature concerning anthropogenic tufa, although this could be attributed to the fact that the tufa observed at Harpur Hill/Brook Bottom is believed to be unique. The study in question should therefore fill this "gap" within the literature and provide a platform for other work/studies within this field.

5. Methodology

5.1 Primary Data Collection.

The study was undertaken over an eleven week period with an initial pilot test undertaken one week prior to the data collection period. Monitoring commenced on the 11th of August 1998 and concluded on the 27th of October 1998, the raw data are provided in Table A5.11 and Table A5.12, Appendix 2.

At the Brook Bottom site, fifteen individual equidistant sites were defined from the adit resurgence (site 1) to a confluence with another stream at site fifteen. A sixteenth site (defined as site zero) was located at the entrance to the adit, approximately 500 metres south-west of the adit exit (Figure 5.12) and temperature, conductivity, and pH were measured at this site.
At each of the fifteen main sample sites, pH, conductivity, and temperature were measured using calibrated meters, and velocities measured using a calibrated flow meter. Discharge data were ascertained using two 90° V-notch weirs which were inserted into the stream at sites eleven and fifteen, discharge levels were then determined from the measured depth of water passing through the V-notch in the weir using the following equation:

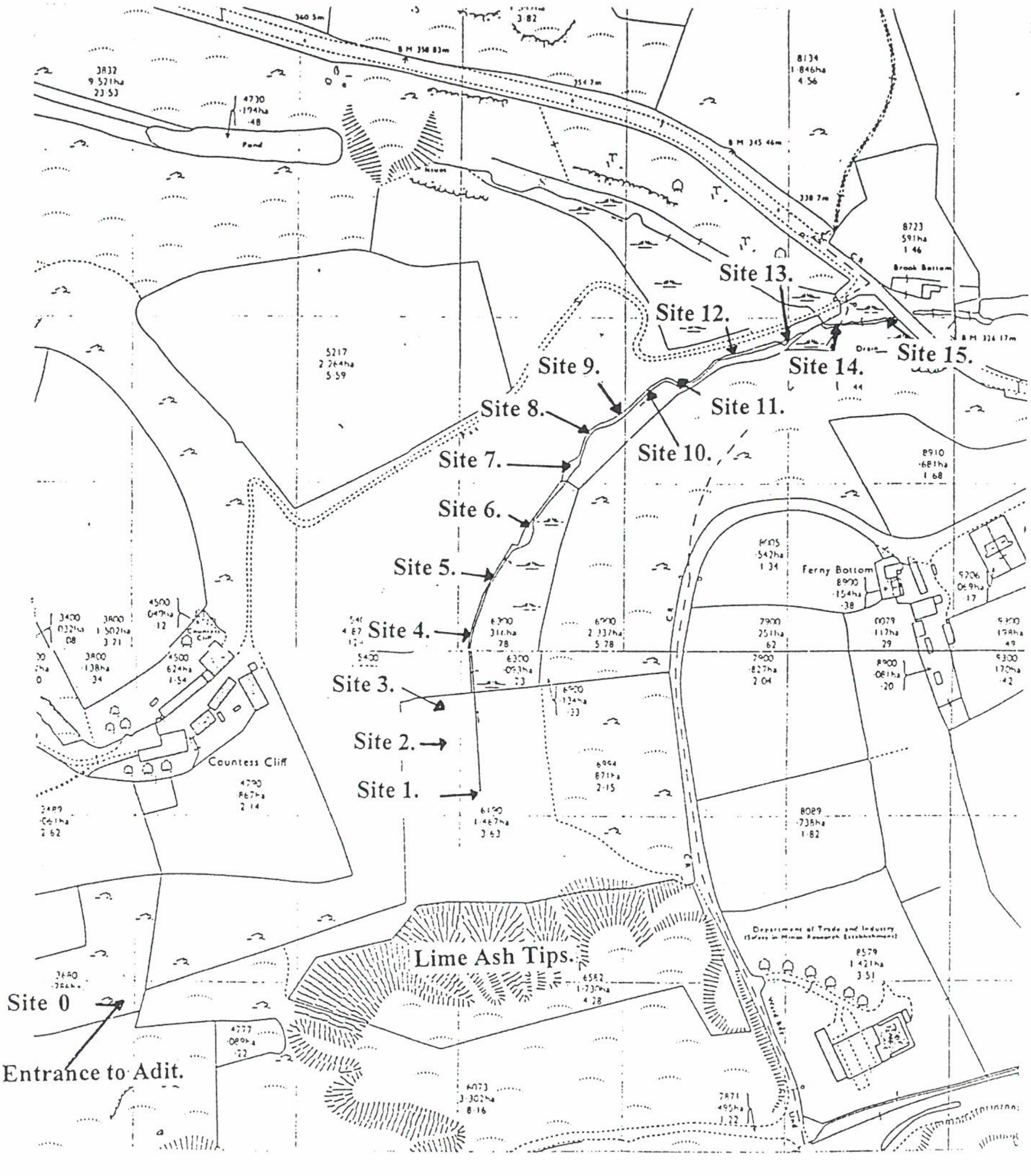
$$\mathbf{1336 \times (h^{2.48})}$$

h = height of water passing through the V-notch in the weir (metres).

In terms of measuring deposition data, it was determined that the most suitable method of recording the weight of any deposit, was the insertion into the stream, of objects with fixed areas, which could be weighed, inserted, and then re-weighed at a future date.

Towler (1977) states that the method of quantitative estimation of the rate of accumulation, using weighed objects at predetermined sites, was developed by S. T. Trudgill. A similar

Figure 5.12: The location of individual sites 0-15 at Brook Bottom



Source: Ordnance Survey, 1:2500, Plan SK 0470-0570, Revised October 1971.

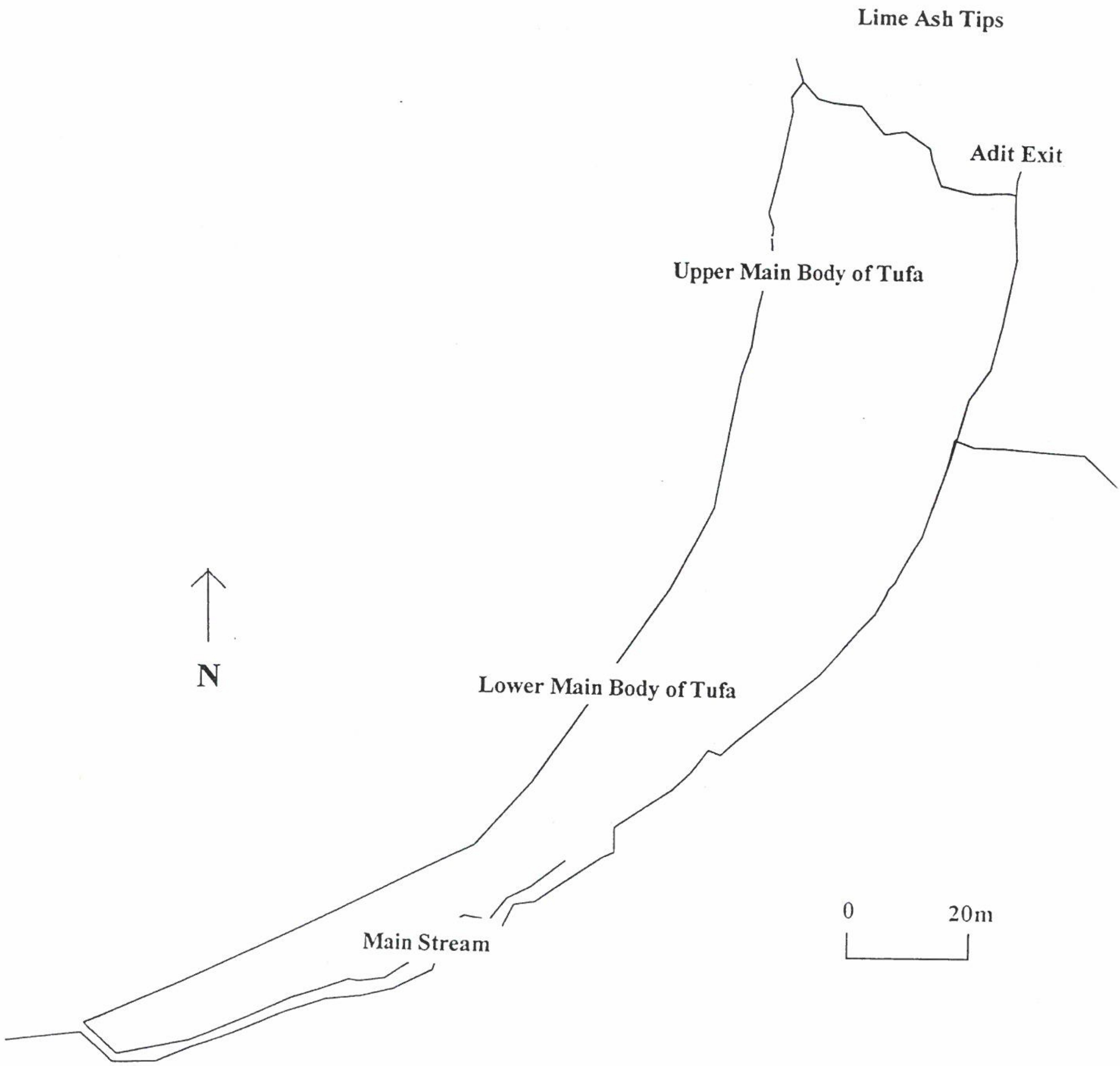
method was employed by Dreybrodt *et al* (1992) to measure calcite deposition rates from a small spring fed stream. As alternative methods to determine the rates of deposition have not been identified within any of the literature consulted, the method developed by Trudgill has been employed in this study.

In terms of the object itself, it was decided that microscope slides would be a successful option as they have a fixed area and can be weighed and re-weighed with relative ease. To determine the slide placement two options were considered; firstly to place the microscope slides upon a fixed object within the stream and secondly to simply place the slides on the stream bed. In order to judge the most successful option, a pilot test was conducted on the 4th of August 1998, whereby three slides were placed upon a building brick at site one, and four slides were simply placed in the stream at site six. On the 11th of August 1998 the results of the test run were assessed, at site one all the slides were in position encrusted with a measurable deposit. At site six however, only one slide could be located which also contained a measurable deposit.

From the results of this test run it was decided that the study should be conducted using microscope slides with a fixed area of 19.76 cm^2, placed upon a fixed object, and as with the test run, building bricks were used. Each week, three previously weighed slides were placed approximately two centimetres apart on each brick at sites 1-15. The following week, the tufa-encrusted slides were extracted, replaced with a new set of previously weighed slides, and taken to a laboratory at the University of Huddersfield to be re-weighed. This procedure was undertaken at each site, every seven days for the period 18/08/98 – 27/10/98.

In order to ascertain an accurate and up-to-date map of the stream/tufa deposit a survey of the site was undertaken with the aid of Dr Paul Hardwick and a PhD student, Katie Kirk, using a theodolite/total station. The data were transferred into a Civilcad programme from which an accurate map was obtained (see Figure 5.13).

Figure 5.13: A map of the Brook Bottom site created using a theodolite/total station.



Finally, following the eleven-week data recording period, water samples were taken from the stream and from a number of springs in the local vicinity of the site. These water samples were analysed in terms of their water chemistry to identify any significant differences between stream water and local spring water. This data is provided within Table A5.12, Appendix 2.

5.2 Secondary data

The secondary data used within the study were obtained from a number of sources. Ordnance Survey maps of the Brook Bottom site were obtained from Buxton library and an attempt was made to determine the date of actual survey as opposed to the publishing date. The survey dates from the four Ordnance survey maps were, 1883, 1938, 1948 and 1971. Each map was converted to a scale of 1:2500 and individual overlays were produced. A digital planimeter was then employed to determine the area covered by the lime ash tips on each of the maps and thus to aid in the assessment of the history of the Brook Bottom site.

Both rainfall and air temperature data used in the data analysis, were obtained from the High Peak Borough Council, in Buxton, with local literature concerning the site, the Harpur Hill area, and the Buxton lime trade obtained from both Buxton Library and the Matlock public Records office. Finally, aerial photographs of the site, dating from 1971, 1984, 1989, and 1995, were attained from the Peak District National Park centre in Bakewell, the best example of which is shown in Figure A5.20, Appendix 3.

5.3 Limitations of the methods/ data sources

In terms of the methods of data collection, a number of limitations can be identified. Firstly, on removal of the microscope slides, there was the possibility of the re-solution of the deposit. However, it was considered from simple calculations, that any re-solution that did take place would be minimal and would not affect the results to any significant degree. Secondly, if the primary data collection had been undertaken over a longer period, it may have been possible to identify seasonal changes within the data set. Thirdly, in terms of the methods of data collection, more representative results concerning the rates of deposition may have been achieved if the recording sites were situated further into the stream/tufa deposit, rather than in close proximity to the stream bank. However, this would have created difficulties in safely extracting slides from the stream and would have caused considerable damage to the tufa/terraces.

In terms of the limitations of the data sources, both the aerial photographs and Ordnance Survey maps can be considered. The aerial photographs of the site were limited to four dates, 1971, 1984, 1989, and 1995, and the scale of the photographs made identification of features difficult and subsequently limited the analysis. Finally, it would have been desirable to have obtained a greater number of early maps, particularly during the period 1850-1950, this would have aided the interpretation of the history of the site and may have provided more accurate conclusions.

6. Results

The full data/results of the weekly water quality data and the recorded deposition on each slide during the period 18/08/98 – 27/10/98 are provided within appendix 2.

6.1 Deposition Data

As three slides were used at each sample site, to record the deposition data, the results may be represented as the minimum deposition rate (lightest slide), the maximum deposition rate (heaviest slide) or as mean average deposition rate (Appendix 4). It was decided that the mean deposition rate would most suitably illustrate the results.

Figure 6.11 illustrates the mean weight of deposition for sites 1-15, for the first six recording dates 18/08/98 – 22/09/98. This graph shows that generally the mean rate of deposition is between 0.00 and 0.04 grams per cm^2 per week at each site (1-15). The graph displays a clear trend in the data between sites 1 – 4, however, downstream of site four there appears to be little coherence in the data.

The rate of deposition increases from site one to site two, increases again from site two to a peak at site three, and decreases between site three and four, this trend is evident for each of the six recording dates. Site three appears to be the area of greatest deposition with values of 0.05803 g/cm^2/week and 0.05111 g/cm^2/week for recording dates 01/09/98 and 08/09/98 respectively. From site four through to site fifteen the data display both increases and decreases in the rate of deposition, however important peaks to note are site seven (0.04588 g/cm^2/week) and site ten (0.04285 g/cm^2/week) at recording dates 01/09/98 and 15/09/98 respectively.

Figure 6.12 illustrates the mean weight of deposition for sites 1-15 for the final five recording dates 29/09/98 – 27/10/98. This graph displays a clearer trend between the rate of deposition

Figure 6.11. Mean Deposition Weights for Sites 1-15.

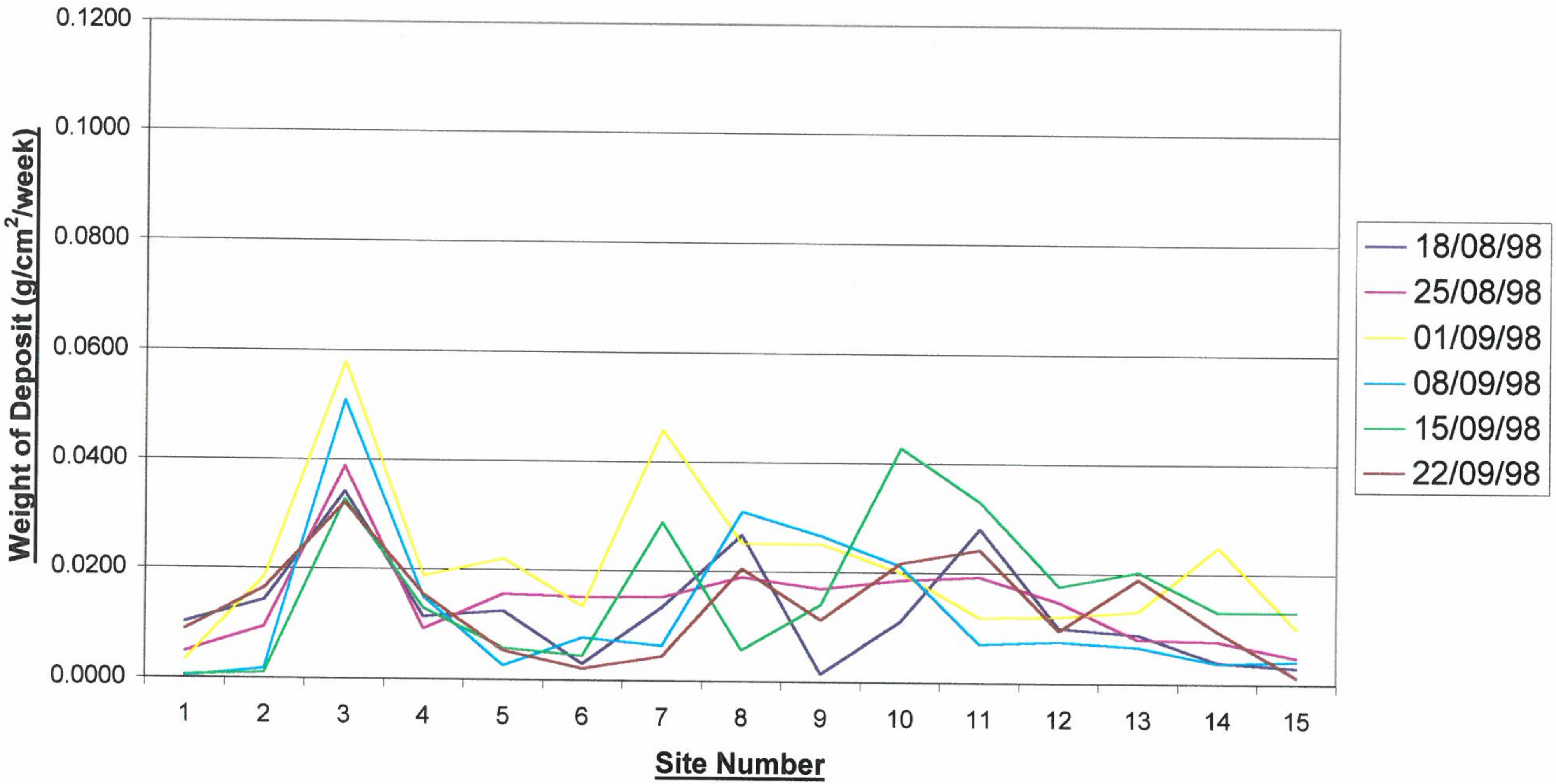
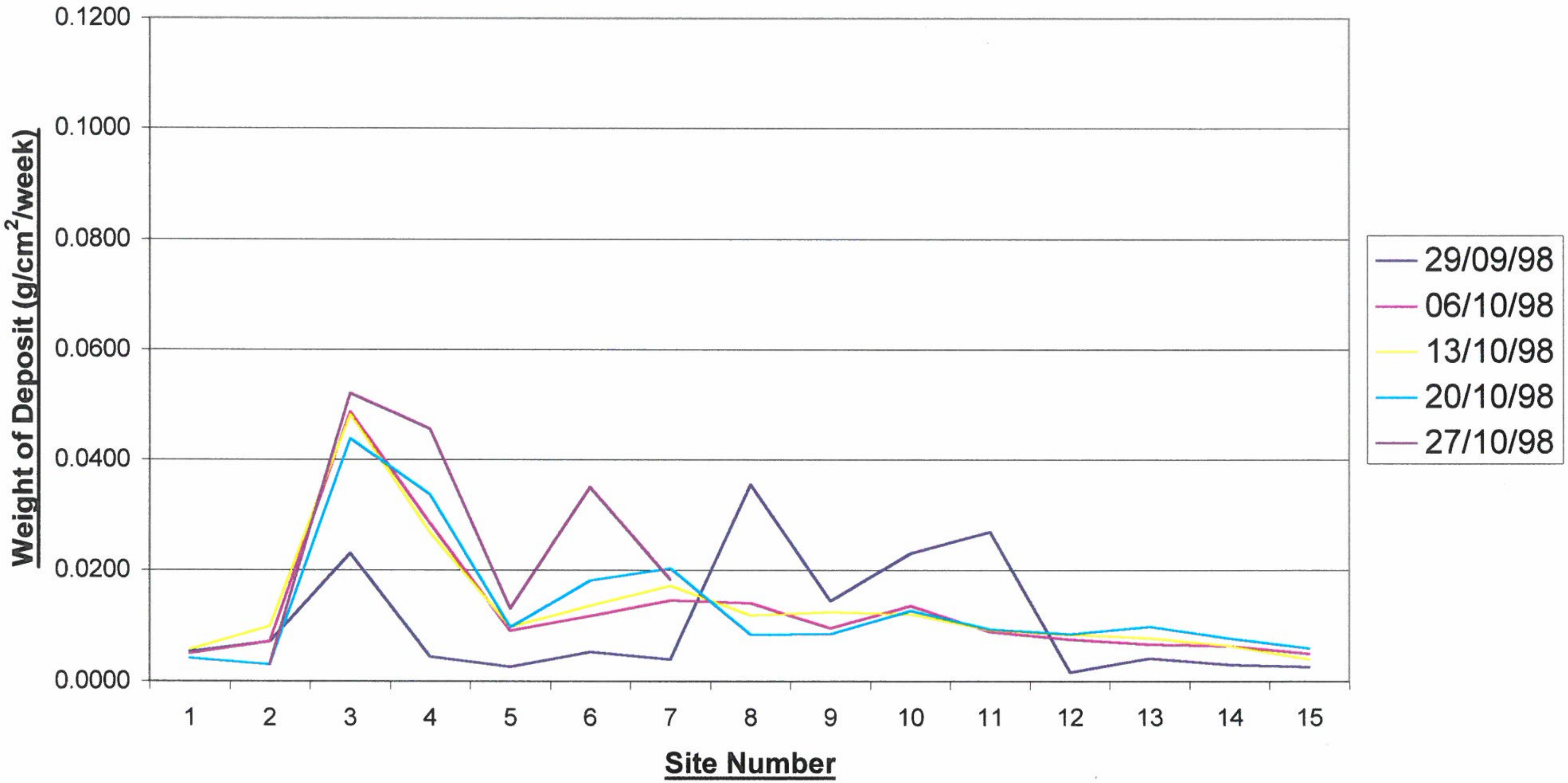


Figure 6.12. Mean Deposition Weights for Sites 1-15.



and site number; again, as with Figure 6.11, the mean rate of deposition is generally between 0.000 and 0.040 g/cm^2/week at each site (1-15).

As with Figure 6.11 the graph shows a clear trend in the data between sites 1-4, however, unlike Figure 6.11, there appears to be an identifiable trend in the data downstream of site four relating to the recording dates 06/10/98, 13/10/98 and 20/10/98. Again, the rate of deposition generally increases from site one to a peak of approximately 0.05 g/cm^2/week at site three, followed by a decrease in the rate of deposition at sites four and five. Downstream of site five, the data for the recording date 29/09/98 does not appear to follow any coherent pattern, however, does show a similar trend to that seen in Figure 6.11.

Data ascertained during the last week of the study (27/10/98), were not recorded beyond site seven as due to the high discharge of the stream, the slides were lost. Finally the data for recording dates 06/10/98, 13/10/98, and 20/10/98 do show a trend between the site number and deposition rate, particularly from site ten to site fifteen. At site ten all three recording dates show a rate of deposition of approximately 0.012 g/cm^2/week, this generally decreases downstream to a deposition rate of approximately 0.005 g/cm^2/week for all three recording dates.

6.2 Water Temperatures

The water temperatures recorded at sites 0-15 for the first six recording dates of the investigation, 18/08/98 – 22/09/98, are shown in Figure 6.21. The graph clearly shows a diverse range in temperatures 7.8 ^{0}C–19.7 ^{0}C, ascertained between each recording date. The graph does however, show a general trend within the data for each recording date. Firstly each temperature rises from site zero generally to a peak at site three, temperatures then generally fall between sites three and five, rise again at sites six and seven, and finally temperatures generally decrease slightly from site eight, then fluctuate between sites nine to fifteen.

Figure 6.21. Water Temperatures Recorded at Sites 0-15.

Figure 6.22 Illustrates the water temperatures recorded at sites 0-15 for the last five recording dates of the study, 29/09/98 – 27/10/98. The graph shows two trends in the data, firstly, the water temperature data recorded on the 29/09/98 appears to coincide with the trend identified in Figure 6.21, whilst the water temperatures recorded between 06/10/98 – 27/10/98 show a different pattern. Each water temperature recorded during this period initially has a low temperature of approximately 7.5 ^{0}C at site zero, water temperatures generally rise slightly downstream to site seven at approximately 9.0 ^{0}C, then generally decrease slightly from site seven through to site fifteen where water temperatures are approximately 8.5 ^{0}C.

The water temperatures recorded on the final dates of the study are generally low and constant from site zero through to site fifteen, and the temperatures recorded are significantly lower than those recorded during the first few weeks of the study.

6.3 Water pH

Figure 6.30 Illustrates the pH levels recorded at sites 0-15 for the first six recording dates of the study, 18/08/98 – 22/09/98. The graph shows two main trends within the data, firstly, the pH data recorded on the 15/09/98 has an initial pH of 7.56 at site zero. The pH generally increases from site zero through to site twelve (pH 8.77), and subsequently decreases from site twelve through to site fifteen (pH 8.40).

The other five sets of data show an entirely different trend, initially the pH levels are relatively high, however, the range of values is quite large (between pH 9.19 and pH 12.35). The pH values generally increase downstream to site three, where the highest recorded value is pH 12.97. pH levels then decrease slightly between sites three and six, and drop substantially at site seven, the lowest value recorded exhibiting a pH of 8.79. pH levels then rise from site seven to site eight, and with the exception of two recording dates, decrease downstream to site fifteen where levels are approximately pH 11.5.

Figure 6.22. Water Temperatures Recorded at Sites 0-15.

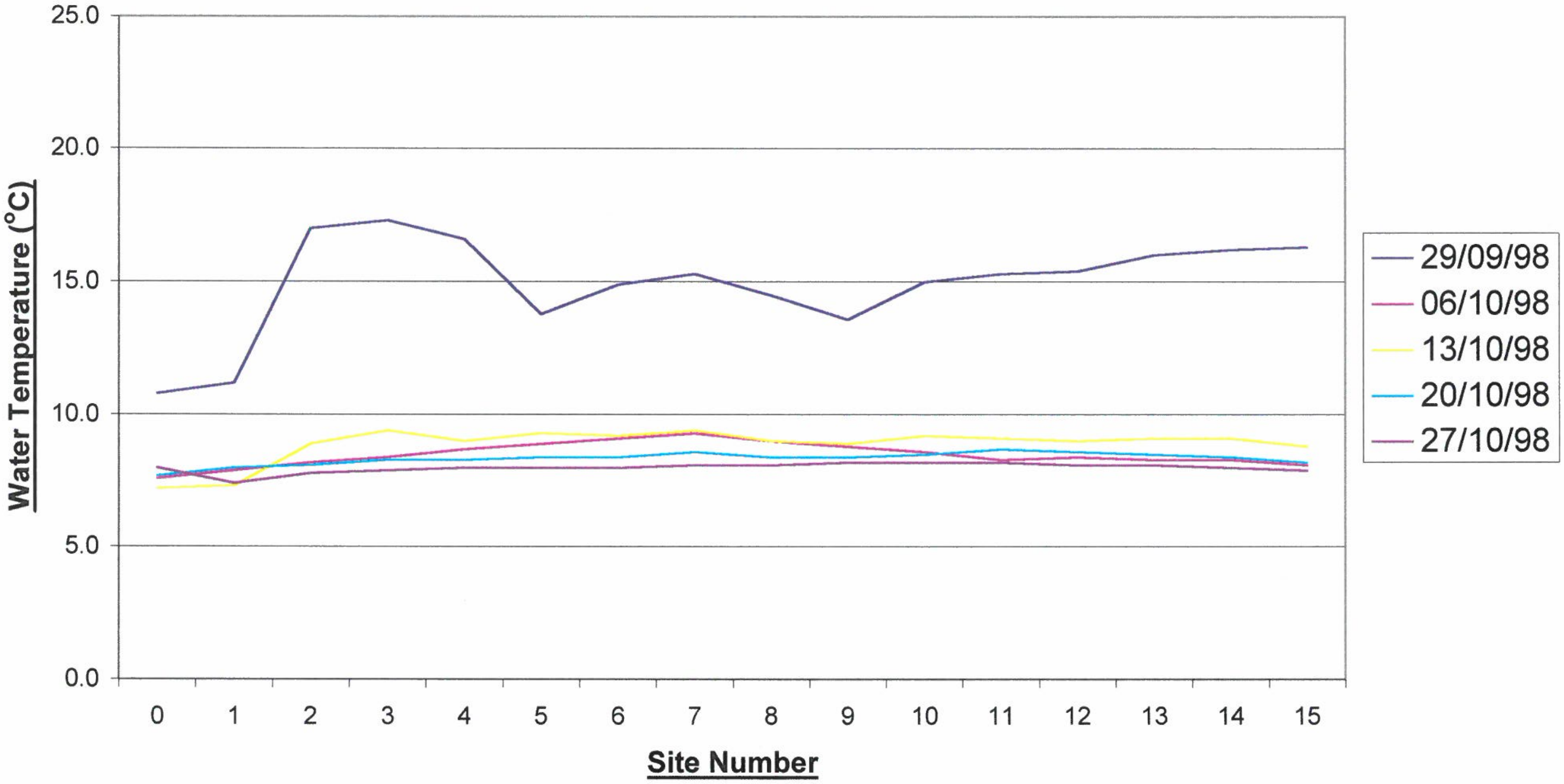
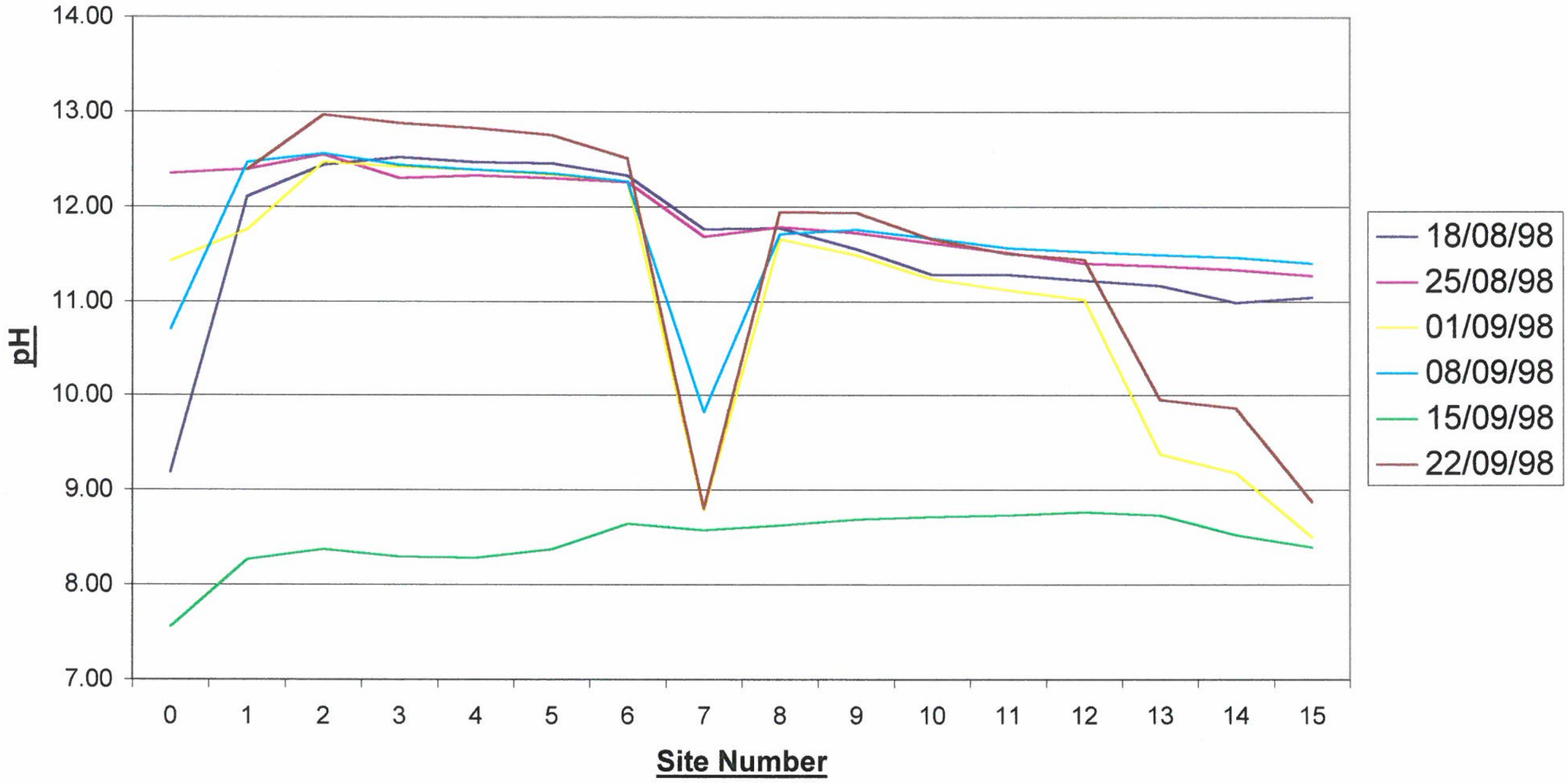


Figure 6.30. pH Levels Recorded at Sites 0-15.



The recording dates that are the exception are 01/09/98 and the 22/09/98, on these dates the pH levels increased from site twelve downstream to site fifteen where the recorded values are approximately pH 8.5.

Figure 6.31 Illustrates the pH levels recorded at sites 0-15 for the final five recording dates of the investigation, 29/09/98 – 27/10/98. The graph displays a sharp contrast to Figure 6.30, whereby no distinctive trends are evident within the data set. The data for the 29/09/98 appears to conform to the general trend identified in Figure 6.30, however, the four final sets of data do not follow this pattern, and perhaps can be more closely linked with the data ascertained on the 15/09/98 in Figure 6.30. Finally, the four final sets of data (06/10/98 – 27/10/98) display relatively low pH values, with three of the four data sets possessing a range approximately between pH 7.5 and pH 8.5.

6.4 Water Conductivity

Figure 6.40 Illustrates the conductivity levels recorded at sites 0-15 for the first six recording dates of the study, 18/08/98 – 22/09/98. The graph shows a distinct relationship or trend within the data set. In general, conductivity levels rise significantly from site zero to a peak at site three, where the highest level recorded was 6.68 mS. Conductivity levels then decrease downstream of site three through to site seven to a level approximate to that recorded at site zero. Downstream of site seven, conductivity levels rise slightly at site eight and subsequently decrease through to site fifteen.

The exception to this rule is the conductivity data recorded on the 15/09/98, here the initial conductivity at site zero is similar to that recorded previously, around 0.40 mS, however, this conductivity level remains constant downstream from site zero to site fifteen.

Figure 6.41 Illustrates the conductivity levels recorded at sites 0-15 for the final five recording dates of the investigation, 29/09/98 – 27/10/98. The results in Figure 6.41 are strikingly

Figure 6.31. pH Levels Recorded at Sites 0-15.

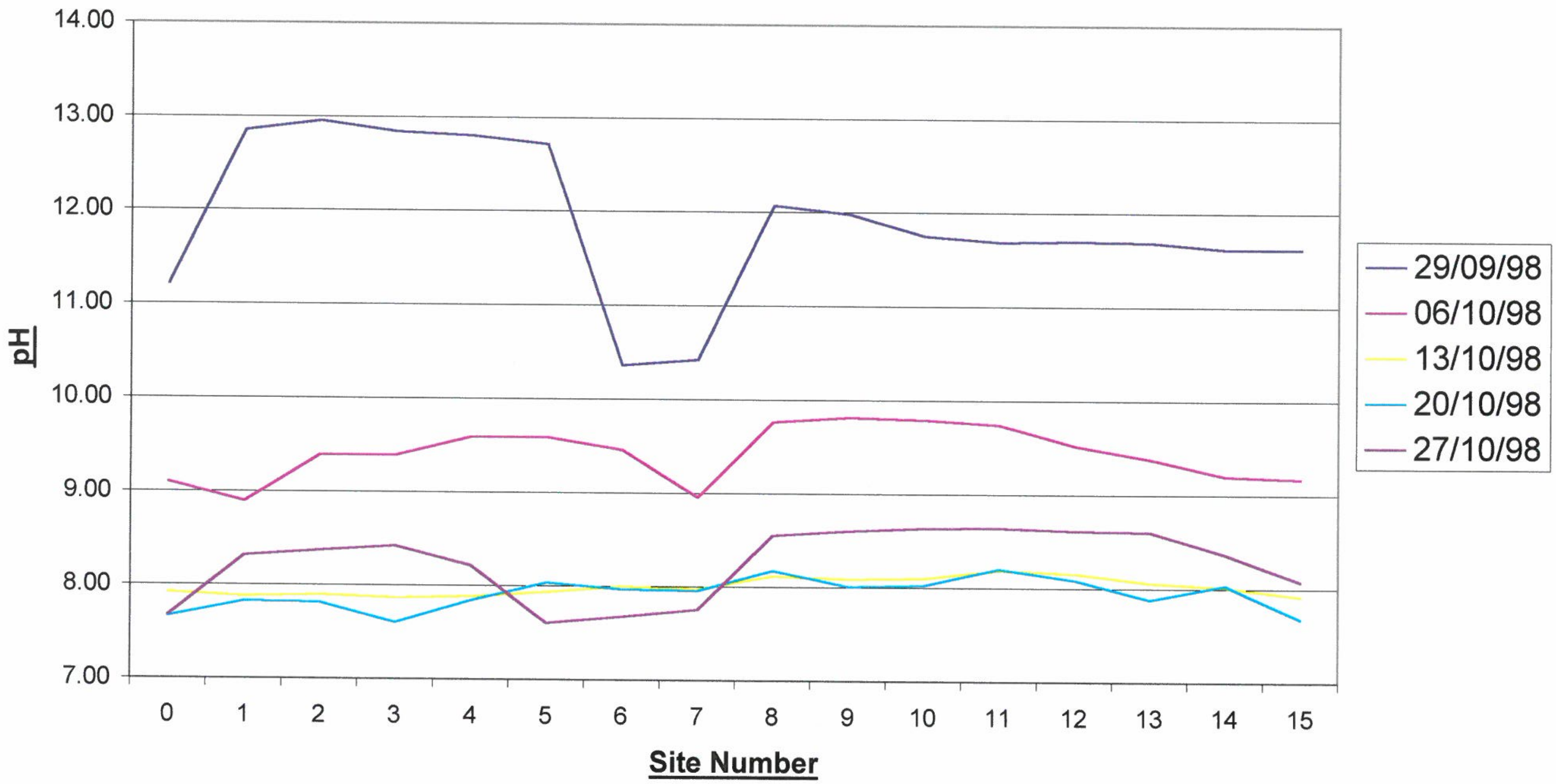


Figure 6.40. Conductivity Levels Recorded at Sites 0-15.

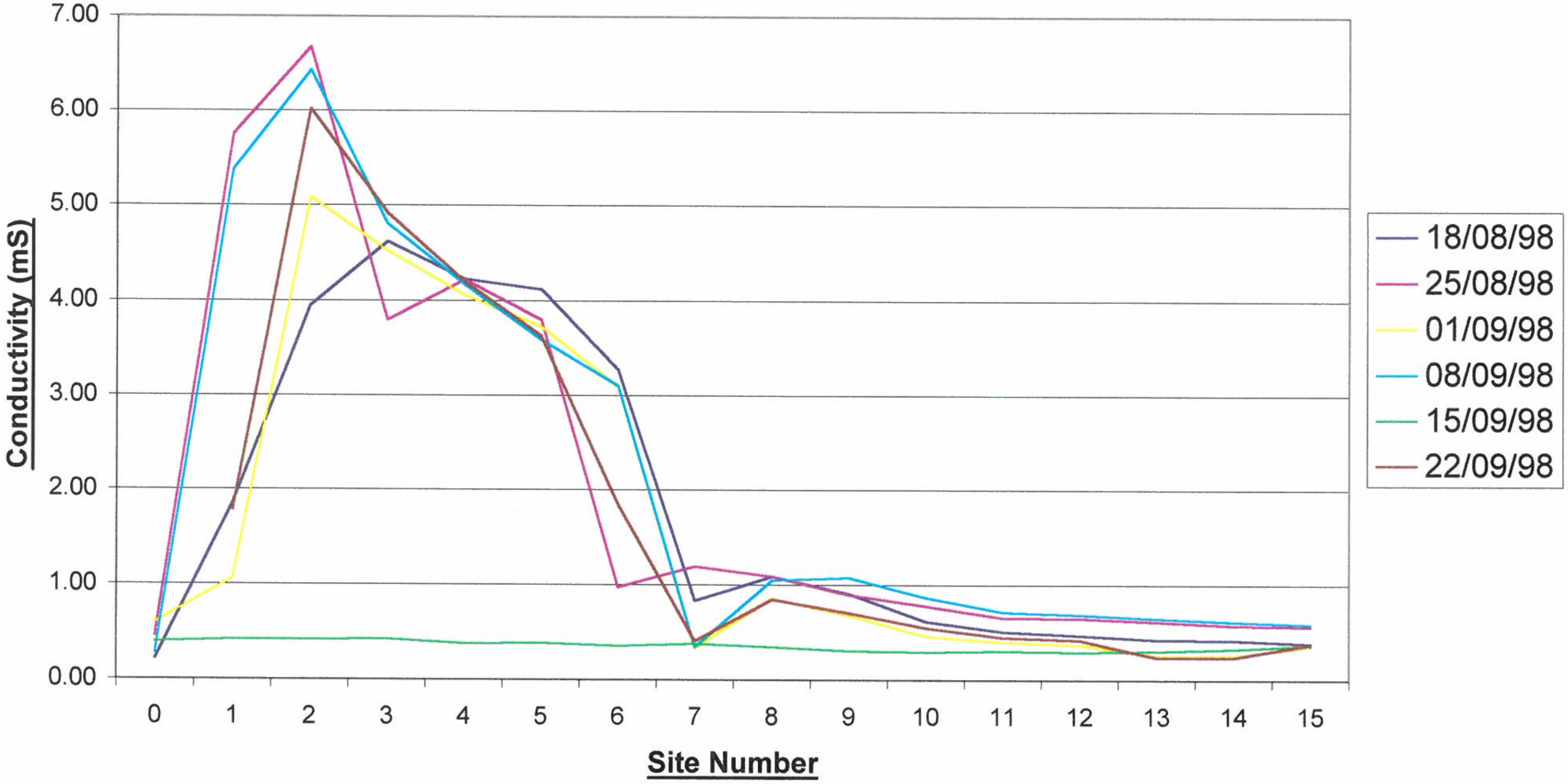
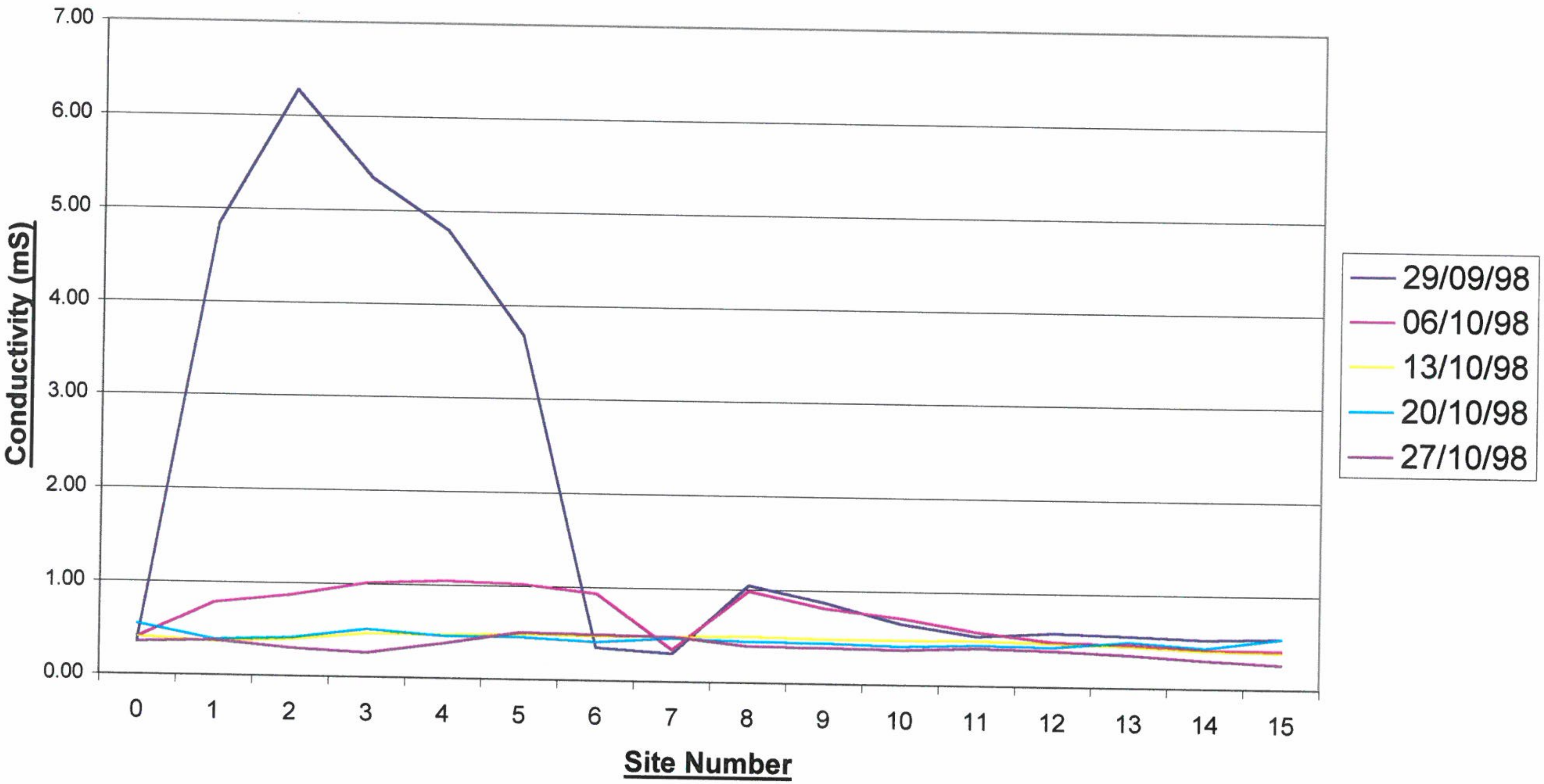


Figure 6.41. Conductivity Levels Recorded at Sites 0-15.



different to those shown in Figure 6.40. The conductivity data recorded on the 29/09/98 appears to follow the same trend as the data seen in Figure 6.40, however, the final four data sets show a different trend. Initially the conductivity levels at site zero are similar to those recorded previously (approximately 0.40 mS), these levels are generally maintained through to site fifteen, with the recorded conductivity's between 0.30 and 1.00 mS, significantly lower than the conductivity levels seen in Figure 6.40.

6.5 Stream Velocity/Discharge

Figure 6.50 illustrates the stream velocities recorded at sites 1-15 for the first six recording dates of the study, 18/08/98 – 22/09/98. The results in Figure 6.50 show a general relationship between site number and stream velocity. In general water velocities decrease, or maintain the same velocity between sites one and two, then decrease sharply at site three. Stream velocity fluctuates slightly between sites three and seven, and generally increases steadily downstream of site seven through to site fifteen.

In terms of values, the velocities recorded during the first six weeks of the investigation are relatively low, with the highest value (0.137 m/s) recorded at site one during the second week of the study 25/08/98. At site three, zero velocity (0.00 m/s) was recorded during the first six weeks of the study, a similar situation was evident at site seven. Finally, the velocities recorded between sites seven and fifteen spanned a wide range, however, even the maximum values recorded (0.119 m/s and 0.114 m/s) are not significantly great.

Figure 6.51 illustrates the stream velocities recorded at sites 1-15 for the final five recording dates of the investigation, 29/09/98 – 27/10/98. It must be stressed at this point that Figure 6.51 is shown as the same scale as Figure 6.50 although the results are strikingly different. The results in Figure 6.51 show that in general, stream velocities decrease from site one downstream

Figure 6.50. Stream Velocities at Sites 1-15.

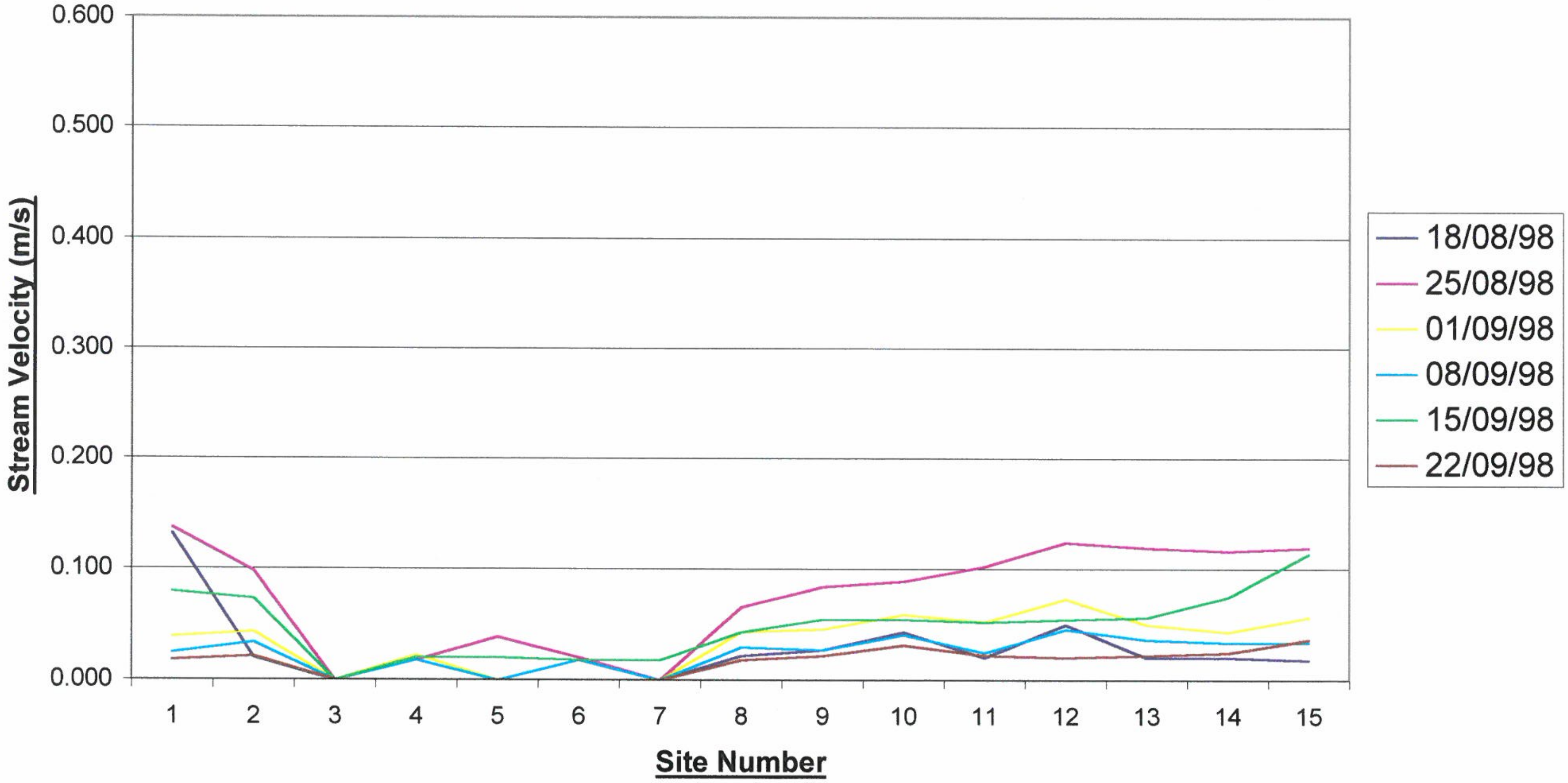
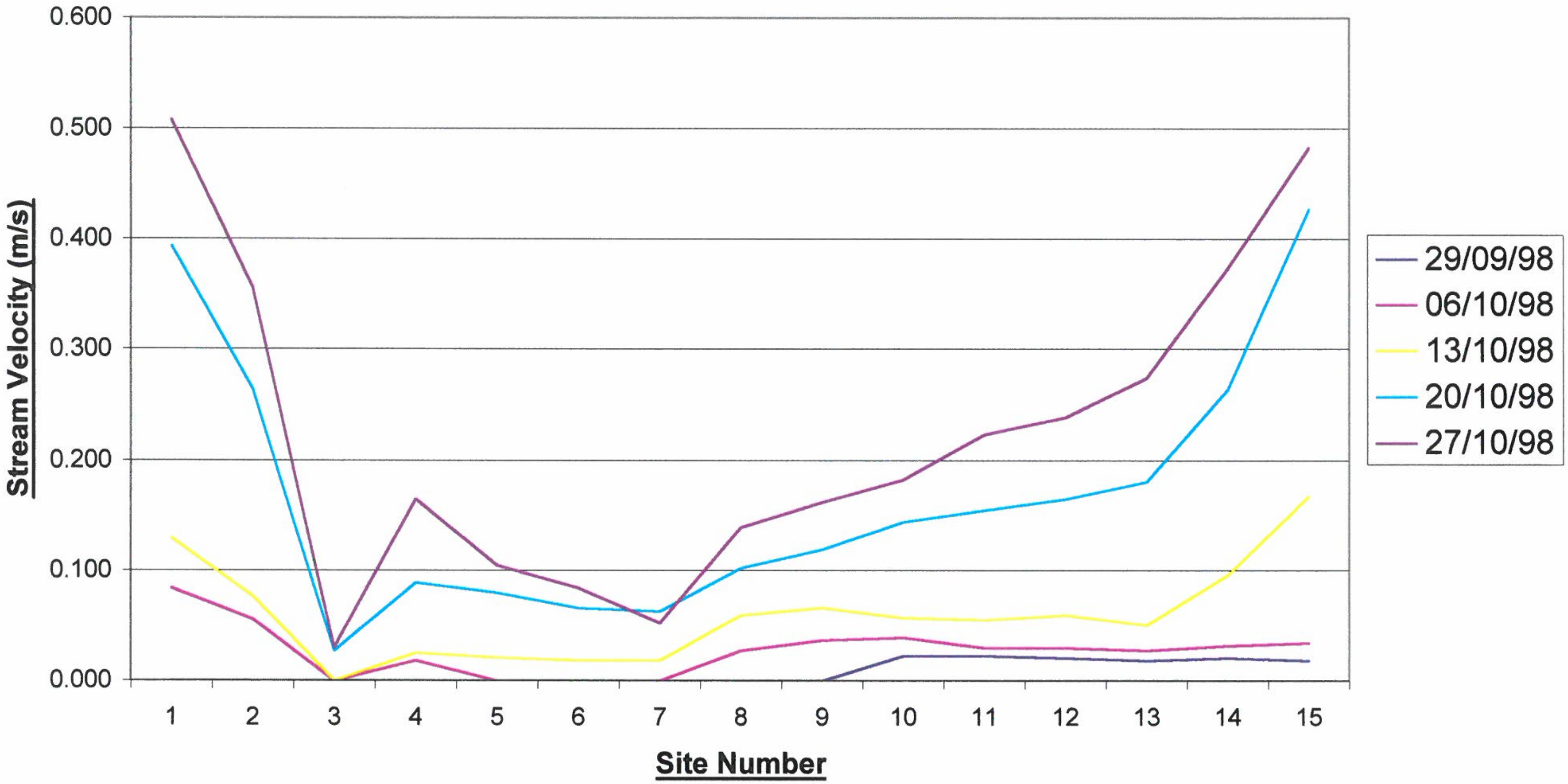


Figure 6.51. Stream Velocities at Sites 1-15.



to site three, again as with Figure 6.50, stream velocities generally fluctuate between site three and seven, and subsequently increase downstream of site seven.

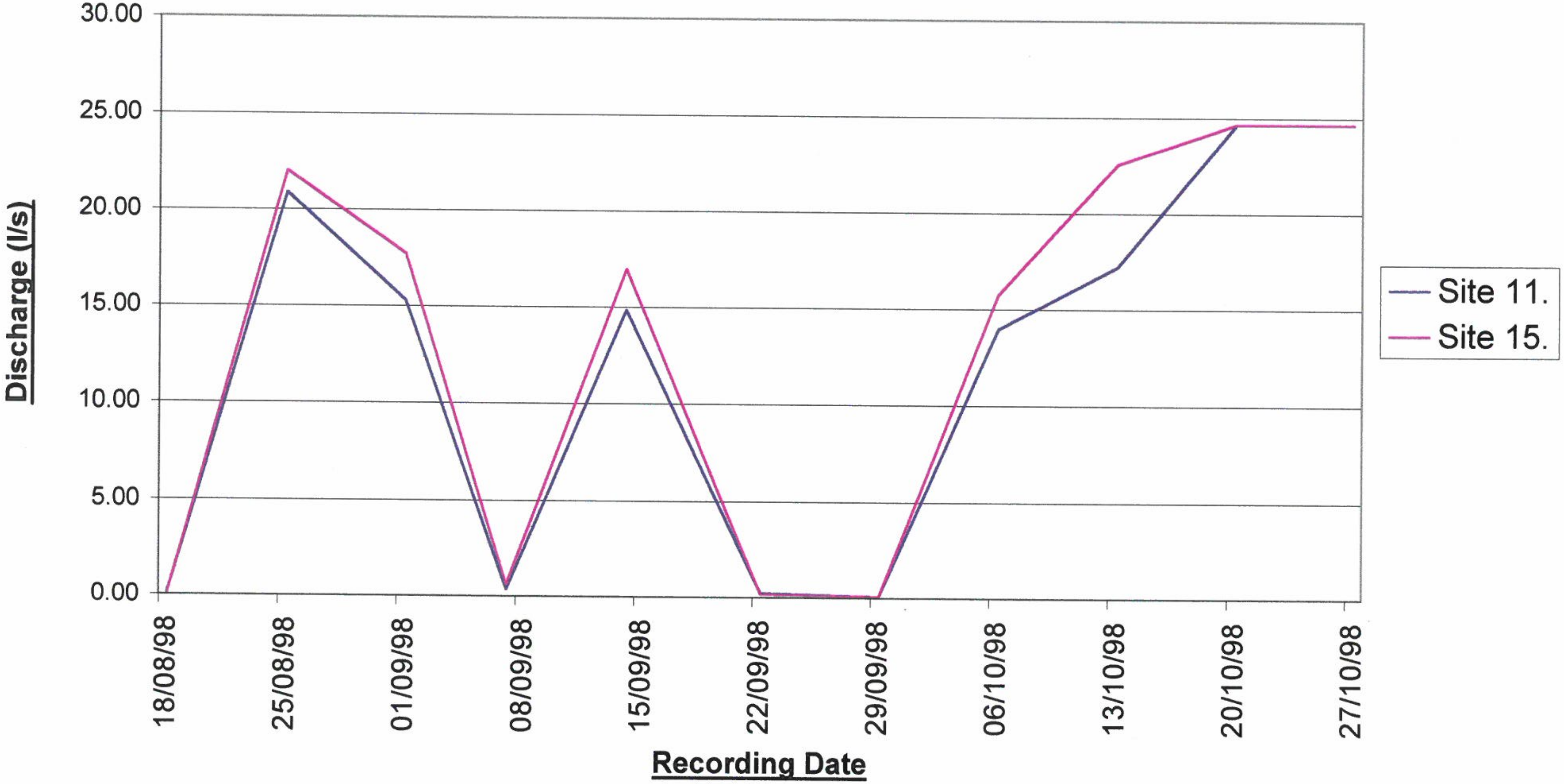
In terms of values, it is clearly evident that the stream velocities recorded during the final five weeks of the study are significantly greater then stream velocities recorded during the first six weeks of the study. It appears that the final two weeks of the study provided the highest velocity values of the investigation, for example, stream velocities of 0.394 m/s and 0.508 m/s were recorded at site one for recording dates 20/10/98 and 27/10/98 respectively. However, as with other recording dates, relatively low velocities were recorded at site three, and to some degree at site seven.

Finally, Figure 6.52 Illustrates the stream discharge recorded at sites 11 and 15, from this data it can be ascertained that discharge is variable, i.e. over the eleven weeks of the study there are periods of high and low discharge. High discharges occur on the 25/08/98 (c. 21.0 l/s), 01/09/98 (c. 16.0 l/s), 15/09/98 (c. 15.0 l/s), 06/10/98 (c. 14.0 l/s), 13/10/98 (c. 19.0 l/s), 20/10/98 (> 24.68 l/s) and the 27/10/98 (> 24.68 l/s). Whilst low discharges occur on the 18/08/98 (c. 0.1 l/s), 08/09/98 (c. 0.50 l/s), 22/09/98 (c. 0.2 l/s) and the 29/09/98 (c. 0.09 l/s).

Actual discharge measurements could not be recorded for the final two weeks of the investigation (20/10/98 and 27/10/98). The discharge levels of the stream on these dates were extremely high and thus breached the v-notch weirs, however, the discharge can be assumed to be greater than 24.68 l/s.

Both v-notch weirs at site eleven and fifteen record approximately the same discharge levels, with the exception of two data recording dates 06/10/98 and 13/10/98, where site fifteen experienced a higher discharge. However, this is due to site fifteen being located downstream of the confluence with a second stream, this is shown in figure 5.12.

Figure 6.52. Stream Discharge at Sites 11 and 15.



6.6 Water Chemistry Results

The water samples taken on the 1st and 6th of November 1998 were analysed in terms of their chemical composition, the results of which are provided in Table A6.61, Appendix 2. The samples collected on the 1st of November do not show any outstanding results in terms of the chemical composition or significant differences between sites. The samples collected on the 6th of November again, shows similar nondescript results, with the exception of one strikingly large value of 666 (Ca mg/l) within the water sample, this value of 666 mg/l is clearly greater than other data in the same column (see Figure 6.62). The water sample, from which this large value of Calcium was derived, was taken from an area described as the "lagoon spring", this area is shown in Plate 6.63 and Plate 6.64.

6.7 Planimeter Results

The results of the planimeter are surprising; essentially the area of the lime ash tips shown on the ordnance survey maps decreases, as the maps become more recent. Table 6.71 displays the results recorded using the planimeter on the three Ordnance Surveys maps of 1938, 1948 and 1971.

Table 6.71

Map Date	Scale	Result of Planimeter	Area (m^2)
1938	1.2500	505	31563
1948	1.2500	610	38125
1971	1.2500	230	14375

Maps A6.72, A6.73, and A6.74 in Appendix 5 are overlays of the 1938, 1948 and 1971 Ordnance Survey maps, respectively. These maps overlay a base map that was produced in

Figure 6.62: Water Chemistry Tests (06/11/98)

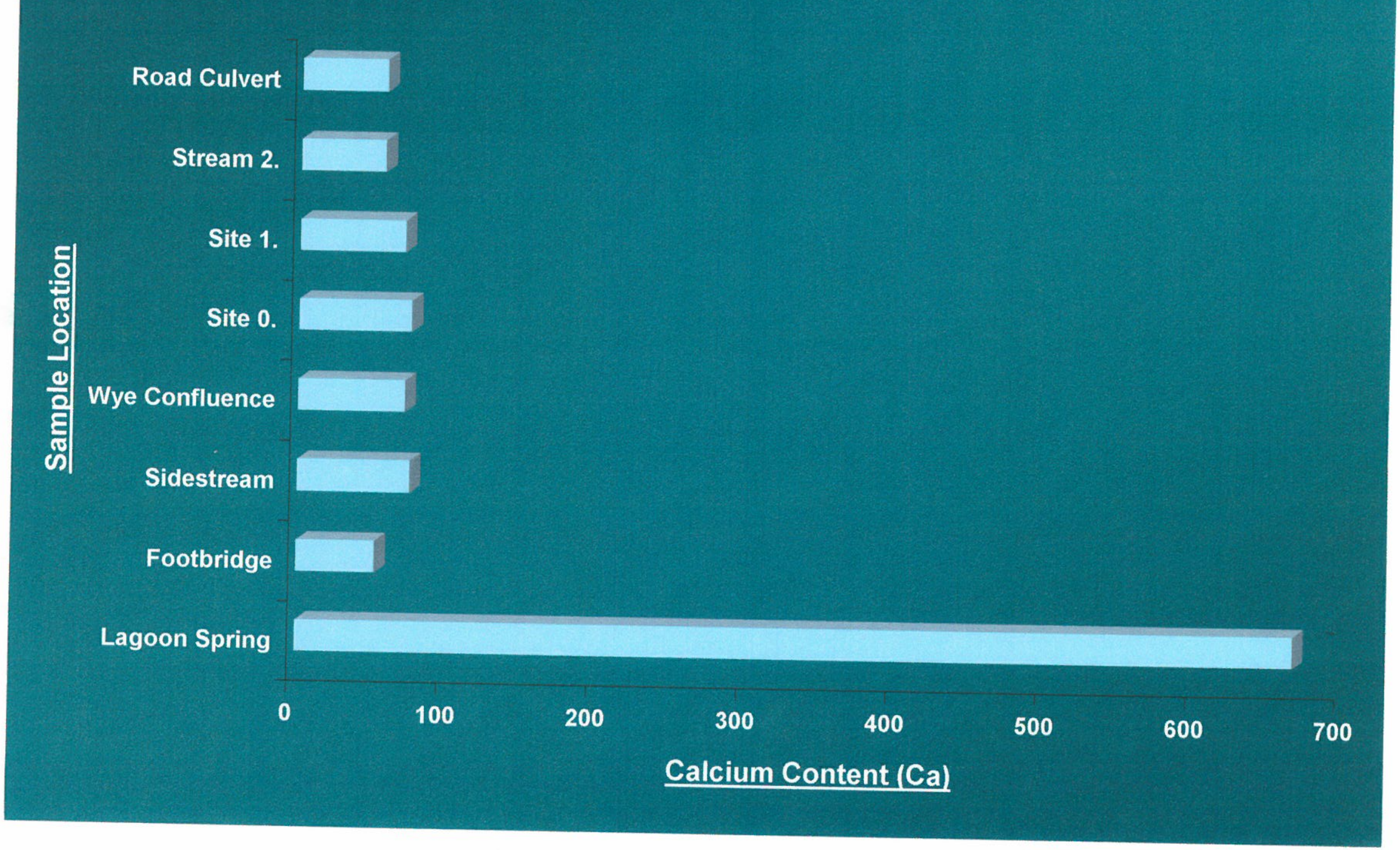


Plate 6.63: The area described as the "lagoon spring".

Plate 6.64: The area described as the "lagoon spring" is located in the far right of the picture.

1883; the base map clearly shows the Brook Bottom site prior to any tipping of lime ash. Both the 1938 and 1948 maps (map A6.72 and map A6.73) show a similar extent of the lime ash tips, in particular, on both maps the lime ash extends outwards towards the adit exit. Map A6.74 however, does not show the lime ash tips extending as far as the adit exit; this would therefore account for the low planimeter result for this map.

Finally, other features to note on map A6.74 are that firstly, the lime ash tips are now represented in a more contoured fashion and secondly, there appears to be slight modifications in the stream channel when compared to map A6.72 and map A6.73.

7. Analysis

In an attempt to understand the influences on tufa deposition, the relationship between four environmental parameters and deposition rates was investigated. The four parameters were: conductivity at each site on the date of slide removal, pH at each site on the date of slide removal, air temperature (recorded at Buxton), and total rainfall at Buxton over seven days prior to slide removal.

7.1 Conductivity

For each week (18/08/98-27/10/98) the relationship between conductivity and the mean rate of deposition was investigated, with the results for each recording date plotted in scatter graphs (Appendix 6). In conjunction with this, the relationship between conductivity and the rate of deposition at each site (1-15) over the whole recording period (18/08/98-27/10/98) was also investigated, again, the results were plotted in a scatter graphs (Appendix 7). The scatter graphs within Appendix 6 and 7 display a wide scatter with no clearly recognisable trends within time and space.

7.2 pH

Similarly, for each week (18/08/98-27/10/98) the relationship between pH and the mean rate of deposition was investigated, with the results for each recording date plotted in scatter graphs (Appendix 8). The relationship between pH and the rate of deposition at each site (1-15) over the whole recording period (18/08/98-27/10/98) was also investigated, again, the results were plotted in a scatter graphs (Appendix 9). As with conductivity, the graphs within Appendix 8 and 9 show a wide scatter with no recognisable trends in both time and space.

7.3 Air Temperature

Mean air temperature data was plotted against the mean deposition rate recorded at each site (Appendix 10). On initial inspection many of the scatter graphs appeared to show some relationship between mean temperature and the rate of deposition (e.g. Figures 7.30, 7.31), therefore, a correlation analysis was undertaken to determine the significance of this relationship. Table 7.32 shows the results of the correlation analysis for each site over the period 18/08/98-20/10/98. An r-value of +1.0 would indicate a perfect positive relationship, an r-value of –1.0 indicates a perfect negative correlation, and an r-value of 0.0 indicates the complete absence of any statistical relationship (Shaw and Wheeler, 1994). Most sites show little or no correlation between the rate of deposition and mean temperature, with the range in r-values typically between -0.4 to +0.3. However, site four displays a strong negative correlation (-0.84984), whilst site eight displays a strong positive correlation (0.750575). As site eight shows a strong positive relationship, site four shows a strong negative relationship, and all other sites show no relationship, the results suggest that temperature does not exert a significant influence on tufa deposition.

7.4 Total Rainfall

To analyse the influence of total rainfall on the mean rate of deposition, the total rainfall during the seven-day period whilst the slides were situated within the stream was plotted against the mean deposition rate recorded at each site (Appendix 11). Again, on initial inspection many of the scatter graphs appeared to show some relationship between total rainfall and the mean rate of deposition (e.g. Figures 7.40, 7.41), therefore, a correlation analysis was undertaken (Table 7.42). At most sites the r-values range between –0.4 to +3.0 although, sites four, six and eight show a stronger positive correlation (0.57) and (0.68). r^2 is the percentage of variation that can be explained in the y values by x, if this is calculated for the results at site four and site six

Figure 7.30: A Scatter Graph of Mean Temperature Against the Mean Rate of Deposition at Site Eight.

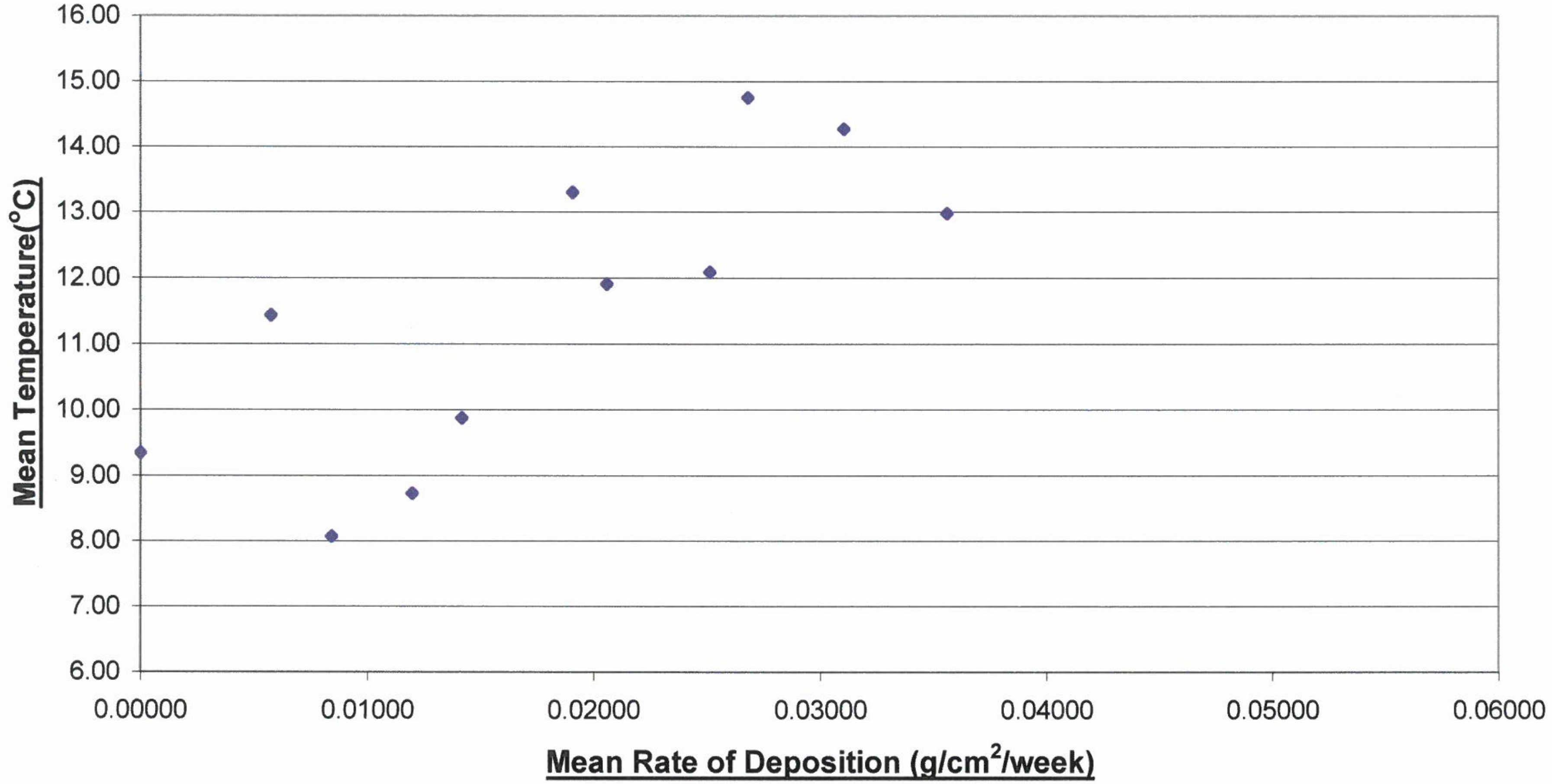


Figure 7.31. A Scatter Graph of Mean Temperature Against the Mean Rate of Deposition at Site Nine.

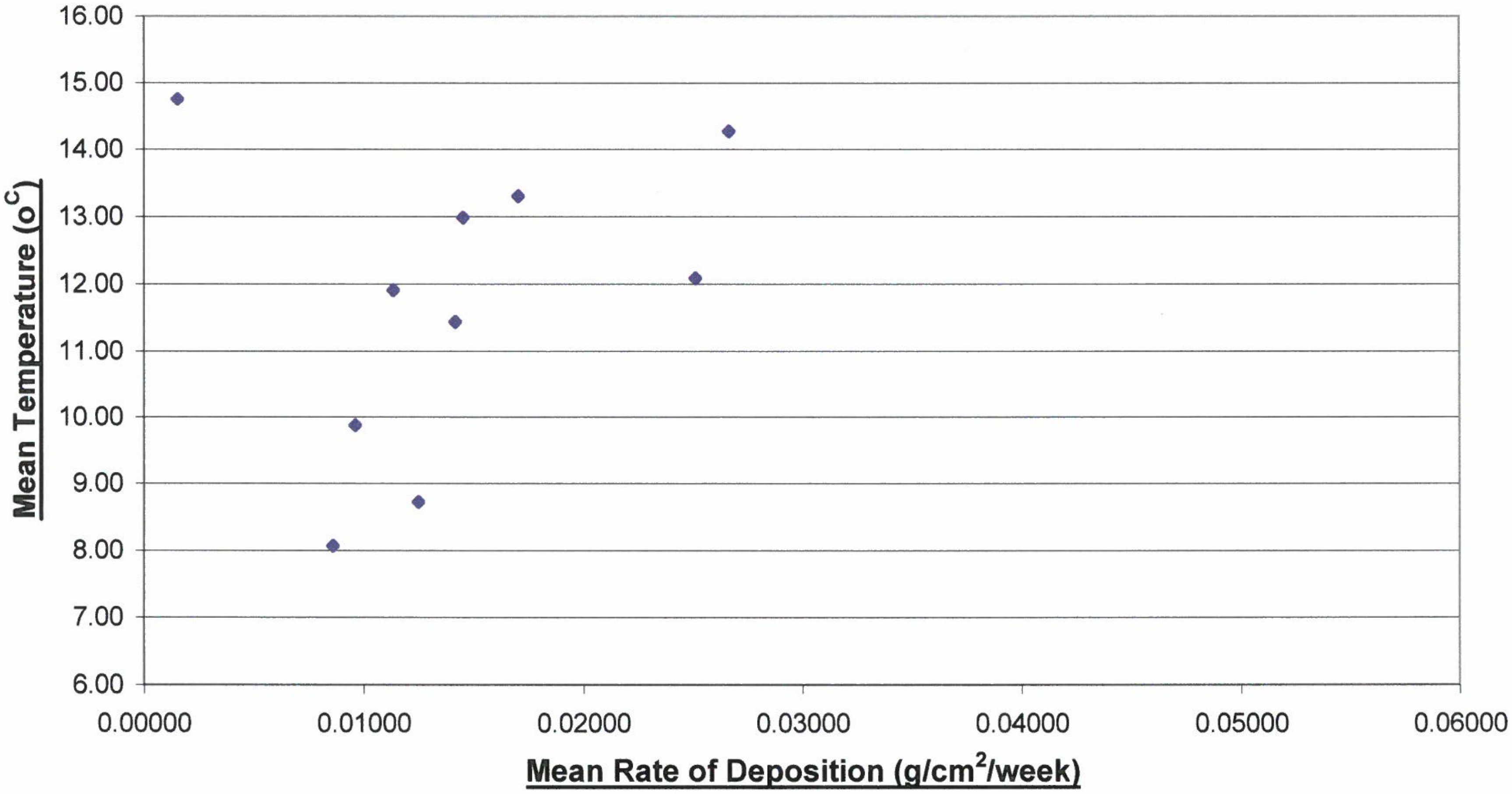


Table 7.32: Correlation of the Mean Rate of Deposition with Mean Temperature Recorded at Buxton Over the Period (18/08/98-20/10/98).

Site 1	*Column 1*	*Column 2*
Column 1	1	
Column 2	0.103981	1

Site 2	*Column 1*	*Column 2*
Column 1	1	
Column 2	0.208783	1

Site 3	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.27752	1

Site 4	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.84984	1

Site 5	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.02345	1

Site 6	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.59063	1

Site 7	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.23563	1

Site 8	*Column 1*	*Column 2*
Column 1	1	
Column 2	0.750575	1

Site 9	*Column 1*	*Column 2*
Column 1	1	
Column 2	0.234816	1

Site 10	*Column 1*	*Column 2*
Column 1	1	
Column 2	0.178669	1

Site 11	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.3266	1

Site 12	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.46291	1

Site 13	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.46239	1

Site 14	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.11962	1

Site 15	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.18426	1

Figure 7.40. A Scatter Graph of Total Rainfall Against the Mean Rate of Deposition at Site Three.

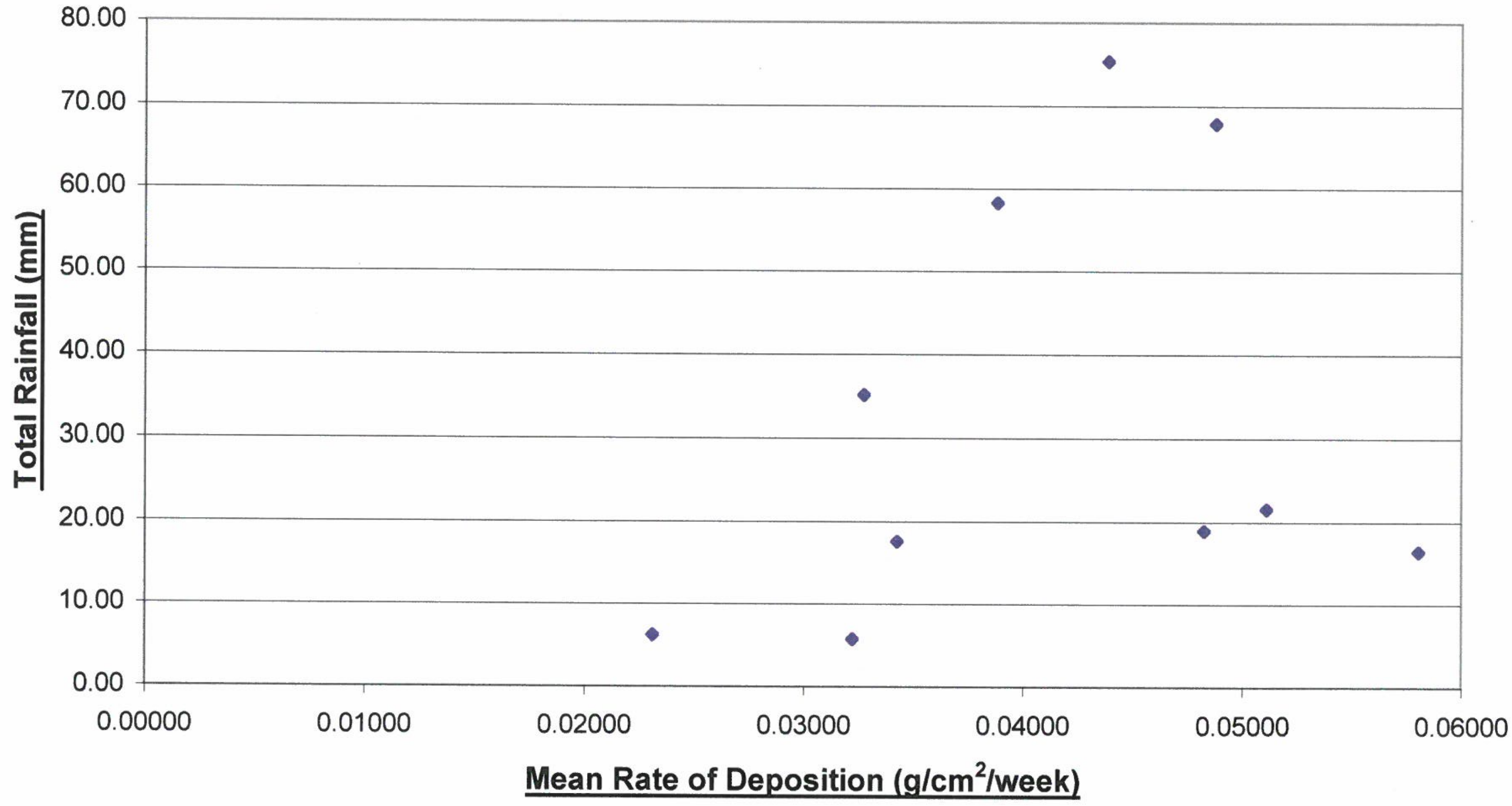


Figure 7.41. A Scatter Graph of Total Rainfall Against the Mean Rate of Deposition at Site Four.

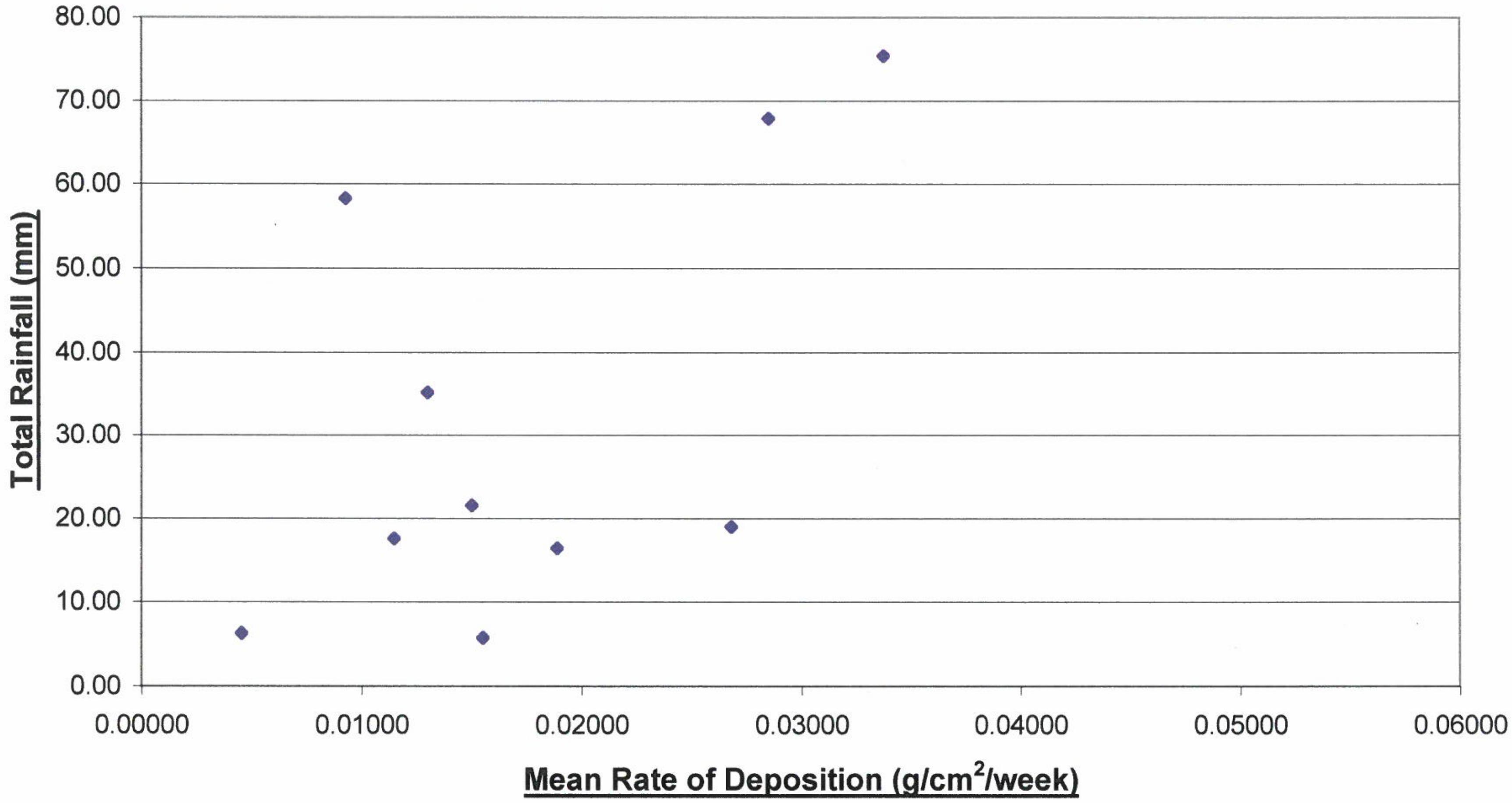


Table 7.42: Correlation of the Mean Rate of Deposition with Total Rainfall at Buxton, Recorded on the 7 Days Prior to Slide Extraction Over the Period (18/08/98-20/10/98).

Site 1	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.2421	1

Site 2	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.4615	1

Site 3	*Column 1*	*Column 2*
Column 1	1	
Column 2	0.259352	1

Site 4	*Column 1*	*Column 2*
Column 1	1	
Column 2	0.569831	1

Site 5	*Column 1*	*Column 2*
Column 1	1	
Column 2	0.184193	1

Site 6	*Column 1*	*Column 2*
Column 1	1	
Column 2	0.680169	1

Site 7	*Column 1*	*Column 2*
Column 1	1	
Column 2	0.146151	1

Site 8	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.60765	1

Site 9	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.20721	1

Site 10	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.19151	1

Site 11	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.25098	1

Site 12	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.1405	1

Site 13	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.2652	1

Site 14	*Column 1*	*Column 2*
Column 1	1	
Column 2	-0.07882	1

Site15	*Column 1*	*Column 2*
Column 1	1	
Column 2	0.234011	1

(Appendix 12), only 32% and 46% respectively, of the variation can be explained. As only three sites show any significant relationship and all other sites show no relationship, the results suggest that rainfall does not exert a significant influence on tufa deposition.

7.5 Long-term Deposition Rates

When extrapolating short-term data to long-term, caution must be taken, as the extrapolated results may not be particularly representative of longer-term trends. However, it was felt that extrapolation of the short-term deposition data would provide an indication of rates of deposition over longer periods of time (Appendix 13). Firstly, the mean of the thirty deposition weights recorded at each site during the period 18/08/98 – 20/01/98 (10 weeks) was calculated. This value, for example, 0.8123g at site x, was divided by the area of a microscope slide to determine the mean deposition rate (g/cm^2/week) over the 10 week period 18/08/98-20/10/98.

Mean weight of deposit: 0.8123g

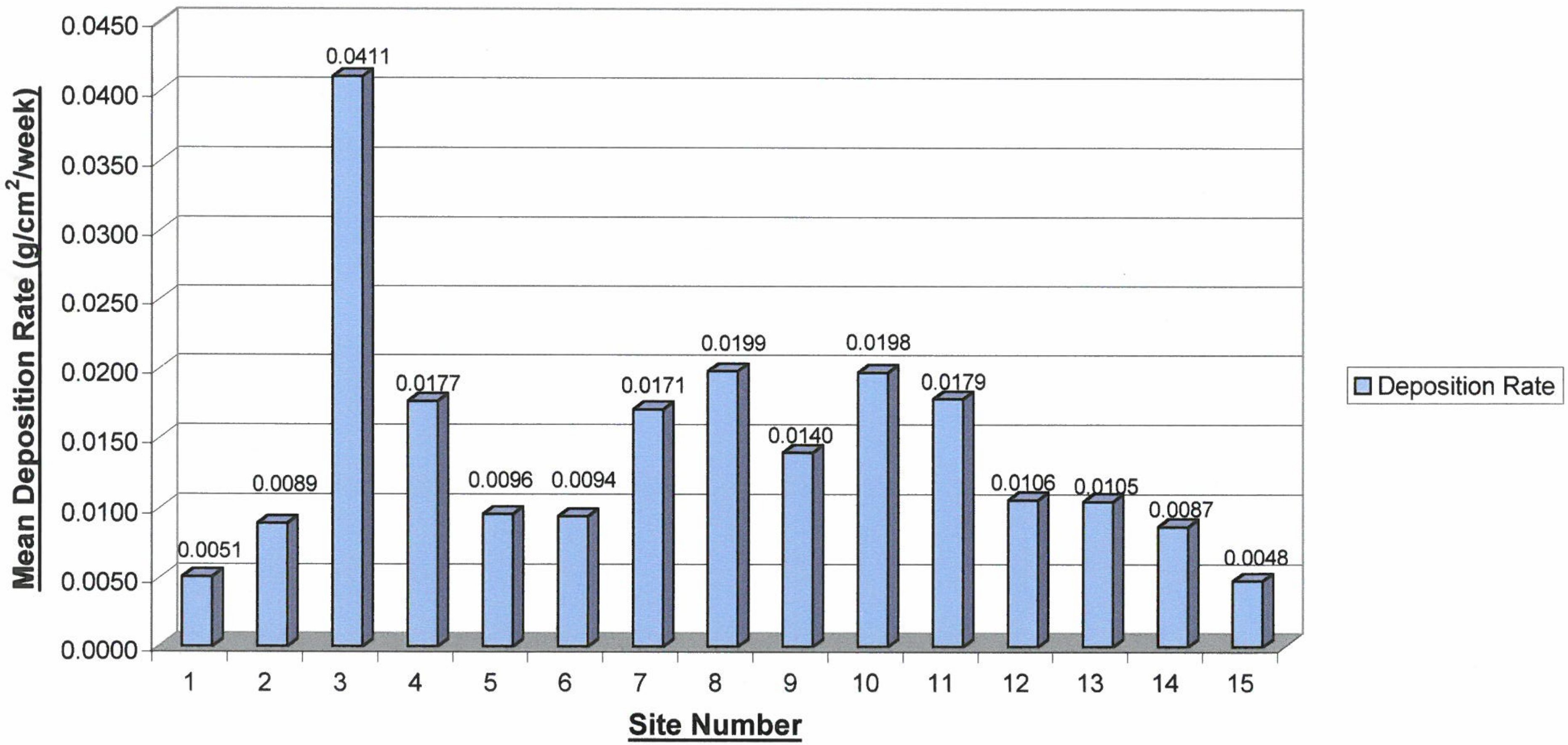
Area of microscope slide: 19.76 cm^2

$$\frac{\textbf{Mean weight of deposit}}{\textbf{Area of microscope slide}} = \textbf{Rate of deposition (g/cm}^2\textbf{/week)}$$

Thus: 0.8123/19.76 = <u>0.0411 g/cm^2/week</u>

Figure 7.50 shows the mean weekly deposition rate for each site over the period 18/08/98-20/10/98. The results shown on the graph show a low mean deposition rate at site one (0.0051 g/cm^2/week) which rises slightly at site two and rises dramatically at site three to a peak of 0.0411 g/cm^2/week. The mean deposition rate decreases at site four and again between sites five and six, then increases again at site seven and eight to 0.0199 g/cm^2/week. At site nine the mean deposition rate drops slightly to 0.0140 g/cm^2/week, however, returns to a level close to that of site eight at site ten. Downstream of site ten the mean rate of deposition steadily decreases, with the rate at the final site (site fifteen) displaying a similar mean deposition rate to that of the first site (site one).

Figure 7.50: Mean Weekly Deposition Rate Over the Period 18/08/98 - 20/10/98.



Analysis.

The mean deposition rates were then multiplied by fifty-two to estimate the rate of deposition over a one year period, for example:

Rate of deposition for 1 year: = 0.0411 g/cm^2/week * 52 weeks = 2.138 g/cm^2/year

To determine the rate of deposition in terms of depth it is necessary to know the bulk density of the tufa. However, the bulk density of the tufa at Brook Bottom was not measured, although Towler (1977, p.89) ascertained that "*one cubic centimetre of tufa weighs approximately two grams*". Therefore the bulk density of the tufa at Brook Bottom was assumed to be 2.0 g/cm^3 and the calculations of the depth of deposition were carried out using this value.

To determine the depth of deposition in centimetres per year (cm/y), the rate of deposition in g/cm^2/year (e.g. 2.138) is divided by the bulk density of the tufa (2g/cm^3).

Rate of deposition: 2.138 g/cm^2/year

Bulk density of tufa: 2 g/cm^3

$$\frac{\textbf{Rate of deposition}}{\textbf{Bulk density of tufa}} = \textbf{Depth of deposition cm/year}$$

Thus: 2.138/2.0 = 1.07 cm/year

Finally, this value was extrapolated up to ten or one hundred years by multiplying this value by a factor of ten, for example:

1.07 cm/year * 10 = 10.7 cm/10 years

1.07 cm/year * 100 = 107 cm/ 100 years or 1.07 m/100 years.

The extrapolated depths of deposition results for each site assuming a bulk density of 2g/cm^3 are shown in Figures 7.51 and 7.52.

Figure 7.51: Mean Depth of Deposition per Year Assuming a Bulk Density of 2g/cm^3

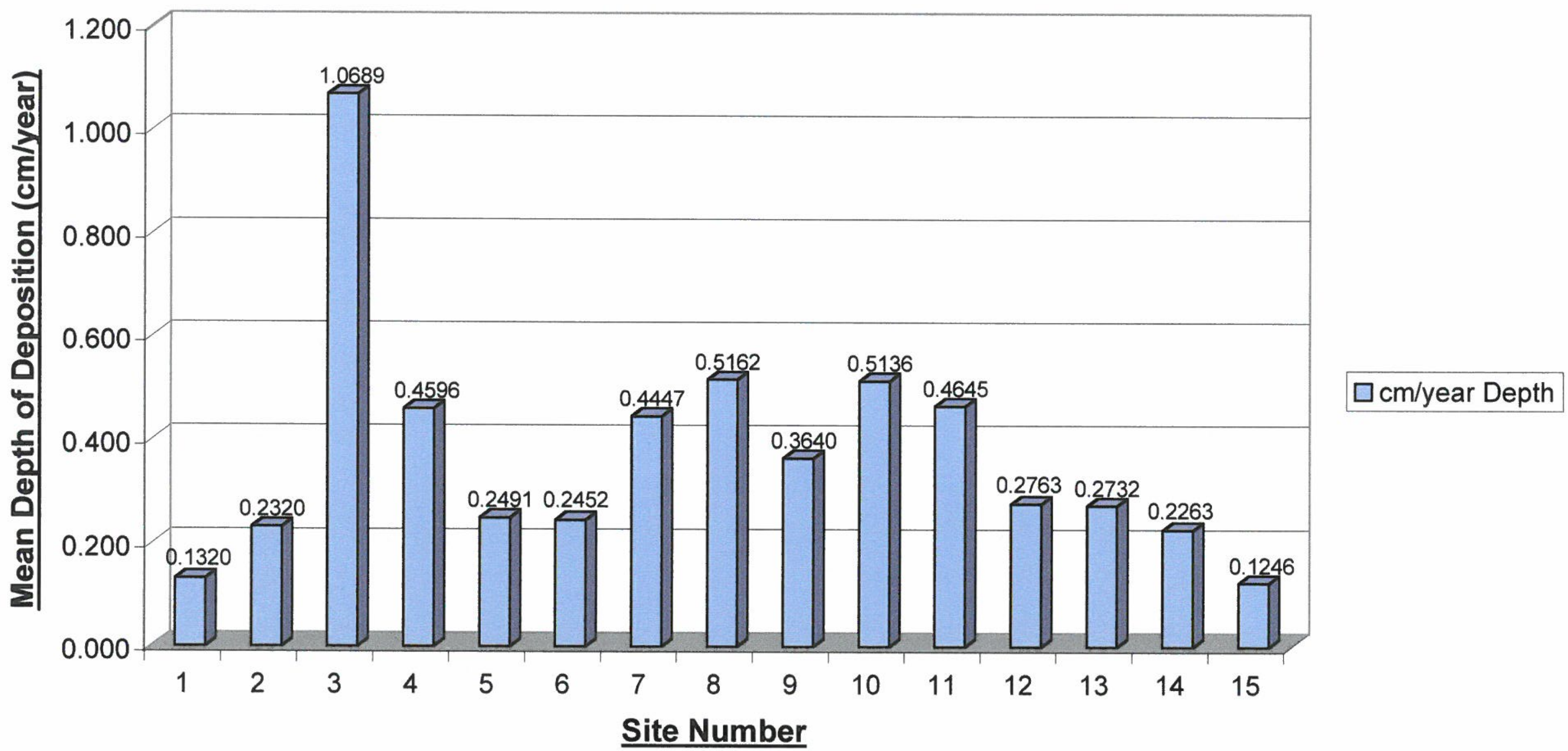
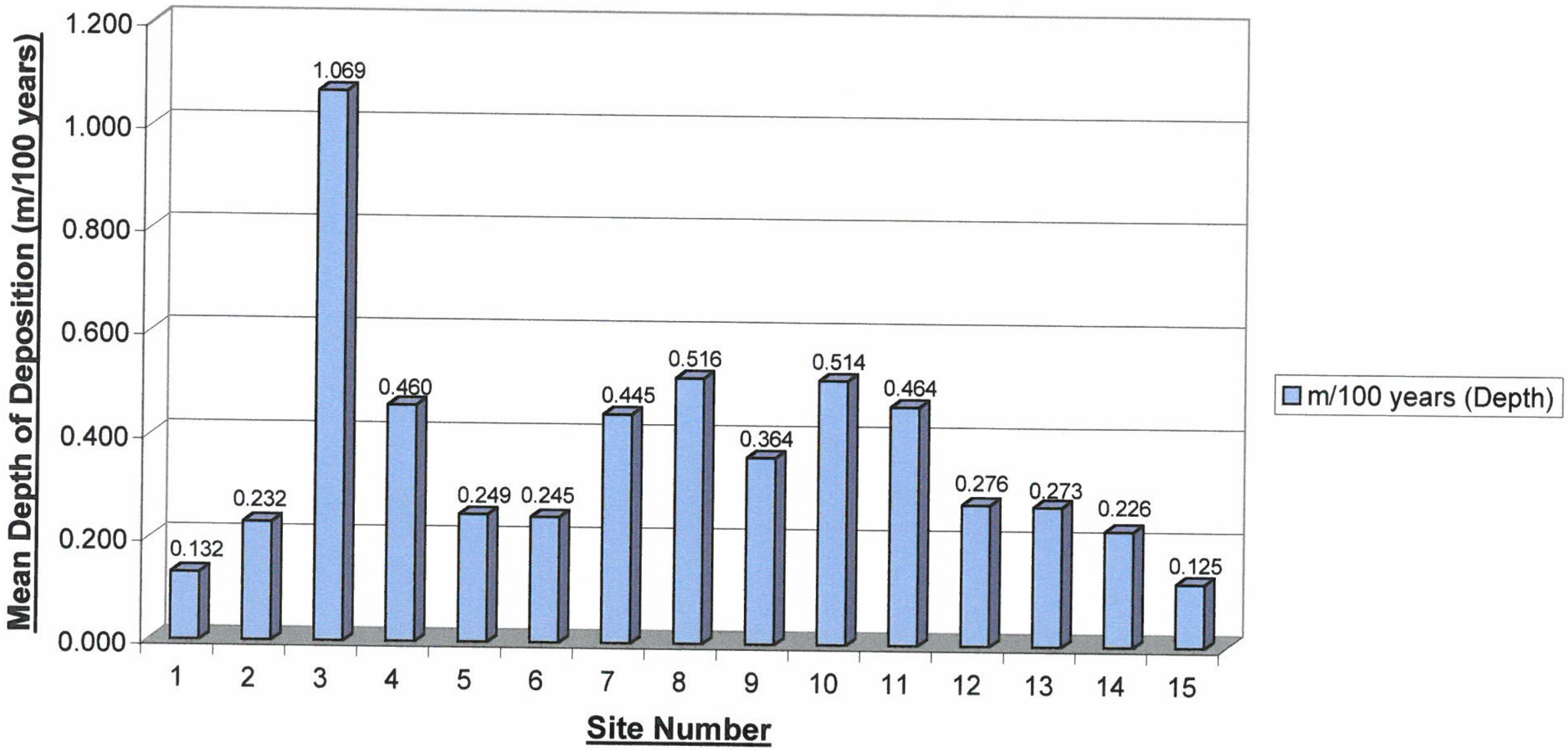


Figure 7.52: Mean Depth of Deposition Over 100 Years Assuming a Bulk Density of $2 g/cm^2$



Analysis.

Assuming that the bulk density of the tufa at Brook Bottom is approximately 2.0g/cm^3 it can be estimated that a maximum of 0.1246 cm/year is deposited at the Brook Bottom site. It is clear from Figures 7.51 and 7.52, that generally, the depth of deposition is relatively low at sites one and two, very high at site three, low at sites five and six, moderately high between sites seven and eleven, then decreasing steadily downstream of site eleven to a level close to that recorded at site one. If the data is extrapolated over one hundred years the rapid rate of deposition can be noted (Figure 7.52), with the greatest area of deposition around site three where some 1.069 metres of tufa could be deposited in one hundred years. It is evident from the historical maps of the area, that the tufa deposit was not present in 1883 and must have formed some time after this date. It is also known that the first terrace, which is essentially a dry stone wall which the tufa has built up behind, in close proximity to site three, is approximately one metre in height. Therefore, the extrapolated value for one hundred years of deposition (1.069 m/100 years) is quite feasible.

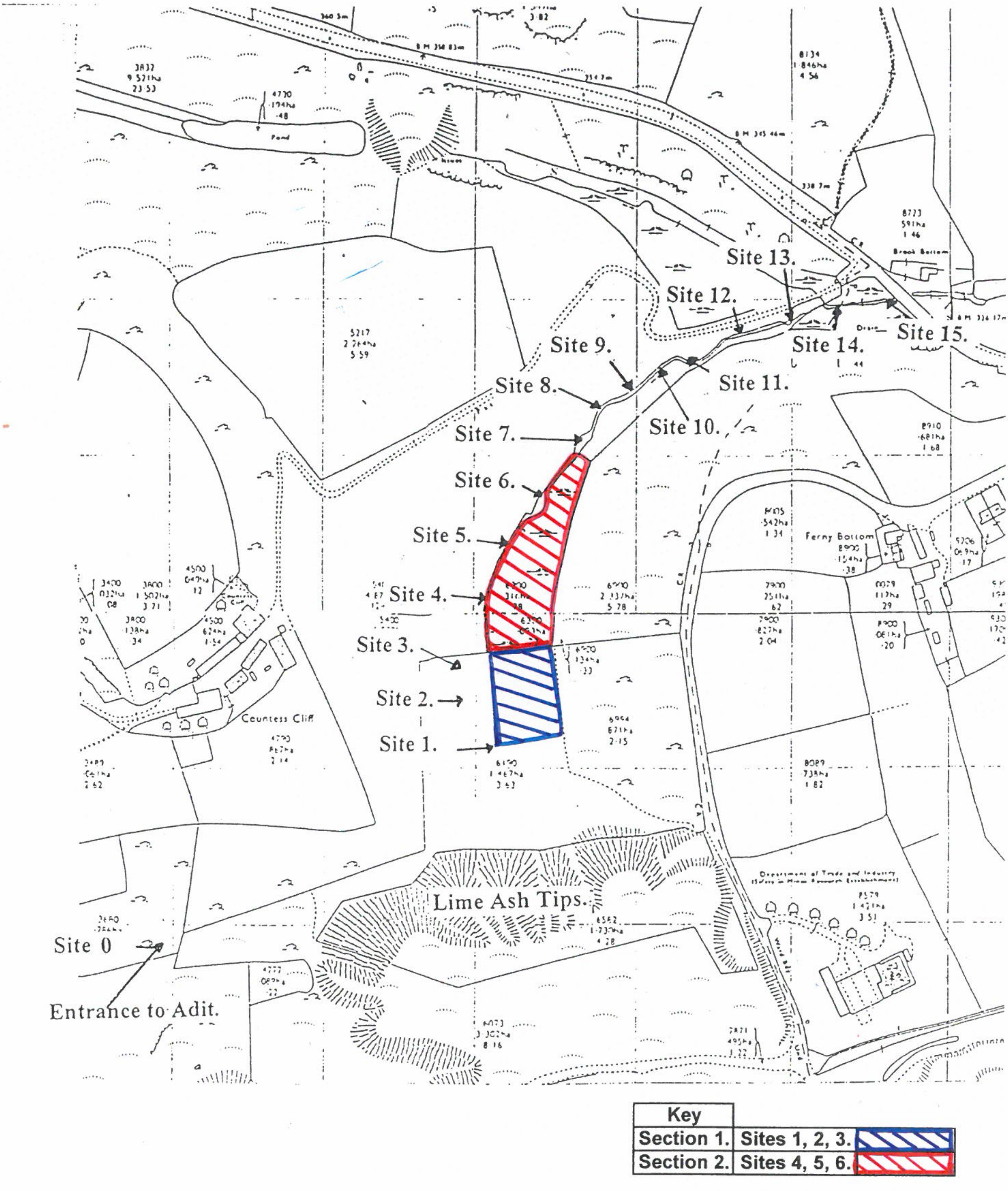
In terms of the total deposition over the area, the area can be broken down into two sections (Figure 7.53). Firstly, the upper main body of the tufa which encompasses sites one, two and three and secondly, the lower main body of tufa which encompasses sites four, five and six. The mean rate of deposition for the three sites can be calculated and multiplied by 10,000 to determine the rate of deposition per m^2. This can then be multiplied by the area of each section to ascertain the deposition in grams over the section in one week. Finally this value can be multiplied by a factor of ten to determine the deposition over the section in kilograms and tonnes respectively.

For example:

Section 1 (Sites 1, 2, 3) Mean rate of deposition = 0.0184 g/cm^2/week

Thus: 0.0184 *10000 = 184 g/m^2/week

Figure 7.53: The Location of the Two Individual Sections



Source: Ordnance Survey, 1:2500, Plan SK 0470-0570, Revised October 1971.

Area of Section 1 (sites 1, 2, 3)		=	3639 m^2
Thus:	184 * 3639	=	669576 g/section/week
Thus:	669576/1000	=	669.6 kg/section/week
	669.576/1000	=	0.6696 t/section/week

The two sections of the main tufa body (Figure 7.53) receive a substantial amount of deposition, with both sections receiving over 0.5 (t) of deposit each week. It is quite conceivable on the evidence of this data, although only estimates, that the tufa deposit at Brook bottom could have formed in a relatively short period of approximately 100 years.

8. Discussion

The analysis of the relationship between the rate of deposition and environmental parameters (conductivity, pH, mean temperature and total rainfall) showed that there is little or no relationship between the two. It is quite clear from the analysis that the correlation between the rate of deposition and each of the environmental parameters varies considerably between sites. However, referring back to the raw deposition data (Table A5.11 appendix 2), it can be noted that the weight of deposit also varies considerably between the individual slides at each site. The three slides placed at each site were approximately 2 cm apart, whilst the weight of deposit on each slide varied by as much as 1.43 grams. Therefore, because deposition varied substantially between areas 2 cm apart, subsequently this would result in large differences between sites in terms of the relationship between the rate of deposition and the selected environmental parameters.

The results suggest that the rate of tufa deposition at the Brook Bottom site is not directly controlled by the environmental parameters measured, rather, it may be that the chemical kinetics of the solution/precipitation are the most important factors controlling the precipitation.

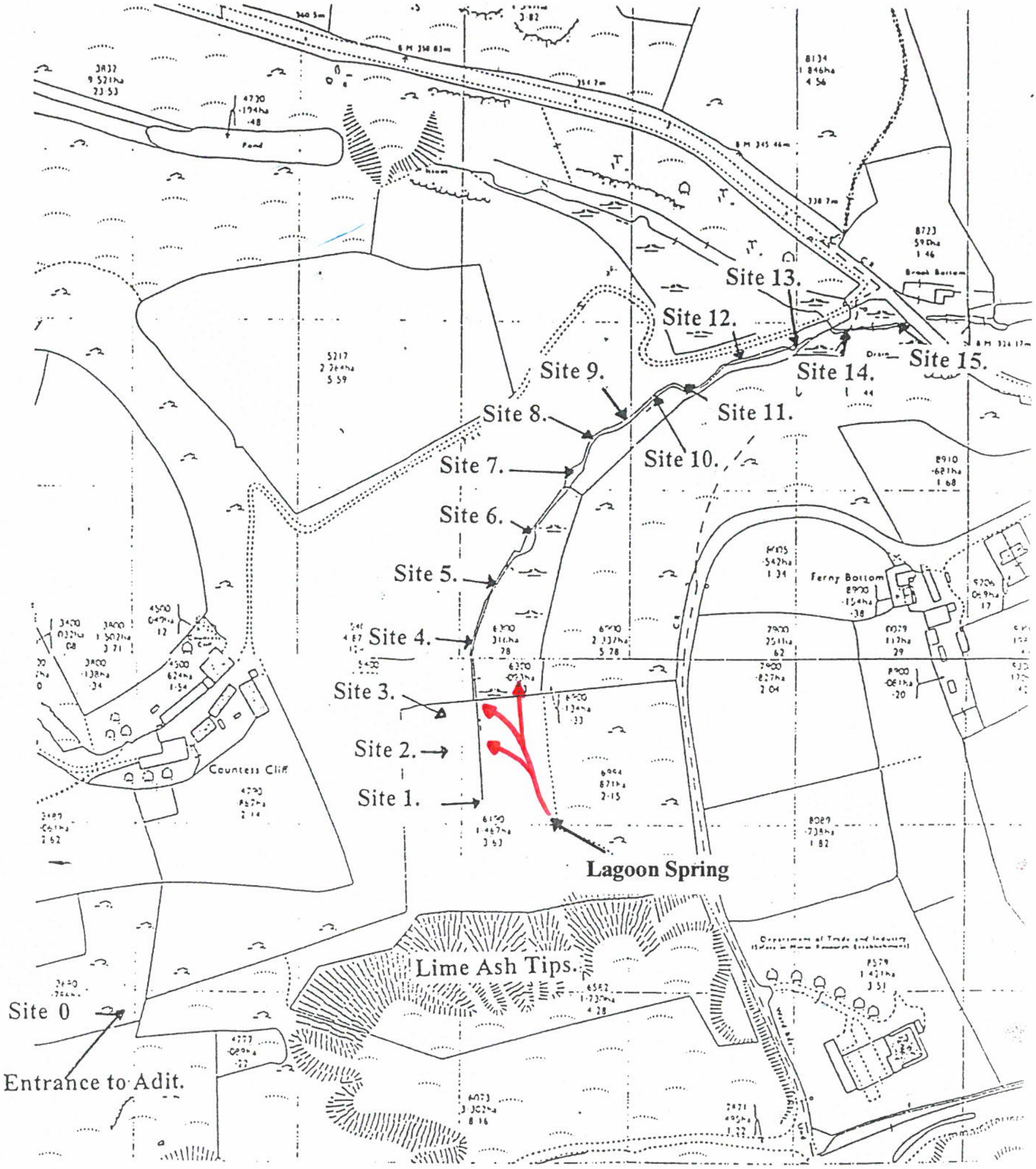
The results also suggest that the deposition of tufa is varying both in space and time, with micro-scale, meso-scale and macro-scale variations. Firstly, at the micro-scale there were large-scale differences in deposition on slides just two centimetres apart, it is possible this may mask variations at a larger scale. At the meso-scale there are undoubtedly variations in the rate of deposition around each particular site, although the placement of the bricks at the designated sites was constrained by both time and safety. At the macro-scale however, broad downstream trends are evident (Figure 7.50). The deposition at Brook Bottom is most likely a function of location. Site one is located at the exit of the adit. Here, saturated water drips into the adit from the overlying lime ash tips, however, the stream water does not directly come into contact with the lime ash, therefore, deposition rates are relatively low. Site two, directly downstream of site one, showed a deposition rate almost twice that of site one, with site three, directly downstream of site two, showing a deposition rate approximately four and a half times the magnitude of that recorded at site two.

Referring back to Figure 6.62 it is probable that the supersaturated water exiting from the "lagoon spring" (Plate 6.63, 6.64), which exhibited a calcium content of 666 mg/l, contributes to the increased deposition rates at site two and more particularly site three (Figure 8.01). It is also probable that the spring water from the "lagoon spring" also contributes to the elevated pH and conductivity levels recorded at this site.

At site four, deposition rates are less than half that recorded at site three, this is probably due to the high rate of tufa deposition at site three, thus the stream water is less saturated downstream of this site. Sites five and six experience a relatively low rate of deposition (approximately 0.0095 $g/cm^2/week$) this is due to their location (Appendix 14 Plate A8.02, A8.03). Sites five and six were located out of the main stream, but within a small side stream (Plate 8.04). Placing the bricks/slides within the main stream would have created difficulties in safely extracting and replacing the slides and would have caused inevitable damage to the tufa and terraces. As the slides were located out of the main stream less water flowed over the bricks and slides, less water leads to less deposition taking place. Undoubtedly, the rate of deposition would have been significantly greater, and possibly equal to that of sites four and seven, if sites five and six were located in the main body of the tufa. Figure 8.05 shows the mean weekly rate of deposition at sites in the main flow (excluding sites five and six). The graph shows a clearer downstream trend in the mean weekly rate of deposition with the omission of the two sites located outside the main stream flow.

The rate of deposition increases to a level at seven, similar to that recorded at site four, and increases again downstream at site eight to approximately 0.020 $g/cm^2/week$. Here, sites eight

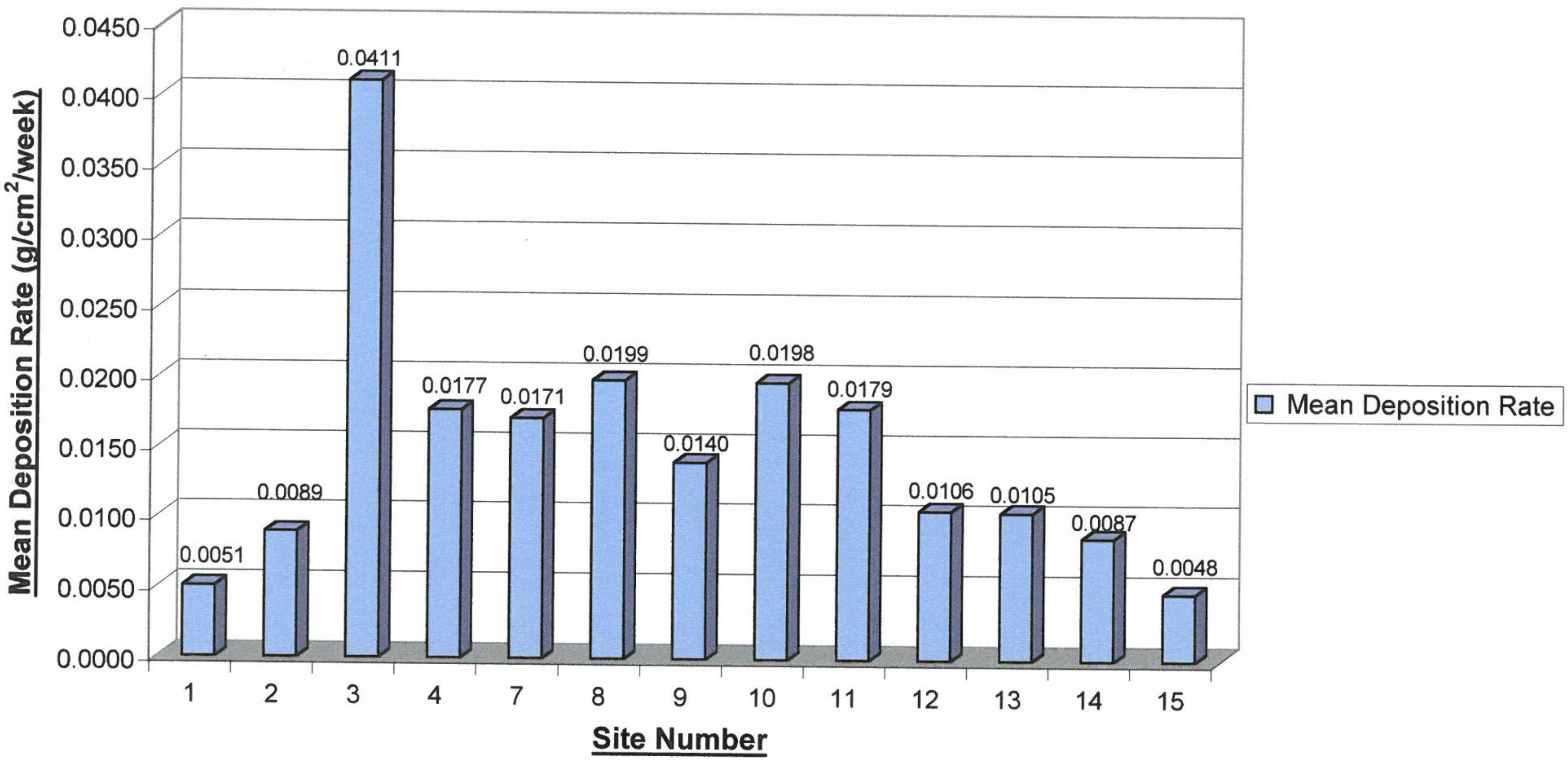
Figure 8.01: The possible route of super-saturated water from the lagoon spring, influencing the rate of deposition, and elevated pH and conductivity levels at sites two and three.



Source: Ordnance Survey, 1:2500, Plan SK 0470-0570, Revised October 1971.

Plate 8.04: The location of sites five and six within the small stream visible in the far left of the photograph.

Figure 8.05: Weekly Mean Deposition Rate Over the Period (18/08/98-20/10/98)



through to site fifteen are located within the main stream which forms downstream of the second main terrace. Site nine shows a decrease in the rate of deposition however, it is still within a range of that recorded at sites ten and eleven.

It is between sites eight and eleven where the majority of the smaller tufa terraces have been formed (Plate 8.06). Most of the tufa has however, has been deposited upstream of site seven, therefore, relatively few tufa terraces exist downstream of site eleven and the rates of deposition recorded at sites twelve and thirteen are relatively low at approximately 0.01 g/cm^2/week.

The rate of deposition decreases further at site fourteen to 0.0087 g/cm^2/week, and again at the final site, fifteen, to a level approximately equal to that recorded at site one (circa. 0.0050 g/cm^2/week). Sites fourteen and fifteen, although still located within the Brook Bottom stream, are situated downstream of the confluence with a tributary stream (Plate 8.07). Therefore the Brook Bottom stream is "diluted" by water from the tributary stream, and thus deposition rates are noticeably lower at sites fourteen and fifteen relative to sites upstream of the confluence.

Although the rate of deposition recorded at site fifteen appears to be a low value in comparison with deposition rates recorded at sites further upstream, it is still at a rate which far exceeds that of natural tufa depositing streams. Viles and Goudie (1990, p. 31) state that tufa deposition rates are " *highly variable, ranging from <1mm per year to circa 0.5 m per year, depending on environmental factors and also the method of measurement/estimation used*" (Table 8.08). High deposition rates of 1-50 cm per year are generally pertain to specific European and North American streams, springs and lakes, whilst tufa depositing streams, springs and lakes in the UK generally possess significantly lower deposition rates. For example, Pentecost (1981) studied the tufa deposits of the Malham district, North Yorkshire, and recorded growth rates of 0.19 – 0.34 mm/year in a natural tufa-depositing stream.

The extrapolated yearly deposition rates for the Brook Bottom site are clearly greater than rates of deposition recorded at other sites in the UK, and perhaps greater, or equal to the high rates of

Plate 8.06: A number of tufa small terraces between sites eight and eleven.

Plate 8.07: The confluence of the Brook Bottom stream with a tributary stream.

Table 8.08: Selected tufa deposition rates

Location	Rate (mm a^{-1})	Method/reference
Gwynedd, Wales	0.21–0.80	Various methods Pentecost, 1978
Malham Tarn, North Yorkshire	0.01 – 1.30	Various methods Pentecost, 1981
Gordale Beck, North Yorkshire	1–8	Historical records Pentecost, 1978
Howgill Beck North Yorkshire	0.19–0.34	Historical records Pentecost, 1978
Waterfall Beck, North Yorks	9	Pentecost, 1987
Rivulites, various UK locations	0.16–1.59	Direct measurements Pentecost, 1978
Plitvice, Yugoslavia	circa 10	Emeis *et al.*, 1987
Tivoli, Italy	circa 8–107	Laminar counts Chafetz and Folk, 1984
Yellowstone Park	180	Bargar, 1978
Hula Valley, Israel	0.32 ± 0.10	Dated layers Heimann and Sass, 1989
Raclawka, Poland	10	Pazdur *et al.*, 1988
Walker Lake Nevada (laminated rinds on shoreline)	circa 2	Laminar counts Newton and Grossman, 1988
Mammoth Hot Springs	20–560	Allen, 1934
Bee Creek, Texas	0.60	Experimental dam Folk *et al.*, 1985

Source: Viles, H. A. and Goudie, A. S. (1990) Tufas, travertines and allied carbonate deposits, *Progress in Physical Geography*, 14, 19-41.

deposition measured in foreign tufa-depositing springs, rivers and lakes. Zaihua *et al* (1995) describe heavy deposition of tufa in Huanglong Ravine, China, as approximately 5 mm/year, furthermore, Yuan (1991) states: *"A temple built in this area in 1620 A.D. is nowadays completely covered by tufa, with an estimated thickness of 1.8-2.0 meters, showing that those high deposition rates have been maintained over several centuries."*

This so-called "heavy" rate of deposition is similar to that measured at sites eight and ten at Brook Bottom, whereas, the deposition rate measured at site three, must be regarded as an extreme level of deposition and at a magnitude not recorded at any naturally tufa-depositing stream in the UK.

Aside from rates of deposition, the water's conductivity, and the water pH recorded at the Brook Bottom site also exceed the levels recorded in other studies of tufa depositing springs, streams and lakes in the UK. For example, Table 8.09 and Table 8.10 present some general chemical characteristics of the springheads of tufa-depositing streams near Malham Tarn (Pentecost, 1981), and monthly water chemistry data for the River Lathkill, Derbyshire, respectively (Pedley *et al*, 1996). The pH values recorded at the Brook Bottom site over the eleven week recording period show a range of between pH 7.61 – pH 12.97, a far greater range than those recorded in the studies by Pentecost (1981) and Pedley *et al* (1996). The pH values recorded at the Brook Bottom site are often in excess of pH 9, therefore, the Brook Bottom stream exhibits a far greater degree of alkalinity than natural tufa-depositing streams in the UK.

Table 8.11 presents selected water chemistry data from tufa-depositing springs, rivers and lakes (Viles and Goudie, 1991). The greatest mean annual pH was ascertained by Newton and Grossman (1988), at Walker Lake, Nevada, where a pH of 9.45 was recorded. Over the eleven weeks of data recording at the Brook Bottom site an mean of pH 10.2 was recorded which far exceeds the pH values recorded at Walker Lake, Nevada (Newton and Grossman, 1988), and other foreign tufa-depositing springs, rivers and lakes.

Table 8.09: General chemical characteristics of the springheads of tufa-depositing streams near Malham Tarn.

Springhead	pH	t°C	Ca^{++}(mM l^{-1})	HCO_3^-(mM l^{-1})	SATCAL	Date
Cote Gill	7.5	7	1.25	2.20	0.94	5.2.78
Cowside Beck	7.6	7	1.41	2.70	1.01	14.5.73
Gordale Beck	8.2	16	1.87	3.78	1.12	..
Howgill	7.5	8	1.27	2.27	0.94	5.2.78
Howgill tributary	7.4	9	1.77	3.68	1.00	14.5.73
Lower Beck	8.0	7	1.31	2.65	1.06	..
Waterfall Beck	7.5	6	1.37	2.74	1.00	..

Source: Pentecost, A. (1981) The tufa deposits of the Malham district, North Yorkshire, Field Studies, 5, 3, 365-387.

Table 8.10: Monthly water chemistry data for the River Lathkill, Derbyshire.

Sample date	Temperature (°C)	Na^+ (mmol l^{-1})	K^+ (mmol l^{-1})	Mg^{2+} (mmol l^{-1})	Ca^{2+} (mmol l^{-1})	Cl^- (mmol l^{-1})	HCO_3^{-}* (mmol l^{-1})	SO_4^{2-} (mmol l^{-1})	NO_3^- (mmol l^{-1})	ALK (meq l^{-1})	TIC* (mmol l^{-1})	pH	log Ω (calcite)
14.10.93	9.0	0.56	0.05	0.20	2.72	0.70	3.79	0.26	0.08	4.03	4.00	8.3	0.99
5.11.93	9.0	0.48	0.04	0.24	2.67	0.85	3.92	0.26	0.07	4.08	4.12	8.1	0.79
22.11.93	6.0	0.46	0.04	0.21	2.60	0.76	3.75	0.25	0.08	3.93	3.94	8.2	0.82
20.12.93	7.0	0.41	0.04	0.13	2.77	0.59	3.48	0.26	0.08	3.65	3.66	8.2	0.83
1.2.94	7.0	0.46	0.03	0.16	2.72	0.70	3.85	0.27	0.08	4.01	4.05	8.1	0.76
10.2.94	7.0	0.50	0.04	0.17	2.59	0.73	3.66	0.27	0.08	3.83	3.84	8.2	0.82
2.3.94	8.0	0.47	0.04	0.15	2.54	0.71	3.37	0.28	0.08	3.54	3.54	8.2	0.80
30.4.94	11.0	0.49	0.03	0.20	2.49	0.82	3.25	0.27	0.06	3.46	3.42	8.3	0.92
22.5.94	8.0	0.53	0.03	0.24	2.57	0.90	3.47	0.27	0.06	3.64	3.64	8.2	0.81
7.6.94	8.0	0.54	0.03	0.24	2.52	0.90	3.42	0.25	0.06	3.62	3.60	8.3	0.90
21.7.94	15.0	0.60	0.03	0.28	2.42	0.96	3.12	0.25	0.05	3.34	3.30	8.3	0.95
15.8.94	12.0	0.63	0.03	0.29	2.44	1.07	3.21	0.27	–	3.42	3.39	8.3	0.92
Mean	9.0	0.51	0.04	0.21	2.59	0.81	3.52	0.26	0.07	3.71	3.71	8.2	0.86

Source: Pedley, M., Andrews, J., Ordonez, S., Garcia del Cura, M. A., Martin, J. G. and Taylor, D. (1996) Does climate control the morphological fabric of freshwater carbonates? A comparative study of Holocene barrage tufas from Spain and Britain, Palaeogeography, Palaeoclimatology, Palaeoecology, 121, 239-257.

Table 8.11: Selected water chemistry data from tufa-depositing springs, rivers and lakes.

Location	pH*	Ca^{2+} (mg l^{-1})	Reference/Notes
Springs			
Roquefort les Cascades, Pyrenees (Stn 1)	7.32	85.30	Dandurand *et al.*, 1982 Mean of six measurements 1978–79.
Springhead of Gordale Beck, North Yorkshire	8.20	74.9	Pentecost, 1981
Springhead of Waterfall Beck, North Yorkshire	7.50	54.9	Pentecost, 1981
Rivers			
Gordale Beck North Yorkshire	8.02	69.3	Pentecost, 1987
Waterfall Beck, North Yorkshire	8.14	49.7	Pentecost, 1987
Mastiles West Stream, North Yorkshire	8.12	70.1	Pentecost, 1987
Dulce River, Spain	7.00	68.1	Ordonez and Garcia del Cura, 1983
River Tajuna, Spain	7.30	28.1	Ordonez and Garcia del Cura, 1983
Falling Spring Creek, Va	7.91	149	Herman and Lorah, 1987 Mean of observations from different stations, taken July 1984
Lakes			
Malham Tarn, North Yorkshire	8.10	41.3	Pentecost, 1987
Walker Lake, Nevada	9.45	11.0	Newton and Grossman, 1988 Sampling strategy unknown
Plitvice Lakes, Yugoslavia	–	94.6	Emeis *et al.*, 1987 Average value, sampling strategy unknown

Source: Viles, H. A. and Goudie, A. S. (1990) Tufas, travertines and allied carbonate deposits, *Progress in Physical Geography*, 14, 19-41.

Discussion.

Clearly the Brook Bottom site is unique in terms of the rate of deposition and the water chemistry. It is also thought to be unique as an anthropogenic tufa-depositing stream and consequently the site is worthy of wider recognition. It is also important to recognise that as there are no other anthropogenic forms of this type, comparisons in terms of the rate of deposition and water chemistry have to be made with studies based on natural tufa-depositing streams, springs and lakes.

In terms of the development of the Brook Bottom site since 1883, it would be fair to suggest that the dumping of lime ash commenced circa 1890. The construction of the wagon repair works at Harpur Hill at this time, allowed the transportation of lime ash from the Hoffman Kiln works to the Brook Bottom site. The deposition of tufa would have initially occurred at a low rate, and the present form of the site suggests that initial tufa deposition occurred in the upper main body (i.e. between sites 1-3). The rate of deposition would have increased as the dumping of lime ash increased. Between 1883 and 1944 it is probable that greatest deposition of tufa occurred between sites 1-7 with additional changes in the morphology of the stream channel between sites 7-15. Post 1944, lime production at the Hoffman Kiln, Harpur Hill ceased; therefore, it is probable that the deposition rate following this period was at an equivalent rate to the mean deposition rate recorded over the eleven week study. During this period deposition has been greatest in the upper main body (sites 1-3), followed by a lower rate of deposition in the lower main body (sites 4-7). It is conceivable that during this period the smaller tufa terraces observed between sites eight and thirteen were formed, coupled with slight changes in the morphology of the stream channel.

In terms of the future of the site, if the eleven week study period is representative of longer term trends then it is likely that the greatest deposition will continue to occur within the main body of the tufa (sites 1-7). It is also likely that the deposition will occur at a rate equivalent to that recorded over the eleven weeks of the study. For example, over the next 100 years, site three may experience an increase of over one metre in the depth of tufa, however, this level of deposition would breach the first terrace, thus, the rate of deposition may increase downstream of this site. From the extrapolated results over 100 years (Figure, 7.52) it is probable that sites eight through to eleven will experience the greatest change. Here, it is likely, on the basis of the results over the eleven week study, that the tufa terraces will increase greatly in size, the analysis suggests an increase in the depth of tufa of between approximately 0.5 – 0.7 metres over the next 100 years. This increase would subsequently raise the level of the stream thus, the morphology of the stream channel will change considerably. At present tufa deposition at the second main terrace has allowed water to breach the stone wall which "contains" the main body of the tufa. It is probable that this breach of the wall took place in the last 10-15 years as small terraces have formed within a small stream channel, this stream re-joins the main stream between sites fourteen and fifteen (Plate 8.12). It is therefore likely, that over the next few years this "new stream" will become exploited, the terraces within the channel will grow and may subsequently change the morphology of the river channel and terraces downstream of site seven.

Limitations of the methods/data sources have been considered previously (section 5.3) however, limitations of the results and data analysis have not been stated. The main limitations are:

- The eleven-week study ran from August to October therefore, any seasonal changes in deposition rates would not be apparent from the results of the study, deposition rates at Brook Bottom may increase or decrease during winter. For example, Viles and Goudie (1991, p. 31) state: *"In many cases seasonal fluctuations in precipitation rates are observed*".

- It was not possible to integrate the aerial photographs obtained from the Peak District National Park Centre within the analysis, as the photographs were of a scale too large to allow interpretation.

Plate 8.12: The small tributary stream re-joining the main channel between sites fourteen and fifteen.

- Only four maps of the Brook Bottom site since 1883 are available, this therefore, restricted the analysis and did not allow a detailed review of the development of the site.

- As stated previously caution must be taken when extrapolating short-term data over a long-term period as the results may not be particularly representative. However, the extrapolated long-term data provides a basis for predicting the future development and for determining the past history of the Brook Bottom site.

- In the analysis, the rate of deposition was calculated/extrapolated over two selected areas, again, the extrapolated results may not be particularly representative. Although, the extrapolated long-term data does provide a basis for predicting the future development and for determining the possible future of the site.

- Finally, as stated earlier, the tufa phenomena at Brook Bottom is an anthropogenic form of a tufa-depositing stream. It is believed that there are no other anthropogenic forms of this type and thus comparisons in terms of the rate of deposition and water chemistry have been made with the results of studies based on natural tufa-depositing streams, springs and lakes.

9. Conclusion

A number of conclusions can be drawn from the study of the anthropogenic tufa at Brook Bottom:

1. The rate of tufa deposition at the Brook Bottom site ranges from 0.0048 – 0.0411 $g/cm^2/week$, notably greater than rates recorded in studies of natural tufa-depositing streams, springs and lakes in the UK. Similarly, the pH and conductivity levels recorded at the Brook Bottom site over the eleven-week study period are greater than those recorded in studies of natural tufa-depositing streams, springs and lakes, both in the UK and abroad.

2 The rate of deposition at the Brook Bottom site varies in both time and space. At both the micro and meso-scale, large variations in the rate of deposition are apparent. However, at the macro-scale or over longer periods of time broad trends within the deposition data can be recognised.

3. Analysis of the data set showed that no clear relationship exists between the rate of deposition and the selected environmental parameters, pH, conductivity, total rainfall and mean temperature.

4. The anthropogenic tufa at Brook Bottom originated or began to form circa. 1890, when the construction of the wagon repair works at Harpur Hill allowed the transportation of lime ash from the Hoffman Kiln works to the Brook Bottom site. The tufa has therefore developed to its present state in a surprising short period of approximately 110 years.

5. The greatest deposition takes place between sites one and seven, however, the analysis of the data set has also shown that rates of deposition are high between sites seven to eleven. The current situation at Brook Bottom is however, a changing one, particularly with the development of a second smaller stream in close proximity to site seven, which, over the next 100 years will undoubtedly change and affect the current stream and tufa terrace morphologies.

The study has achieved it's two central aims, firstly, to determine the rate of tufa deposition and it's distribution in time and space, and secondly, to determine the development of Brook Bottom since 1883, and the possible future of the site. However, there is undoubtedly a wide scope for future study. Further research may include:

- Detailed investigations into the chemistry of the stream water and comparison of the results with similar research undertaken on natural tufa-depositing streams in the UK and abroad.

- The analysis/correlation of the rate of deposition with other parameters, either environmental, or relating to water chemistry, for example, the degree of calcite saturation.

- A long-term study of the rate of deposition, for example, a year-long investigation, with data collection on a weekly basis. A study of this type would highlight any seasonal disparities within the data set/rate of deposition.

- A study concerning the effects upon the tufa deposit at Brook Bottom of a relatively recent slope failure which occurred in close proximity to the entrance of the adit (site zero). This slope failure is shown in Plate 9.01. Observations made at the Brook Bottom

Plate 9.01: The recent slope failure in close proximity to the entrance of the adit (site zero).

site in late October, 1998, suggested that clastic and organic material brought down with the slope failure was entering the adit entrance and subsequently being deposited over the tufa between sites one and three.

- A study evaluating the changes in the colour of the tufa terraces. During the study period (18/08/98-27/10/98) the colour of the terraces, particularly downstream of site seven, was found to change from a light brown colour during periods of low flow, to a creamy white colour during periods of high flow (Plates 9.02, 9.03). It is possible that the colour changes are due to ochreous material leaching from the marsh adjacent to the Brook Bottom stream between sites seven and eleven and staining the terraces a light brown colour (Plate 9.04 and 9.05).

Plate 9.02: The colour of the terraces during low flow.

Plate 9.03: The colour of the terraces during high flow.

Plate 9.04: Ocherous material leaching from the marsh adjacent to the Brook Bottom stream.

Plate 9.05: Ocherous material leaching from the marsh adjacent to the Brook Bottom stream.

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