Environment Agency,
Lake District National
Park Authority

Environmental Appraisal of Derwentwater Low Water Levels

Volume 1 : Hydrological & Geological Study

RKL-ARUP

Chris Foley

EA: Water Resources - Box 1

Environment Agency, Lake District National Park Authority

Derwentwater Low Water Levels

Hydrological & Geological Study

January 1999

Ove Arup & Partners Consulting Engineers
Admiral House Rose Wharf 78 East Street Leeds LS9 8EE
Telephone +44 (0)113 242 8498 Facsimile +44 (0)113 242 8573

Job number 55390

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1. INTRODUCTION

RKL-Arup have been appointed by the Environment Agency and the Lake District National Park Authority, to undertake an environmental appraisal of Derwentwater Low Water Levels.

The National Park Authority produced a management plan for the lake in 1996. Public consultation for this management plan indicated that the low minimum lake level experienced in 1995 was a cause for concern for the lake users. The Lake District National Park Authority and the Environment Agency therefore commissioned this study to determine if the minimum lake level in Derwentwater was descreasing. The study was also to provide options to manage the minimum lake level and to undertake an environmental appraisal of these options. Studies were undertaken to determine how the ecology, recreational use of the lake, archaeology, agriculture, and landscape would be affected by changes to the minimum lake level.

This Environmental Appraisal was undertaken by RKL-Arup working in association with the Institute of Freshwater Ecology and the Smeeden Foreman Partnership.

The study has been reported in three volumes:

Volume 1 - Hydrological and Geological Study

Volume 2 - Ecological Appraisal

Volume 3 - Management Options.

This report forms Volume 1.

This report has been prepared by RKL-Arup for the use of the Environment Agency and the Lake District National Park Authority in response to their particular instructions. It is not intended for and should not be relied upon by any third party and no responsibility is undertaken to any third party.

2. STUDY AREA

2.1 The Site

Derwentwater is the third largest lake in the Lake District in Cumbria. It is situated south-west of Keswick and is in the Lake District National Park. As shown in Figure 1, Derwentwater is aligned north-south and is approximately 4.5km in length and 1.25km in width. It is centred on National Grid Reference NY260210. In normal conditions, Derwentwater has a surface area of approximately 6.7km². The catchment area of the lake is approximately 85km².

The main river feeder into Derwentwater is the River Derwent. This rises in the Borrowdale Fells and enters at the southern end of the lake. Many smaller becks enter the lake from the east and the west. The catchment is amongst the steepest and wettest in England. The lake discharges at the northern end over a natural sill barrier into a continuation of the River Derwent.

The topography to the south-west falls steeply from Cat Bells at 451mOD to a general shoreline level of 75mOD. To the south-east the topography is again steep, falling from Castlerigg Fell and Bleaberry Fell to the shoreline (Figure 2). To the north and south there are significant 'wash lands' where the River Derwent enters and leaves the lake (Figure 3).

The River Greta enters into the River Derwent 400m downstream of the lake. The River Greta catchment area to its confluence with the River Derwent is approximately 150km², shown on Figure 1, and takes in tributaries from the Blencathra, Matterdale Common and Helvellyn range, together with St Johns Beck from Thirlmere. The River Derwent then flows over the gauging station at Portinscale.

3. GEOLOGY OF THE DERWENTWATER AREA

3.1 Introduction

Derwentwater is situated within the Borrowdale area. The geology of the area has been established to determine if it has any effects on the low water level events at Derwentwater. The general geology, lake formation, and sedimentation are discussed below.

3.2 General Geological Formations

The Borrowdale area includes a broad basin containing the lakes Bassenthwaite and Derwentwater.

Derwentwater is underlain by the hard rocks of the Borrowdale Volcanic Series in the south and the softer Skiddaw Slates to the north and west. The valley has been substantially modified by glacial processes throughout the Quaternary ice age period during which the valley was deepened and Derwentwater and Bassenthwaite formed a continuous lake. A basal layer of lodgement till was deposited over the length of the valley as the glaciers advanced down Borrowdale.

During the glacial recession there were several stages of glacial advance and retreat leading to the deposition of moraines impounding a series of glacial lakes within Borrowdale of which Derwentwater and Bassenthwaite are two examples. Glacial meltwaters began the process of erosion of the moraines which held them back. The meltwaters brought with them large amounts of sediment which were laid down as lake deposits.

Since the end of the ice age erosion and sedimentation processes have continued to take place and modify the landscape to its present form. The process of erosion of the moraine that forms the sill of Derwentwater is a natural process as the River Derwent re-establishes its equilibrium and down cuts through the superficial deposits to the level of Bassenthwaite.

The geology of Derwentwater has been established through examining geological maps, memoirs and aerial photography. A sketch map showing the main geological features including the Regionally Important Geological/Geomorphological Sites (RIGS) at Crow Park, Castle Head, Friars Crag and the southern delta, is shown on Figure 4.

3.3 Geology

3.3.1 Skiddaw Slates

The Skiddaw Slates comprise a sequence of altered mudstone and sandstone which are of Ordovician age. The slates have been altered mechanically by intense folding and thermally by igneous intrusions associated with the Borrowdale Volcanics. The Skiddaw Slates are heavily cleaved and fractured which facilitates weathering and erosion of the rocks generally leading to a high but softer, more rounded, topography at the northern end and western side of Derwentwater.

3.3.2 Borrowdale Volcanic Series

The Borrowdale Volcanic Series comprise a series of volcanic lavas, ashes and agglomerates of Ordovician Age. The sequence is not as structurally contorted as the Skiddaw Slates and is more competent and resistant to erosion. Consequently the rocks of the Borrowdale Volcanic Series form the high mountains and crags at the southern end and eastern side of Borrowdale.

It is considered that much of the volcanic lavas, ashes and agglomerates of the Borrowdale Volcanic Series emerged from a volcano to the south of Keswick. A volcanic plug of dolerite exists at Castle Head which is considered to be the site of the volcano giving rise to the volcanic series of rocks to the south of Derwentwater.

3.3.3 Quaternary Geology

The Quaternary geology encompasses the glacial erosion of Borrowdale, the deposition of glacial deposits in the form of moraine and lake deposits during the retreat of the glaciers and the subsequent recent erosion and deposition of sediments. Throughout the last glaciation the general movement of ice was northwards down Borrowdale over the North Cumbrian Plain before joining ice from the Southern Uplands and moving via the Solway Firth into the Irish Sea. Ice joined the main flow down the Greta valley merging in the area of Keswick. A continuous valley would have existed joining together Seathwaite, Langthwaite, Derwentwater through to Bassenthwaite. The valley would have been over deepened from its current base although not to the extent of other lakes such as Windermere and Wastwater.

3.3.4 Glacial Moraine

The advance of the glaciers within Borrowdale will have left some basal lodgement till comprising disrupted local rock of Borrowdale Volcanics and Skiddaw Slates as a very stiff blue clay with sand and gravel. This glacial till remains in the form of hummocky and striated deposits which typically form the base of Derwentwater and Bassenthwaite.

Superimposed on these are the less well consolidated ablation tills dumped by the receding glaciers and comprising a mixture of sand gravel and boulders. These deposits typically form the natural barriers that impound Bassenthwaite and Derwentwater and formerly impounded lakes in Seathwaite and Langthwaite. The small islands in Derwentwater also typically comprise piles of granular material left as the glaciers receded. The village of Portinscale and the Derwentwater Hotel are situated on the western end of the moraine that has been substantially eroded by the action of the River Greta and River Derwent and lies beneath the flood plain between the Derwentwater Hotel and Keswick . At Keswick the generally higher ground on which the town is built is a series of glacial moraine drumlins.

The pedestrian bridge close to the Derwentwater Hotel is at the site of the former road bridge prior to the relatively new A66 crossing. The original crossing is likely to have been at a point where shallows occurred and probably a former fording point existed. The shallow area would be due to the down cutting of the river through the glacial moraine deposits. The shallow nature of this area is likely now to be masked to some extent by the construction of the Portinscale weir. There are outcrops of some very coarse material in the form of boulders in the river bank below the Derwentwater Hotel which may represent the line of the glacial moraine.

3.3.5 Lake Deposits

To the rear of the glacial moraines, lakes were formed. These lakes overflowed during the rapid thaw of the glaciers and later substantial winter runoff leading to the erosion of the moraines and the formation of the lake outfalls. The lakes were impounded at a level greater than their former preglacial levels and as a consequence were not in equilibrium. The lake outfalls are naturally eroded to re-establish equilibrium. Bassenthwaite lake is impounded by glacial moraine at its northern end by the outfall which has effectively been stabilised by the construction of a bridge with a protective scour pad. Derwentwater outfall is not protected and consequently an idealised equilibrium will only be reached when Derwentwater achieves the same level as Bassenthwaite. At the same time as erosion is taking place there is deposition of sediment in the delta into Bassenthwaite from the River Derwent, Newlands Beck and the

River Greta. In Seathwaite and Langthwaite valley there are former glacial lakes retained by glacial moraines which have been eroded and infilled by lake sediments such that they only become lakes at time of very high rainfall. The lake deposits are generally laminated clays and silts with occasional sand and gravel layers which occur as flood detritus.

3.3.6 Ground Conditions at the Sill of Derwentwater

At the site of the sill or lake outfall the ground conditions are likely to be a complex arrangement of glacial till, glacial moraine and fluvial deposits. Without detailed site investigation information it is difficult to define exactly what materials form the sill. The ground conditions at the sill have therefore been conjectured from historical reports of the foundation conditions for the railway line abutments downstream, aerial photograph analysis and site walkover information. It is estimated that the total thickness of superficial deposits above bedrock is approximately 10 to 20m.

The ground conditions at the sill are broadly formed in two layers. The lowest layer above bedrock is likely to comprise a stiff to very stiff blue clay with a little sand, gravel and cobbles. The blue clay is a basal lodgement till derived from reworked Skiddaw Slates. Above this layer it is likely to be a much more granular material comprising predominantly sand, gravel and some boulders with a silt and clay matrix. This material is a combination of a glacial moraine and glacial outwash deposit formed at the head of the retreating Borrowdale glacier. At the near surface and adjacent to the sill area the material is likely to be more recent deposits of sand, silt and clay.

3.4 Recent Geological Processes

3.4.1 Erosion

Erosion has continued as a geological process since the ice age removing material from the sill of Derwentwater. This process may have been accelerated by human activity through the building of weirs, removal of weirs, creation of stepping stone crossings, bridge abutments and river straightening. Major events which may have influenced the rate of erosion of the sill of Derwentwater include:

- The straightening of the River Derwent through the flood plain
- Drainage measures to either side of the River Derwent on the flood plain
- Construction of the railway bridge abutments
- Construction of the A66 bridge abutments
- Construction of the weir at Portinscale
- Removal of weirs on the River Greta in Keswick
- Construction and removal of landing stages close to the outfall.

3.4.2 Sedimentation

Sedimentation continues to take place with the deposition of lake deposits at the southern end of Derwentwater. The effect of grazing on the fells generally increases the rate of soil erosion leading to a greater amount of sediment load and consequently sedimentation. The overall effect of sedimentation will be to reduce the depth of water in the lake.

3.5 Discussion

The erosion of the sill of Derwentwater and sedimentation in the lake are natural processes which started following the recession of the Quaternary ice glaciers. Erosion is a relatively fast process in geological time, but it would still take many thousands of years for the sill to completely erode and the sedimentation processes to fill Derwentwater. The rate of erosion of the sill may have been influenced by the activities of man with the building and removal of structures on or adjacent to the River Derwent and River Greta.

4. HYDROLOGY

4.1 Introduction

The hydrological study aims to:

- assess if lake levels on Derwentwater have fallen.
- identify possible causes of the fall in lake levels.
- assess the likely frequency of low lake levels.

4.2 Data Collection

In a hydrological study the extent and quality of the available data is important. The data available affects the hydrological methods used and the accuracy of the results. The data obtained and used in this study is described in the following sections.

4.2.1 Rainfall Data

Eight raingauges, as shown on Figure 1, were identified as being useful for the determination of rainfall within the Derwentwater catchment. Data for these raingauges was obtained from the Environment Agency and the Meteorological Office.

A summary of the availability of raingauge data is shown in Table 1 below. However, problems with data file corruption meant that Styhead No. 1 raingauge was not used.

Rainguage	Station No.	Altitude (mAOD)	Data Record	Remarks
Derwent Island	592733	88	1871-1965	
Styhead Tarn	592431	449	1864-1986	
Styhead No. 1	592428	335	1952-1997	Original data file corrupted
Sprinkling Tarn	592430	605	1864-1986	
Grisedale Bridge	6000286	146	1878-1991	
Seathwaite	592448	129	1867-1991	
Thirlmere (The Nook)	592764	189	1961-1997	
Dale Head Hall	592846	189	1894-1993	

Table 1: Raingauges

In Table 1 the Data Record refers to the earliest and latest year in which rainfall was recorded. However, there are considerable gaps of rainfall data within the data record of several of the raingauges. The actual length of data record for each raingauge is shown in Figure 5.

Table 1 and Figure 5 show that rainfall data from 1864 to 1997 is, at varying times, available from as little as one to as many as seven raingauges.

The raingauges listed in Table 1 vary in altitude from 88 m AOD to 605 m AOD. In mountainous areas the amount of rainfall measured at a raingauge is highly dependent on the altitude at which the raingauge is placed. For example, for the same time period, a raingauge placed on the top of the fells is likely to measure higher rainfalls than a raingauge placed within the valley bottom. The amount of rainfall recorded for a time period will therefore be highly dependent on the position of the raingauge(s) available. In order to produce a reliable and consistent record, therefore, a method must be used to convert rainfall recorded at a single raingauge to an average depth of rainfall across the entire catchment. For this study, the average amount of rainfall across the whole catchment draining into Derwentwater was determined using a version of the Hypsometric Method. This method is described in Appendix A.

Due to the long period of records available for analysis (134 years), and the possible time delay between rainfall and observed changes in lake level, monthly values of rainfall have been used.

4.2.2 Evapotranspiration, Lake Evaporation and Effective Rainfall

Not all of the rainfall that falls within the Derwentwater catchment will run off from the land and end up in Derwentwater. Some will be lost due to evaporation from the soil and water bodies and due to transpiration from vegetation.

This method of water loss is known as Evapotranspiration and may be estimated using meteorological and land use data. Hence, the effective rainfall within the Derwentwater catchment may be calculated as follows:

$$\text{Effective rainfall} = \text{Measured rainfall} - \text{Actual Evapotranspiration} \pm \text{Change in soil moisture} \qquad \textbf{(equation 1)}$$

Estimates of monthly Potential Evapotranspiration (PE_t) at Keswick since 1918 were obtained from the Environment Agency's PET-CALC computer program. Estimates of PE_t obtained from PET-CALC indicated that differences in PE_t for the same month in different years were relatively small and hence average values for each month, obtained from post-1918 data, were used to calculate the PE_t for pre 1918.

These estimates of Potential Evapotranspiration losses were then converted to an estimated Actual Evapotranspiration (cf. Shaw 1991).

The Penman 1 method (cf. Shaw 1991) was used to estimate evaporation losses from the lake itself.

4.2.3 River Flow Data

No continuous direct measurements of flow in the River Derwent directly downstream of the outfall of Derwentwater were available. An estimate of the lake outflow was therefore achieved by using daily discharge records from two nearby gauging stations, Portinscale and Low Briery. The location of the gauging stations is shown on Figure 6. The gauging station details are given in Table 2.

Station	Station No.	River	Catchment Area (km^2)	Record Start	Record Finish
Portinscale	751007	Derwent	237	1976	Ongoing
Low Briery	750806	Greta	146	1976	Ongoing

Table 2 : Portinscale and Low Briery Gauging Station Details

As no other significant watercourses enter the River Derwent between these two gauging stations, an estimate of the outflow from Derwentwater may be obtained by subtracting the flow measured at Low Briery from that measured at Portinscale.

This could lead to differences between actual and estimated lake outflows due to a 5km^2 area of land between the two gauging stations that is not within the Derwentwater catchment area. Errors due to this are thought to be minimal due to the relatively small size of this additional catchment area compared to the 85 km^2 draining into Derwentwater, and as much of this area is covered by the town of Keswick.

Most of the rain falling on to land within Keswick will enter the town's drainage system rather than running off into the river or infiltrating into the ground and slowly seeping into the River Greta. The drainage system of Keswick drains to the sewage works on the Wath Beck, which joins the River Derwent downstream of Portinscale.

Errors due to this additional catchment area were assessed by using several Environment Agency (EA) spot measurements taken in the River Derwent, downstream of the lake outflow. The results of spot gaugings using current meters were plotted against estimated lake outflow using Portinscale and Low Briary gauging stations. The plot is shown in Figure 7. The plot shows that the two sets of measurements are similar, suggesting that reasonable estimates of lake outflow may be obtained using the available EA gauging stations, although some discrepancies can be seen.

4.2.4 Lake levels

The availability of records of lake level are obviously critical in a study regarding current and historical lake levels. Several potential sources of lake level data have been investigated and the results of this are described as follows.

4.2.4.1 Environment Agency Level Recorders

Data is available from the three Environment Agency level recorders, at Fawe Park, Lodore and Keswick Campsite as shown on Figure 6. Details of the level recorders are shown in Table 3 below.

Level Recorder	Station Number	Record from
Fawe Park	750103	May 1983
Lodore	750106	July 1995
Keswick Campsite	750200	April 1996

Table 3: Lake Level Recorders

Daily lake level records are available for Derwentwater from May 1983 to the present. However, there is a gap in data from January 1990 to April 1993.

The level recorder in the River Derwent at Keswick Campsite has not been levelled and so data from this gauge cannot, at present, be used to determine water levels.

The Fawe Park level recorder provides data on lake levels from May 1983 to July 1995. However, it is unsuitable for measurement of very low lake levels as it tends to bottom out at low levels. This occurs when the actual lake level falls below the lowest measurable level of the level recorder, and thus the level recorder measures a higher lake level than the real lake level. Periods when the Fawe Park level recorder bottomed out were removed from the analysis. These periods are listed in Table 4.

Period	Minimum Recorded Lake Level (mAOD)
8 August to 2 September 1983	74.60
21 May to 1 June 1984	74.61
30 September to 6 October 1986	74.61
19 May to 24 May 1988	74.61
3 November to 9 November 1993	74.55

Table 4 : Periods when the Fawe Park Level Recorded bottomed out

The level at which the level recorder bottoms out is constant apart from November 1993. The lower level at which this recorder bottoms out could be due to clearance of sediment from within the stilling well. The period 15 March 1995 to 4 May 1995 was also not used in the analysis as it appeared that the level recorder was stuck at a constant level during this period.

When more than one lake level recorder was available the average value of the recorded levels was taken as the lake level. Removing periods when obvious errors occurred (see above) the average difference between daily average lake levels recorded by the Fawe Park and Lodore level recorders was 0.02 m. This is regarded as a small difference and is most likely due to the effect of wind-induced waves on measured lake levels.

4.2.4.2 Historical Data

As Environment Agency data records begin in 1983, additional historical data, as described below were investigated and used in the historic determination of lake levels.

A report on the River Derwent catchment by Hydrocomp (1976) indicates that continuously recording lake level measurement devices were present on Derwentwater between 1973 and 1975. Despite significant investigations, however, this data has not been located.

It has become a custom that the Mayor of Keswick lays a stone tablet during exceptionally dry periods. These tablets are placed at the lake low water level at Friars Crag. Tablets have been laid since 1893. Eleven measurements of minimum lake level are available from this source. The tablet dates and levels are shown in Table 5.

Tablet Year	Level (mOD)	Remarks
1893	74.648	
1925	74.716	
1939	74.727	
1940	74.633	
1976	74.523	Tablet inscribed "Barbara M. Robinson - Mayor"
1980	74.508	
1983	74.496	
1989	74.475	
1992	74.473	
1994	74.714	Dubious accuracy-lowest level not recorded?
1995	74.376	

Table 5: Friars Crag Tablet Lake Levels

It is important to remember that the Friars Crag tablets are not a formalised method of recording lake levels, but appear to have been carried out on an ad hoc basis, presumably being influenced by the wishes of the local population. This is likely to depend in part on the perceived severity of the drought period, which would presumably be increased during regional or national droughts and periods of increased pressures on the lake, such as increased water demand or lake usage. The recording of all very low lake levels by the Friars Crag tablets would therefore not necessarily be expected. From examination of the effective rainfall record, however, six out of the eight driest periods this century have been marked by a tablet at Friars Crag, with the exception of periods during or shortly after the World Wars. This indicates that the Friars Crag tablets provide a good sample of minimum lake levels on Derwentwater.

Mill (1895) lists three additional significantly low water levels measured on Derwentwater during the last Century, the earliest of which dates back to 1868. Mill (1895) also refers to a record of daily measurements of lake level that were taken on Derwent Isle during the last century. A variety of Records Offices and organisations have been contacted, but this data has not been located.

4.3 Assessment of Trend in Minimum Lake Levels

An initial assessment as to whether minimum lake levels in Derwentwater have fallen over the last one hundred years may be achieved by plotting the lake levels recorded by the Friars Crag tablets against time. This is shown in Figure 8.

Figure 8 appears to indicate that a significant long-term trend in minimum lake levels is present on Derwentwater. However, the 1994 lake level is an anomaly to this apparently steady trend of a decrease in minimum lake levels with time. The reason for this may in part be explained by comparing the lake levels recorded on the tablets with those recorded by the Environment Agency level recorders.

When the minimum levels identified by the tablets at Friars Crag and those recorded by the Environment Agency lake level recorders are available in the same year, the lake levels may be compared. These are listed in Table 6 below.

Date	Tablet Level (mAOD)	Recorder Level (mAOD)	Difference (cm)
1989	74.48	74.51	-3.8
1994	74.71	74.51	20.6
1995	74.38	74.38	-0.4

Table 6: Differences between minimum lake levels (m AOD) measured by the Friars Crag tablets and Environment Agency level recorders

Although the Fawe Park level recorder was operating during August 1983 when a tablet was also placed at Friars Crag the level recorder had bottomed out and thus the recorded low lake level may not be compared with that identified by the tablet. The lake level recorded by the tablet during this year (74.50 m AOD) was, however, lower than the level at which the lake level recorder bottomed out (74.60 m AOD) allowing some confidence to be placed in the tablet data for 1983.

The 1995 data agrees significantly while the 1989 levels are within reasonable error bands. The difference in level identified during 1994 (20.4 cm) may, however, cast some doubt over the accuracy of the minimum lake levels recorded by the other tablets at Friars Crag. The difference between the minimum lake level recorded by the level recorder and the Friars Crag tablet is significant, and is almost as great as the apparent decline in minimum lake levels over the last one hundred and thirty years. It is apparent that the 1994 tablet was placed incorrectly, and that this is the reason for the outlying point in Figure 6. It should be noted that if one tablet has been placed incorrectly then other tablets may also be placed incorrectly. There is therefore the possibility of uncertainty in minimum lake levels recorded by the Friars Crag tablets.

Another uncertainty associated with the sole use of the tablet data to determine trends in lake levels, may be related to the reason for these tablets existing in the first place. The tablets at Friars Crag have traditionally been placed to record periods of exceptionally low lake level. Hence this data set has been 'filtered' so that it contains only very low lake levels. It may well be that the minimum lake levels recorded at Friars Crag are generally those that were close to or lower than previously observed minimum lake levels, higher lake levels being deemed as 'insignificant'. This would therefore cause an apparent trend in the recorded minimum lake levels, when in fact the minimum lake level could be fluctuating up and down.

Possible influences on minimum lake levels are therefore considered in more detail to assess whether a trend in minimum lake levels does actually exist.

4.4 Potential Reasons for Observed Decline in Minimum Lake Levels

The three most likely causes of a fall in lake level are climate change, catchment land use change and erosion of the lake sill. Climate change and land use change could have caused an increase in the severity and duration of droughts, causing a reduction in lake levels. These factors are considered below.

4.4.1 Past Change in Catchment Characteristics

Major land use changes that might change catchment hydrology and sediment budgets are urbanisation, afforestation, sheep stocking density and land drainage. None of these changes appear to have occurred to any hydrologically significant degree in the catchment area, which is largely mountainous and dominated by wet upland soils. They have therefore not been considered further in this analysis.

Changes in land use such as land drainage, sheep grazing densities and footpath erosion may, however, lead to a change in the sediment budget of a catchment. They may produce bare surfaces, which can provide sediment sources, and preferential surface flow pathways along which sediment can be transported. However, the lake will act as a buffer to any changes in the sediment regime as the majority of sediment will simply settle out in the lake and will not effect changes in outfall conditions.

4.4.2 Climate Change

A preliminary assessment of possible climate change effects on the hydrology of Derwentwater can be made using the 134 years of rainfall data available.

Figures 9, 10 and 11 show monthly rainfall, summer (April to September) rainfall and 5-year mean summer rainfall depths since 1864 for the Derwentwater catchment, respectively.

As shown on Figure 9 no trend can be seen from the plot of monthly rainfall values since 1864. Both high and low values are distributed reasonably evenly throughout the period and there is no apparent trend in monthly rainfall values throughout this period.

Figure 10 indicates that the minimum summer rainfall amounts, during very dry years in the late twentieth century, are no lower than they have been during the rest of the record and that their frequency is not significantly different either. The maximum summer rainfalls during the last twenty years or so are typically lower than those during the mid-twentieth century. This situation does not appear to be significantly different to that experienced during the thirty years around the turn of the last century. Trends in maximum summer rainfall would not affect minimum lake levels reached as minimum rainfall values control the minimum lake levels.

Figure 11 does not show a trend through time in rainfall, although it does show that the last five years have been exceptionally dry. This is mainly due to the severity and length of drought experienced in 1995 and 1996. It does not indicate that a consistent and irreversible change in climate is occurring.

In summary, the long-term rainfall record does not indicate a significant trend in minimum rainfall values and hence does not indicate that climate change is a cause for a steady decrease in minimum lake levels.

4.4.3 Erosion of Lake Sill

Before flowing out of Derwentwater into the River Derwent water must flow over a raised area of lake bed at the mouth of the lake outflow. As previously described in the geology section this 'sill' area is a natural geological feature and is one of the factors controlling the flow of water out of the lake.

The hydraulics of water flow mean that there is a consistent relationship between the rate of flow out of the lake and the depth of water above the top of the lake sill. If the sill level is lowered, therefore, for the same flow, the lake level will drop. The depth of water above the sill level remains the same, but as the sill is lower, the actual height (mAOD) of the water level will be lower.

Given the geological setting of the area erosion of the lake sill may be the most likely cause of a fall in lake levels.

4.4.3.1 Lake Stage-Discharge Curve

An initial method to determine if the sill level of the lake outflow is falling may be achieved by using recently collected data to examine the stage-discharge relationship for the lake. The stage-discharge relationship for the lake describes the relationship between the rate of flow out of the lake into the River Derwent and the water level on the lake.

If the level of the sill does not change the relation between lake level and riverflow will not change through time. If the sill erodes, however, water levels on the lake will decrease for the same rate of flow and the stage-discharge curve would indicate a trend of decreasing lake levels for the same discharge. Figure 12 shows the stage-discharge relationships between 1983 and 1997. No recorded lake levels were available between January 1990 and April 1993. Figure 12 shows that for the same flow lower lake levels occur for the post-1992 data than for the pre-1990 data, indicating that the outfall is eroding.

This change in sill level was quantified using stage-discharge curves. Daily lake outflow was plotted against daily average lake level, when possible, on logarithmic graph paper to produce a stage-discharge curve. A constant value was then subtracted from the daily lake levels until a straight line plot was observed on logarithmic paper, as shown on Figure 13. The constant value at which the straight line graph is seen, is the effective sill level for the lake. This is the level at which zero flow from the lake would occur. At this level the lake level would be equal to the sill level.

The term 'effective sill level' is used as we are investigating a natural sill rather than a man-made weir. This means that the actual level of the sill is likely to vary across the outflow in response to areas of greater deposition and erosion. There may also be some leakage of water through the material making up the lake sill. The effective sill level therefore corresponds to the level of an imaginary man-made weir across the lake outfall that would operate hydraulically in the same manner as the natural sill.

Due to the data available, several difficulties were encountered in using this method to determine the effective sill level. In 1989 and 1994, the effective sill level could not be accurately determined due to noisy data and a lack of sensitivity to the sill level used. Additionally, in several years (1983, 1989, 1995) multiple stage-discharge curves at low flows were seen. As an example, the daily stage-discharge curve for 1995 can be seen in Figure 14, the lower line at low flows relates to the period 6 August to 23 September 1995. Environment Agency records show that an illegal temporary dam had been placed across the lake outfall during the summer of 1995 and had been removed on 3 August 1995. It would appear that the upper line relates to the lake level being held artificially high by the temporary dam and that the lower line should be used to indicate the true effective sill level. It is possible that the 1983 and 1989 stage-discharge curves therefore also indicate the existence of illegal temporary dams across the lake outfall, or could correspond to other 'one-off' events.

For the majority of years the effective sill level was accurately determined using visual fitting of the stage-discharge curves.

Figure 15 indicates a general decrease in effective sill level through time, although the rate of change in sill level is not constant. It would appear, therefore, that the sill controlling the outflow of water from Derwentwater is eroding, and thus this may be the cause of falling lake levels. This erosion is not continuous, however, and would appear to occur at varying rates. Possible reasons for this are as previously discussed in Section 2.4.

An estimate of the intermediate term trend in lake sill level may be achieved using the report produced by Hydrocomp (1976). This includes the effective sill level of the lake estimated from data recorded from 1973 to 1975. The effect of adding this to the sill levels calculated above can be seen in Figure 16. This suggests that the rate of decrease in sill level was not as great during the 1970s as it has been in recent years.

4.4.3.2 Comparison of Past Lake Levels and Effective Rainfall

Figure 15 indicates that the lake sill has generally been eroding fairly rapidly over the last fifteen years. Figure 16 indicates that the rate of outfall erosion is less when considered over a longer period of twenty five years. The Cumberland River Authority was, however, concerned about low lake levels during the early 1970s, suggesting that some erosion of the lake outfall had been occurring prior to this date.

In order to investigate possible longer-term erosion effects a simple mathematical model was calibrated to simulate monthly average lake level. A model of lake level from effective rainfall (section 4.2.2) data is required as although no trend in climate has been identified, the actual values of rainfall and evapotranspiration during a low flow period will affect the actual lake level attained.

Lake and effective rainfall data for the period 1983 to 1985 were used to produce a model of lake level based on monthly effective rainfall values. This indicated that monthly average lake level was highly dependent on the effective rainfall occurring in the same month. Consideration of the effective rainfall during the preceding month produced a slight improvement in model fit, increasing model r^2 from 0.84 to 0.89 (an r^2 of 1 would indicate that the model simulates lake level exactly). However, the addition of data from an additional month did not improve model fit significantly. The lack of strong dependence of lake level on the effective rainfall of more than two months previous is due partly to the use of a monthly time step, partly because antecedent soil moisture conditions are taken into account when calculating monthly effective rainfall values, and partly due to the rapid response of the catchment.

The following model was found to be most appropriate for estimating lake level from effective rainfall for the period 1983 to 1985:

$$L_x = 0.0013\, R_x + 0.0004\, R_{x-1} + 74.617 \qquad \textbf{(Equation 2)}$$

Where L_x is the average monthly lake level in month x (m AOD), R_x is the total effective rainfall in month x (mm) and R_{x-1} is the total effective rainfall in the month preceding month x (mm). The model r^2 of 0.89 indicates that the model accounts for most of the fluctuations in lake level, but that there is some uncertainty in the model predictions.

From Equation 1 it can be seen that the lake levels are three times as sensitive to the effective rainfall in that month as to the effective rainfall in the previous month. This result was also found when attempting to fit a model of lake level for the period 1994 to 1996 ($r^2 = 0.84$). It would appear, therefore, that the critical effective rainfall governing lake level is:

$$R_{crit} = 0.75R_x + 0.25\,R_{x-1} \qquad \textbf{(Equation 3)}$$

The effective rainfall dataset was therefore used to produce a time series of R_{crit}.

This means that use can be made of the Friars Crag tablet data to investigate trends in lake level throughout the study period without applying the effective rainfall/lake level model. This is advantageous as this will not be subject to any possible errors caused by uncertainty in the model outputs.

Table 7 shows the recorded low lake levels, the two-month rainfall totals and the weighted two-month effective rainfalls associated with the recorded low lake levels.

Table Date	Two-month Rainfall (mm)	R_{crit} (mm)	Level (m AOD)
1893	206	*	74.648
1925	164	10	74.716
1939	235	25	74.727
1940	156	-67	74.633
1976	223	4	74.523
1980	116	-25	74.508
1983	179	-1	74.496
1989	255	22	74.475
1992	278	36	74.473
1995	228	-9	74.376

Table 7 : Historical lake levels and weigted effective rainfall values

* No measured evapotranspiration available

Negative effective rainfall values indicate that all rainfall is lost to evapotranspiration and infiltration into subsurface storage so that streamflows are only being generated by seepage of water from soil and groundwater. The average weighted two-monthly effective rainfall since 1864 is 214mm so it can be seen that all of the periods in the above table are very dry compared to average conditions.

A simple comparison of lake levels to effective rainfall values can be made as there has been no significant land use change within the catchment (Section 3.4.1). The pre-1940 data indicates that little change in minimum lake levels occurred during this period. The 1893 and

1940 levels are very similar, despite the summer of 1940 being somewhat drier, and the 1939 minimum lake level was not lower than the 1925 minimum lake level.

As summarised in Table 8, 1939 and 1989 have very similar climatic characteristics, with both rainfall and effective rainfall being very similar in both years. If no physical changes were occurring to the lake, therefore, it would be expected that the minimum lake levels experienced in the two years would be very similar to one another. In fact, the 1989 lake level is 0.25m lower than the 1939 lake level, a very significant difference. From this it would appear that the lake sill had eroded by an average rate of 5mm per year over this 50 year period.

Table Date	Two-month Rainfall (mm)	Weighted two-month effective rainfall (mm)	Level (m AOD)
1939	235	25	74.727
1989	255	22	74.475

Table 8 : Summary of characteristics of the 1939 and 1989 low lake level events

Further evidence of falling lake levels may also be seen in Table 9. Comparing lake levels in 1940 and 1980, which have similar climatic characteristics, it would appear that lake levels fell by an average value of 3mm per year during this period.

Table Date	Two-month Rainfall (mm)	Weighted two-month effective rainfall (mm)	Level (m AOD)
1940	156	-67	74.633
1980	116	-25	74.508

Table 9 : Summary of characteristics of the 1940 and 1980 low lake level events

A similar trend can be seen when comparing 1980 and 1995 lake levels (see Table 10), the average rate of fall increasing to approximately 9mm per year in this period.

Table Date	Two-month Rainfall (mm)	Weighted two-month effective rainfall (mm)	Level (m AOD)
1980	116	-25	74.508
1995	228	-9	74.376

Table 10 : Summary of characteristics of the 1980 and 1995 low lake level events

It appears, therefore, that similar climatic conditions have produced increasingly low levels throughout this century, with the fall in lake levels appearing to become significant at some time after 1940. It can also be seen from this that the rate of erosion of the sill is not consistent, but varies through time. Reasons for this are discussed below.

4.5 Sill Erosion Rates and Predicting Future Lake Levels

The results of the hydrological investigation indicate that rather than being a smooth process, sill erosion progresses at an irregular rate with periods of slow, gradual erosion being separated by periods of increased erosion. This is likely to be a consequence of both natural and human influenced factors and is difficult to predict.

Natural erosion of the lake sill will be governed by the energy available for erosion in the water flowing over the sill, and the resistance of the sill material to erosion.

The energy available for erosion will depend not only on the magnitude of the discharge flowing over the sill, but also on downstream conditions in the River Greta. In general, higher flows out of Derwentwater will have more energy and thus will cause more erosion. Occasionally, however, the River Greta water levels become high enough to interfere with flow from Derwentwater. If this happens the velocity of water within the Derwent channel will be lower and thus the erosion potential of flows will decrease.

The amount of erosion that actually occurs will also depend on the ability of the material at the surface of the sill at the time of the flow to resist the erosion forces of the water. This will be influenced mainly by the size and cohesiveness of the materials on the sill surface. The lake outfall is composed of glacial till, which are typically highly heterogeneous deposits, consisting of a range of grain sizes from clay to boulders. This means that at any point in time the lake sill may be composed of a variety of materials, each having a different ability to resist erosion. A surface layer of cobbles will have a high resistance to erosion, will protect layers beneath them (*armouring*) and will erode only slowly, even under high flows. Beneath this, however, may be a layer of loose sand which would be easily eroded under even moderate flows and which would therefore erode quickly. The coincidence of low flows with a cobble layer would therefore lead to little or no erosion while high flows over a sandy layer would lead to higher erosion rates.

The natural pattern of erosion is further complicated by human influences, the impacts of which will depend in part on the volume and density of lake users and visitors at any one time. This will be influenced by many factors including the number and timing (e.g. Bank Holidays, weekends or mid-week) of good summer days. Additional erosion of the sill will be caused by any human impact as any disturbance of sediment will increase erosion rates. Obvious impacts include the construction and subsequent removal of landing stages, temporary weirs constructed by children or other parties and scraping of the sill by canoes or other vessels. These events are high frequency, and low magnitude which, although individually are unimportant, could have a significant cumulative effect. The magnitude of the impact of these activities will also depend on the material at the sill surface at the time of the impact, and is difficult to record.

From the above discussion it can be seen that with the present data it is difficult to assess potential future trends in lake levels. Site investigation at the sill could potentially reveal the likely change in resistance of sill materials to erosion with depth. Given the current information, accurate prediction of future changes in lake levels remains difficult. However there is no reason to assume that the lake sill will stop eroding in the near future.

4.6 Likely Frequency of Occurrence of 1995 Lake Levels

In order to assess the frequency of the 1995 low lake level a simple frequency analysis of 134 years of r_{crit} data has been undertaken. The Weibull distribution (Gustard et al 1992) was used in this study and is likely to produce a good estimate of the frequency of occurrence of the effective rainfall experienced during the summer of 1995, given that no consistent trend in climate is evident.

The use of the Weibull distribution, and other similar, distributions, is common in hydrology when trying to estimate the frequency of flood and drought events. They are normally used to extend a short period of observed data to allow an estimate of the magnitude of an event that may occur on average once every one hundred years, or even less frequently.

The Weibull distribution allows the effective rainfall data to be transformed mathematically, so that the frequency curve may be approximated by a straight line (Figure 17). It is then simple to extend this straight line beyond the limits of the measured data to estimate the frequency of a particular drought event occurring.

The Weibull distribution has been found to best represent the distribution of river flows and is the distribution recommended for low flow frequency studies. Using this distribution it is estimated that there is a 10% probability of the climatic conditions that caused the 1995 minimum lake level occurring in any year.

Given the erosion of the sill outfall, however, the lake level experienced in August 1995 may be expected to become increasingly more frequent as the same climatic conditions will give rise to ever decreasing lake levels. It is not possible to accurately predict this change, however, due to the erratic nature of sill erosion, as discussed above.

5. Possible Remediation Measures

The previous sections have identified that the lake level on Derwentwater is falling, that it has recently been falling at a relatively rapid rate and that natural erosion of the lake sill is to be expected given the geological setting of the lake.

While lake-users have expressed difficulty in navigating the lake at low water levels, the impact of low water level on all aspects of the lake and the environment needs to be assessed.

The following options have been reviewed in Volumes 2 and 3 to assess their environmental impact and viability.

- Do nothing
- Map and mark obstacles
- Selected dredging of navigation channels
- Construction of a permanent weir to increase low lake levels
- Construction of a temporary weir to increase low lake levels
- Maintain present minimum lake levels.

6. Summary

The major conclusions of the hydrological and geological study may be summarised as follows :

- Given the geological setting of Derwentwater, natural erosion of the sill is expected
- Friars Crag tablet data indicate that lake levels have fallen. Limitations to this data precludes the drawing of conclusions directly from this information.
- Land use and climate do not appear to have changed significantly over the period of this study and would not therefore explain the decline in lake levels
- Lake stage-discharge curves indicate that the level of the lake sill is falling, although data limitations mean that the results should be treated as indicative rather than absolute.
- Modelling indicates that lake levels are sensitive to the effective rainfall in the previous two months, with effective rainfall in the same month being three times as important as effective rainfall in the previous month.
- Comparison of past lake levels with critical effective rainfall depths over the last 134 years also indicates that lake levels are dropping, and that this is due to the sill level falling. The clearest example of this effect can be seen when comparing the 1939 and 1989 low lake levels (Table 8). Despite having virtually the same climatic conditions the 1989 minimum lake level is 0.25m lower than that experienced in 1939. Given that no other significant changes have occurred within the Derwentwater catchment this may be attributed to falling sill levels.
- Future erosion rates are likely to be erratic, depending on rainfall within the Derwentwater catchment, the material exposed as the sill erodes and human influences.
- It is estimated that there is a 1 in 10 chance that the effective rainfall conditions causing the low lake level experienced in 1995 will occur in any one year.
- Several possible remediation techniques have been identified, and the potential impact of these is considered in Volumes 2 and 3.

Several techniques have been used to investigate whether minimum lake levels on Derwentwater have fallen. These techniques indicate that minimum lake levels are falling, that this is due to erosion of the lake sill and that the rate of this erosion is unpredictable.

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Data Sources

Environment Agency lake level data

Environment Agency PET-CALC potential evapotranspiration data

Environment Agency Raingauge Data

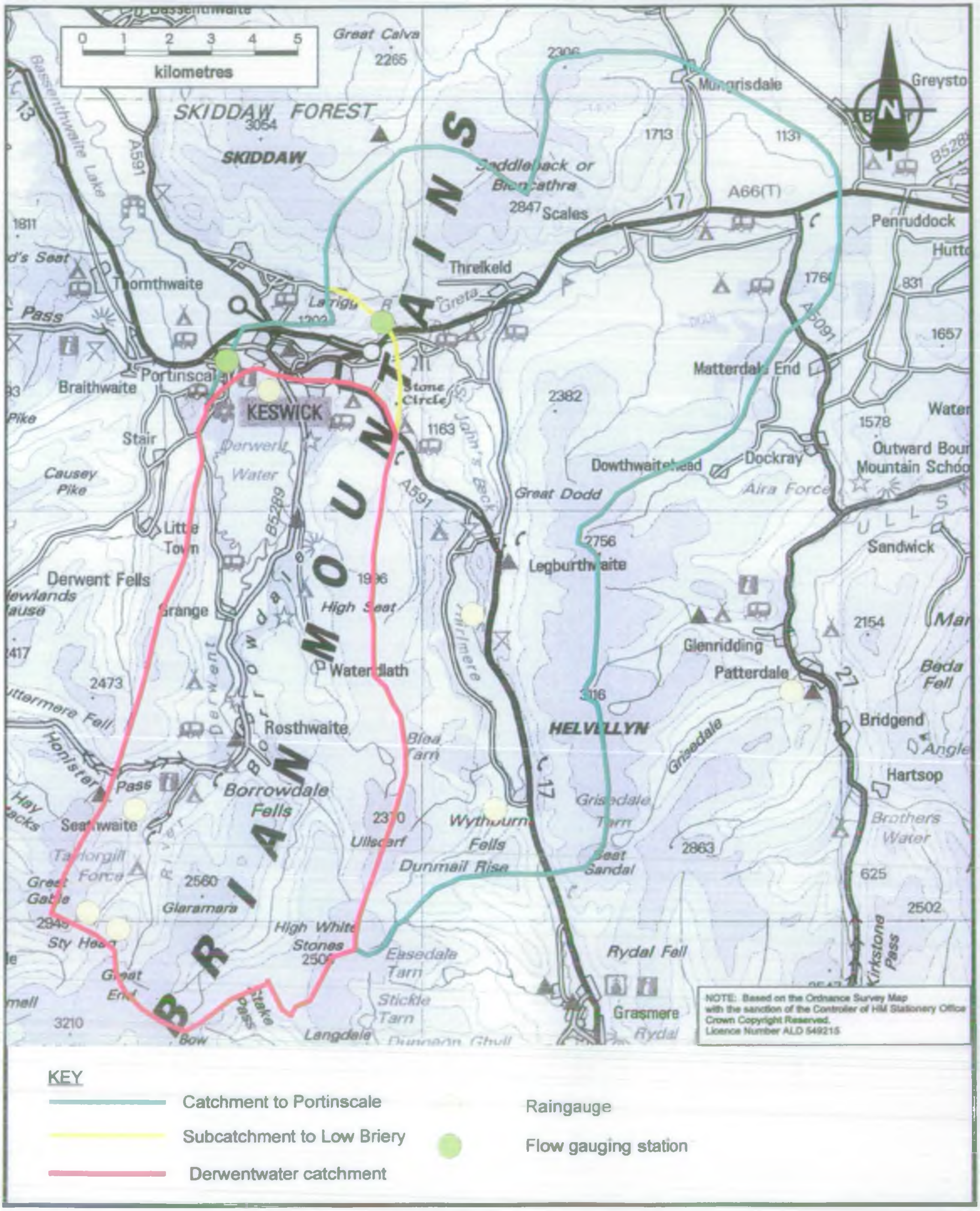
Environment Agency Riverflow Data

Friars Crag tablets survey

Meteorological Office Raingauge Data

Ordnance Survey Landranger 90 Penrith & Keswick (Ambleside) 1:25,000

Figures



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ENVIRONMENT AGENCY
NORTH WEST REGION

Lake District National Park Authority

Derwentwater

January 1999

Approximate position of catchment boundaries, raingauges and flow gauging stations.

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Figure 1

PHOTOGRAPH No 1 - Long distance view from Langtrigg Fell

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North West Region

Lake District
National Park Authority

Derwentwater
January 1999
Landscape Photographs

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Figure 2

PHOTOGRAPH No.2 - View over marsh area to southern end of Derwent Water around the inlet

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Lake District
National Park Authority

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January 1999
Landscape Photographs

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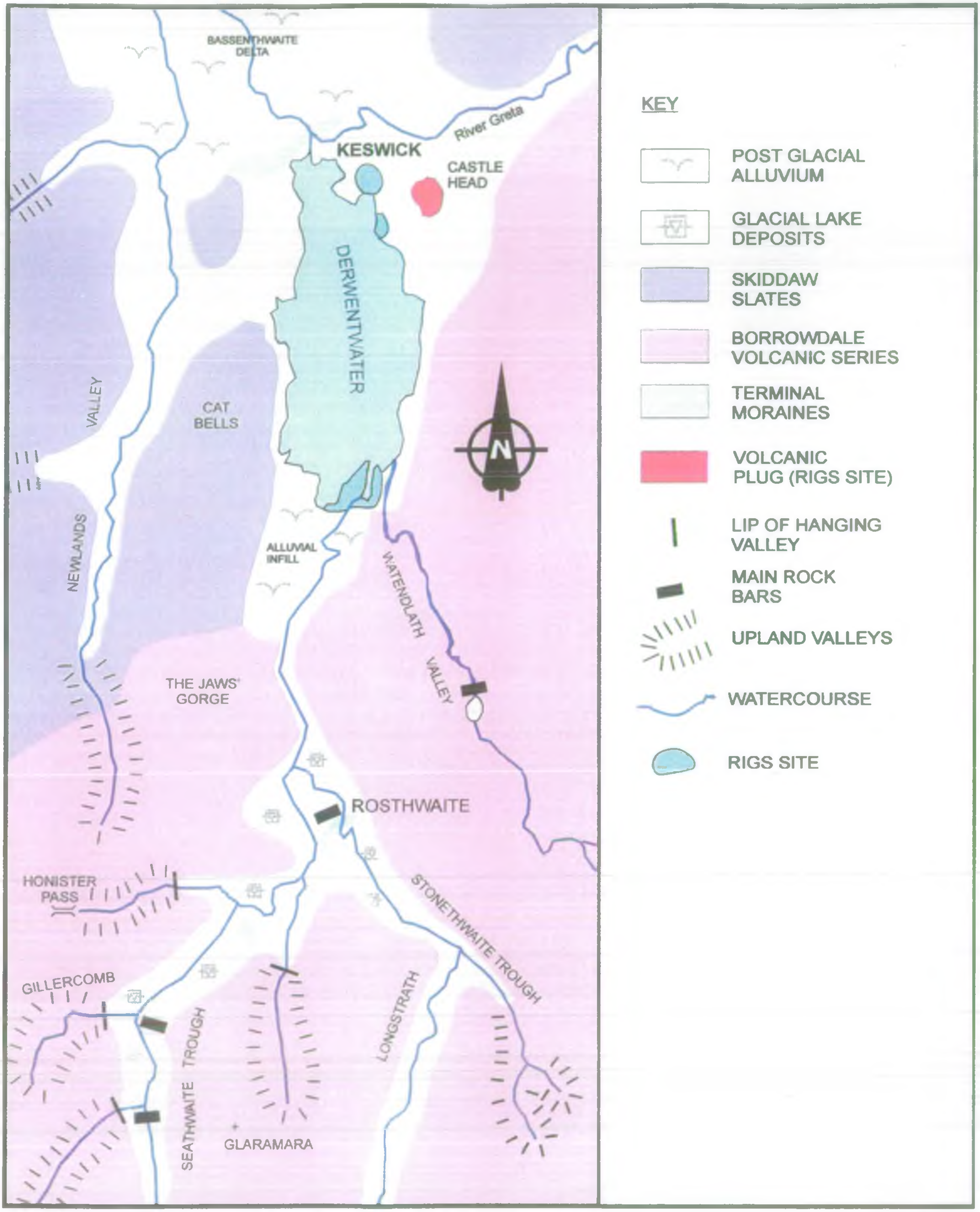
Figure 3



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Derwentwater
January 1999
Sketch Map of Quaternary Features

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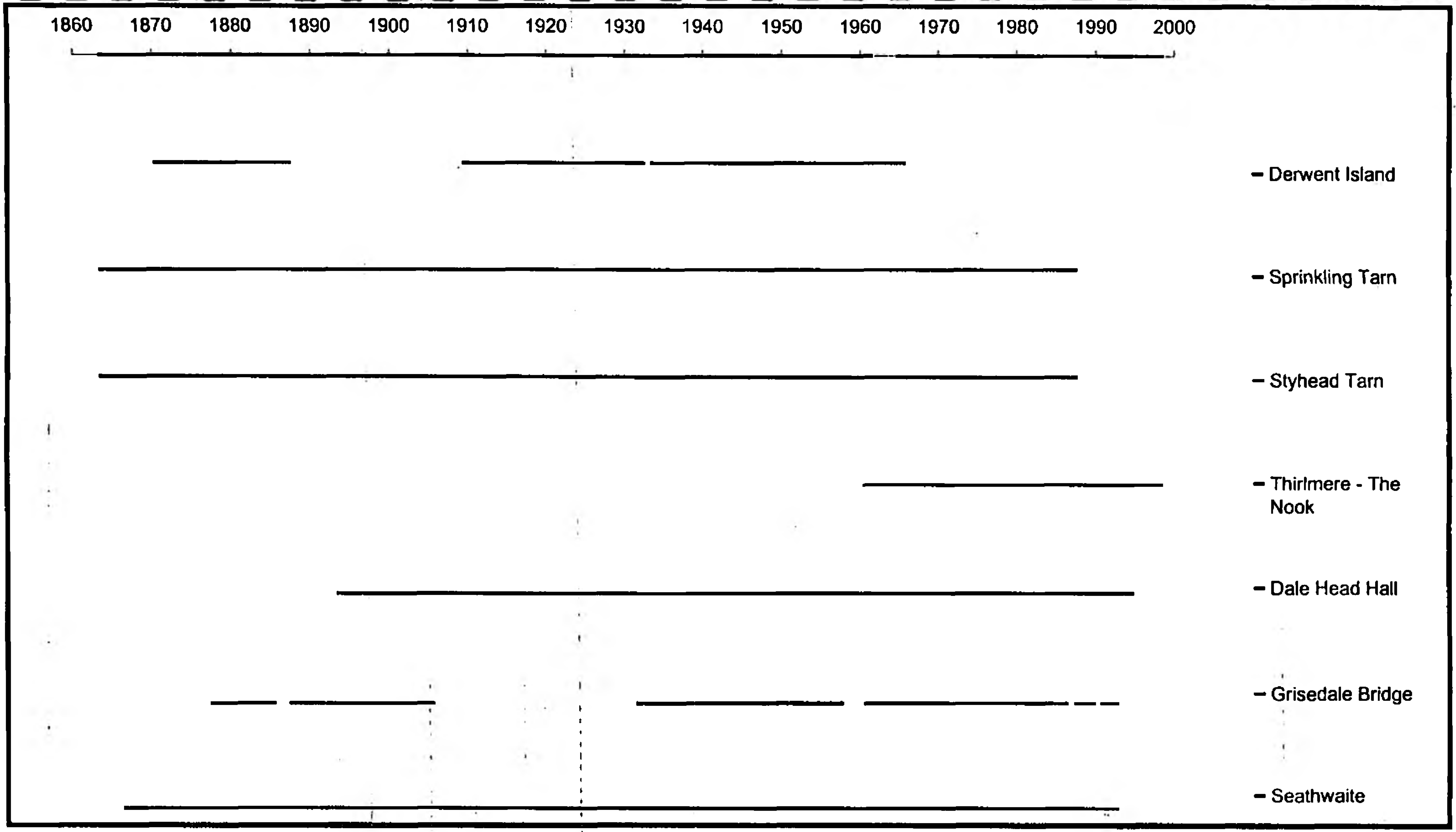
Figure 4



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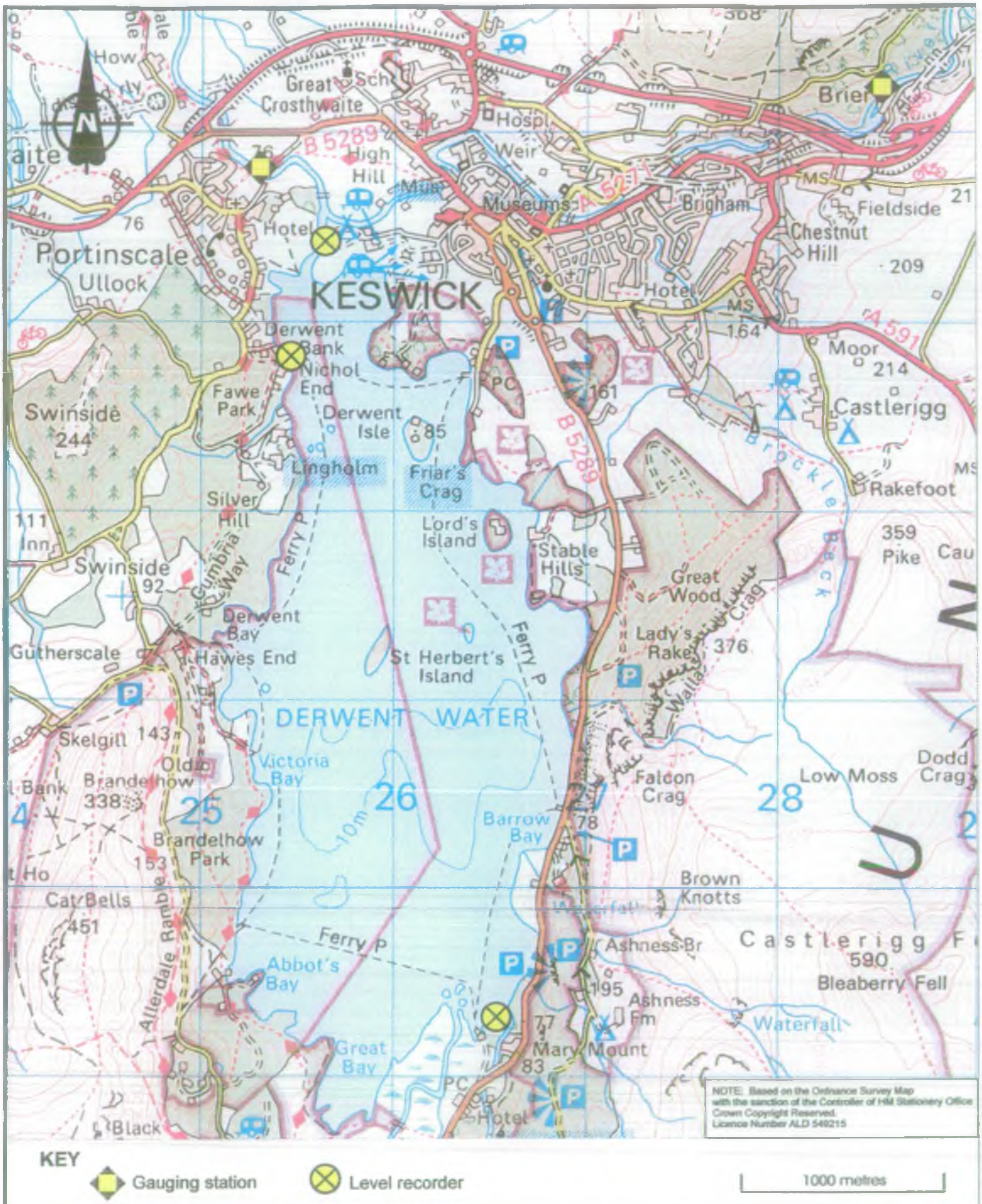
Derwentwater
January 1999
Raingauge Data record

Figure 5



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National Park Authority

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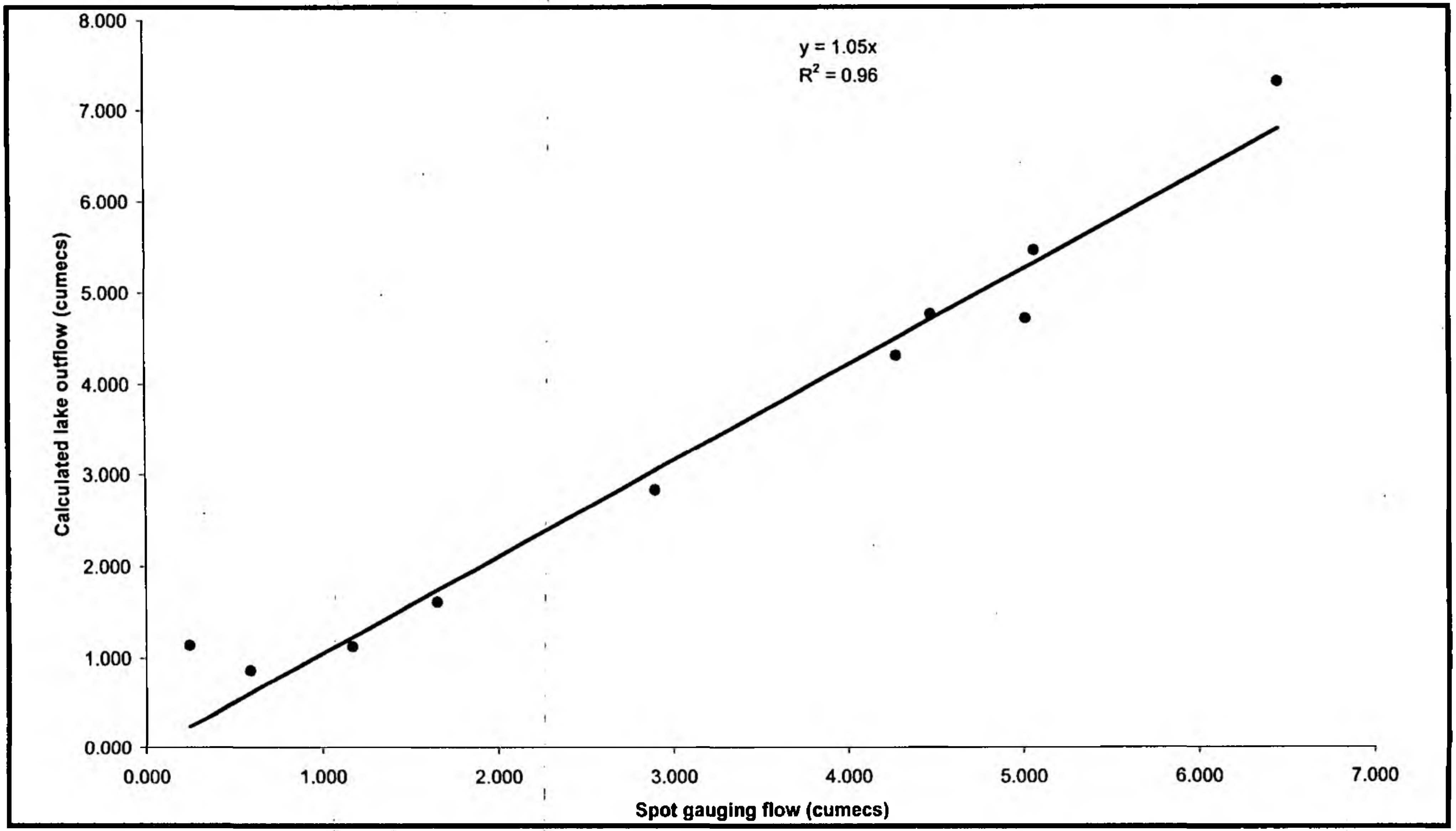
Derwentwater
January 1999
Location of gauging stations and level recorders
Figure 6



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Derwentwater
January 1999
Comparison of direct and indirect estimation of lake outflow
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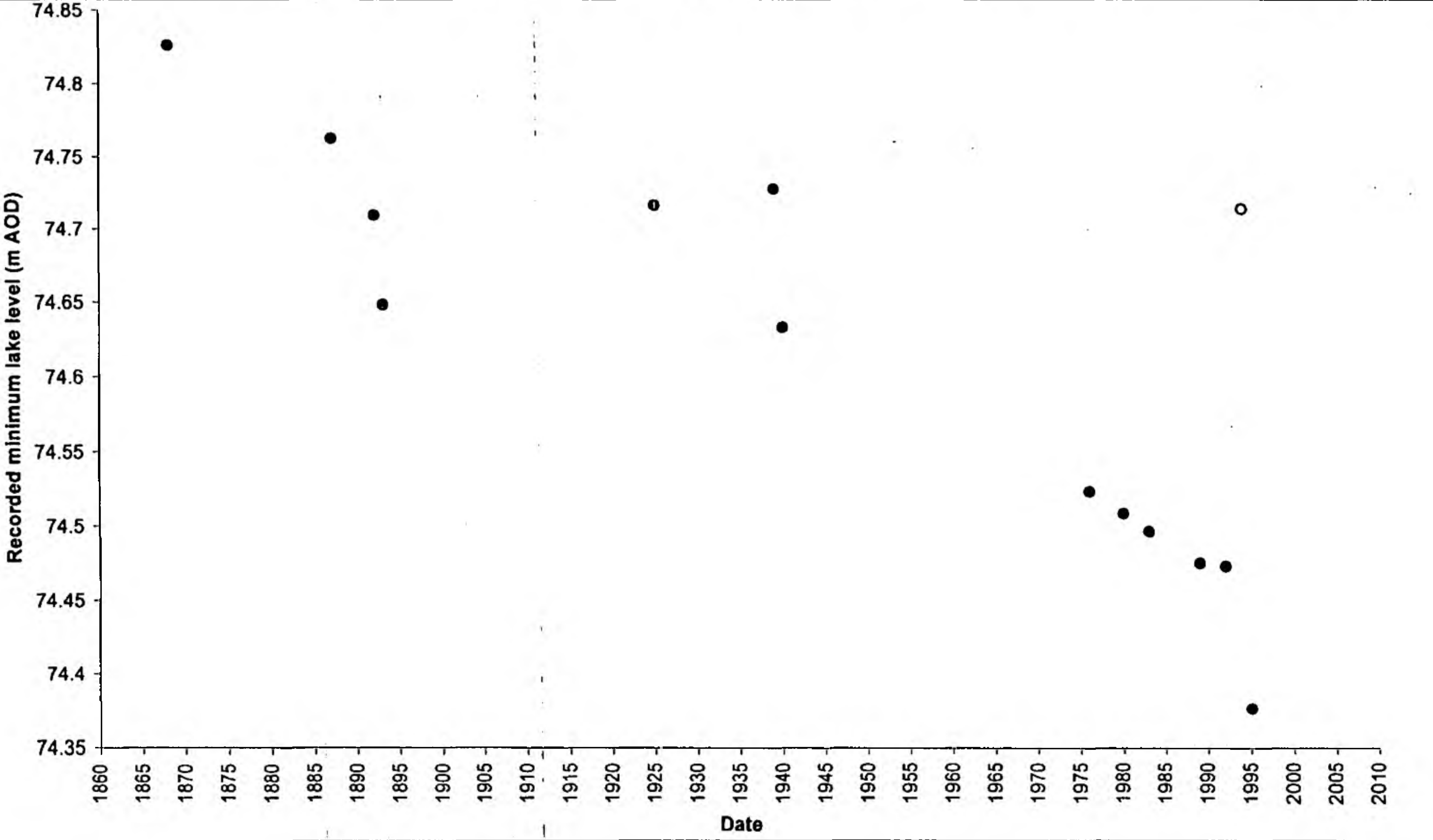
Figure 7



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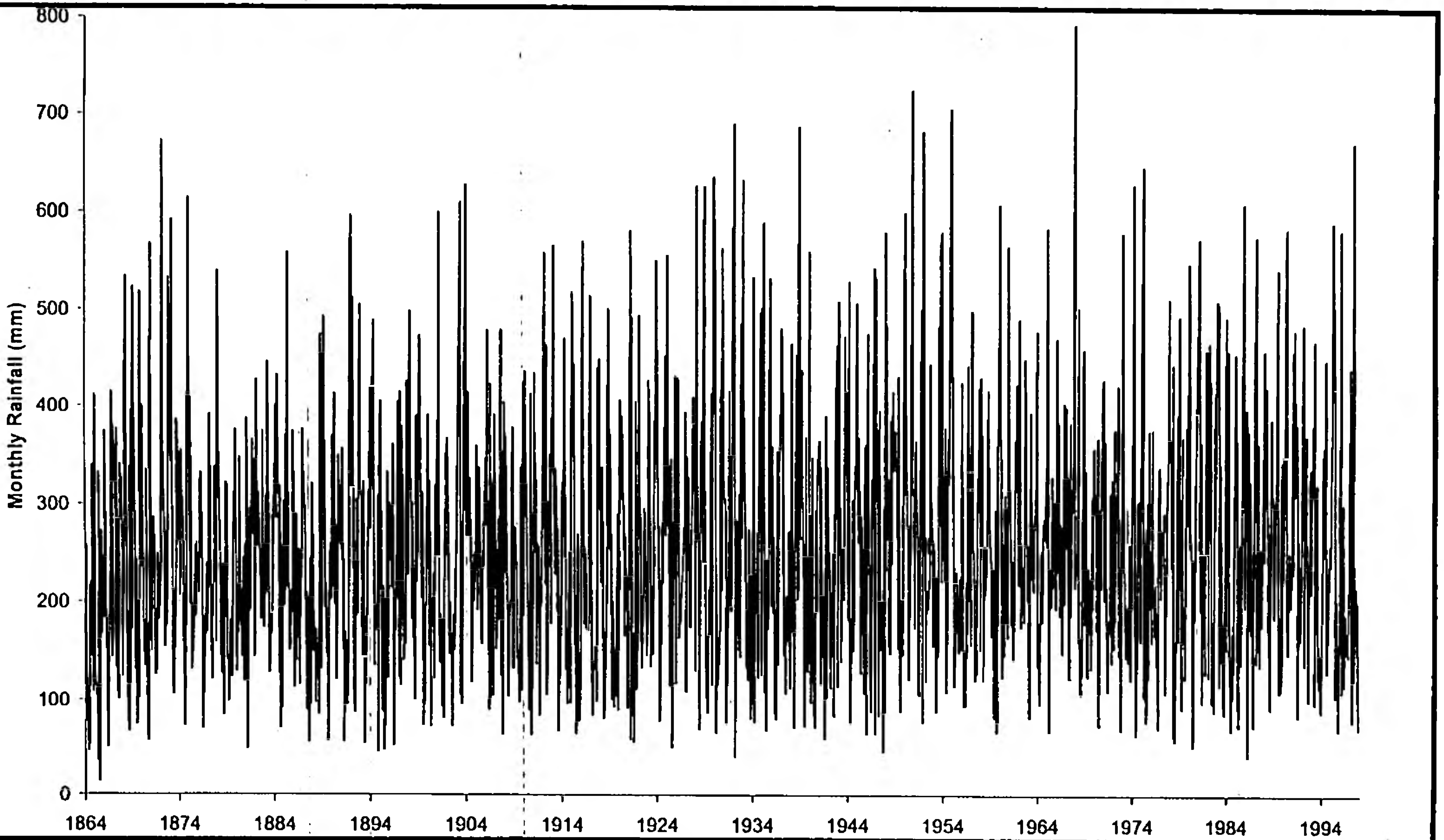
Derwentwater
January 1999
Minimum lake levels from Friars Crag tablets
Figure 8



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Derwentwater
January 1999
Monthly Catchment Rainfall

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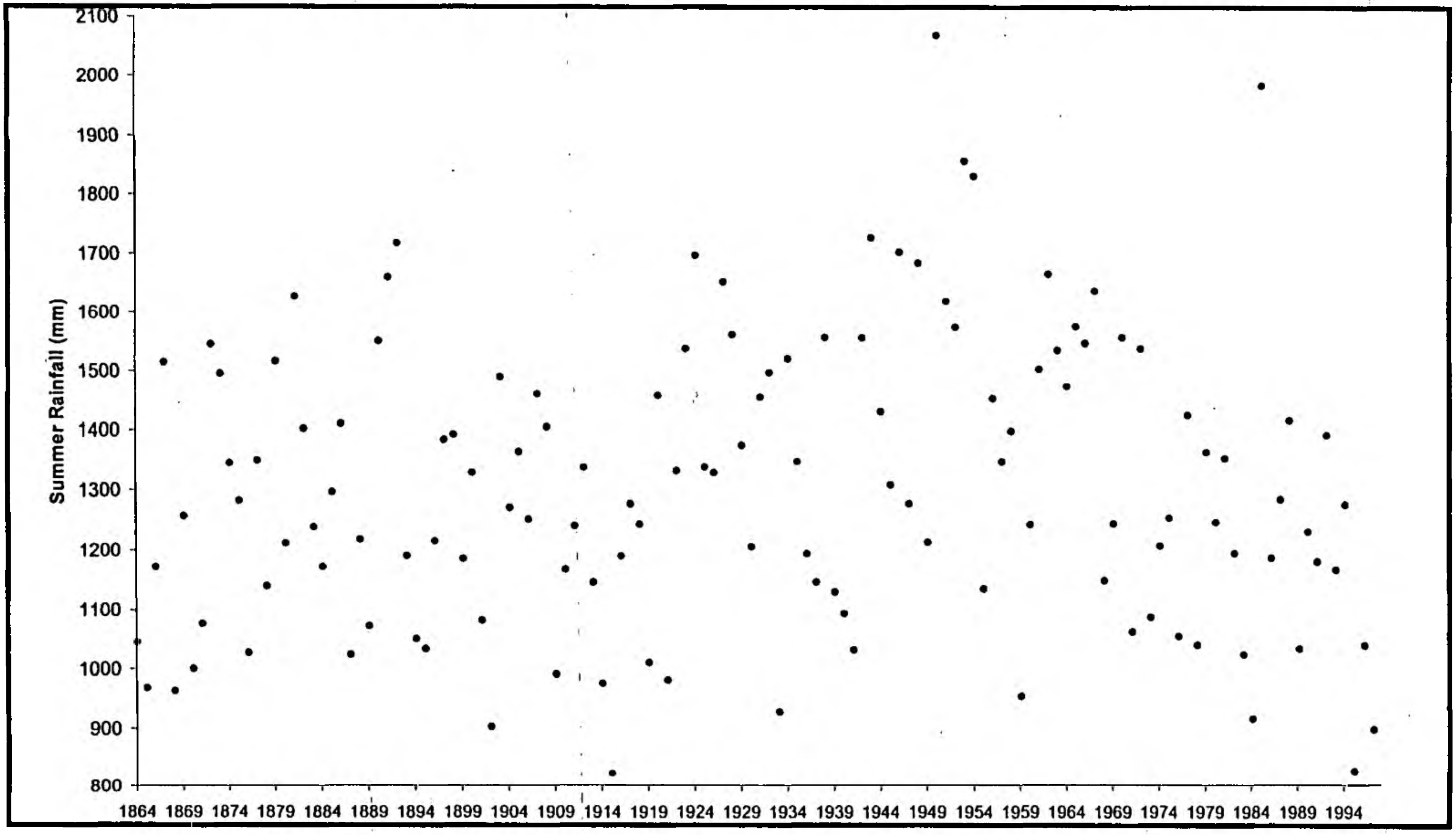
Figure 9



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Derwentwater
January 1999
Summer (April to September)
Catchment Rainfall
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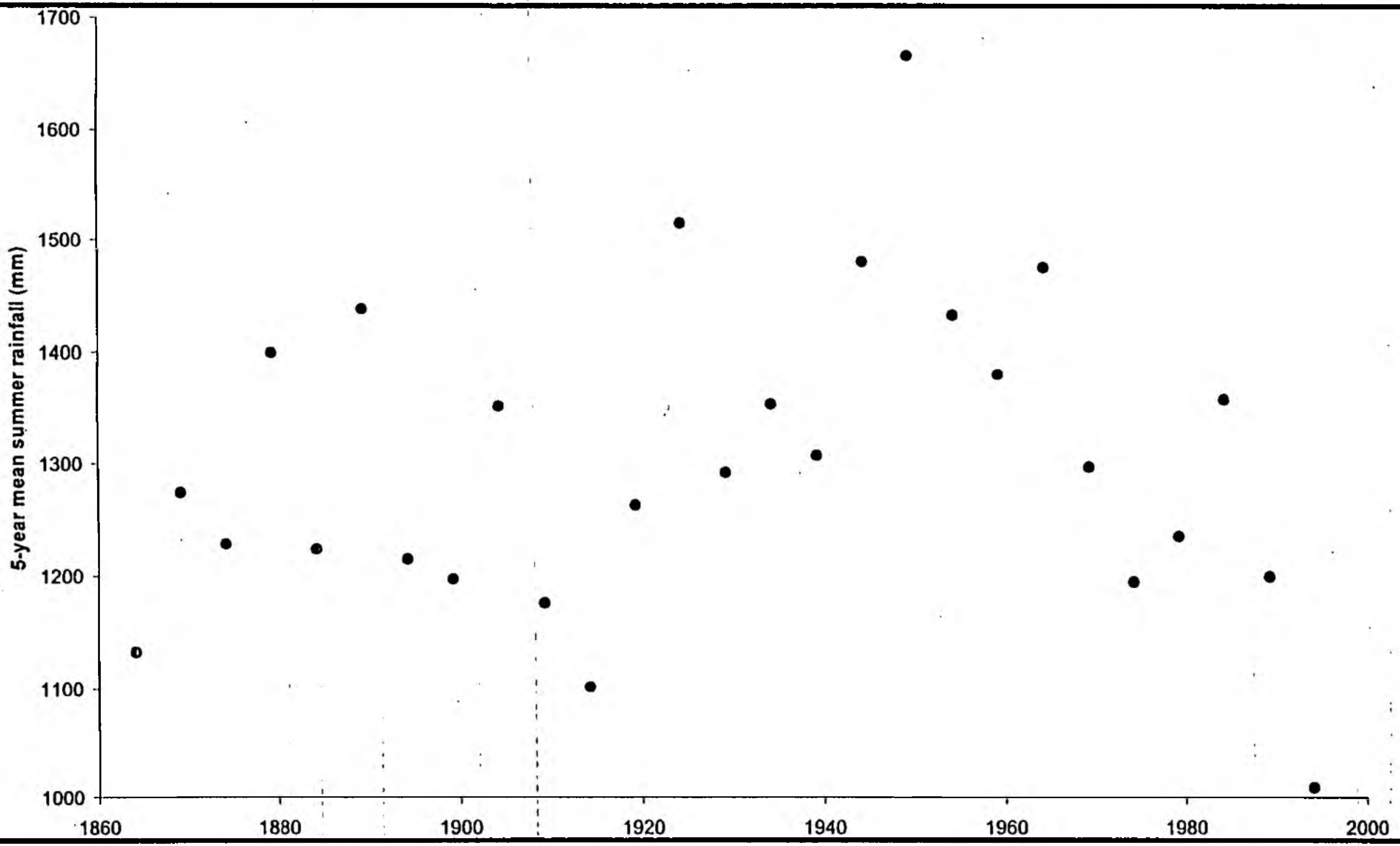
Figure 10



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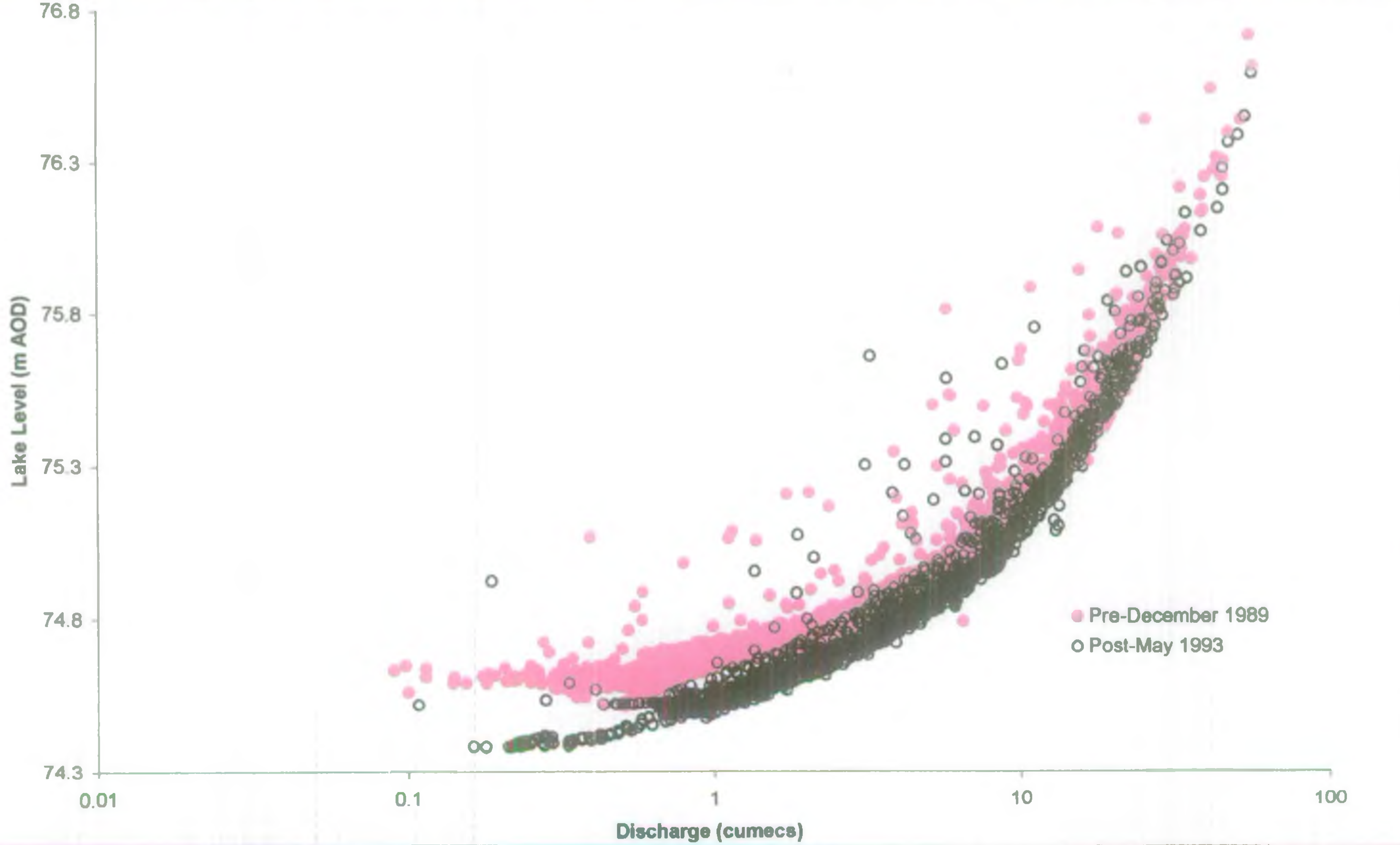
Derwentwater
January 1999
5 Year Mean Summer Catchment Rainfall
Figure 11



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Derwentwater
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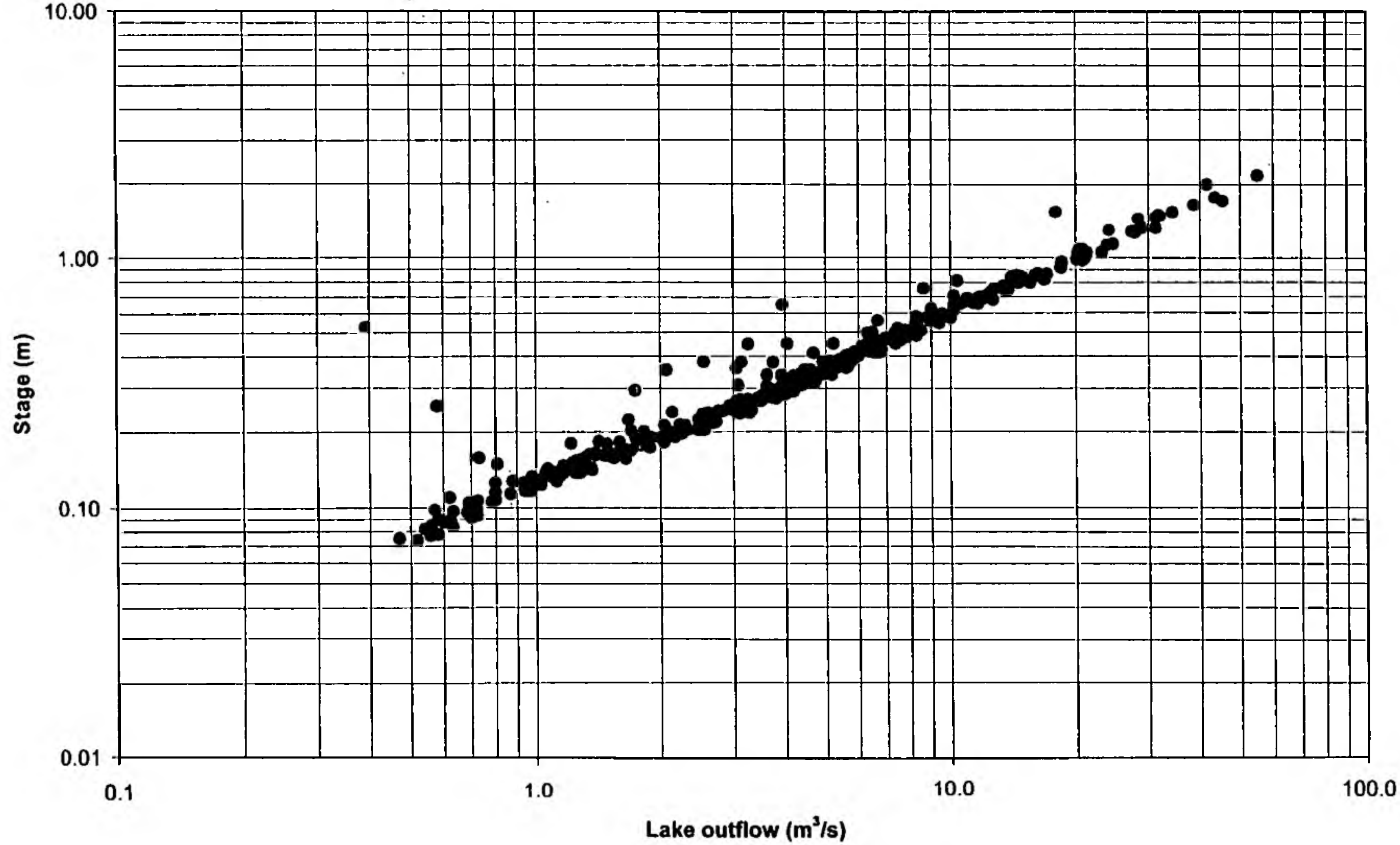
Stage - discharge curves for Derwentwater
Figure 12



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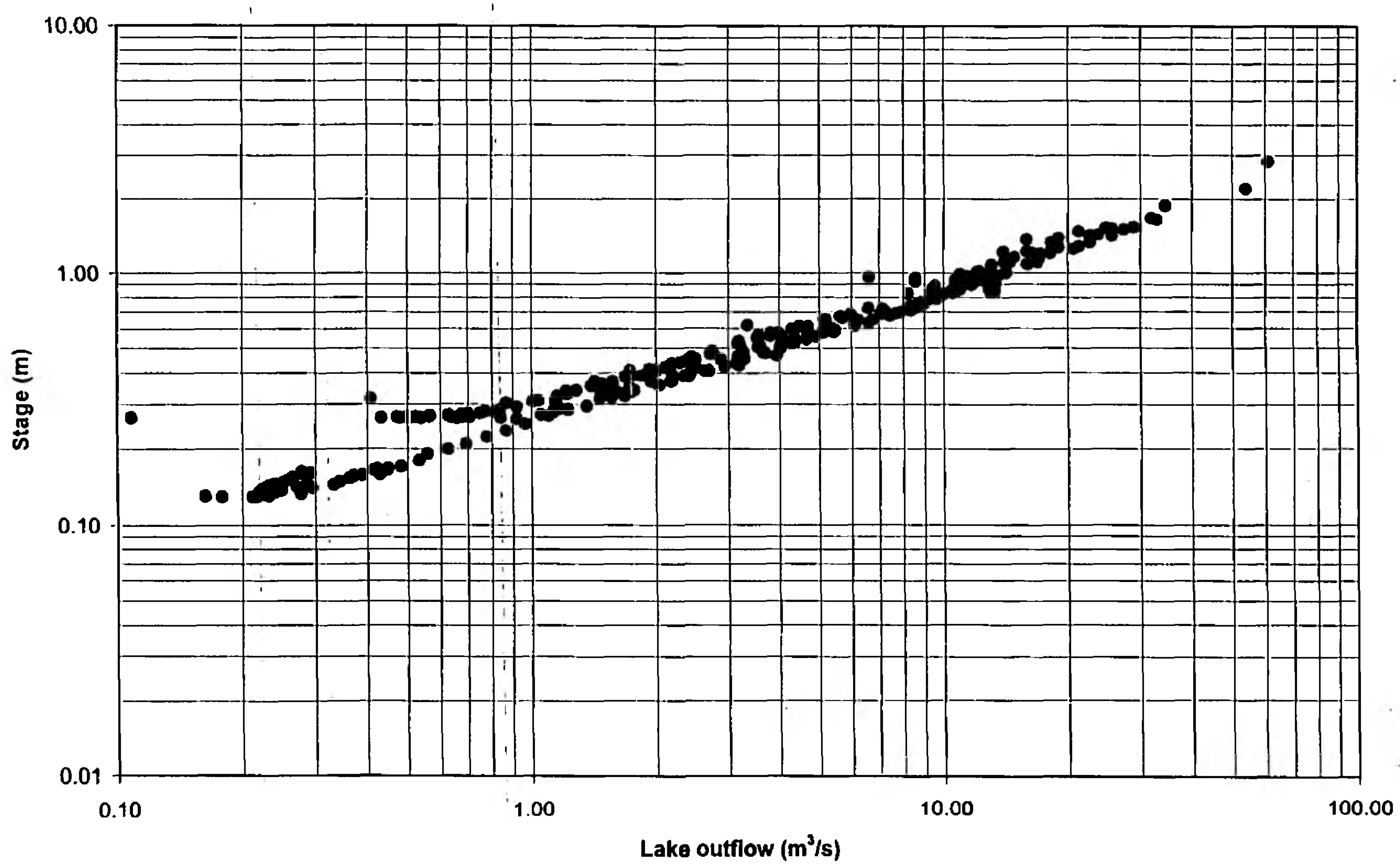
Derwentwater
January 1999
Straight-line fit to stage - discharge curve, 1987
Figure 13



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Derwentwater
January 1999
Daily stage-discharge curve for 1995

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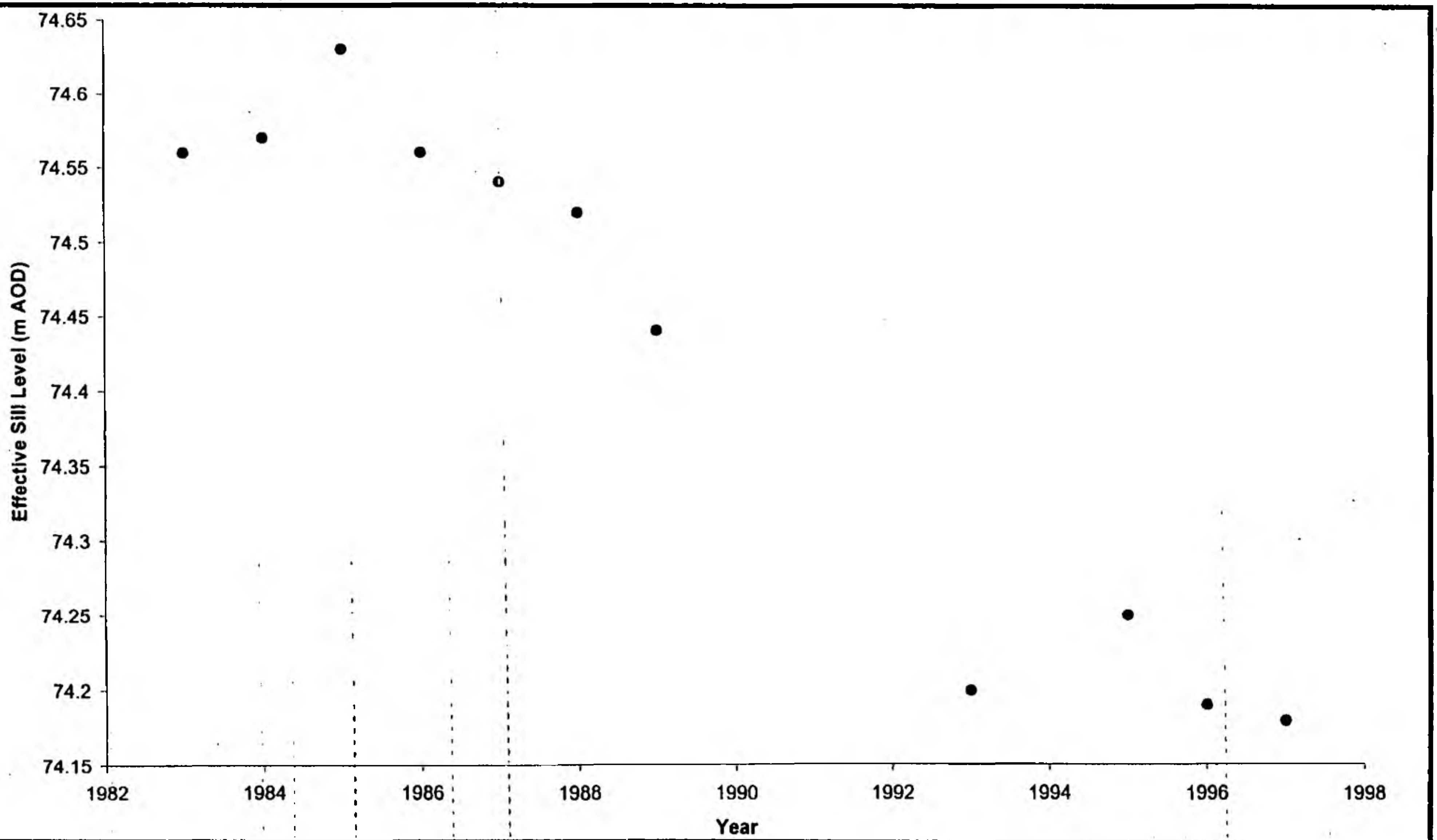
Figure 14



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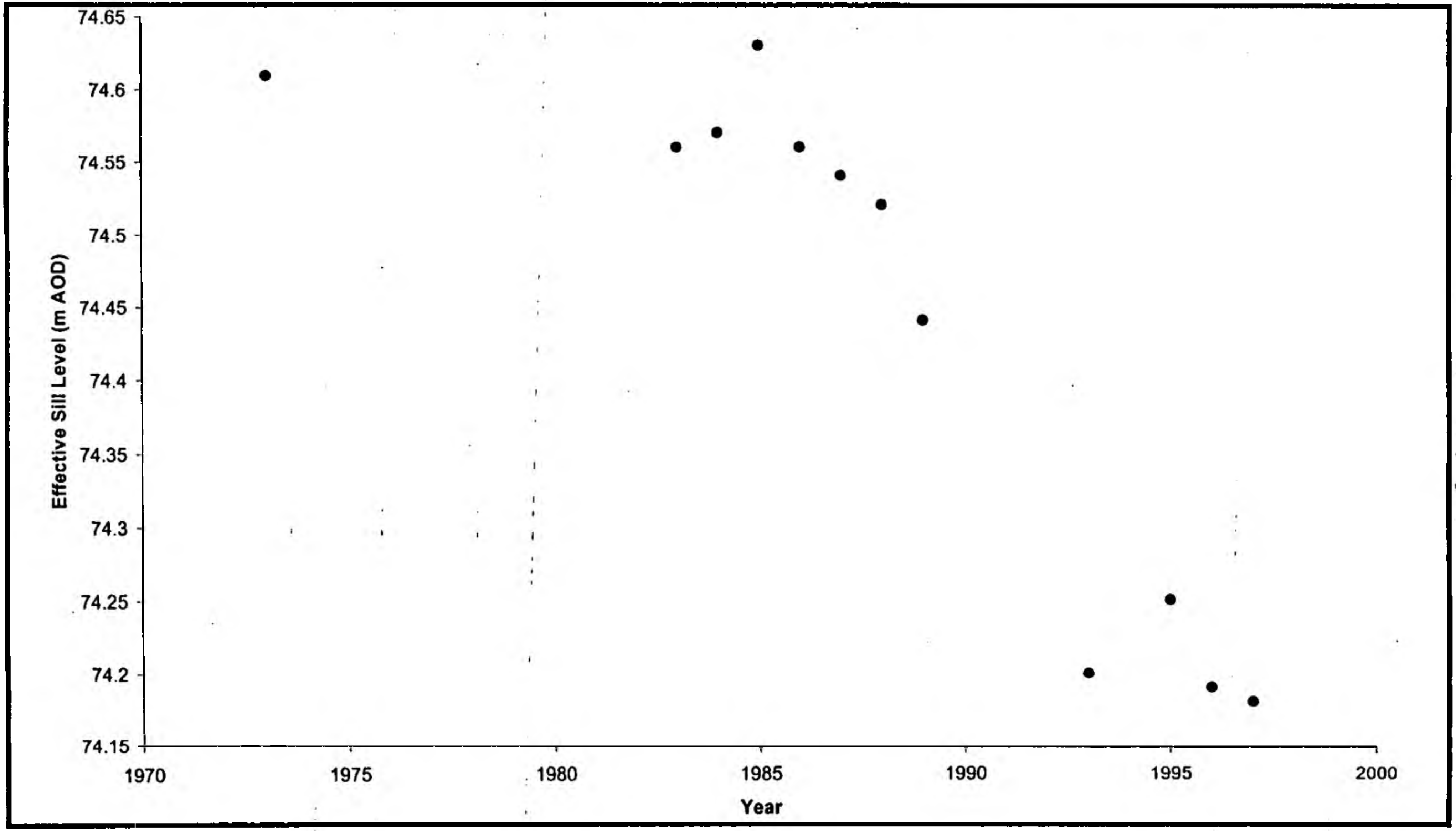
Derwentwater
January 1999
Estimated effective sill levels, 1983 - 1997
Figure 15



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Derwentwater
January 1999
Estimated effective sill levels, 1973 - 1997

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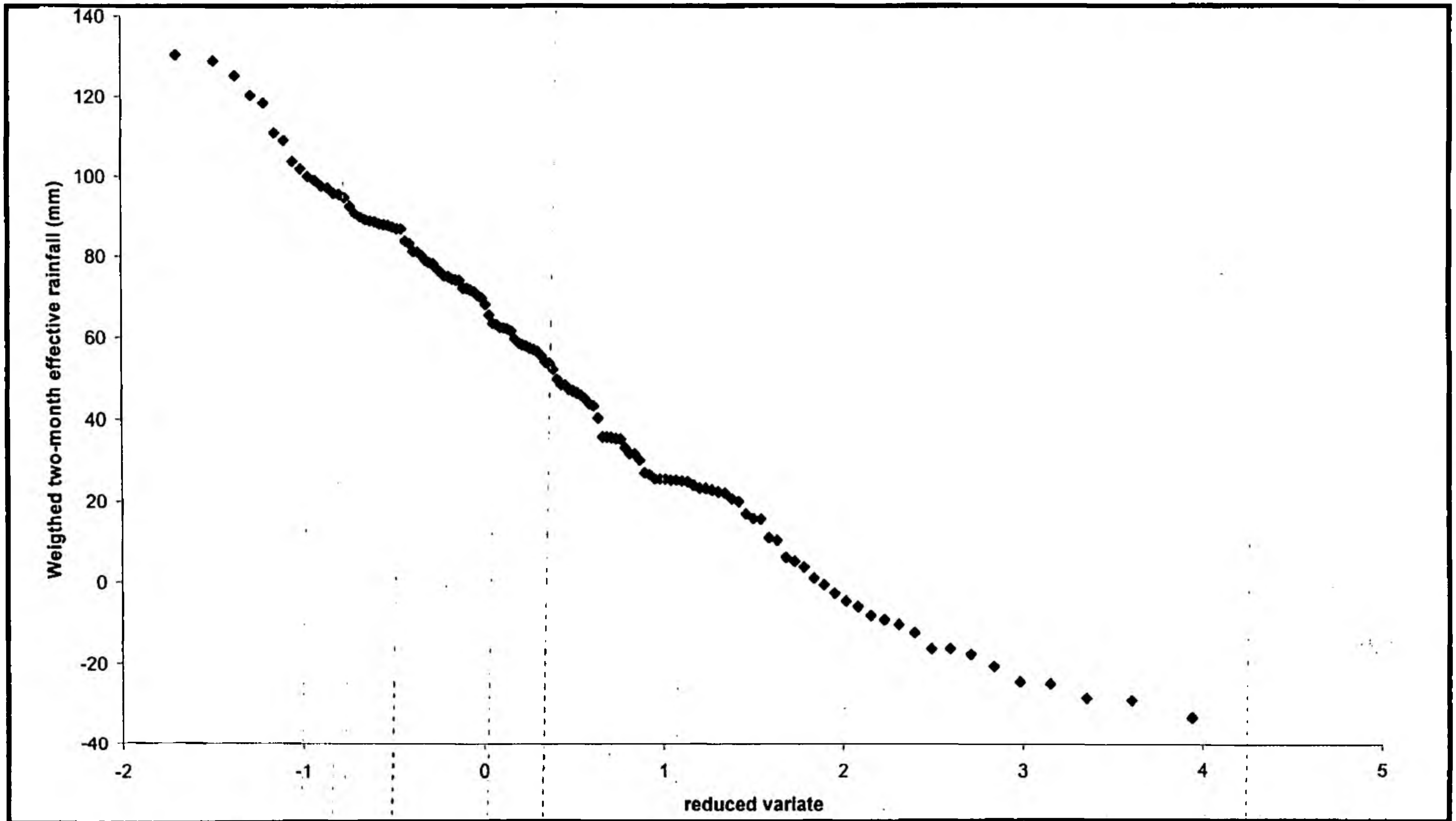
Figure 16



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Effective rainfall frequency curve

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Figure 17

Appendix A

Catchment Average Rainfall

It is expected that a gradient of increasing rainfall with increasing altitude would be observed in the Derwentwater catchment. Figure A1 plots the average monthly difference in rainfall catch between each pair of raingauges against the difference in altitude of the raingauge pairs. This indicates that, as expected, the greater the difference in altitude the greater the difference in rainfall catch, and that average monthly rainfall catch increases by 0.3 mm/m. Note that there is scatter about this line, and that raingauges with similar altitudes may have significant differences in average monthly rainfall catch. This illustrates the spatial variability of rainfall within a catchment and the difficulty in obtaining accurate estimates of rainfall at a raingauge within an upland environment such as this. Differences in raingauge catch may be due to wind and snow causing measurement problems, and the effect that variations in exposure and rainguage siting may have on actual raingauge catches.

Given the strong dependence of altitude on rainfall catch the hypsometric method is likely to produce the best estimates of catchment average rainfall. The methodology followed in this study is described below.

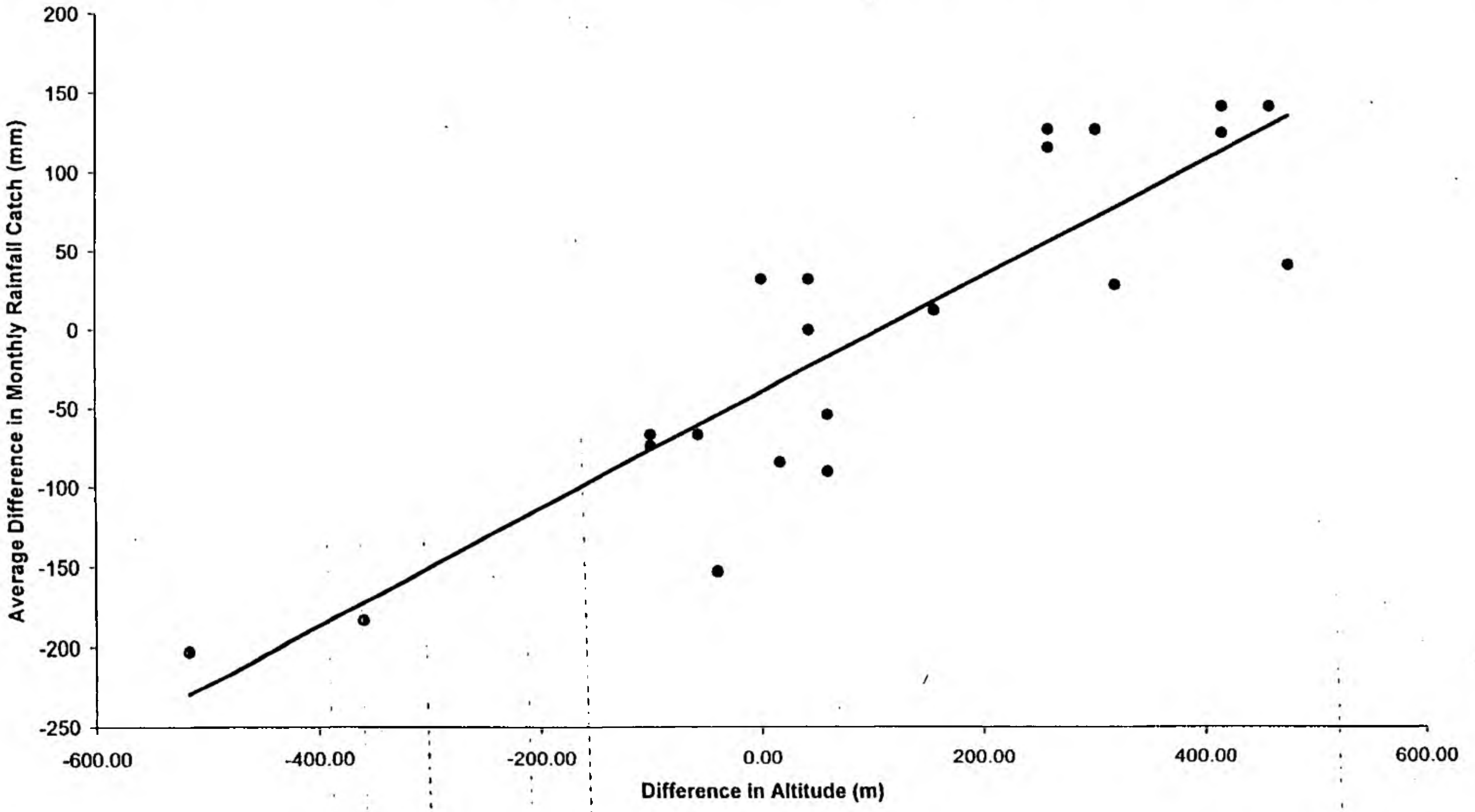
The catchment was first split into altitude bands of 100 m intervals (< 100 m AOD, 100 to 200 m AOD etc.). The area of catchment covered by these bands was then measured, and the fraction of catchment area occupied by each was calculated. The results of this are shown in Table A1 and resulted in the average catchment altitude being calculated as 347 m AOD.

Rainfall measured at any altitude was then converted to an equivalent rainfall within each rainfall band (i.e. at altitudes of 650, 550, 450 m AOD etc.) using the relationship found in Figure A1. If this produced an estimate of rainfall of less than zero

Altitude Range (m AOD)	Mid-point (m AOD)	Cumulative Area (km^2)	Area in band (km^2)	Fraction of total area in band	Cumulative fraction
<100	90	15.7	15.7	0.185	0.185
100-200	150	25.95	10.25	0.121	0.305
200-300	250	34.25	8.3	0.098	0.403
300-400	350	49.025	14.775	0.174	0.576
400-500	450	64.375	15.35	0.180	0.757
500-600	550	76	11.625	0.137	0.894
600-700	650	83.5	7.5	0.088	0.982
700-800	750	84.875	1.375	0.016	0.998
>800	800	85.05	0.175	0.002	1.000

Table A1: Areal distribution of altitude within the Derwentwater catchment

(negative) for any band this estimate was replaced by a value of zero for that band. The estimated rainfall for each band was then weighted by the fractional catchment area of that band to obtain an estimate of average catchment rainfall from that raingauge. If more than one raingauge was available then an average of the estimated catchment average rainfall from each raingauge was taken as the actual catchment average rainfall.



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Derwentwater
January 1999
Dependence of rainfall on altitude

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Figure A1