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Borehole-based investigations of subglacial hydrology

by

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements of Master of Science

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ABSTRACT

The nature and evolution of the subglacial drainage system under part of Haut Glacier d'Arolla, Switzerland was investigated over three summer observation periods using measurements of borehole water level and of the electrical conductivity and turbidity of basal meltwaters. Electrical conductivity profiles, salt traces and video recordings were also carried-out in boreholes to identify the water sources driving water level changes, and to determine patterns of water circulation within boreholes. This was necessary so that the basal water quality measurements could be understood and interpreted with confidence.

In each year, a variable pressure axis (VPA) was identified within the borehole array. Increasing base water levels and decreasing water level fluctuation amplitudes away from the centre of the VPA revealed the presence of a subglacial channel located within an extensive distributed system. A period of high subglacial water pressures following a heavy rainfall event, triggered re-organisation of the subglacial drainage system in the 1993 summer observation period which affected the water level behaviour in all observed boreholes. Subsequent to this, the evolution of a subglacial channel was demonstrated.

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CHAPTER 1: INTRODUCTION

1.1 THESIS RATIONALE:

The objective of this thesis is to describe and explain the nature and evolution of the subglacial drainage system of Haut Glacier d'Arolla, Switzerland. This will be undertaken by the analysis of water level (WL) and basal water quality measurements derived from an array of boreholes drilled to the glacier bed over three summer ablation seasons. Additional borehole-derived data such as electrical conductivity (EC) profiling, borehole salt tracing and borehole video imagery will be employed to improve the accuracy of the interpretations made from the WL and basal water quality measurements.

Knowledge of the configuration of subglacial drainage systems is of great significance to the study of the motion, erosion and weathering regimes of warm-based glaciers. Variations in glacier velocity have been linked to fluctuations in basal water pressure (e.g. Iken, 1981; Kamb et al., 1985), while changes in the chemical characteristics of bulk meltwaters have been associated with different through flow velocities (e.g. Gurnell and Fenn, 1985). Basal water pressure and through flow velocity are largely a function of the structure of the subglacial drainage system, the hydraulic geometry of the individual pathways, and the melt-water discharge (Sharp, 1991).

Subglacial drainage systems may be characterised as being either channelized or distributed in form. Channelized systems consist of channels incised either upwards into glacier ice (Röthlisberger, 1972; Hooke et al., 1990) or downwards into bedrock (Nye, 1973). These channels form efficient networks with the capacity to drain large amounts of meltwater rapidly. Flow through distributed systems may be via meltwater films (Weertman, 1972), permeable subglacial sediment (e.g. Stone, 1993), linked cavities located on the lee side of bedrock bumps (Walder, 1986; Kamb, 1987) or 'canals' above and within unconsolidated sediments (Walder and Fowler, 1994). Distributed systems drain extensive areas of the glacier bed at flow rates 1-2 orders of magnitude lower than those typical of channelized systems.

Both channelized and distributed drainage systems may co-exist beneath a glacier (e.g. Humphrey et al., 1986; Willis et al., 1990; Fountain, 1992). Nienow (1993) proposed that at Haut Glacier d'Arolla, where the two drainage systems apparently co-exist, the channelized system may extend by headward growth during the summer melt season at the expense of the distributed system. The rate of headward growth appeared to be controlled by the retreat of the transient snowline. Seasonal evolution of the drainage system configuration is thus implied.

Due to the physical inaccessibility of the subglacial environment, indirect methods have been employed to infer the configuration of subglacial drainage systems. These methods include theoretical discussions (e.g. Shreve, 1972), forefield mapping (Walder and Hallet, 1979; Hallet and Anderson, 1980; Sharp et al., 1989), salt and dye tracing (e.g. Stenborg, 1969; Fountain, 1993) and the interpretation of bulk meltwater quality characteristics (e.g. Collins, 1979; Tranter et al., 1993; Raymond et al., 1995). All these methods, however, have their limitations.

Although theoretical discussions are an important basis of any scientific research, they must ultimately be tested by empirical observation to determine whether the theory adequately describes the process that it is designed to describe.

Forefield mapping provides a good indication of the scale of the subglacial drainage pathways present under a particular glacier. However, relic drainage pathways are only likely to be preserved in bedrock, so forefield mapping may not be used at glaciers underlain by unconsolidated sediment and is limited to glaciers that have retreated from a previously more extensive position. It is also not known whether all the observed pathways were active at the same time. Finally, no information will be gained concerning the occurrence of channels incised upwards into glacier ice.

Salt and dye tracing experiments provide an indication of through flow velocities (by dividing travel distance by the time from injection to the time of peak concentration in the outflow stream) and the efficiency with which the water is evacuated (from the form of the measured concentration/time curve and values of dispersivity (a measure of the length of individual branches of a subglacial drainage system)). Put simply, a trace that produces high velocities, forms a single peak concentration curve and has low dispersivity values may be interpreted as representing flow through a channelised system. Conversely, low velocities, a broad, multiple peaked concentration curve and high dispersivity values are likely to be more representative of flow through a relatively complex drainage system characterised by many pathways and potential storage sites (i.e. a distributed system). However, the accuracy of calculated flow velocities is affected by factors such as dye adsorption onto sediment (lower dye concentrations are measured), non-detection (the tracer may be stored at the bed and subsequently released at concentrations below the sensitivity of the measuring device) and the use of inaccurate travel distances (use of the straight line distance between the injection point and the snout does not take the sinuosity of the pathways into account). In addition, salt and dye are commonly injected into active moulins which, by their nature, evacuate large amounts of water rapidly and are therefore most likely to be linked to some form of channelised drainage system, thus introducing a bias into the results.

Bulk meltwater quality characteristics such as electrical conductivity and suspended sediment concentration have been used to determine the configuration of subglacial drainage systems. This relies on the assertion that waters flowing through different drainage systems possess different meltwater quality characteristics. For example, water flowing through a channel at the bed is likely to be dilute (due to short residence times) with a high suspended sediment concentration (due to high water flow velocities). Conversely, water flowing through a distributed system is likely to be more concentrated (due to longer residence times) with a lower suspended sediment concentration (due to lower water flow velocities). However, bulk meltwaters are a mixture of both the fast and slow flow components. Determination of the varying proportions of the different components of bulk meltwaters from electrical conductivity and suspended sediment concentration measurements is not a simple process. This has become especially apparent with the realisation that non-conservative mixing occurs when dilute and concentrated waters mix (Raiswell, 1984).

Borehole drilling affords direct access to the glacier bed at chosen point locations. This has allowed for the measurement of basal water pressure (e.g. Hodge, 1976; Engelhardt, 1978; Hantz and Lliboutry, 1983) and water quality (e.g. Stone and Clarke, 1996; Tranter et al., in press), the determination of subglacial sediment characteristics (e.g. Stone and Clarke, 1993; Fischer and Clarke, 1994), down-borehole dye tracing (Fountain, 1993) and down-borehole video imagery (e.g. Pohjola, 1993). Boreholes are becoming increasingly important tools in the study of subglacial drainage system configurations as they now provide the most direct means of observing basal parameters.

The ultimate aim of this thesis is to employ borehole WL and basal water quality measurements to build-up a comprehensive picture of the nature and evolution of the subglacial drainage system over a summer ablation period under a part of Haut Glacier d'Arolla, Switzerland. However, borehole-derived data also have limitations. It has recently been demonstrated that the existence of a borehole can influence the water pressure and water quality measured at the bed (Ketterling, 1995). This is especially true in boreholes which remain open during the summer as changes in subglacial water pressure are registered as changes in borehole WL (this is not the case in boreholes that freeze shut near the base). This demands a flux of water into and out of the borehole over time which can be supplied by any combination of basal, englacial and supraglacial sources. Complex patterns of water circulation may thus develop within the borehole. Sensors placed at the bed may therefore record the character of the water leaving the base of the borehole, rather than the character of the water which would have been draining through the subglacial system had the borehole not existed.

Thus, although boreholes afford direct access to the glacier bed, borehole-derived measurements must be used with caution. Water sources and circulation patterns within a borehole (i.e. the 'plumbing' of the borehole) must first be determined before WLs and basal water quality measurements from that borehole are used to make any inferences about the configuration of the subglacial drainage system (Ketterling, 1995). This will be carried-out with additional information from EC profiling, down-borehole salt tracing and down-borehole video imagery (the description and methods of which will be presented in the following chapters). Once the plumbing of each borehole has been understood, WL and basal water quality measurements can be interpreted with a greater degree of confidence. This will allow for a systematic and detailed description of the nature and evolution of the subglacial drainage system and the discussion of possible explanations for the inferences made. No other study to date has combined such a wide variety of borehole-derived data to determine the temporal and spatial configuration of a subglacial drainage system. This work provides a unique opportunity of observing both the large scale seasonal evolution of the subglacial drainage system as well as its behaviour on diurnal timescales.

1.2 FIELD SITE:

Haut Glacier d'Arolla is located at the head of the Val d'Hérens, Valais, Switzerland (Figure 1.1). It has an area of 6.3km^2, spans an elevation range of 2560 to ~3500m.a.s.l, and is believed to be warm-based. Observations in subglacial cavities (Hubbard, 1992), and by borehole video (Copland et al., in press), together with interpretations of borehole WL measurements (Hubbard et al., 1995) suggest that this glacier is underlain at least partly by unconsolidated sediments.

During the summers of 1992, 1993 and 1995, 70 boreholes were drilled close to the eastern margin of the ablation area of the glacier, some 1.5km from the terminus (Figure 1.1). All the boreholes were drilled within an area of ~260m E/W by ~120m N/S (Figure 1.2a,b and c). Boreholes were identified by the year they were drilled followed by the number assigned during that year (e.g. 92/3 represents borehole number 3 drilled in 1992). Boreholes were drilled using high pressure, hot water (see Appendix I for drilling procedure), and varied in depth from 23m at the margin (93/38) to 144m towards the glacier centre line (93/46).

The location of the borehole array was chosen on the basis of previous dye tracing interpretations and theoretical reconstructions of the subglacial drainage system (Sharp et al., 1993) which predicted that a major drainage channel would develop beneath this part of the glacier during the melt season.

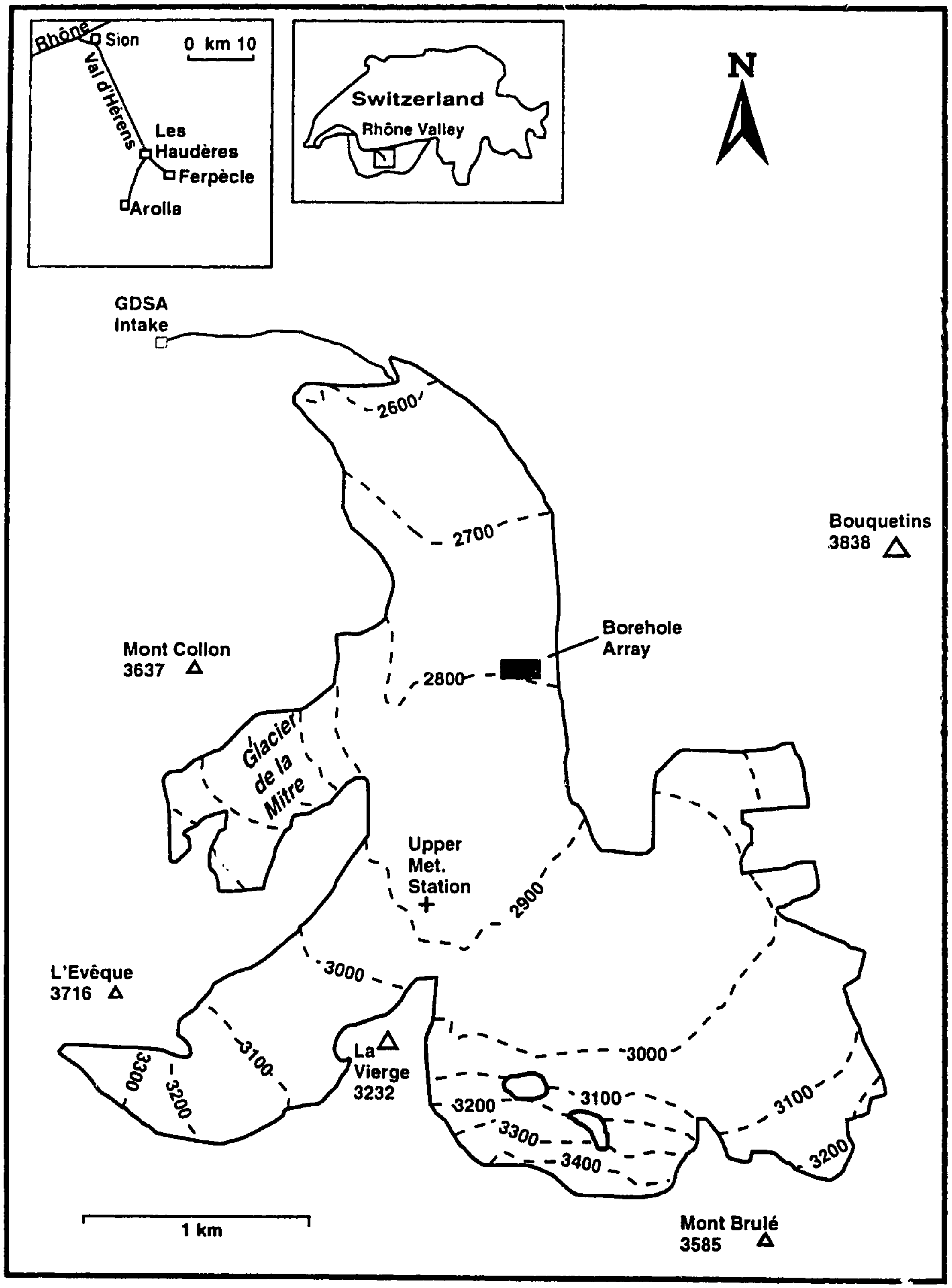

Figure 1.1: Haut Glacier d'Arolla showing the location of the borehole array, GDSA intake and upper meteorological station.

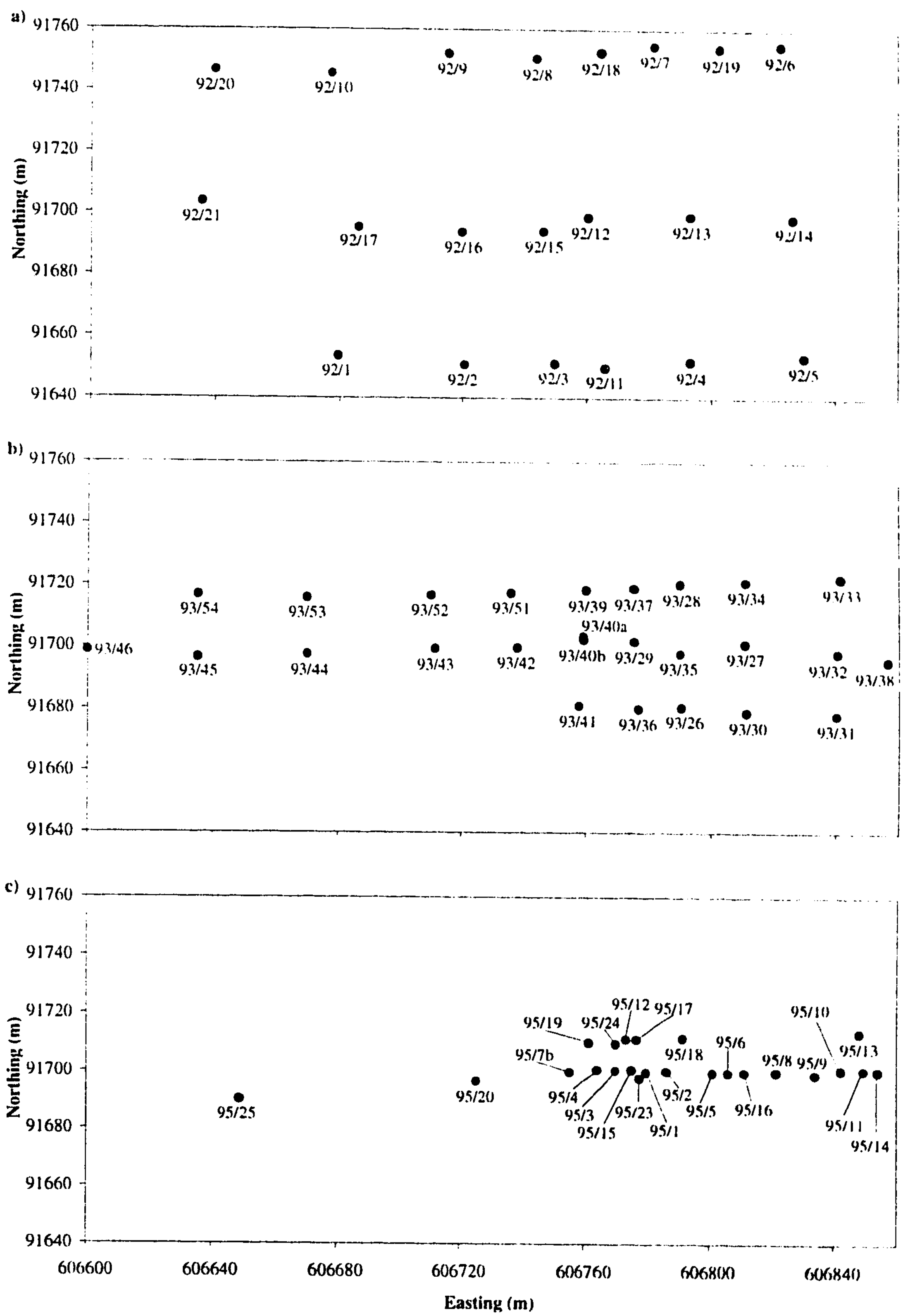

Figure 1.2: Borehole arrays for a) 1992, b) 1993 and c) 1995.

1.3 THESIS OUTLINE:

The study is divided into four sections:

CHAPTER 2: Interpretation of intra- and inter-annual distribution of borehole WL behaviour:

The primary objective is to construct a general picture of the nature of the subglacial drainage system that existed beneath the borehole array in the three observation seasons. This will be undertaken by interpreting the WL behaviour exhibited by each of the boreholes. A simple classification scheme will be employed that categorises borehole WL behaviour to simplify analysis. Once the WL behaviours are classified and their spatial distribution mapped, questions that will be addressed are:

a) What types of WL behaviour can be identified?

b) What information do the classified WL behaviours offer concerning basal water pressure conditions?

c) What is the spatial distribution of the WL behaviours?

d) What information does the spatial distribution of WL behaviours offer concerning the nature of the subglacial drainage system?

e) Does the distribution of the WL behaviours vary between the years? If so, why?

f) Are there any seasonal trends in WL behaviour?

CHAPTER 3: Determination of borehole plumbing for the interpretation of basal water quality measurements:

Before borehole WL and basal water quality measurements are analysed to provide a detailed description and explanation of the nature and evolution of the subglacial drainage system, the water sources and circulation patterns within each borehole must be determined. This will allow for the more accurate interpretation of the WL and basal water quality measurements.

Seven types of data (described in detail in Chapter 3) are used to determine the plumbing of each borehole both within the glacier ice and at the glacier bed.

a) Drilling records

b) Manual and continuous in-situ WL measurements

c) Continuous in-situ electrical conductivity measurements

d) Continuous in-situ turbidity measurements

e) Electrical conductivity profiling

f) Salt tracing

g) Down-borehole video imagery

After analysis of these data, categories of borehole plumbing will be identified and examples of each category presented. Examples of how WL and water quality records can be interpreted once water sources and circulation patterns have been determined will be presented.

CHAPTER 4: Determination of the nature and evolution of the subglacial drainage system:

Once the plumbing of each borehole is understood, a detailed interpretation of WL and basal water quality measurements can be undertaken to provide a comprehensive view of the nature and evolution of the subglacial drainage system over a summer ablation season. Both large scale seasonal evolution of the drainage system and small scale diurnal patterns in the WL and water quality measurements can be identified.

CHAPTER 5: Conclusion:

Interpretations from the previous three chapters will be integrated to demonstrate how a comprehensive description and explanation of the nature and evolution of a subglacial drainage system can be developed from the combination of a range of borehole-derived data.

CHAPTER 2: INTRA- AND INTER-ANNUAL DISTRIBUTION OF BOREHOLE WATER LEVEL BEHAVIOUR

2.1 INTRODUCTION:

In boreholes that remain open during the summer observation season, changes in subglacial water pressure are registered as changes in borehole water level (WL) (e.g. Engelhardt, 1978; Fountain, 1994; Hubbard et al., 1995). As a result, analyses of borehole WL fluctuations are used to infer subglacial hydraulic conditions. Boreholes can be classed as `unconnected' or `connected' depending on the status of the WL. In unconnected boreholes, the WL generally remains stable at the glacier surface and the borehole is thought not to be connected to the subglacial drainage system. Connected boreholes generally exhibit fluctuating WLs, which indicate that the borehole has connected to a drainage system that experiences water pressure fluctuations. The initial WL decrease can occur in three ways: before the bed is reached whilst drilling, immediately as the bed is reached or several hours to several days after drilling. In the first case, an englacial channel is inferred to have been intercepted (e.g. Engelhardt, 1978; Fountain, 1994). In the latter two cases, the borehole drains due to the overpressurization at the bed created by the borehole water column and a connection to the subglacial drainage system is inferred. This connection may be either directly into a drainage pathway such as a channel, or indirectly to a drainage pathway at some distance from the borehole base via some sort of hydraulic link.

Minimum (base) daily WLs and the amplitude of daily WL fluctuations exhibited by an array of boreholes have been used to infer the characteristics of subglacial drainage systems (e.g. Fountain, 1994; Hubbard et al., 1995; Smart, 1996). This use of borehole WL behaviour is based upon the principles of water flow within and under a glacier (Shreve, 1972; Röthlisberger, 1972).

Shreve (1972) demonstrated that the direction of water flow within and at the base of a glacier should be normal to hydraulic equipotential contours, where hydraulic potential (Φ) is given by:

$$\Phi = \rho i g(h-h_b) + \rho w g h_b \qquad (2.1)$$

and ρw and ρi are the densities of water and ice respectively, g is the acceleration due to gravity, and h and h_b are the elevations of the glacier surface and of a point within or at the bed of a glacier, respectively. The first term on the right is therefore the pressure imposed on the water by the weight of the overlying ice, and the second term is the potential elevation of the water due to its height above a datum such as sea level. Equipotentials within a glacier dip upglacier (Figure 2.1a), and water flow at the bed is normal to the equipotential contours created by the intersection of these equipotentials with the bed (Figure 2.1b). Water flow at the bed is thus not necessarily in the direction of the maximum slope of the bed. Shreve thus assumes that water in subglacial channels is always at the ice overburden pressure (IOP) and that the presence of channels has no effect on the direction of water flow at the bed.

Röthlisberger's (1972) treatment of water flow assumes that channel size depends on the balance between two opposing forces: closure by deformation (if the IOP exceeds the water pressure within the channel) and enlargement via melting (produced by the frictional heat of flowing water and sensible heat transfer between flowing water and the surrounding ice). The size of a channel adjusts to changes in the amount of surface meltwater input by these processes. For any significant discharge, the water pressure in a channel will be less than IOP because melt offsets closure and prevents the water pressure from rising to IOP. This has a significant effect on the direction of water flow in areas adjacent to a channel as the low channel pressures create a 'valley' in the equipotential surfaces and divert water flow at the bed towards the channel (Figure 2.1c). However, on short timescales (e.g. diurnal) adjustment of channel size to increasing discharge is not instantaneous as the channel behaves essentially like a rigid pipe.

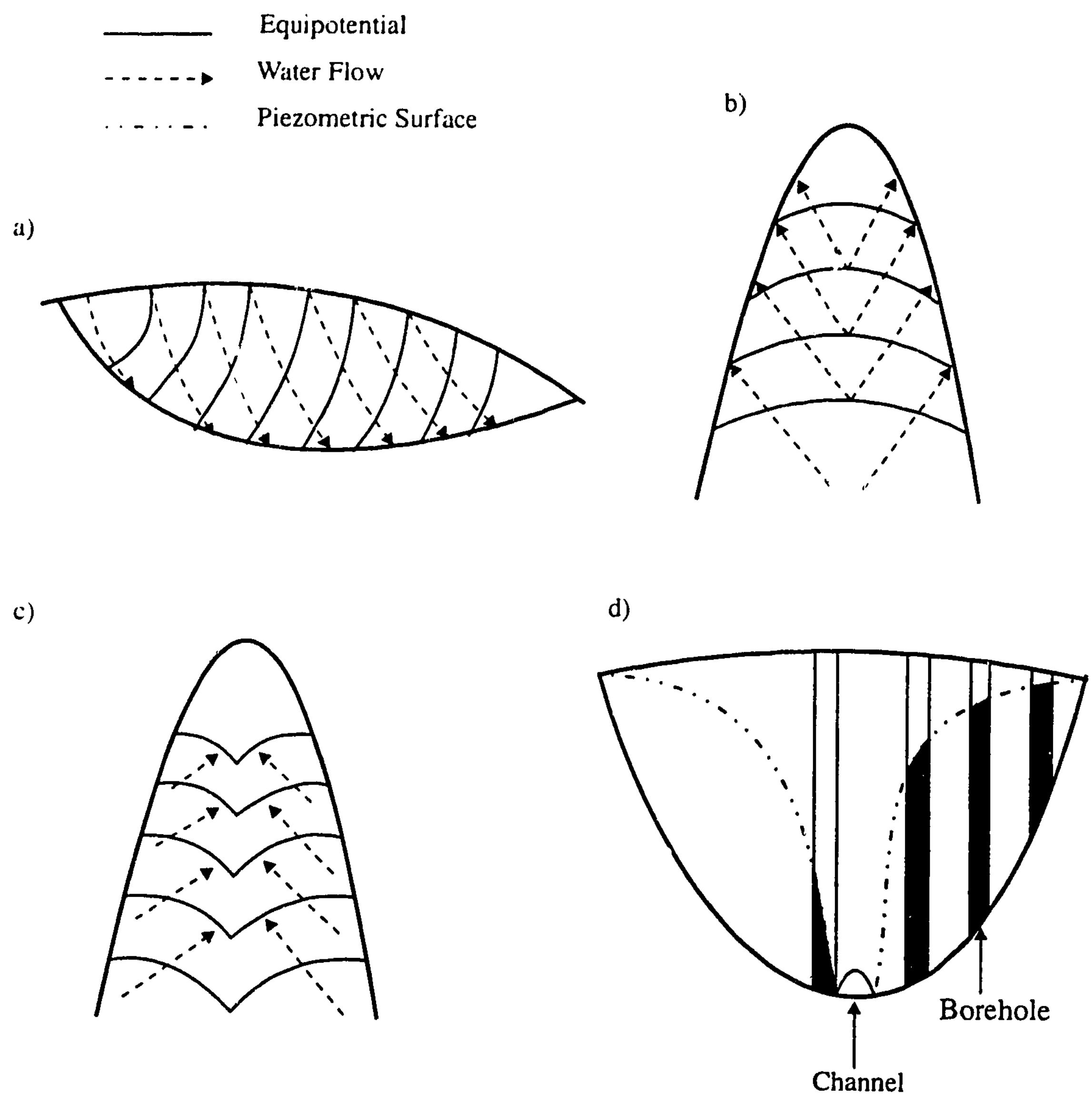

Figure 2.1: a) Longitudinal cross-section through an idealised glacier showing Shreve's equipotential surfaces, b) Plan view of an idealised glacier showing Shreve's equipotential contours and consequent water flow at the bed, c) Plan view of an idealised glacier showing Röthlisberger's 'valley' equipotential surfaces and consequent water flow at the bed, and d) Cross-section through an idealised glacier showing the effect of a channel at a pressure less than IOP on the piezometric surface and borehole water levels.

This is because heat transfer from water to ice is not an instantaneous process, so melt enlargement lags the rising discharge, while creep closure is too slow to shut down the channel as discharge decreases. Water pressure therefore rises with increases in daily discharge, producing discharge-related diurnal cycles in water pressure (e.g. Iken and Bindschadler, 1986; Fountain, 1994; Paterson, 1994).

If a cross-section through an idealised glacier is taken, the presence of a channel at low pressure exerts a 'draw-down' effect on the piezometric surface on either side of the channel (Figure 2.1d) due to the establishment of a hydraulic gradient between the channel and surrounding areas of the bed. If boreholes were drilled on either side of the channel, their WLs would represent this piezometric surface (Figure 2.1d) with increasing base WLs occurring away from the channel (e.g. Fountain, 1994).

If the channel is unable to enlarge instantaneously to accommodate an increase in discharge, the velocity of water flow in the channel must rise to compensate. In a full pipe, this can only happen if the pressure gradient increases. As the water pressure at the snout is fixed at atmospheric pressure, water pressure must rise at all locations upstream of the snout. If the water pressure in the channel rises above that in surrounding areas of the bed, a hydraulic gradient away from the channel is established and lateral transfer of water can occur. Daily water pressure variations in the channel are therefore propagated into the surrounding bed, causing an increase in borehole WL. As channel pressure falls overnight the hydraulic gradient is redirected towards the channel, thus causing water to flow from the surrounding bed back to the channel, allowing borehole WLs to fall. The area within which daily WL fluctuations are observed has been termed a variable pressure axis (VPA) (Hubbard et. al, 1995).

The amplitude of the borehole WL increase will diminish with increasing distance from the channel due to a combination of three factors: a) the pressure wave diffuses with distance from its origin, b) full WL adjustment requires longer than allowed by the daily water pressure forcing (Alley, 1996), and c) subglacial sediment with a low hydraulic conductivity resists the propagation of the pressure wave and reduces its amplitude with increasing distance from its origin (Fountain, 1994; Hubbard et al., 1995).

Therefore, boreholes exhibiting large diurnal WL fluctuations superimposed on low base WLs are thought to be located close to a major channel which becomes increasingly pressurized on a daily basis by daily meltwater inputs. Conversely, boreholes exhibiting high base WLs and low diurnal WL fluctuation amplitudes are thought to represent areas of the bed which are located further from a channel and are less efficiently drained, but are still affected by the presence of the channel. The latter borehole WL behaviour may indicate the presence of a distributed system. Boreholes that remain full and demonstrate no perceptible WL fluctuations (i.e. unconnected) are also likely to be located in a distributed drainage system, but are located too far from the channel to be affected by its daily pressurisation. Unconnected boreholes may also represent areas of the bed which are hydraulically inactive.

Smart (1996) devised a simple classification scheme based on minimum daily WL and diurnal WL fluctuation amplitude, which describes the main characteristics of borehole WL behaviour. He used this scheme to compare WL behaviours between summers and between different areas of a glacier and to infer the configuration of the subglacial drainage system. Quantitative comparisons of the observed WL behaviours were made using a nearest neighbour statistic which allowed Smart to determine whether there was significant clustering of boreholes of a given type a) in space, and b) in space between different years.

The aim of this chapter is to describe and compare the pattern of borehole WL behaviour observed on Haut Glacier d'Arolla in 1992, 1993 and 1995 in order to construct a general picture of the configuration of the subglacial drainage system within the borehole array. This will be achieved using a revised form of the borehole WL classification scheme devised by Smart (1996).

2.2 WATER LEVEL MEASUREMENTS:

Borehole WL measurements were made in two ways: either manually or automatically.

2.2.1 Manual WL measurements:

Manual WL measurements were made using EC profilers which were used to measure both the EC profile of borehole water columns (see Chapter 3) and record the WL of the boreholes. The profilers (see Appendix II) were lowered down the borehole until the WL was reached (if the borehole was not full) and this depth was recorded manually. It was clear when the profiler reached the WL as air readings were zero whilst water readings were >0.5μS cm^{-1}. This method was used in 1992, 1993 and 1995. Manual WL measurements were taken only at irregular intervals during the day (often between 09:00 and 20:00) and mostly in boreholes that were not being monitored automatically.

2.2.2 Automatic in-situ WL measurements:

In-situ WL sensors (see Appendix III) were suspended within a few decimetres of the borehole base. Measurements were logged as means of 30 readings every 10 minutes using Campbell Scientific CR-10 dataloggers. WL measurements are accurate to within 0.5m of water head. Twelve in-situ WL sensors were deployed in the 1993 summer ablation season and 5 in 1995 (Table 2.2). In-situ sensors were deployed only at the end of the 1992 field season and thus do not provide relevant data for the period during which borehole WL behaviour was observed.

2.3 CLASSIFICATION OF WATER LEVEL BEHAVIOUR:

Boreholes were initially classified as either connected or unconnected. Connected boreholes were further classified on the basis of their base WL and daily WL fluctuation amplitude. Base WL is defined as the minimum level attained on a daily basis and is termed DRY (drained), LOW (<50% of IOP), or HIGH (>50% of IOP) (where 50% of IOP is an arbitrary threshold). Diurnal WL fluctuation amplitude is taken as the difference between the base WL and the daily maximum WL and is classified as ZERO (no diurnal signal), LOW (rose by <50% of IOP), or HIGH (rose by >50% of IOP). The classes of WL behaviour are represented by a series of symbols (Table 2.1).

Many borehole WL studies (e.g. Hantz and Lliboutry, 1983; Iken and Bindschadler, 1986; Fountain, 1994) have observed long-term trends in WL behaviour as base WLs and the amplitude and frequency of WL fluctuations increased or decreased throughout the observation season in many connected boreholes. These trends were attributed to a combination of factors including: advection of the borehole base over bedrock bumps, changing connectivity associated with the growth and closure of linking passageways at the bed, growth or closure of the borehole, and variations in the transmissivity of the subglacial sediment layer. This non-stationary behaviour poses a problem for classification of borehole WL behaviours as boreholes may fall into different categories at different stages of the observation period. To overcome this problem, Smart (1996) chose a narrow time window of 2-3 days near the end of the observation season when the maximum number of boreholes was available for classification and when non-stationary WL behaviour was minimal. The limitation of this approach is that only the end-of-season WL behaviour is analysed. This excludes the possibility of analysing changes in WL behaviour over the observation season. These changes may be an indication of subglacial drainage evolution and should be discussed. This issue will be discussed further in Section 2.7.

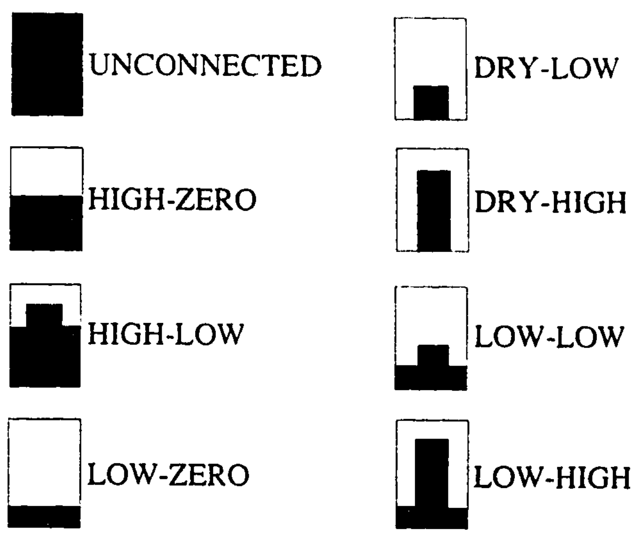

Table 2.1: Symbols for classified WL behaviour.

On Haut Glacier d'Arolla, 56 of the 59 boreholes with WL data were classified on the basis of their WL behaviour within an arbitrarily chosen 5 day period near the end of each observation season (JD 257-261 in 1992; JD 229-233 in 1993; JD 226-230 in 1995) (Table 2.2). The remaining 3 boreholes (93/26,93/40a,95/1) were monitored only during the early part of the observation season as they became constricted, prohibiting further WL measurements. It was thus not possible to determine whether any long-term changes in WL behaviour occurred and these boreholes were therefore not classified.

Classification	1992 (257-261)	1993 (229-233)	1995 (226-230)	Total
UNCONNECTED	2,4,5,6,7,8,9, 10,15,16,17,18, 19,20	31,33,38,44,45, 46,52,53,54	5,6,8,9,25	28
HIGH-ZERO	11		16,20	3
HIGH-LOW	1,3,14	**42,40b,43,51**	7b	8
LOW-LOW	12	39	**2,15,17,18**	6
LOW-ZERO			4,24	1
LOW-HIGH		32,36,37,41		4
DRY-LOW	13			1
DRY-HIGH		**29,30,34,35**		4
Total	20	22	14	56

Table 2.2: Classification of borehole WL behaviours for a five day period in the 1992, 1993 and 1995 observation seasons. Borehole numbers in bold indicate boreholes with in-situ WL records (40a also had in-situ WL data, but measurements ceased before the classification period).

Boreholes can be classified using either manual or in-situ WL measurements. However, classifications based on manual measurements may be less reliable than those based on in-situ measurements as manual measurements may not capture the full range of the daily WL variation. Boreholes with in-situ measurements are thus highlighted in bold in Table 2.2.

The distribution of the classified boreholes is presented in Figure 2.2. All boreholes located tc the west of this array (92/10,92/17,92/20,93/44,93/45,93/46,93/53,93/54,95/25) were classified as UNCONNECTED (except 92/1 which was HIGH-LOW).

No statistical analysis was undertaken on the distribution of Haut Glacier d'Arolla boreholes as the choice of borehole locations was not random. In 1992, a large, evenly-spaced array was drilled covering an area of ~19,000m^2, with distances between boreholes of ~20m E/W and 70m N/S, with the aim of locating the channel inferred to exist in the area by Sharp et al. (1993). In 1993, boreholes were drilled in the area where WL fluctuations were observed in 1992. The array was thus smaller in area (~11,000m^2), with distances between boreholes of 15-20m E/W and 20-25m N/S. In 1995, boreholes were primarily drilled for inclinometry purposes. Boreholes were thus initially drilled in a transect across the glacier from the eastern margin to the centre line. Not until later in the season were more holes drilled within the area of observed WL fluctuations. Boreholes were thus closely spaced (5-10m E/W and ~10m N/S) and covered an area of only ~4000m^2.

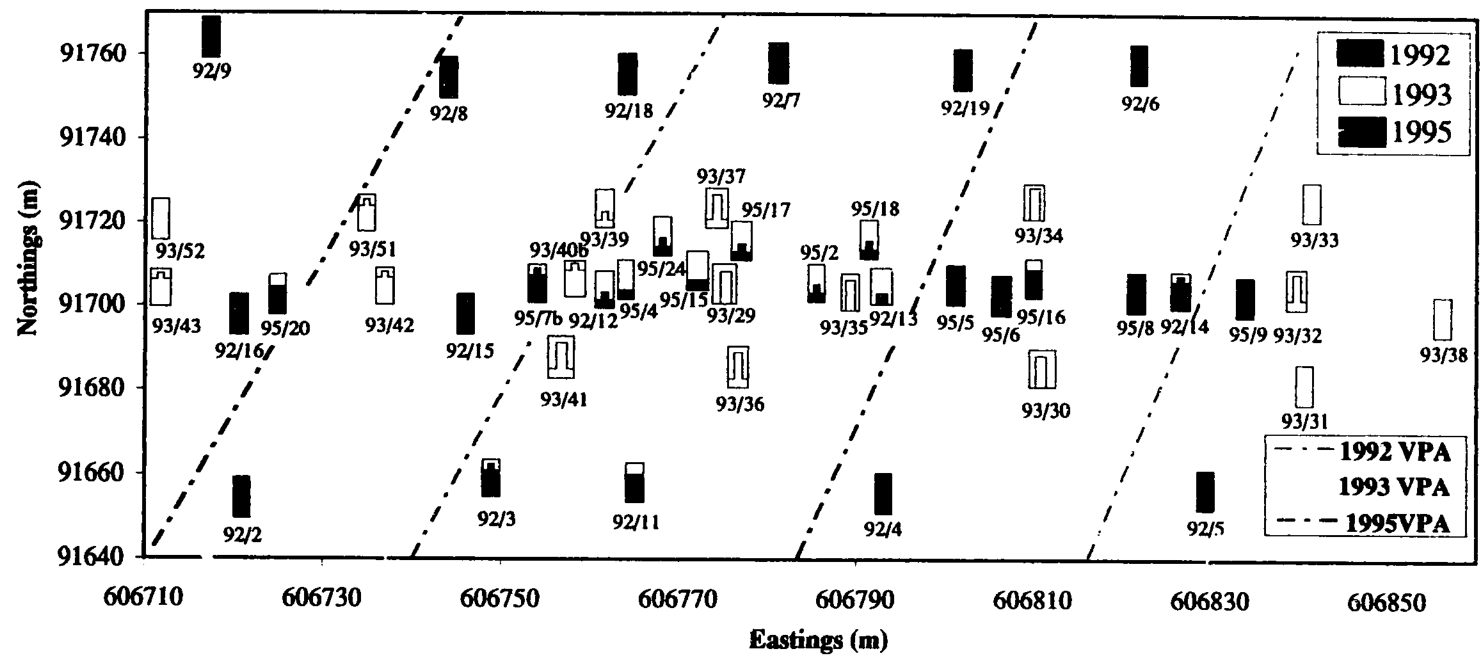

Figure 2.2: Distribution of all classified boreholes in 1992, 1993 and 1995. All boreholes to the west of the array are unconnected.

2.4 SPATIAL DISTRIBUTION OF CLASSIFIED WATER LEVEL BEHAVIOUR:

2.4.1 ANNUAL DISTRIBUTION OF CLASSIFIED WL BEHAVIOUR (Figure 2.2):

1992: A NE-SW trending axis of connected boreholes existed within a main body of UNCONNECTED holes. This axis was not detected in the northern borehole transect. A core zone exhibiting DRY and LOW base WLs (92/13 and 92/12) passed into a transitional zone of HIGH base WLs (92/14, 92/3, 92/11) which was enclosed by an UNCONNECTED zone. 92/1 (20m west of 92/2, off Figure 2.2) was a HIGH-LOW outlier in the UNCONNECTED zone. Only LOW amplitude WL fluctuations were observed.

1993: A NE-SW trending axis in which connected boreholes exhibited DRY-HIGH WL behaviour was present in the core of the borehole array. A progression of WL behaviour was observed with higher base WLs and lower WL fluctuations occurring away from the central core of DRY-HIGH holes. The eastern margin of the array consisted of UNCONNECTED holes.

1995: A NE-SW trending axis of LOW-LOW and LOW-ZERO boreholes existed within an outer zone of mainly UNCONNECTED boreholes. HIGH-LOW (95/7b) and HIGH-ZERO (95/20) holes separated the central boreholes from UNCONNECTED holes to the west. 95/20 is therefore taken to represent the western limit of the connected zone. 95/16 was an anomalous HIGH-ZERO hole within an otherwise UNCONNECTED zone to the east of the central boreholes.

2.4.2 INTER-ANNUAL COMPARISONS OF WL BEHAVIOUR PATTERNS (Figure 2.2):

2.4.2.1 *Width of connected zone:* The width of the connected zone can be measured as the distance between the unconnected boreholes located either side of the connected holes. As there is a gap between these two sets of holes, the boundaries between the unconnected and connected zones are subjective. The width of the connected zone in the 3 years was approximately 80m (±5m) in 1992, 120m (±10m) in 1993, and 70m (±5m) in 1995.

2.4.2.2 *WL behaviour in the connected zone:* 1993 exhibited the lowest base WLs and the highest WL fluctuation amplitudes (up to ~80m). Only low WL fluctuations were exhibited in 1992 and 1995 (~10-15m in 1992; ~1-30m in 1995).

2.5 POSSIBLE REASONS FOR THE OBSERVED DISTRIBUTION OF BOREHOLE WL BEHAVIOUR:

The late-season borehole WL behaviours observed in 1992, 1993 and 1995 demonstrate the presence of a VPA bounded on either side by an area of high, stable water pressure. The borehole WL behaviour and the width of the VPA measured in 1993 suggest that a well developed channel characterised by strong daily pressure cycles existed at the bed in the centre of the VPA during the 1993 5 day classification period. This channel appears to have been surrounded by a distributed drainage system as base WLs increased and WL fluctuation amplitudes decreased away from the inferred channel. WL behaviour in 1992 and 1995 was different to that in 1993 in three main ways:

a) DRY boreholes occurred only in 1993 and not in 1992 (except 92/13) and 1995;
b) There were no HIGH WL fluctuations in 1992 and 1995 as there were in 1993; and
c) The VPA was wider in 1993 than in 1992 and 1995.

In the light of these differences in WL behaviour, the question to be asked is why was 1993 so different from 1992 and 1995? These differences were most likely caused by different meltwater input regimes to the glacier in each year. The daily input and flow of meltwater within and beneath a glacier is the major process of channel formation as it is the frictional heat created by flowing water and the sensible heat transfer between the flowing water and the surrounding ice that melts the channel walls and enlarges the channel. Consequently, the amount of daily meltwater input determines whether a channel becomes pressurised or not and what magnitude of pressurization occurs. However, channel pressurization also depends on channel size, which is dependent on antecedent meltwater input history. These factors ultimately have an effect on the WL behaviour observed. The magnitude of daily meltwater input (and indirectly, channel size) to a particular part of a glacier is likely to be dependent on two main factors: meteorological conditions and snowline position.

2.5.1 Meteorological Conditions:

Air temperature has an obvious positive relationship with melt rates (Braithwaite, 1981). As air temperature increases, melt rates and thus meltwater inputs increase. However, in order for melt rates to remain consistently high, air temperature must also remain consistently positive. This is due to the retarding effect of sub-zero temperatures on melt rates. If the air temperature remains above zero, surface melting will always occur to some degree, but if sub-zero air temperatures occur, the meltwater on the glacier surface will re-freeze. Cooling of the surface will occur from longwave radiation losses and conduction from the ice to the cooler overlying atmosphere. The temperature of the ice surface then has to be brought back to zero before melt can resume. The onset of melt is therefore retarded.

Periods of snowfall during the melt season will also retard the melting of ice as snow has a higher albedo than glacier ice. Thus, incoming solar radiation is reflected to a greater degree by snow than ice and the energy available for melting is reduced. In addition, meltwater inputs to a glacier are damped by storage within the snowpack. Finally, if the snowpack has been removed, periods of rainfall may enhance surface melting and in themselves represent an input of water to a glacier's hydrological system.

2.5.2 Snowline Position:

Snow on the glacier surface acts as a storage site for meltwater and thus damps the diurnal variability in inputs of meltwater to the subglacial drainage system. This is well demonstrated by the large slush fields that cover the glacier during the early parts of the ablation season. Snow cover may also plug moulin entrances, inhibiting meltwater input to the subglacial drainage system. As the snowline retreats, low albedo, impermeable ice surfaces are exposed which produce rapid runoff and strongly peaked diurnal meltwater inputs to moulins and crevasses which are likely to be linked to the subglacial drainage system. The onset of peaked diurnal meltwater inputs as the snowline retreats is thought to be significant in destabilising the distributed system at the bed and initiating channel development and rapid channel enlargement at Haut Glacier d'Arolla (Nienow, 1993; Nienow et al., submitted). Nienow proposed that the channelised system at Haut Glacier d'Arolla expanded upglacier during the summer melt season at a rate similar to the rate of snowline retreat, as this determined when peaked meltwater input cycles commenced.

2.6 DISCUSSION:

The influence of meltwater inputs on the WL behaviour observed in each year will be discussed and reasons for why the observed differences occurred will be suggested.

Meteorological and discharge data for 1993, 1992 and 1995 (Figures 2.3, 2.4 and 2.5) were supplied by Grande Dixence S.A. (GDSA), a hydro-electric company that captures water from Haut Glacier d'Arolla. The meteorological data were measured at Bricola weather station located 8km N.N.E from Haut Glacier d'Arolla. Discharge was measured at the GDSA intake structure located ~1km from the glacier terminus (Figure 1.1).

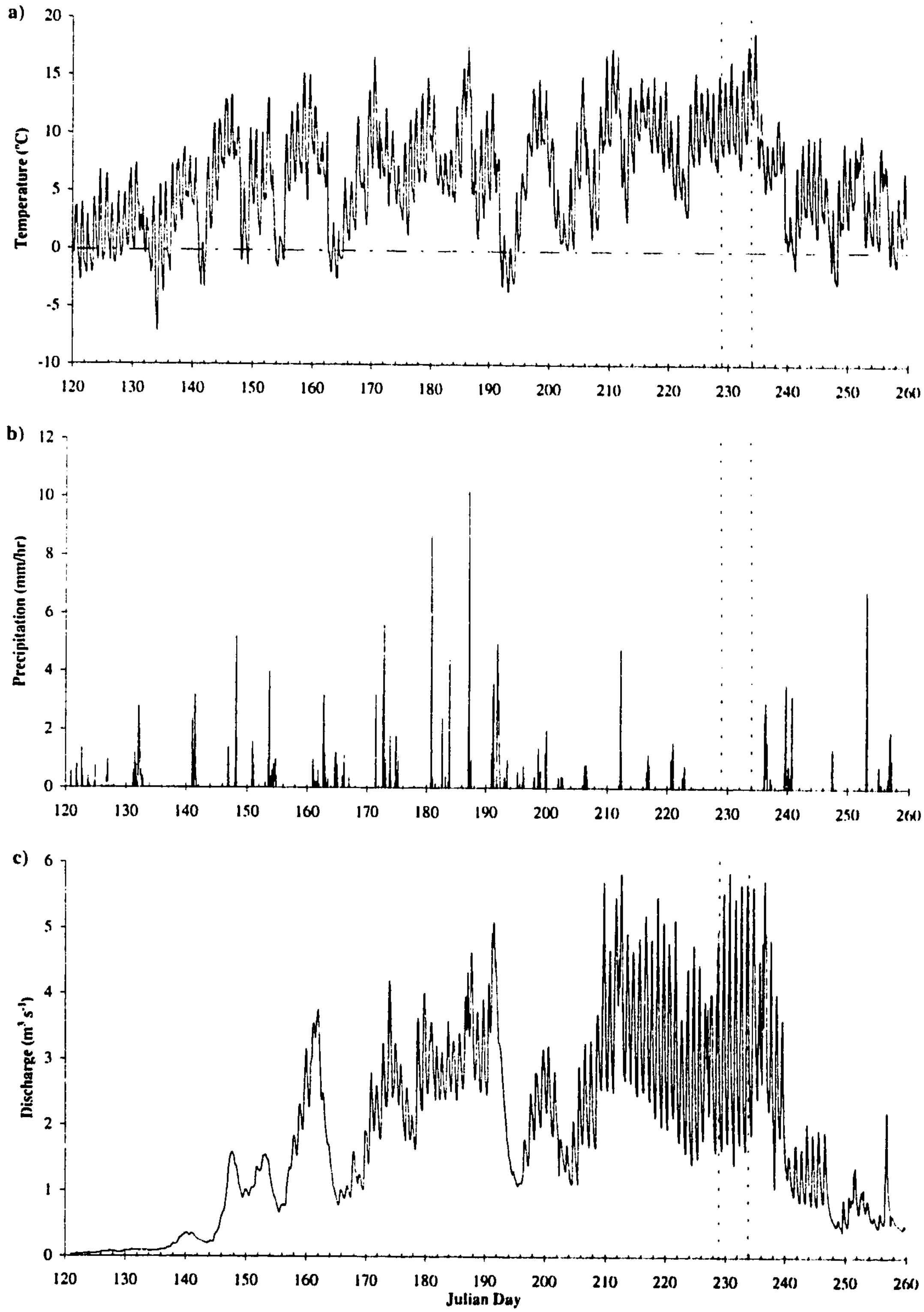

Figure 2.3: 1993 a) temperature, b) precipitation, and c) discharge. Dashed lines represent 5 day classification period. See text for data sources.

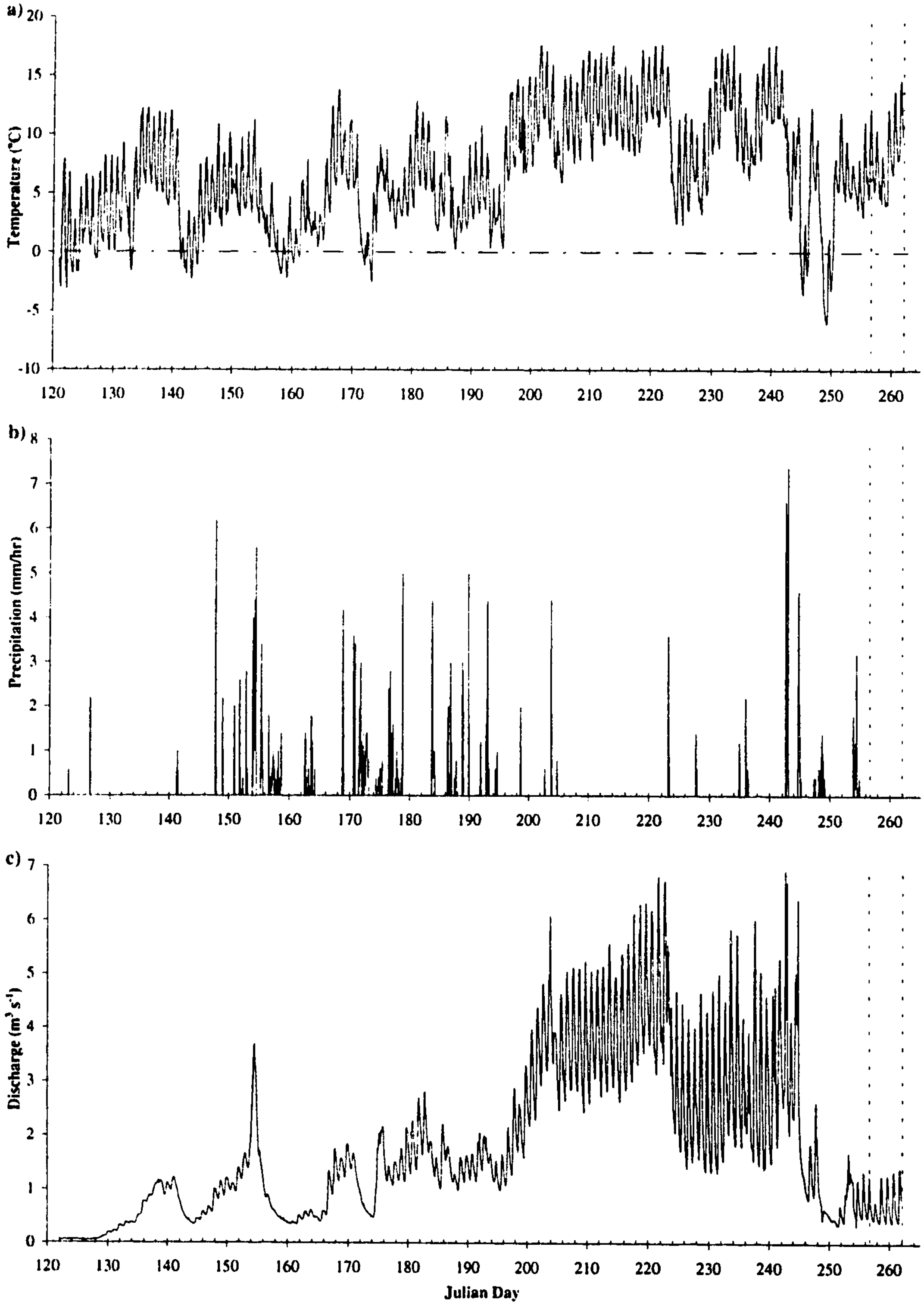

Figure 2.4: 1992 a) temperature, b) precipitation, and c) discharge. Dashed lines represent 5 day classification period. See text for data sources.

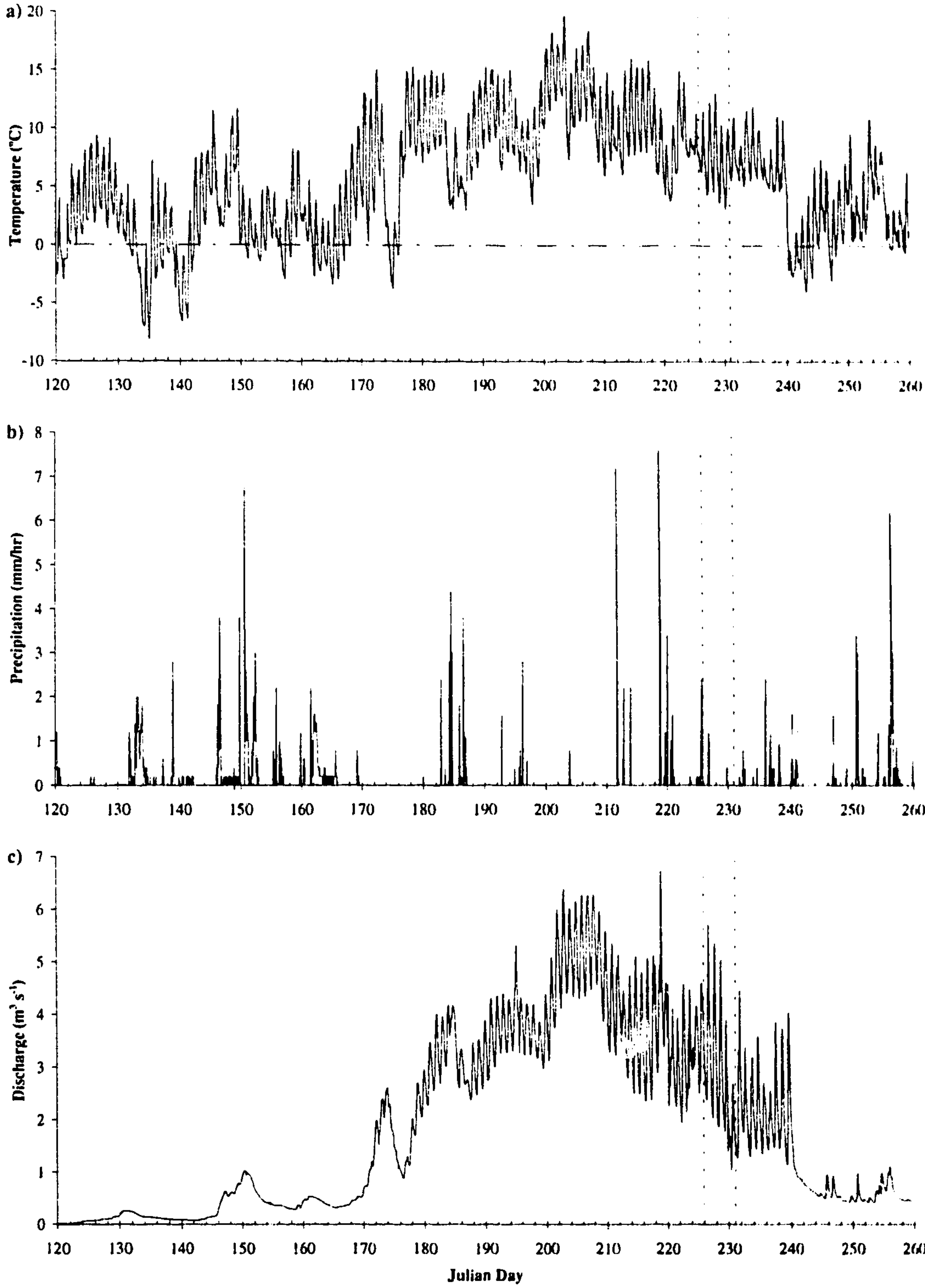

Figure 2.5: 1995 a) temperature, b) precipitation, and c) discharge. Dashed lines represent 5 day classification period. See text for data sources.

Snowline positions were taken from observations made during regular ablation surveys at a series of permanent stakes drilled in a transect up the centreline of the glacier. In these surveys, the glacier surface was described as consisting of either 'snow' or 'ice'.

2.6.1 1993:

The 5 day window period in 1993 (JD 229-233) occurred during the warmest period of the summer (Figure 2.3a) when the highest discharges associated with the highest diurnal discharge fluctuations were recorded (Figure 2.3c) and when snow covered only the upper 1km of the glacier. Daily meltwater inputs were thus likely to have been peaked and high. If a subglacial channel existed beneath the borehole array during the 5 day classification period, these conditions were likely to have been favourable for strong, daily channel pressurisation resulting in the propagation of a pressure wave away from the channel into the surrounding areas of the bed. The WL behaviour exhibited in the 5 day window period in 1993 suggests that such a channel did exist and that it was bounded by a distributed system. DRY base WLs and HIGH WL fluctuations in 93/29, 93/35 and 93/34 demonstrate that a channel located close to these holes became strongly pressurised during the day by high, peaked meltwater inputs, but returned to atmospheric pressure overnight when these meltwater inputs ceased. WL fluctuations observed in holes distant from these central holes show that channel pressurisation produced a hydraulic gradient away from the channel towards the surrounding areas of the bed, thus enabling the propagation of a pressure wave away from the channel. The decrease in WL fluctuation amplitude with distance from the central holes demonstrates the diffusion of the pressure wave with distance from its origin. Increasing base WLs away from the central DRY-HIGH holes (e.g. 93/41 and 93/42) represent the increase in the piezometric surface away from the channel (Section 2.1). As base WLs in the central holes were DRY and base WLs increased in the surrounding distributed system, a hydraulic gradient towards the channel from the surrounding areas of the bed must have developed, allowing the distributed system to drain overnight. Hydraulic gradients are therefore inferred to have reversed between the channel and the surrounding distributed system on a daily basis.

The relatively large width of the VPA in 1993 may be associated with the period of time over which the inferred channel was able to develop before the 5 day classification period. The 1993 ablation survey showed that snow had retreated from the borehole array by JD 200 and that no further snowfall occurred between then and the end of the summer observation period on JD 233. Air temperatures remained consistently above zero from JD 204 onwards (Figure 2.3a). Thus, favourable conditions for the production of peaked daily meltwater input cycles existed from JD 204 until the end of the observation period. These cycles will have increased in amplitude as the snowline retreated over the summer, exposing larger areas of low albedo, impermeable ice. This is demonstrated by the development of peaked daily bulk discharge cycles (Figure 2.3c). If the suggestion that the development of a channelised drainage system at a point on the glacier is initiated as the snowline retreats from that point is correct (Nienow, 1993; Nienow et. al, submitted), then the development of a subglacial channelised system in the 1993 borehole array would have been initiated ~JD 204. This channelised system would thus have had ~25 days (JD 204-229) within which to develop before the 5 day classification period (JD 229-233). Sustained high discharge over this 25 day period (Figure 2.3c) will have been significant in promoting the development of this channelised system. High daily water pressure fluctuations driven by high, peaked discharge over the 25 day period are likely to have been propagated away from the channel to distal parts of the surrounding bed, thus explaining the observed width of the VPA.

2.6.2 1992:

The DRY base WL in 92/13 suggests the possible presence of a subglacial channel at atmospheric pressure. Increasing base WLs with increasing distance from 92/13 suggest that this channel was surrounded by a distributed system that was constantly pressurised. However, the presence of only LOW WL fluctuations demonstrates that this inferred channel could not be pressurised sufficiently by the meltwater inputs to promote HIGH WL fluctuations.

The 5 day classification period in 1992 (JD 257-261) occurred near the end of the summer ablation season and followed a period of cool temperatures (JD 245-250) when snowfall occurred (Figures 2.4 a and b). This likely resulted in the low discharge measured after JD 245 (Figure 2.4c). Conditions for peaked daily meltwater inputs were thus not favourable for significant channel pressurisation, and may thus explain the lack of HIGH WL fluctuations in 1992.

The size of the inferred channel during the 5 day classification period may also explain why no HIGH WL fluctuations were observed. A period of high, peaked discharge associated with high temperatures occurred between JD 205 (when the snowline retreated from the borehole array) and JD 223 (when snow had been removed from most of the glacier) (Figures 2.4a and c). These conditions are likely to have promoted the development and growth of a channelised system beneath Haut Glacier d'Arolla to efficiently evacuate large volumes of meltwater. This channelised system is likely to have begun to close by ice deformation after JD 245, when discharge decreased significantly and there was unlikely to have been sufficient meltwater to offset closure. As such closure is not instantaneous, the channel would have been too large to be significantly pressurised by the declining meltwater inputs. This may explain why a DRY base WL was observed (channel drained to atmospheric pressure overnight), why only LOW WL fluctuations occurred in the 5 day classification period, and why the VPA was narrower than that in 1993 (pressure fluctuations in the channel were not great enough to reach distant parts of the bed).

It is therefore proposed that the WL behaviour observed in the 1992 5 day classification period represents the existence of an 'oversized' channel which had evacuated past high levels of discharge, but was subjected to only low meltwater inputs during the 5 day classification period. This channel was located within a distributed drainage system. Had drilling been undertaken between ~JD 205 and JD 223, it is possible that WL behaviour similar to that in 1993 would have been observed due to consistent high air temperatures and resulting high, daily peaked discharge.

2.6.3 1995:

The WL behaviour observed in the 1995 5 day classification period (JD 226-230) demonstrates that if a channel did exist within the borehole array (as was inferred in 1992 and 1993), it was constantly pressurised as no DRY base WLs were observed. In addition, the pressure in this channel did not rise significantly on a daily basis as only LOW WL fluctuations were observed and the width of the VPA was narrow. LOW WL fluctuations may have been due to reduced or damped meltwater inputs to the inferred channel as the snowline was ~2.7km from the glacier snout during the 5 day classification period. As snow still covered much of the upper glacier catchment, peaked meltwater inputs would have been reduced and damped due to the high albedo and storage capacity of the snow. The 5 day classification period also occurred on the downward trend of the seasonal discharge curve (Figure 2.5c) which may also explain the lack of HIGH WL fluctuations in 1995.

The 1995 WL behaviour does not conclusively point to the presence of a channel located within the borehole array during the 5 day classification period. Another possible explanation for the observed WL behaviour is that boreholes with LOW base WLs represent areas of the bed which were able to accommodate most of the water that was originally in the boreholes after they were drilled. The LOW WL fluctuations may not necessarily have been driven by basally-derived inputs, but by daily supraglacial and/or englacial inputs which exceeded the rate of drainage from the boreholes during the day, and drained from the boreholes overnight when the inputs ceased. In boreholes that exhibited no WL fluctuations (95/4 and 95/15), the rate of melt input is likely to have been equal to the rate of output. Boreholes with LOW base WLs may therefore represent areas of the bed with a higher hydraulic conductivity than areas of the bed characterised by unconnected boreholes.

2.7 CHANGING BOREHOLE WATER LEVEL BEHAVIOUR OVER AN OBSERVATION SEASON:

The above discussion has attempted to demonstrate the character of the subglacial drainage system within the three observation years. However, as mentioned in Section 2.3, the classification of borehole WL behaviour in a five day period at the end of each season excludes the possibility of identifying changes in borehole WL behaviour over an observation season. Such changes may indicate evolution of the subglacial drainage system (e.g. Nienow, 1993; Fountain, 1994; Nienow et al., submitted).

The revised version of the Smart (1996) classification system was applied to all the borehole WL data in each year over the entire observation season. Of the 56 boreholes classified in the original 5 day classification period, 10 demonstrated changes in WL behaviour over the observation periods. Two of these were from 1992 (92/4 and 92/13), seven were from 1993 (93/29, 93/32, 93/34, 93/35, 93/36, 93/41, 93/43) and the other was from 1995 (95/2). As WL behaviour in 1993 changed more than in the other two observation years, and as 1993 is the focus of Chapter 4, the WL behaviour changes of the 1993 boreholes will be discussed here.

With the exception of 93/43, all the boreholes with changing WL behaviour demonstrated increases in WL fluctuation amplitude (Figure 2.6). 93/29 and 93/36 exhibited DRY-HIGH and DRY-LOW WL behaviour respectively, between JD 195 and JD 199. As the base WLs in the boreholes surrounding 93/29 and 93/36 were either LOW or HIGH over this period, it is likely that the DRY base WLs in 93/29 and 93/36 represent conditions in an isolated area of the bed. This area may have been a region of bed separation where a cavity filled during the day from daily supraglacial and/or englacial meltwater inputs to the boreholes and drained completely overnight when these inputs ceased.

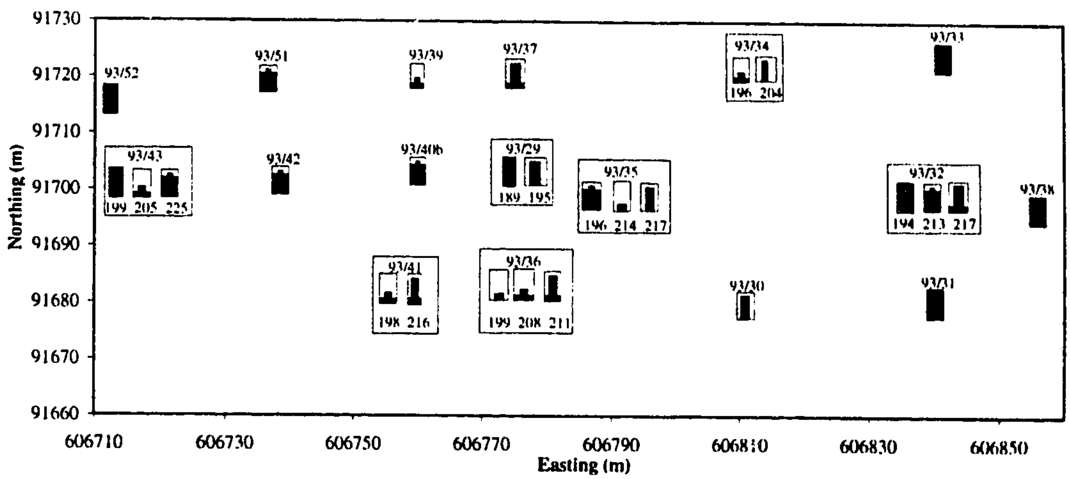

Figure 2.6: Distribution of classified boreholes in 1993 highlighting those holes that changed classification over the summer observation period (in boxes). The value below each classification symbol is the Julian day on which the WL behaviour changed on.

Between JD 204 and JD 217 there was a general trend towards decreasing base WLs and/or increasing WL fluctuation amplitudes in boreholes located towards the centre of the array. These changes in WL behaviour might indicate the gradual development of a channel in the centre of the borehole array. This would have resulted from water pressure in the areas of the bed surrounding the inferred channel being drawn-down by low water pressure in the channel (causing decreasing base WLs) and the channel becoming more significantly pressurised from increases in meltwater inputs that are inferred from increasing bulk discharge over this period (Figure 2.3c) (causing increasing WL fluctuation amplitudes). Increasing bulk discharge after ~JD 206 is likely to have resulted from the retreating snowline which was ~2.5km from the glacier snout on JD 214. As the snowline retreated, low albedo, impermeable ice surfaces were exposed which allowed rapid, peaked meltwater production and runoff. The period within which significant changes in WL behaviour occurred appears to have coincided with the removal of much of the snowpack from the glacier and a consequent increase in peaked bulk discharge. It is therefore proposed that the observed changes in WL behaviour, especially between JD 204 and JD 217, occurred in response to a common forcing (the onset of high, peaked meltwater inputs as the snowline retreated which promoted the gradual development of a channel) and not in response to random forcings on individual boreholes (e.g. a localised change in the hydraulic conductivity of the sediment at the base of a borehole or varying amounts of local supraglacial and/or englacial meltwater inputs to individual boreholes).

93/43 demonstrated slightly different behaviour. This borehole connected on JD 205 and exhibited LOW-LOW WL behaviour until JD 225 when its base WL rose to HIGH. Thus, a connection event was followed by a disconnection. This may have been caused by a number of factors such as a reduction in the hydraulic conductivity of sediment near the base of the borehole or the advection of the borehole base onto a bedrock bump.

The evolution of the subglacial drainage system in 1993 will be discussed in greater detail in Chapter 4.

2.8 SUMMARY:

The use of the borehole WL behaviour classification system has allowed the general pattern of WL behaviour within the borehole array to be analysed. In all three observation years a central zone of connected boreholes was located within a wider area of generally unconnected or high standing boreholes. Daily WL fluctuations in the connected area were greatest in 1993 as was the VPA width. The WL behaviour in the 5 day window period of 1993 suggests the presence of a well developed channel located within a more extensive distributed system. The daily pressurisation of the channel (indicated by the WL fluctuations) was detected to a reduced degree with increasing distance from the channel (indicated by decreasing WL fluctuation amplitudes away from the channel). In 1992, it was inferred that a channel did exist at the centre of the VPA, but that this channel was too large to be significantly pressurised by the decreasing meltwater inputs during the window period. This accounted for the LOW WL fluctuations observed, the DRY and LOW base WLs in the central holes and the narrow VPA width. The presence of a channel within the 1995 borehole array was not conclusively demonstrated. If a channel did exist, meltwater inputs during the window period may not have been great enough to significantly pressurise the inferred channel to register HIGH amplitude WL fluctuations due to the snow cover which persisted in the upper glacier catchment. Another suggestion was that the distribution of the WL behaviour represented areas of the bed with different values of hydraulic conductivity and that WL fluctuations were driven by supraglacial and/or englacial inputs.

The classification system has also been used to highlight changing borehole WL behaviour over an observation season. It was suggested that the observed changes in WL behaviour (which occurred over a 13 day period) represented the gradual growth and development of a subglacial channel within the borehole array. The development of the inferred channel was thought to have been initiated by the retreat of the snowline which allowed high, peaked meltwater inputs to the subglacial drainage system.

Despite the utility of a simple classification system for categorising a highly variable WL data set, two main limitations are encountered. Firstly, the classification system totally masks short-term events (e.g. the influence of rainfall on the WL curve) and it does not allow for the identification of WL trends within the categories. The WL fluctuation amplitude is either ZERO, LOW or HIGH and changing amplitudes within these categories cannot be identified. These short-term events and trends may be just as significant in describing the nature and evolution of the drainage system as the general WL behaviour. Secondly, the WL data are taken at face value. No account is taken of whether the borehole is actually connected to the bed or not. From observations at the surface, WL fluctuations are just as likely to be induced by daily meltwater inputs to the top of the borehole as by inputs from the base of the borehole and no account is taken of englacial influences. Without information concerning the water sources and circulation patterns within the observed boreholes, the interpretation of WL behaviour is problematic and may be unreliable. These factors will be addressed in the following chapters.

CHAPTER 3: DETERMINATION OF BOREHOLE PLUMBING FOR THE INTERPRETATION OF BASAL WATER QUALITY MEASUREMENTS

3.1 INTRODUCTION:

Measurements of EC and turbidity (Tu) recorded by in-situ probes positioned at the base of boreholes, have been used to interpret the character of subglacial drainage systems (Stone et al., 1993; Hubbard et al., 1995; Stone and Clarke, 1996). EC was used to infer the source of water: low EC representing solute-poor melt, higher EC representing water that had remained at the bed for longer periods of time acquiring solute (Brown et al., 1994). Variations in Tu were thought to result from the fluvial entrainment and transport of sediment particles due to increasing basal water flow velocities either near the probe or at some distance away from the probe. By combining EC and Tu measurements, inferences about basal water velocity, subglacial water provenance, the hydraulic conductivity of basal sediments and changes in the drainage system morphology were made and used to describe the character of subglacial drainage systems (e.g. Stone et al., 1993; Hubbard et al., 1995; Stone and Clarke, 1996).

The thermal regime of the glacier in which the boreholes are drilled determines the reliability of the in-situ water quality records as indicators of *true* basal water quality and thus their use for characterising subglacial drainage systems. Boreholes drilled in predominantly cold glaciers seal rapidly by water freezing and rarely encounter englacial drainage structures (e.g. Trapridge Glacier: Stone et al., 1993; Stone and Clarke, 1996). Such conditions are ideal for measuring basal water quality as the presence of the borehole imposes a negligible influence on the water quality measured at its base. However, measurements of basal water quality from the base of boreholes drilled in warm-based glaciers (e.g. Haut Glacier d'Arolla: Hubbard et al., 1995) are likely to be less representative of *true* basal water quality conditions as these boreholes remain open throughout the summer and are thus prone to englacial and supraglacial influences.

A significant number of boreholes that have been drilled in warm-based glaciers intercepted one or more englacial connections (detected by the sudden drop of the drill tip or of the borehole water level during drilling) (e.g. Engelhardt, 1978; Hantz and Lliboutry, 1983; Iken and Bindschadler, 1986; Fountain, 1994). The existence of englacial connections has also been inferred by down-borehole salt tracing (Hooke et al., 1988). Such observations can now be verified using down-borehole video imagery which allows for the direct identification of englacial inputs and outputs (englacial channels) and storage locations (englacial voids) (Pohjola, 1994; Harper and Humphrey, 1995; Copland et al., in press). Direct supraglacial inputs to the tops of boreholes have also been observed (e.g. Engelhardt, 1978). WL variations and water circulation within 'open' boreholes are thus likely to be significantly influenced by englacial and supraglacial inputs and outputs.

An 'open' borehole can thus store both basally and supra/englacially derived water if basal pressures are great enough to force water into the borehole and/or impede drainage from it. In-situ probes at the base of 'open' boreholes may therefore not be continually monitoring changes in basal water quality, but rather the characteristics of water entering and exiting the base of the boreholes, which may be basally and/or supra/englacially derived. In-situ water quality measurements may also reflect water exiting the borehole mixing with water flowing past the base of the borehole. In-situ water quality measurements in 'open' boreholes may therefore rarely represent *true* basal water quality conditions.

As a result, it is clearly necessary to determine the source and circulation of water within each borehole (i.e. determine borehole plumbing) before attempting to interpret in-situ water quality measurements. This is the objective of the present chapter. A number of data collection techniques used to identify the sources and circulation of water within boreholes will be presented. After analysis of these data, a classification of borehole plumbing will be suggested and applied to all of the boreholes drilled on Haut Glacier d'Arolla. Finally, examples of each borehole plumbing category will be discussed.

3.2 DATA SOURCES:

Seven types of data allow the determination of borehole plumbing. These can be viewed in a hierarchical fashion as each data source supplements the inferences made by the previous one. Thus, a borehole that has data from all seven sources will be associated with more accurate and reliable interpretations than a borehole with data from only one source. The seven data sources are: drilling records, continuous in-situ and manual WLs, continuous in-situ EC measurements, continuous in-situ Tu measurements, EC profiling, salt tracing and borehole video imagery.

3.2.1 Drilling Records:

Records are kept concerning the status of the borehole WL during drilling. If the WL drops before the bed is reached, the depth at which the drill tip lies is recorded (Table 3.1). If the borehole proceeds to refill from the continuous input of drill fluid (supraglacial water), it is inferred that an englacial void of finite volume has been intercepted. If the borehole does not refill, the interception of an englacial channel is inferred. Subsequent to drilling, records are kept of the time and duration of borehole reaming (unblocking of borehole constrictions with the drill to allow measuring instruments to be lowered to the base of a borehole) as this represents an artificial input of supraglacial water to a borehole. Some anomalous WL, and water quality behaviour may be explained by this artificial introduction of water into the borehole, therefore reaming records aid the interpretation of the WL and water quality measurements.

BOREHOLE NUMBER	DRILLING RECORDS
93/26	Connected at bed - dry
93/27	Connected at 32m bs - stopped drilling
93/28	Stopped at 82m ab(rocks) - not at bed
93/30	Connected at 35m bs and at bed
93/36	Connected at bed - dry
93/40a	Connected 31m ab-WL dropped to 30m ab
93/41	Connected 5m ab (WL↓to 15m ab)
93/42	Connected at 33,57 and 96 m ab
93/44	Void at 50m ab, re-filled
95/7b	Connected at 34m ab
95/8	Connected at 20.5m ab

Table 3.1: Borehole drilling records. Depths are given as metres above the bed (m ab) and metres below the surface (m bs).

3.2.2 Continuous in-situ and manual WLs:

As discussed in Chapter 2, initial analysis of WL data provides an indication of whether a borehole is connected to the basal drainage system (drop in WL) and of the proximity of the borehole to the source of WL forcing (amplitude of WL fluctuation). Boreholes with continuous in-situ WL measurements have more reliable WL data than boreholes with manual WL measurements as measurements are taken continuously throughout the observation season (unless technical difficulties arise) rather than at irregular times during the day (see section 2.2 for methods of in-situ and manual WL measurements). In order to determine the source of the water that drives WL variations, both types of WL measurements must be supplemented by the following types of data.

3.2.3 Continuous in-situ EC measurements:

EC is proportional to the concentration of ions in solution and can be used as a surrogate for total dissolved solids (TDS). Although the conductivity of solutions is affected by factors such as temperature, ionic composition, pH and sediment load (Fenn, 1987), measurements of EC in this study are used solely to provide an indication of the TDS of the sampled water.

Sharp (1991) discussed five factors that primarily govern the extent of solute acquisition by glacial meltwaters: the chemistry of the source waters, the availability of protons, the duration of contact between meltwaters and weatherable rock material, the grain size, shape and mineralogical properties of particulate rock material in the subglacial environment, and the ratio between meltwater volume and the surface area of rock material available for weathering. Consequently, different types of drainage system may be characterised in terms of characteristic values of the above properties. As detailed water chemistry analysis is not the focus of this study, EC values will be taken as an indication of the relative contact times between meltwaters and weatherable rock material. Thus, dilute water represents water that has spent little time in contact with weatherable rock material and is therefore likely to represent recently produced meltwater. More concentrated water is thought to have spent a longer period of time in contact with weatherable rock material and may therefore represent water that has been stored at the bed for a period of time. The remaining four factors discussed by Sharp (1991) are recognised, but are not the focus of this study. Measured EC of meltwaters can therefore be used as an indication of the source of the water; recently derived-surface melt characterised by low EC versus basally-derived water characterised by higher EC.

EC measurements may also vary due to the mixing of waters characterised by different conductivities. This is exemplified by an inverse relationship between bulk discharge and EC (Fenn, 1987; from Tsidjiore Nouve, Switzerland). When discharge was low, high EC (~50μS cm^{-1}) represented the overnight drainage of stored water, whilst rising discharge was associated with a decrease in EC (~15μS cm^{-1}) due to the evacuation of the daily melt. The mixing of stored water and supraglacial meltwater was demonstrated as the EC during the day did not descend to values characterised by supraglacial meltwaters (<10μS cm^{-1}). This mixing process must also be considered when interpreting EC measurements.

In 1993 and 1995, EC was recorded continuously by in-situ automated sensors placed within a few decimetres of the bed (see Appendix III for sensor construction and calibration details). Measurements were logged as means of 30 readings every 10 minutes using Campbell Scientific CR-10 data loggers and EC values are presented as measured in water at c. 0°C. In-situ measurements were taken in 13 boreholes in 1993 and in 5 boreholes in 1995 (Table 3.2). From this point, EC measurements recorded by in-situ sensors will be referred to as 'in-situ EC'.

SENSOR	**1993**	**1995**
EC	27, 29, 30, 34, 35, 36, 37, 40a, 40b, 41, 42, 43, 51	2, 4, 15, 17, 18
Tu		N/A

Table 3.2: Boreholes monitored by in-situ EC and Tu sensors in 1993 and 1995.

A frequency histogram of in-situ EC measured over the three years of observation exhibits four EC modes (designated Modes 1, 2, 3 and 4) at 0-10, 11-40, 41-80 and 81-150μS cm^{-1} (Figure 3.1). The first three modes are similar to the three EC modes observed on Haut Glacier d'Arolla in 1992 by Tranter et al. (in press). This study inferred that Mode 1 waters represented dilute supraglacial ice melt and drill fluid; Mode 2 waters represented subglacial channel water as they were slightly less concentrated in the major ions than bulk glacial runoff; and Mode 3 waters were derived from flow in a distributed system where residence times at the bed were of the order of a few months or less. Mode 4 waters which were not detected in 1992, may represent water that had spent considerable time at the bed in storage or in a distributed system. However, it must be kept in mind that the definitions of these modal EC groups are crude, as no account has been taken of the process of mixing as a means of producing these groups. As no chemical analysis has been undertaken, the importance of this process cannot be quantified. Thus, by applying these modal EC categories, measured in-situ EC has the potential to act as a crude natural tracer of water source.

3.2.4 Continuous in-situ Tu measurements:

Turbidity results from the fluvial entrainment and transport of sediment particles (Stone and Clarke, 1996) which may be caused by:

a) increasing flow velocities exerting a shear stress on sediment at the ice-bed interface. Particles are dislodged when the shear stress is great enough and these particles may be transported as suspended sediment if they are small enough.

b) direct mechanical action of rapidly sliding ice (e.g. during mini-surges; Humphrey et al., 1986).

c) exposure of new areas of the bed to turbulent flow when high water pressure within a channel may cause ice-bed separation (Walder and Fowler, 1994).

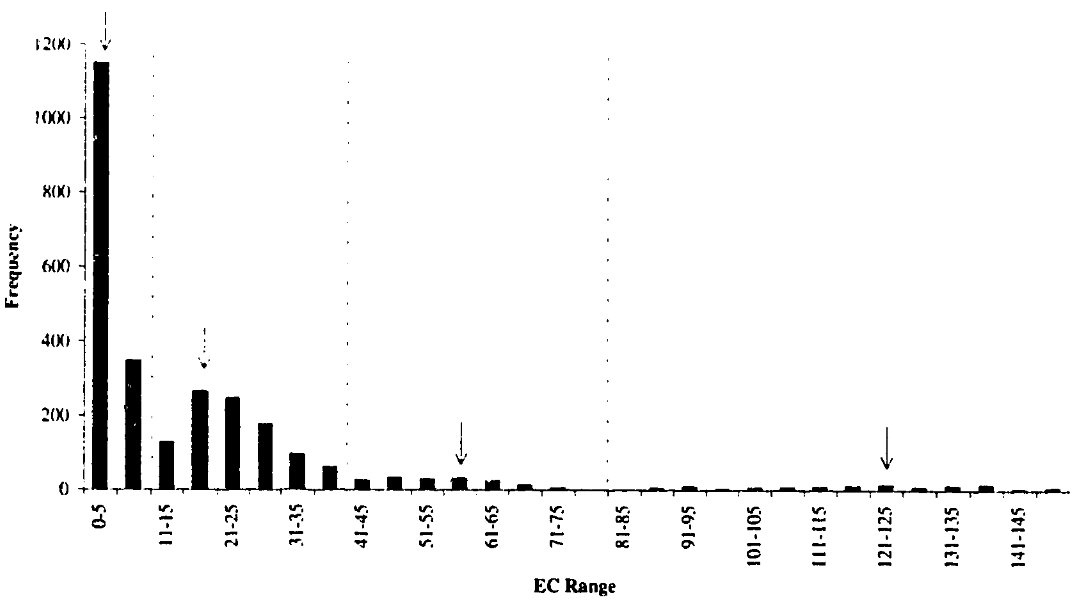

Figure 3.1: Frequency histogram of in-situ EC measured in 1992, 1993 and 1995. Arrows indicate modal EC ranges.

Stone and Clarke (1996) used Tu pulses measured at the base of one borehole (initiated by the sudden drainage of another borehole) to determine the velocity of flow between boreholes during the drainage event. This could be calculated as the distance between the two boreholes was known. Hubbard et al. (1995) interpreted the arrival of Tu pulses measured in boreholes located at increasing distances from an inferred channel as demonstrating water being forced across the bed laterally from the channel as the water pressure increased within the channel. Tu pulses can thus be used as natural tracers of flow at the bed.

As with EC, Tu was measured continuously in 13 boreholes in 1993 (Table 3.2) by automated in-situ sensors placed within a few decimetres of the bed (see Appendix III for construction and calibration details). Measurements were also logged as means of 30 readings every 10 minutes using Campbell Scientific CR-10 data loggers. Tu is presented as relative turbidity (Tu[r]), defined as:

$$Tu[r] = (Tu[c]-Tu[s])/Tu[c] \qquad (3.1)$$

where Tu[c] and Tu[s] are the turbidity signals recorded in clear water and the sample, respectively. Clear water therefore has a Tu[r] of 0 and highly turbid water a Tu[r] of 1. From this point, Tu[r] measured by in-situ sensors will be referred to as 'in-situ Tu'.

3.2.5 EC Profiling:

The modal EC categories discussed above can also be used to identify the source and circulation of water within a borehole. The latter is only possible if the borehole water column exhibits an EC *stratification* where more than one mode of water exists. In such a case, waters of different modes are separated by a *condocline*. Patterns of water circulation within a borehole can be deduced by monitoring the movement (if any) of the EC stratification.

EC profiling was conducted in 1992, 1993 and 1995 (see Appendix II for construction and calibration details of EC profilers). The EC profiler was lowered down the borehole until the WL was reached (if the borehole was not full) and this depth was recorded. It was clear when the profiler reached the WL as air readings were zero whilst water readings were >0.5μS cm^{-1}. EC readings were taken just below the WL and subsequently at 5m intervals until the bed was reached. EC profilers were also used to monitor WLs in boreholes that were not monitored by in-situ pressure sensors.

Of the 70 boreholes drilled in 1992, 1993 and 1995, 59 were profiled. Four major EC stratification categories have been identified in these 59 boreholes:

a) **Type 1:** Mode 1 water only. Exhibits no EC stratification.
b) **Type 1/2:** Mode 1 water overlying Mode 2 water.
c) **Type 1⇒1/2:** Mode 2 water enters the base of a Mode 1 water column on a diurnal basis.
d) **Type 1/2/3:** Mode 1 water overlies Mode 2 water which overlies Mode 3 water.

These four categories represent 54 of the 59 boreholes profiled. The remaining 5 boreholes exhibit anomalous EC stratifications (1/2/4⇒1/3/4, 2/3/2, 1⇒1/2⇒1/2/3, 2/3⇒1/2/3 and 2⇒1/2 (where the arrows indicate a change in the stratification type during the observation season)). By combining the manual and in-situ WL records with the EC profiling data, a general idea of the plumbing of each borehole can be gained. Three main borehole plumbing types are identified:

a) **Unconnected:** the borehole remains full and no movement in the EC stratification (if present) is observed.
b) **Compound:** WL variations are observed and movement of the EC stratification occurs (especially near the bed). Inputs and outputs may be from any combination of supraglacial, englacial or basal sources.

c) **Englacially connected:** WL variations are observed, but there is no movement in the basal EC stratification indicating that englacial and/or supraglacial inputs and outputs are driving the WL variations .

3.2.6 Borehole Salt Tracing:

Dissolved salt can be used as an artificial tracer of water flow within a borehole water column (Hooke et al., 1988). Its use is especially advantageous as the EC values produced can be much greater than the highest EC values of natural borehole waters if sufficient salt is used. This enables tracing in boreholes that possess no EC stratification and clearer monitoring of flow in those that do, allowing for the identification of possible englacial and basal inputs and outputs.

To conduct a salt trace, a 1cm diameter plastic hose was taped to 100m of the EC profiler cable so that the hose outlet was directly above the sensor. This attachment was necessary to weight the hose sufficiently for it to reach depths of up to 100m bs. The hose and cable were lowered to the desired injection depth and secured. 1kg of table salt was dissolved in a 14 gallon bucket of supraglacial water and poured down a funnel into the hose. The saline solution was flushed down the hose with fresh meltwater. Profiles were subsequently logged at c. 20-30 minute intervals with readings taken every m bs. The additional weight of the hose physically prevented a shorter time interval between profiles Salt traces were undertaken in boreholes 93/37 and 93/41, the results of which will be discussed in section 3.4.4.

3.2.7 Borehole video imagery:

In 1995 a GeoVision Micro™ colour borehole video camera (see Appendix IV for further details) was used to record the internal properties of 11 boreholes. A view of the internal properties of the boreholes was afforded by a small colour monitor whilst the camera was being lowered down the borehole and the image was recorded simultaneously on a video cassette which allowed for more detailed inspection of interesting features. Written logs of the borehole properties were produced after repeated inspection of the video recordings.

The video logs provided useful information on three aspects of the internal properties of the boreholes. These were:

a) **Internal structure of borehole walls:** identified englacial channels (both passive and active) and voids.
b) **Water quality:** indicated whether the water was clear or turbid.
c) **Bed conditions:** demonstrated the nature of the bed.

Table 3.3 presents statistics on relevant features observed on the video logs. Borehole video imagery allows for the verification and/or refinement of interpretations made from the data sources discussed above as direct observations of the internal properties of the boreholes are afforded. The addition of borehole video imagery as a data source for interpreting borehole plumbing can thus significantly increase the reliability of such interpretations.

Borehole Feature	Frequency
Video reached bed	6
See bed	4
No. of englacial voids	16 (in 7 boreholes)
No.of englacial channels	5 (2 possibly active)
See water quality stratification	7

Table 3.3: Features seen in video logs from 11 boreholes drilled in 1995.

3.3 CLASSIFICATION OF BOREHOLE PLUMBING:

All the data gathered were compiled and analysed to determine the water sources and patterns of water circulation in each borehole drilled over the three summers. Four categories of borehole plumbing are identified and one category with anomalous behaviour is also included (Table 3.4). These categories have expanded on the ones identified by the EC profiling discussed above. The five categories are:

1) **Unconnected:** the borehole remains full throughout the observation season. Two types of unconnected borehole are recognised:

a) **Unstratified:** no EC stratification is present.
b) **Stratified:** EC stratification within the borehole water column is observed.

The unconnected boreholes are differentiated in terms of their EC stratification because it is possible that basal EC may indicate the bed type; whether it is a hard bed (EC may remain low and stable) or one composed of unconsolidated sediment (EC may increase over time due to the acquisition of solute from suspended sediment disturbed when the drill hit the bed).

2) **Passively connected:** a drop in the borehole WL is recorded during drilling, but the borehole re-fills and remains full throughout the season. This behaviour indicates the presence of an englacial void of finite volume. No connection to the subglacial drainage system via the bed is inferred despite the lowering of the WL.

3) **Englacially connected:** WL variations occur, but EC stratification at the bed remains stable. This suggests that water enters and exits the borehole via an englacial channel located above the condocline. Supraglacial inputs may also contribute to the rise in the WL.

4) Actively connected: the WL falls when the bed is reached during drilling or after the borehole has been completed. WL and EC stratification variations (especially at the bed) are observed either on a daily basis or over a period of several days. This indicates that the borehole has a basal connection. Englacial inputs and outputs and supraglacial inputs often have an additional influence on the WL and the EC stratification.

5) Anomalous behaviour: three instances of borehole behaviour that do not fall into the above categories have been identified. These will be discussed in the following section.

The following section will present examples of boreholes in each of these categories and explain how the classifications were reached.

CATEGORY	YEAR	BOREHOLE NUMBER	TOTAL
UNCONNECTED	1992	2,6,8,9,10,16,17,20	
(UNSTRATIFIED)	1993	31,53	11
	1995	6	
UNCONNECTED	1992	7,15,18,19	
(STRATIFIED)	1993	33,38,45,46,52,54	12
	1995	9,25	
PASSIVELY	1992	4,11	
CONNECTED	1993	44	8
	1995	5,7b,8,20,24	
ENGLACIALLY	1992	1,3	
CONNECTED	1993	35,39,42	7
	1995	2,15	
ACTIVELY	1992	12,13,14	
CONNECTED	1993	26,29,30,32,34,36, 37,40a,40b,41,43,51	18
	1995	1,4,18	
ANOMALOUS	1992	5	3
	1995	16,17	

Table 3.4: Final classification of borehole plumbing based on all available data sources.

3.4 EXAMPLES OF BOREHOLE PLUMBING CATEGORIES:

3.4.1 Unconnected:

3.4.1.1 *Unstratified:* **92/2:** EC profiles taken over a period of 20 days illustrate that the WL remained at the surface throughout and the water column consisted of Mode 1 water only. This borehole was thus filled with the supraglacial water used for drilling. Low basal EC of 3μS cm^{-1} suggests that the bed was bedrock at this location. If unconsolidated sediment had been present, it is likely that drilling would have disturbed the sediment and the basal EC would have increased with time due to solute acquisition.

3.4.1.2 *Stratified:* **92/7:** EC profiles (Figure 3.2) demonstrate that a consistent layer of Mode 2 water existed in the lower 25m of this borehole and that this was overlain by a stable layer of Mode 1 water. This EC stratification may indicate that the bed at this point consisted of unconsolidated sediment. Sediment may have been put into suspension by drilling disturbances, allowing the water at the base of the borehole to acquire solute.

3.4.2 Englacially connected:

3.4.2.1 **93/39:** A 5m layer of Mode 4 water remained stable at the base of the borehole whilst the daily WL increase consisted of Mode 1 water (Figure 3.3). Overnight, the Mode 1 water drained to ~15m ab without affecting the Mode 4 water at the base of the borehole. This suggests that there was no basal connection and that the Mode 1 water drained and possibly entered via an englacial channel ~15m ab. Supraglacial inputs were also likely to be a major source of water for the daily WL rise.

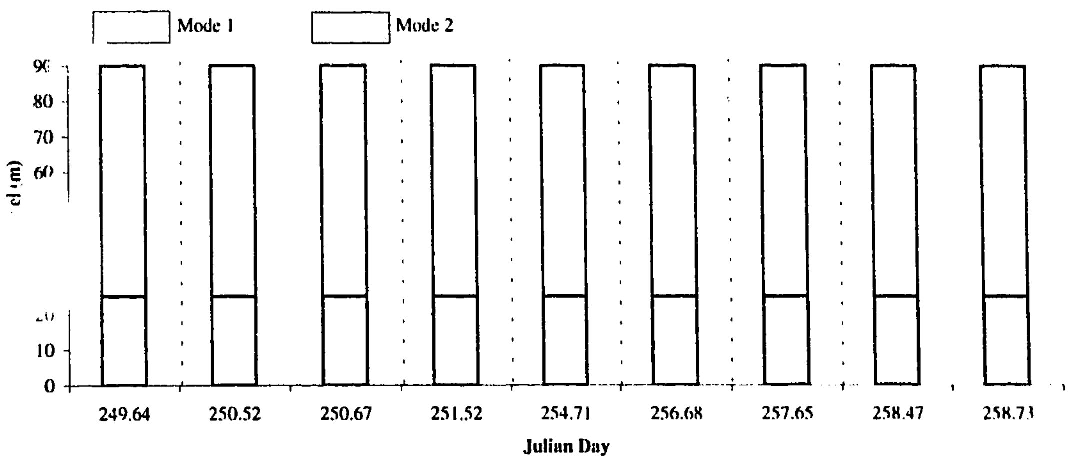

Figure 3.2: 92/7 EC profiles. Borehole depth = 90m.

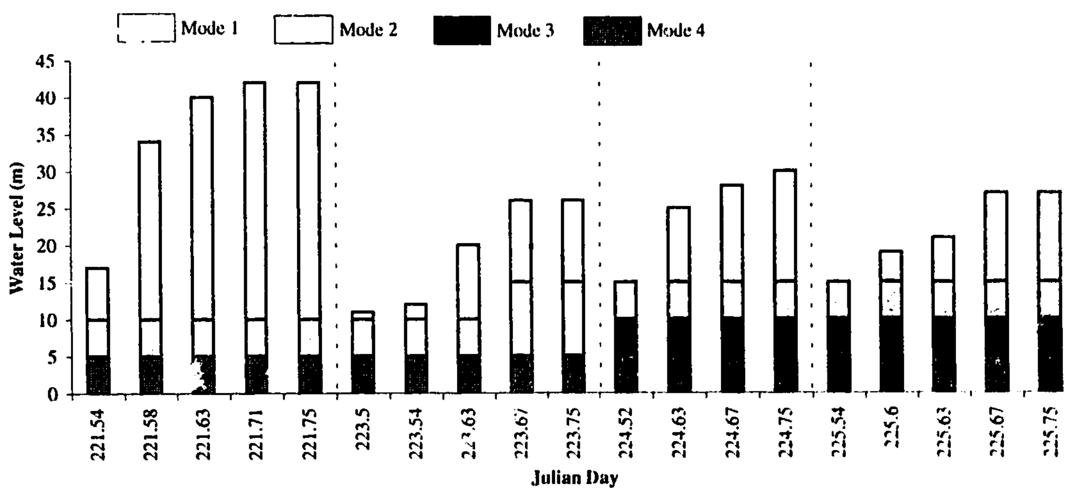

Figure 3.3: 93/39 EC profiles. Borehole depth = 100m.

3.4.2.2 **95/2:** This borehole drained to a depth of 32m ab two days after drilling was completed on JD 210. EC stratification recorded below 32m ab before and after the borehole drained was identical. This suggests that drainage occurred via an englacial channel located 32m ab and not via the base of the borehole.

In-situ WL and EC probes were installed at the base of 95/2 6 days after it had drained (Figure 3.4). Basal EC rose steadily from ~18-28μS cm^{-1} over a period of 10 days, suggesting that no basal flow was occurring and that solute acquisition was the cause of the increase in EC. The WL increases (produced by Mode 1 water) were sporadic and coincided either with high temperature days (JD 222 and 227), rainfall (JD 225) or periods of reaming (JD 228). The water drained back to 32m ab overnight (except on JD 227 and 228). This again suggests the presence of an englacial channel.

Video imagery identified a round englacial channel of ~2cm diameter at 36.8m ab. The Tu of the water was significantly greater below the level of this channel. This corresponds with the EC profiling data which show a stable layer of Mode 2 water below this level (Figure 3.4) (Note: the difference in WL between manual WL measurements and the video log is due to the use of different instruments to measure depth below the ice surface. Such differences will occur throughout this chapter). WL variations are therefore inferred to be derived from englacial and/or supraglacial sources with no significant flow of water occurring at the bed.

3.4.3 Passively connected:

95/8: Drilling records state that this borehole drained during drilling when the drill tip was 27m bs. The borehole re-filled as drilling continued and remained full for the rest of the season. This implies that an englacial void of finite volume was intercepted, the borehole draining until the void was filled and then re-filling with the continual additions of drill fluid. The video logs support this interpretation as a narrow, longitudinal void ~60cm high and 7cm wide was observed at a depth of 26.8m bs. This feature is likely to be a partially closed remnant crevasse. The boundary between clear and turbid water revealed by the video logs corresponds well with the condocline between Mode 1 and Mode 2 water measured by EC profiling (Figure 3.5). The stable water quality boundaries suggest that no perceptible water flow was occurring at the bed which may possibly consist of unconsolidated sediment due to the high Tu of the basal water.

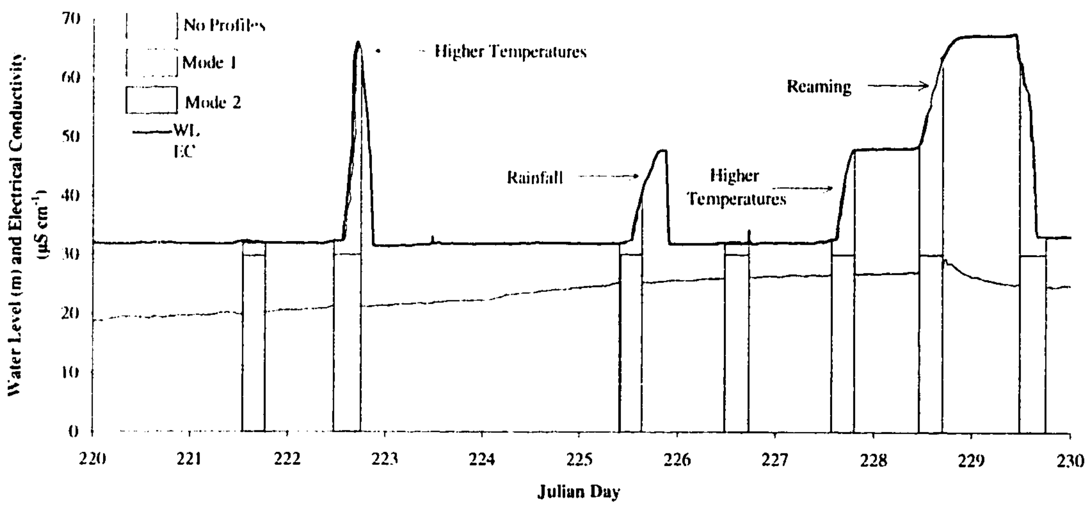

Figure 3.4: 95/2 in-situ WL and EC and EC profiles. Borehole depth = 96.5m.

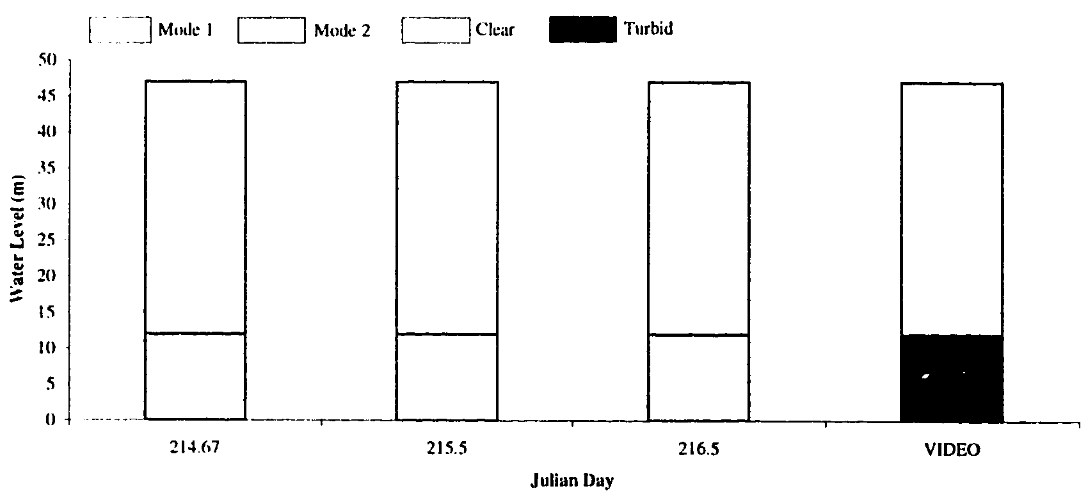

Figure 3.5: 95/8 EC profiling and video log measurements. Borehole depth = 47.5m.

3.4.4 Actively connected:

3.4.4.1 **93/37:** This borehole drained on the night that it was drilled and subsequently exhibited daily, high amplitude WL fluctuations (80-90m) and in-situ EC cycles (~3-20μS cm^{-1}) (Figure 3.6a and b). EC profiling data (Figure 3.6a) demonstrate that a plug of Mode 2 water entered the base of the borehole in the early afternoon followed by Mode 1 water. The rate at which the Mode 2 layer rose up the borehole was equal to the rate of WL increase. This suggests that the borehole was fed primarily from the bed. This interpretation is supported by the results of a salt trace (Figure 3.7). The layer of dissolved salt (introduced at 7m ab before the WL began to rise) rose up the borehole as a coherent layer (despite disruptions in the lower 40m) at the same rate as the WL increase. This salt layer was clearly forced up by significantly lower EC water entering the base of the borehole. The Tu signal (Figure 3.6b) was complex, though peaks did occur during periods of rapidly rising and falling WL. This demonstrates the flow of water at the base of the borehole. Consequently, it is concluded that 93/37 was fed primarily from the bed.

Based upon this interpretation, the EC profiling data can be used to interpret the in-situ EC cycles. The in-situ EC decreased from ~20-3μS cm^{-1} on the rising WL limb and returned to ~20μS cm^{-1} on the falling limb (Figure 3.6b). EC profiling data illustrate that this EC cycle represents Mode 2 water being forced up the borehole by Mode 1 water as the WL rose. As the WL fell, the Mode 1 water drained from the base of the borehole followed by the Mode 2 water (Figure 3.6a). The water draining from the borehole was also likely to have been mixing with water flowing past the base of the borehole at the bed. The in-situ EC signal therefore only reflected *true* basal water quality as the WL rose. Measurements made as the borehole drained simply reflected the composition of the water that had been stored in the borehole during the day. Measurements of *true* basal conditions would next be made after the borehole had drained completely.

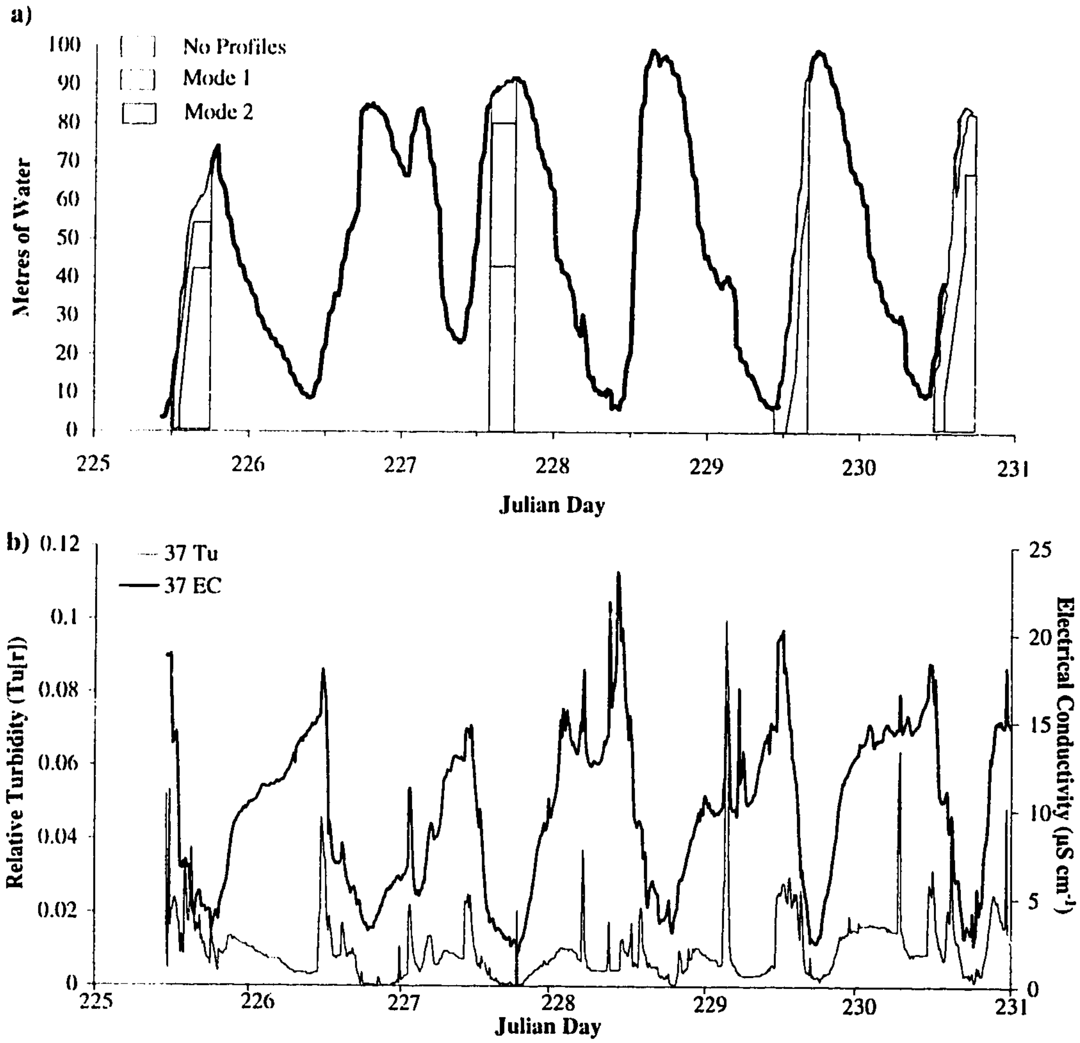

Figure 3.7: 93/37 a) in-situ WL and EC profiles and b) in-situ EC and Tu.

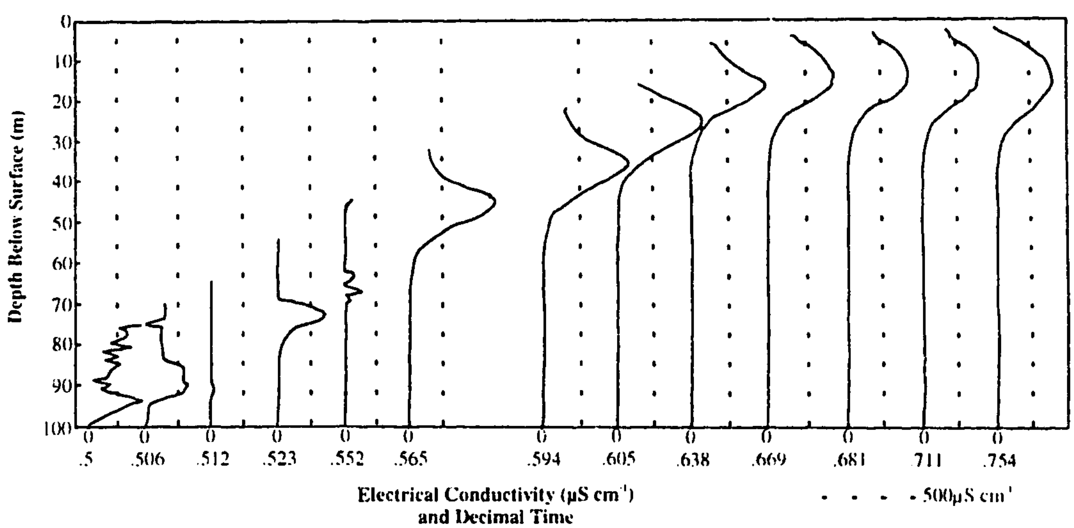

Figure 3.7: 93/37 Salt trace profiles conducted on JD 232.

3.4.4.2 **93/41:** This borehole connected 5m ab during drilling and the WL drained to 15m ab. Subsequently, daily WL fluctuations occurred throughout the observation period (Figure 3.8a). The in-situ EC and Tu records (Figure 3.8b) exhibited semi-diurnal cycles (except on JD 222 and 223 for Tu) which occurred on both the rising and falling limbs of the WL cycle. EC profiles (Figure 3.8a) aid the initial interpretation of these in-situ records. The borehole initially filled with supraglacial and/or englacial inputs. Subsequently, a sharp, ephemeral peak of Mode 2 water entered and exited the borehole under rising WL conditions. The flow of water at the base of the borehole that generated this input of Mode 2 water was represented by the first Tu peak in the semi-diurnal cycle. The subsequent downflux of this Mode 2 water was likely the result of supraglacial and englacial additions to the water column which forced the Mode 2 water out of the base of the borehole.

A salt trace conducted on JD 231 and accompanying in-situ EC and Tu data (Figure 3.9a and b) contribute further to this interpretation. Salt water was injected 20m ab at JD 231.552 when the WL was 39m ab and the natural spike of Mode 2 water had already been registered at the bed (**i**). Profiles 1 to 13 illustrate the movement of the salt water up the borehole.

i) *Profile 1:* ~4000μS cm^{-1} water (**A**) was capped by lower EC `noise' (**B**) possibly induced by the failure to adequately flush the salt water from the hose before the hose was removed from the borehole (Ketterling, 1995).

ii) *Profile 2:* **A** was forced up the water column by lower EC water below. **B** became a coherent unit of ~750μS cm^{-1} probably due to mixing by the profiler.

iii) *Profiles 3 and 4:* **A** disappeared from the water column. **B** became a well defined peak of ~500μS cm^{-1} and rose up the borehole. It is suggested that an englacial channel existed ~30m ab. As **A** rose past 30m ab it exited the borehole via this englacial channel.

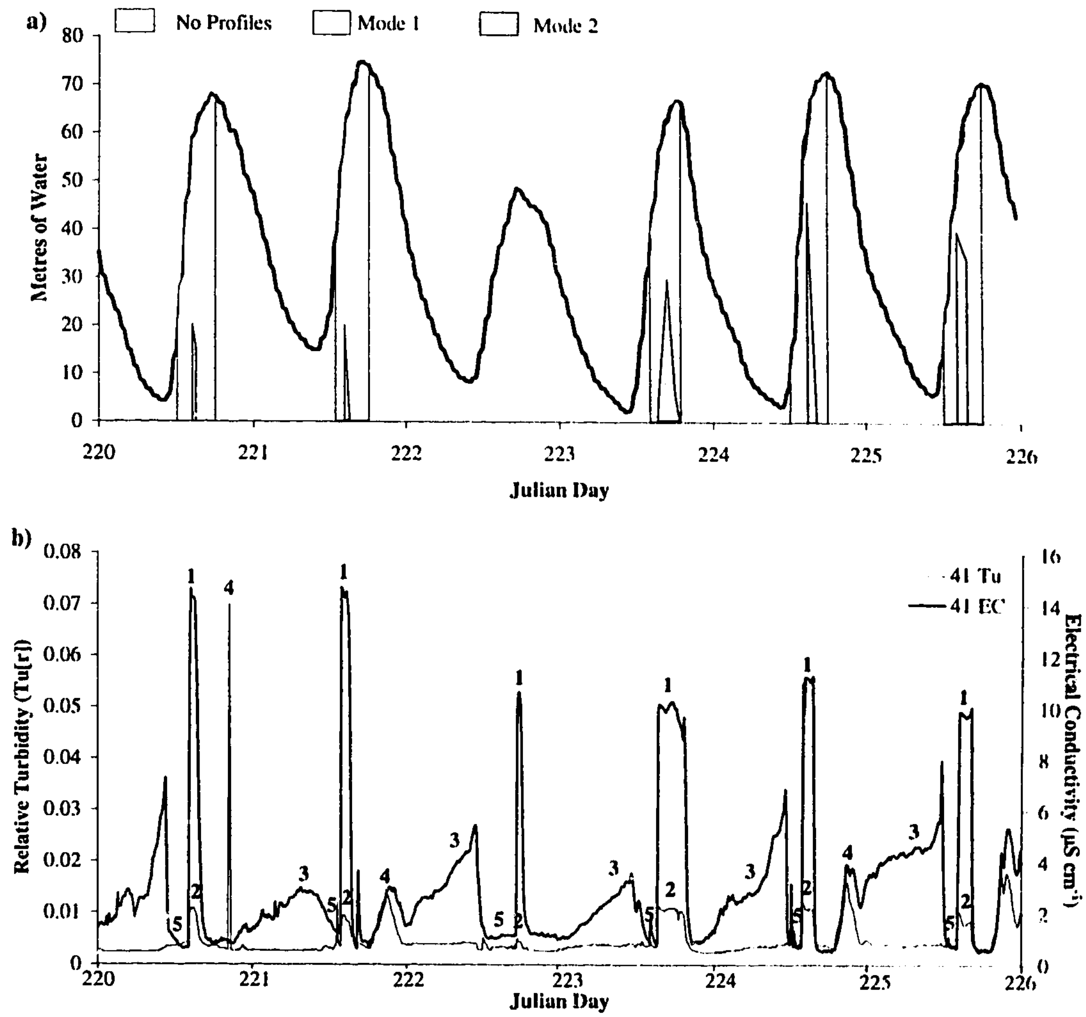

Figure 3.8: H41 a) in-situ WL and EC profiles and b) in-situ EC and Tu.

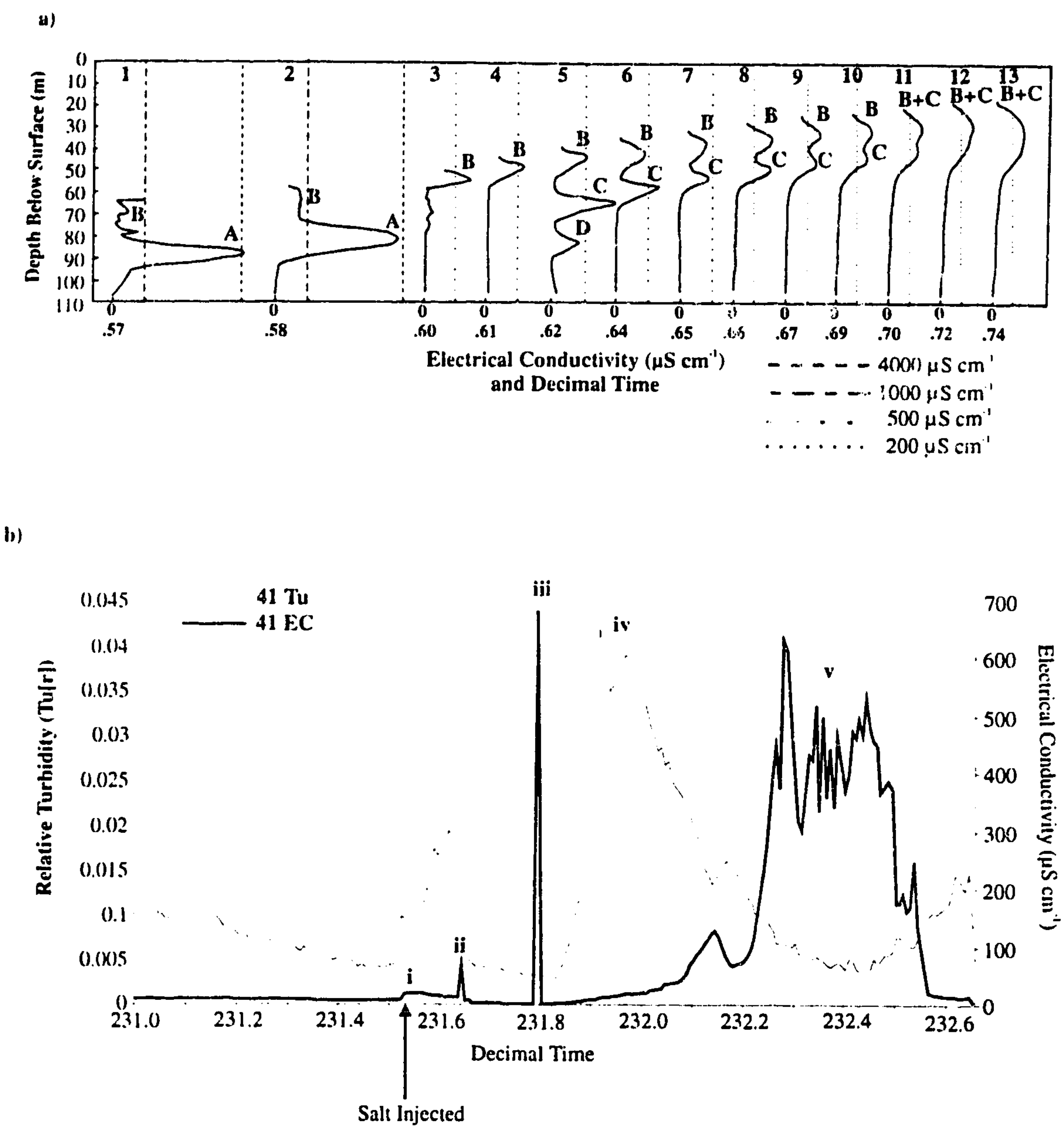

Figure 3.9: a) 93/41 salt trace profiles conducted on JD 231, b) 93/41 in-situ EC and Tu measurements for JD 231-232.

iv) *Profiles 5 and 6:* two slugs of salt water (**C** and **D**) appeared. These are thought to represent the reintroduction of **A** as water in the englacial channel backed-up due to increasing water pressures at the bed. **A** had therefore not been entirely evacuated from the englacial channel. Once **A** was reintroduced, the continued englacial inflow split the salt layer into **C** and **D**, forcing **C** up and **D** down the borehole. A spike of 68μS cm^{-1} registered at the bed at 231.625 (**ii**) suggests that only a small proportion of **D** left the base of the borehole as **D** was initially measured as ~500μS cm^{-1}. The englacial channel intercepted at 5m ab during drilling may have drained much of **D**.

v) *Profiles 7-13:* **B** and **C** rose up the borehole and eventually merged due to diffusion and mixing by profiling disturbance. The WL started to fall between profiles 12 and 13.

vi) *Post-profiling observations:* At JD 231.76 (35 minutes after the WL started to fall) a second salt trace was undertaken in 93/41 to demonstrate the outflux of water from the base of the borehole as the WL fell. Four minutes after the salt was injected at 20m ab, an ephemeral peak of 684μS cm^{-1} was registered by the in-situ sensor (**iii**), thus confirming the rapid outflow of water via the base of the borehole. Following this, the second Tu peak of the semi-diurnal cycle occurred as the borehole drained (**iv**) and **B+C** were eventually recorded leaving the base of the borehole between 232.18 and 232.52 as the water drained overnight (**v**).

Interpretations from the salt trace experiment demonstrate the complex nature of water circulation within 93/41 and the controlling influence of englacial inputs and outputs on this circulation. Although water was introduced to the borehole via the base during the day, englacial outputs and inputs acted as a sink and source for some of this water. The re-introduction of water from the englacial input at 30m ab forced water back out of the base of the borehole even under conditions of rising WL. Water that drained from the base of the borehole overnight was thus unlikely to be exactly the same water that entered via the base during the day.

With the improved knowledge of water circulation within 93/41, the in-situ EC and Tu records (Figure 3.8b) can be interpreted more accurately. The high, ephemeral EC peak (1) represents basal water rapidly entering and exiting the borehole, the downflux imposed by the activation of the englacial input ~30m ab being responsible for the rapid exit of the Mode 2 water. The flow of water at the base of the borehole is demonstrated by the coincident Tu peak (2). The lower EC 'shoulder' (3) represents the dilution of relatively concentrated basal water flowing past the base of the borehole by the outflow of relatively dilute englacial water from the borehole as the WL fell. Tu peaks that occurred during the initial period of falling WL and rising EC (4) again demonstrate flow at the base of the borehole as rapid outflow stirred up basal water into the base of the borehole. Low EC values that separate the lower EC 'shoulder' and the high EC peak (5) represent supraglacial inputs reaching the bed in the late morning at the onset of the daily melt cycle.

A problem with this interpretation is highlighted by EC profiles recorded on JD 224 and 225 as Mode 2 water rose above the level of the inferred englacial channel at 30m ab. In such a case, the activation of the englacial input (which is inferred to force the Mode 2 water out of the borehole base) should have split the column of Mode 2 water at 30m ab. This would have left an isolated layer of Mode 2 water above the level of the englacial input. Such an isolated layer of Mode 2 water was not detected in the JD 224 and 225 profiles. This could be explained by the dilution of the uppermost portion of Mode 2 water from the rising input of englacial water that was exemplified by the rise of salt slug **C** in the salt trace.

According to this interpretation, *true* basal water quality is recorded only during the initial input of basal water to the base of the borehole. The remaining measurements represent the flow of basal and englacial water out of the borehole base and subsequent mixing of this water with water flowing across the bed.

3.4.4.3 **92/14:** The daily WL variations exhibited by this borehole mainly consisted of Mode 1 water (Figure 3.10). EC profiling revealed that an ephemeral layer of Mode 2 water entered the base of the borehole on a daily basis. Had this Mode 2 water not been recorded, the WL variations might have been interpreted to have originated solely from supraglacial and/or englacial inputs. The entry of the Mode 2 water indicates that basal inputs and outputs were at least partially responsible for the WL fluctuations.

3.4.5 Anomalous behaviour:

3.4.5.1 **92/5:** This borehole remained full for the entire observation season. EC profiles illustrate that for a period of 15 days after the borehole was completed, the water column exhibited a stable EC stratification with a 10m layer of Mode 2 water overlain by Mode 1 water (Figure 3.11). However, subsequent EC profiles show that the water column consisted mainly of Mode 2 water capped by only 5m of Mode 1 water. This demonstrates that Mode 2 water must have been forced up from the bed. As the borehole was already full, no change in WL could be observed and no artesian flow was recorded. The flow of water out of the borehole top was probably accommodated by the surface weathering crust of the glacier or by gradual outflow over the surface, both of which would have been imperceptible. Had no EC profiling been undertaken, this borehole would have been classified as unconnected, when in reality a basal connection had developed.

3.4.5.2 **95/16:** This borehole drained to a depth of 23m ab 30 minutes after drilling was completed. EC profiles illustrate that the WL remained at this level for the next two weeks and that the water column consisted of Mode 1 water throughout. With these data it appears that the borehole drained to an englacial void after drilling and would therefore have been classified as passively connected. However, observations from the borehole video log suggest otherwise. First, the logs show that a significant amount of supraglacial water was pouring down the sides of the borehole walls. Second, two englacial channels were observed at 32.1 and 26.3m ab. These appeared to be active channels feeding the borehole with water.

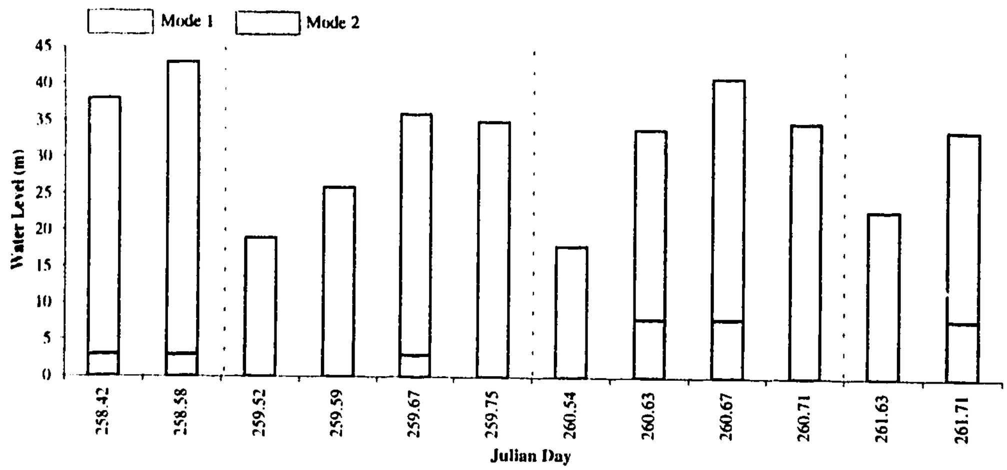

Figure 3.10: 92/14 EC profiles. Borehole depth = 48m.

Figure 3.1 ´92/5 EC profiles. Borehole depth = 50m.

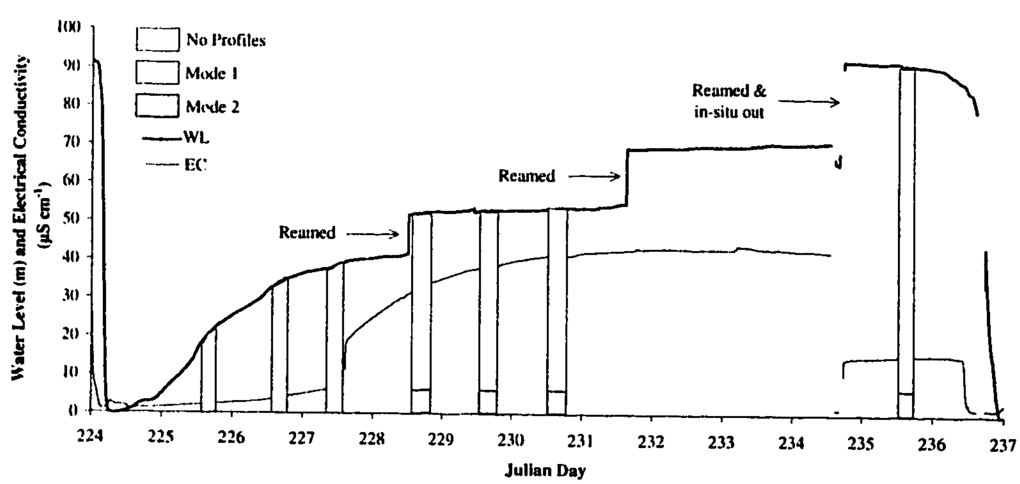

Figure 3.12: 95/17 in-situ WL and EC and EC profiles. Borehole depth = 91.5m.

Had the borehole been passively connected to an englacial void, a daily increase in WL should have occurred due to the observed inputs of supra- and englacial water. The fact that no WL increase was registered implies that there must have been an englacial or basal output. This output must have continually adjusted to the input volume such that the outputs and inputs were equal and no change in WL was recorded. This borehole was therefore not passively connected, but either englacially or actively connected. As no EC stratification existed in the water column and the video log showed that the water column was clear throughout, it is not possible to determine in which of these categories this borehole should be placed.

3.4.5.3 **95/17:** This borehole drained to the bed the day after it was drilled and then filled slowly for 5 days until reaming on JD 223 eventually re-filled it. Drainage to the bed occurred early on JD 224 flushing high EC water out of the base of the borehole (Figure 3.12). This would indicate that a connection had been made with the basal drainage system, but the borehole re-filled over the next 12 days with supraglacial water and reaming additions. EC profiles illustrate that after JD 228 the basal EC stratification remained stable whilst in-situ EC increased slowly (except on JD 227) possibly due to solute acquisition. The step in in-situ EC on JD 227 and the subsequent introduction of a 5m layer of Mode 2 water to the base of the water column suggests that a basal inflow occurred on JD 227. 95/17 filled by JD 234 and finally drained to the bed again on JD 236. This behaviour indicates sporadic basal connections due to overpressurization at the bed followed by the rapid closure of the connection after drainage.

3.5 DISTRIBUTION OF THE CLASSIFIED BOREHOLES:

By mapping the distribution of these categories (Figure 3.13) a clustering of actively connected boreholes is clearly highlighted (Figure 3.13b). The centre of the VPA identified in Chapter 2 is at the centre of this cluster. The WL and water quality variations measured in these boreholes are likely to be a response to channel pressure fluctuations, but some of the WL and water quality measurements may be attributed to supraglacial and englacial inputs and outputs.

Unconnected boreholes generally surround the actively connected cluster (Figure 3.13a). These represent areas of the bed that are not efficiently drained by the subglacial drainage system and that are not influenced by pressure fluctuations within the VPA. The distribution of unconnected unstratified and stratified boreholes (Figure 3.13 c and d) does not demonstrate any particular pattern. This may indicate that a) the hypothesis that the EC at the base of an unconnected borehole could be used as an indication of bed type is wrong, or b) the composition of the bed is heterogeneous at a scale small enough to be detected by the spacing of the boreholes drilled.

Five of the seven englacially connected boreholes lie within the centre of the VPA (Figure 3.13e). This appears to support the contention that the location of channels at the glacier bed is likely to correlate closely with the location of channels on the glacier surface (Sharp et al., 1993). This could explain why moulins fed by surface streams tended to be clustered along reconstructed lines of major subglacial pathways. Englacial channels are obviously needed to transmit meltwater to the bed, and are thus likely to be most common in the vicinity of both supraglacial and subglacial channelised systems.

Passively connected boreholes are located at the margins of the VPA (Figure 3.13f) and may demonstrate areas where relict crevasses or englacial channels exist.

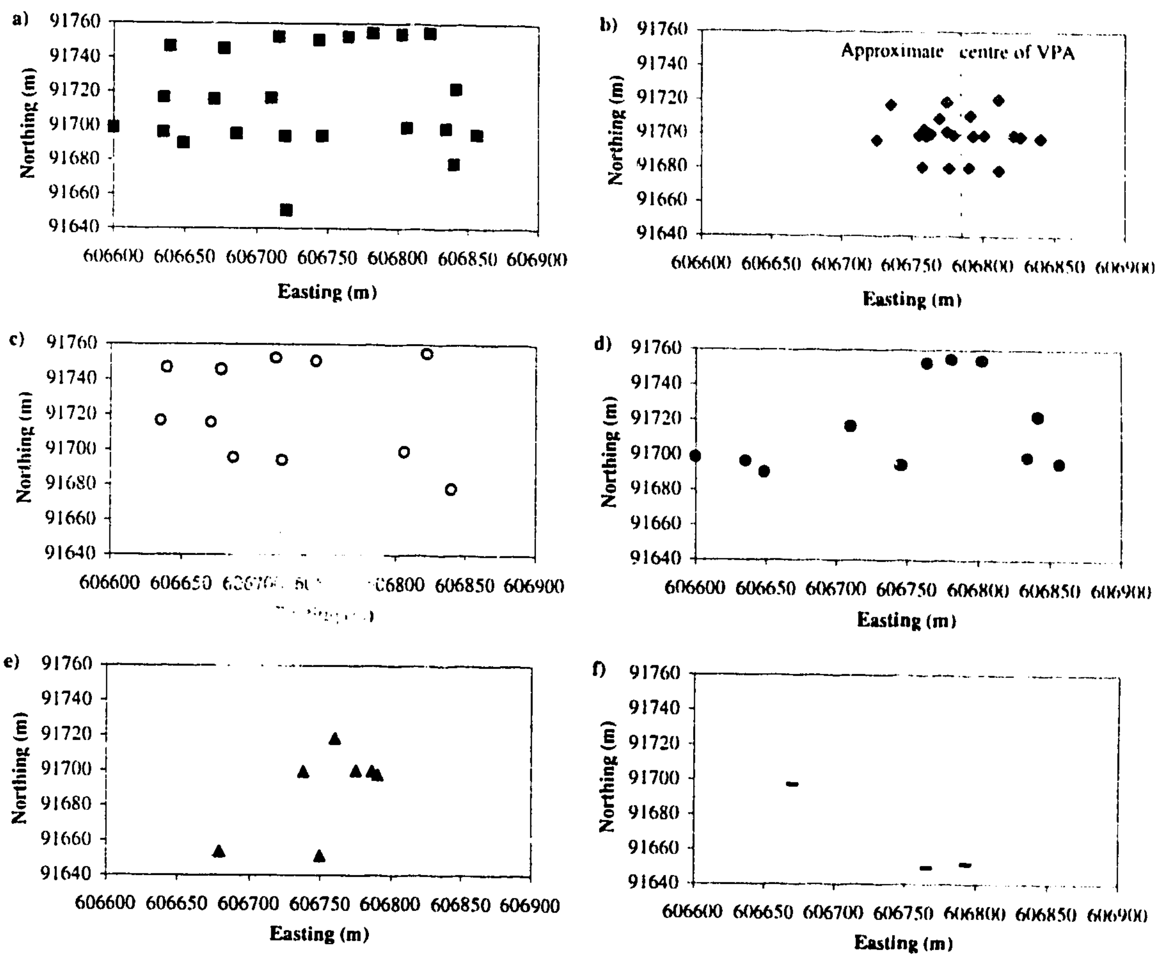

Figure 3.13: Distribution of classified boreholes; a) unconnected, b) actively connected, c) unconnected unstratified, d) unconnected stratified, e) englacially connected, and f) passively connected.

3.6 SUMMARY:

The need for determining the source and circulation of water within `open' boreholes prior to the interpretation of their in-situ water quality records has been demonstrated. A series of data sources has been presented which, if used in conjunction with each other, can provide a detailed interpretation of the plumbing of individual boreholes. A classification scheme of borehole plumbing has been devised which allows for the identification of boreholes that may require special attention when analysing their in-situ water quality records. If supra and/or englacial influences are dominant, in-situ water quality records may not necessarily measure the continuous characteristics of *true* basal water. Instead, the sensors may be measuring the quality of water draining from a borehole (under conditions of both rising and falling WL), and the mixing of this water with water flowing across the bed past the base of the borehole.

It is proposed that the classification and analysis of borehole water sources and circulation should be an integral part of any study of `open' borehole WL and water quality behaviour if accurate interpretations are to be made.

CHAPTER 4: SEASONAL RE-ORGANISATION OF SUBGLACIAL DRAINAGE INFERRED FROM MEASUREMENTS IN BOREHOLES

4.1 INTRODUCTION:

Chapters 2 and 3 were concerned with identifying the late season subglacial drainage configuration in the borehole array from the distribution of borehole WL behaviour and with ways of using drilling records, EC profiling, salt tracing and borehole video imagery to determine the water source and patterns of water circulation within boreholes so that in-situ water quality measurements can be interpreted with confidence. This chapter will use the understanding gained from the previous chapters to describe and explain the seasonal re-organisation of the subglacial drainage system within the 1993 borehole array.

As discussed in Chapter 2, Nienow (1993) inferred that a system of major drainage channels (characterised by rapid flow velocities and low dispersivities) developed within the lower 3.3 km of the 4.0 km long glacier during the 1989-1991 melt seasons. This system appeared to develop by headward growth at a rate controlled by the retreat of the transient snowline on the glacier surface, and replaced a distributed drainage system (characterised by low flow velocities and high dispersivities) as the main means of evacuating water from the lower part of the glacier. The distributed system was the principal means of drainage throughout the year in the upper 0.7 km of the glacier, and it appeared to survive in residual form in areas between major channels in the lower glacier during the melt season (Nienow et al., in press).

In mid-August 1993 (JD 228-234), Hubbard et al. (1995) identified a variable pressure axis (VPA) characterised by diurnal water pressure variations. These were inferred to be driven by diurnal variations in discharge within a channel located at the centre of this axis. Diurnal reversals in the direction of the hydraulic gradient between the channel and surrounding areas of the bed appeared to drive water out of the channel during the afternoon and back to it overnight. The resulting flows appeared to a) selectively remove fine material from basal sediments in the area around the channel, with the result that the hydraulic conductivity of the basal sediment layer decreased exponentially with distance from the channel, and/or b) create micro-channel links between the main subglacial channel and surrounding areas of the bed which concentrated flow at the ice-sediment interface.

In this chapter, thirty one-day time series of in-situ WL, EC and Tu are used to determine how the subglacial drainage configuration described by Hubbard et al. (1995) developed during the 1993 melt season.

4.2 ANALYSIS OF IN-SITU RECORDS:

As all the discussion is focused on 1993 data, borehole numbers are given the prefix `H' instead of `93'. Interpretations are based on analyses of data from 7 boreholes: H29, H34, H35, H36, H40a, H41 and H42. These were located either side of the channel that was inferred to have existed at the centre of the VPA in August 1993 by Hubbard et al. (1995) (Figure 4.1); H29 and H35 being the closest boreholes to the channel (~5m away). All of these boreholes were classified as *actively connected* in Chapter 3 (except for H35 and H42 which were classified as *englacially connected*). H41 and H34 have the most continuous in-situ WL, EC and Tu records spanning the period July 22 to August 21 (JD 203-233), and they also have good EC profiling coverage. Note that in the H34 water quality records, measurements of EC and Tu are removed when the WL is recorded as zero. Records from H35 and H29 are used interchangeably to represent near-channel conditions since WL varied synchronously at the end of the observation period in these holes (Hubbard et al., 1995). The WL record for H35 is continuous, but water quality data are not used as the base of the borehole is thought to have been blind (see further discussion below). In-situ instruments were thus measuring the quality of stagnant water at the base of H35. The WL and water quality records for H29 are patchy, but are used instead of H35 whenever possible so that water quality behaviour can be examined.

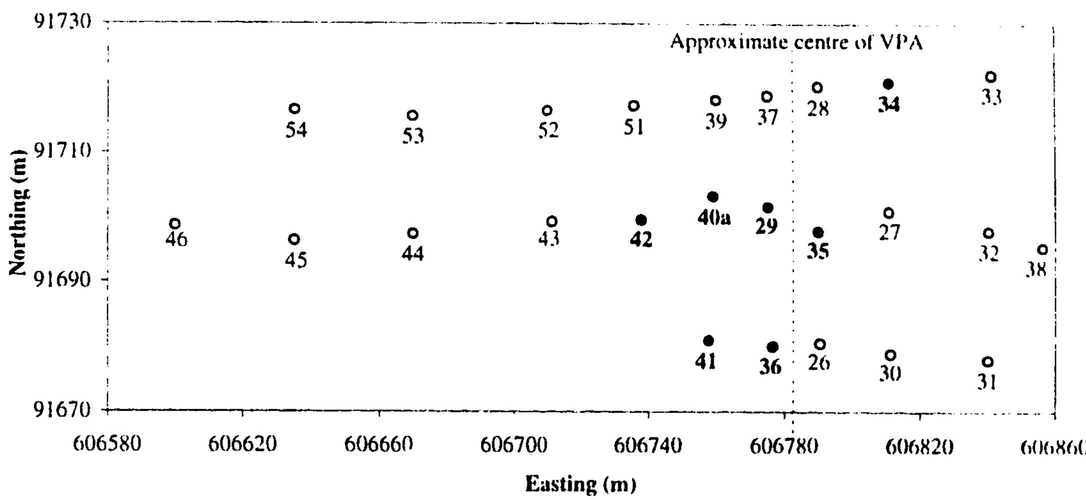

Figure 4.1: 1993 borehole array highlighting the location of the seven holes discussed in this chapter (in bold).

Only WL measurements for H36, H40a and H42 are included as insufficient profiling data are available to allow reliable interpretation of the in-situ water quality measurements. H40a WL measurements are only available from JD 203 to JD 220.

Calculations of the difference in WL between adjacent pairs of boreholes (head difference; HD) are used to infer the likely pattern of water flow at the glacier bed. A more accurate parameter for inferring the pattern of water flow at the bed is the hydraulic gradient as the direction of water flow is determined by the slope of the hydraulic potential surface. However, hydraulic gradients have not been calculated because: a) the shape and slope of all holes have not been measured by inclinometry, thus the position of the base of each borehole is uncertain, and b) the true form of the hydraulic potential surface cannot be reconstructed as there are no data available between the isolated borehole points. Although HD is not as reliable an indicator of the pattern of water flow at the bed as the hydraulic gradient as true reversals in water flow may not be seen, HD is used as a general indicator of the pattern of water flow at the bed in this chapter. Following discussions in Chapter 3, measurements of in-situ EC and Tu are used as indicators of the provenance of water and the flow of water at the base of boreholes, respectively. Meteorological and discharge data from JD 198 to JD 233 (Figure 4.2) are included for discussion purposes. These were measured at the upper meteorological station and the GDSA intake, respectively (Figure 1.1).

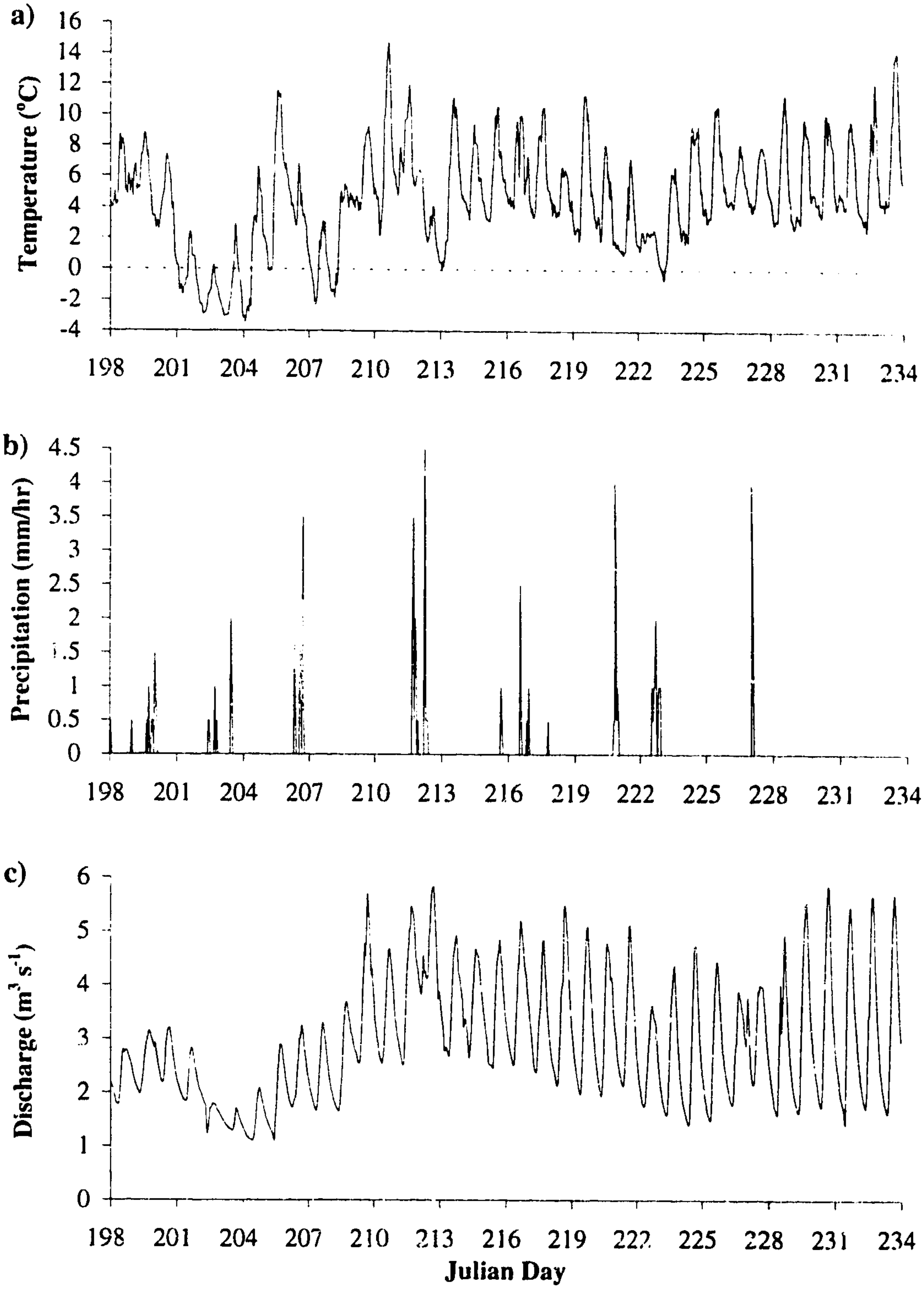

Figure 4.2: 1993 a) temperature, b) precipitation, and c) discharge from JD 198 to JD 233. See text for data sources.

In-situ records of WL, HD and water quality display significant changes over the study period. These changes involve:

a) the daily minimum or background levels of the data series (Figures 4.3-4.7);

b) the frequency and amplitude of fluctuations in the data series (Figure 4.8); and

c) the relative timing of fluctuations in the data series in different boreholes (Figure 4.9).

On the basis of identification of intervals of especially marked or rapid change in one or more data series, the measurement period was split into five sub-periods (JD 203-208; 209-214; 215-219; 220-224; 225-233), which were used as a framework for interpreting the evolution of the subglacial drainage system. In making this subdivision, particular emphasis was placed on records of WL and HD, since these parameters probably drive changes in basal water quality behaviour. Having established the subdivision, cross-correlation methods were used to quantify changes between sub-periods in (a) the degree of correlation, and (b) lead-lag relationships between different data series. Prior to analysis, the data series were detrended by calculating a 25 point running mean, subtracting this from the raw data, dividing the data into the relevant periods and then re-expressing them as standardised residuals from the running mean of each period. Analyses were performed using the statistical package *SPSS for Windows 6.1*. Maximum cross-correlation coefficients and associated lags were used to express the degree of coherence between different data series (Tables 4.1 and 4.2).

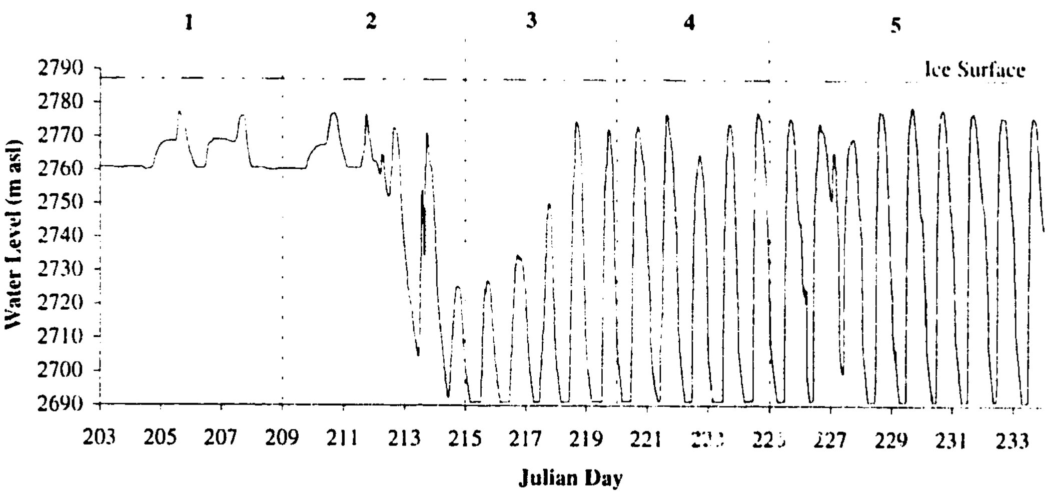

Figure 4.3: H35 WL from JD 203 to JD 233.

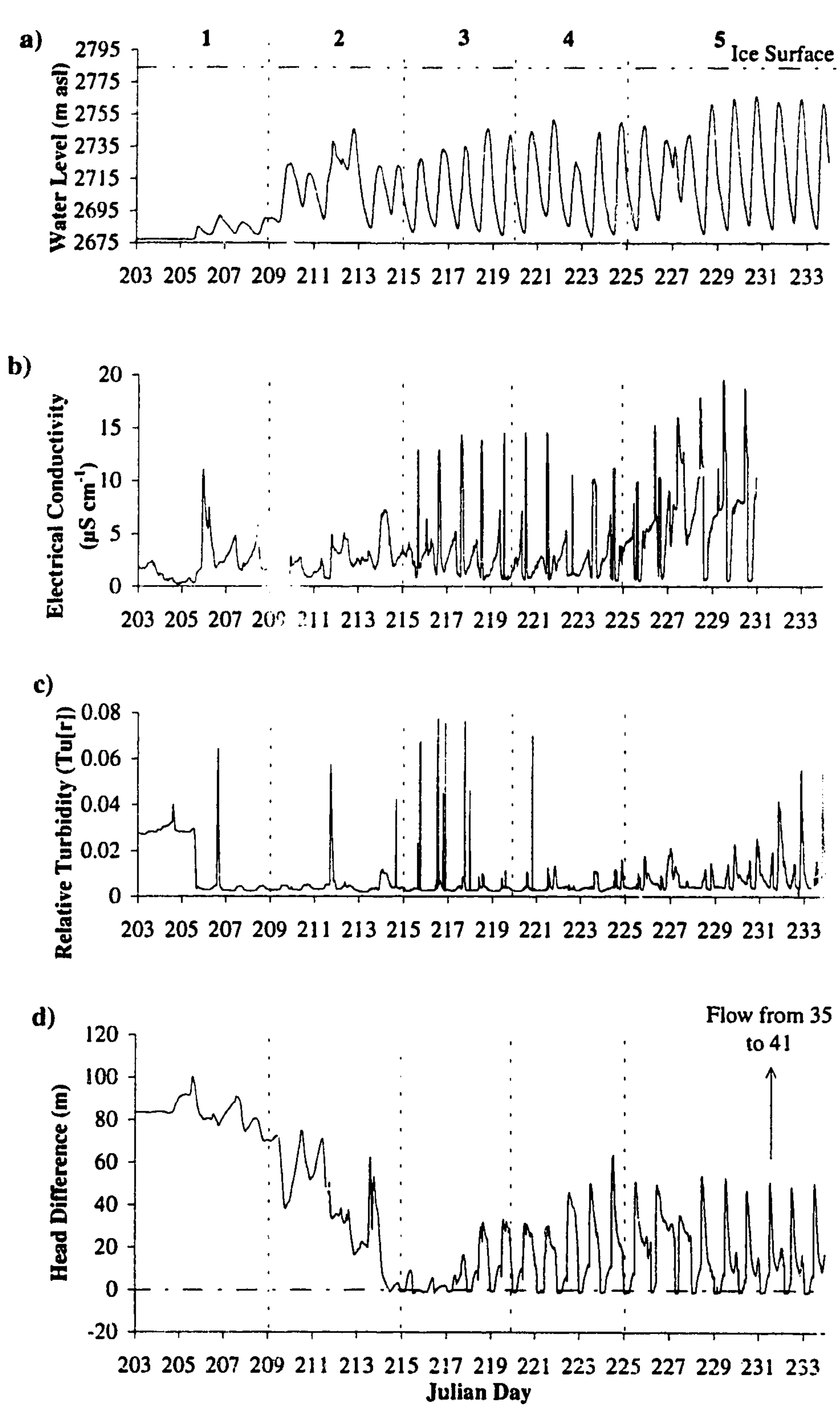

Figure 4.4: H41 measurements from JD 203 to JD 233; a) WL, b) in-situ EC, c) in-situ Tu, and d) H35-H41 HD.

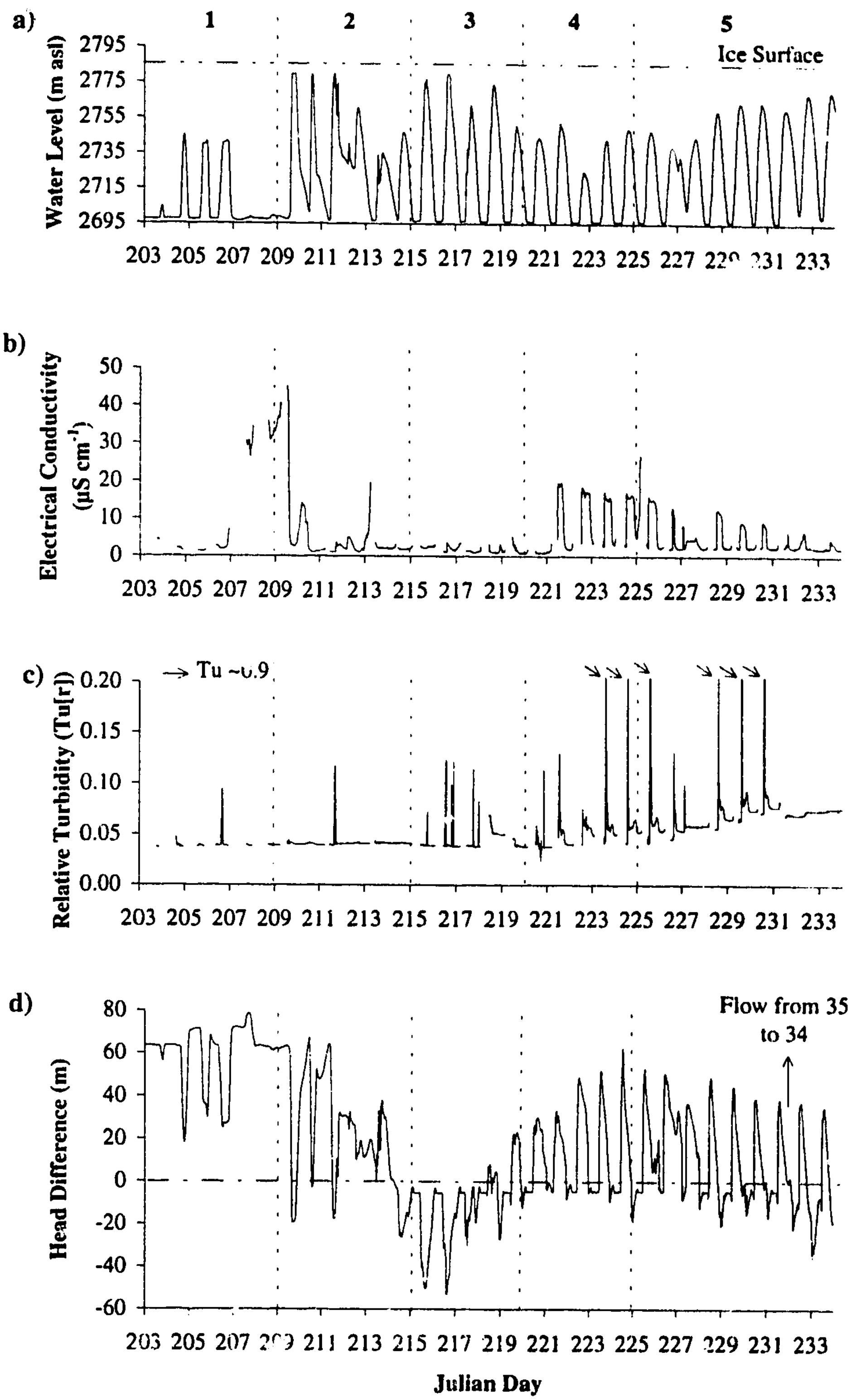

Figure 4.5: H34 measurements from JD 203 to JD 233; a) WL, b) in-situ EC, c) in-situ Tu, and d) H35-H34 HD. Note: EC and Tu values have been removed for dry WL readings.

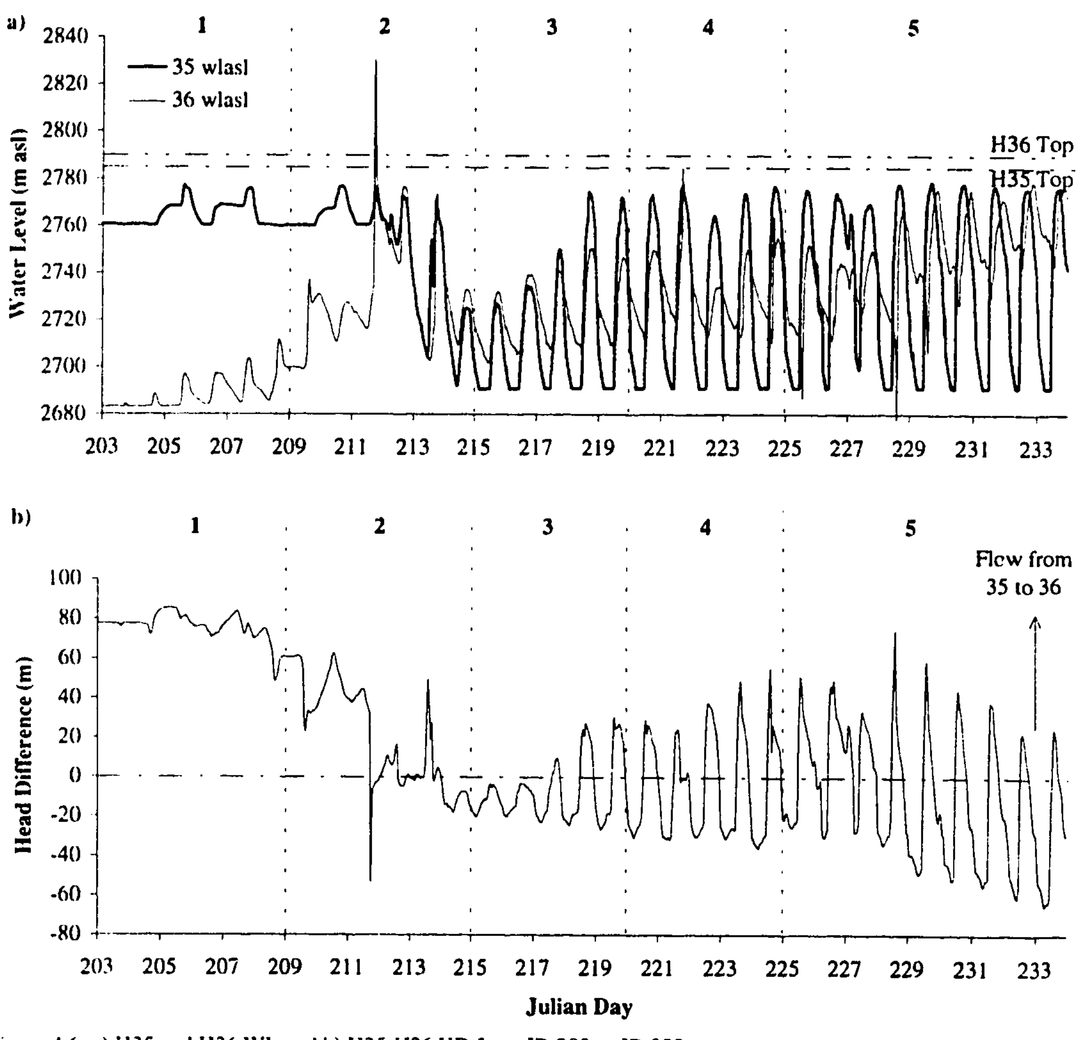

Figure 4.6: a) H35 and H36 WL and b) H35-H36 HD from JD 203 to JD 233.

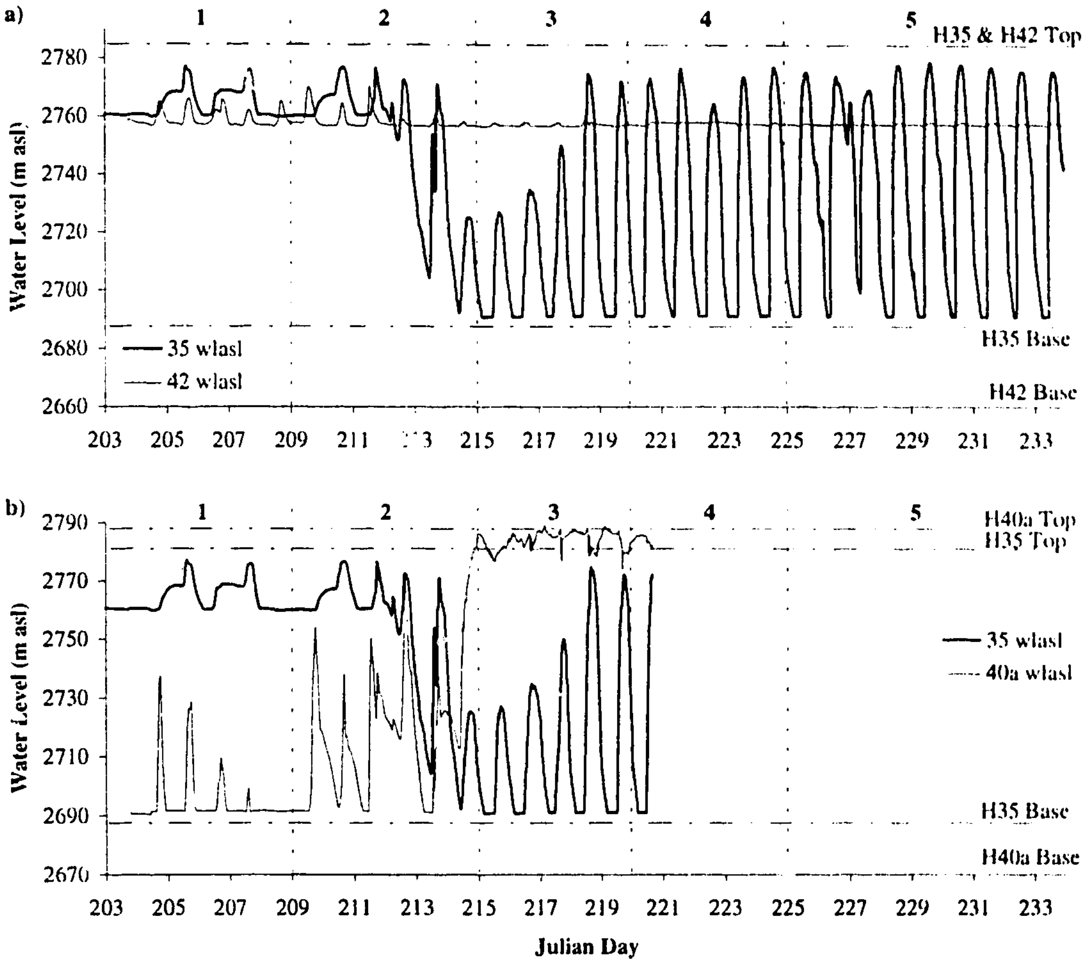

Figure 4.7: a) H35 and H42 WL from JD 203 to JD 233 and b) H35 and H40a WL from JD 203 to JD 220.

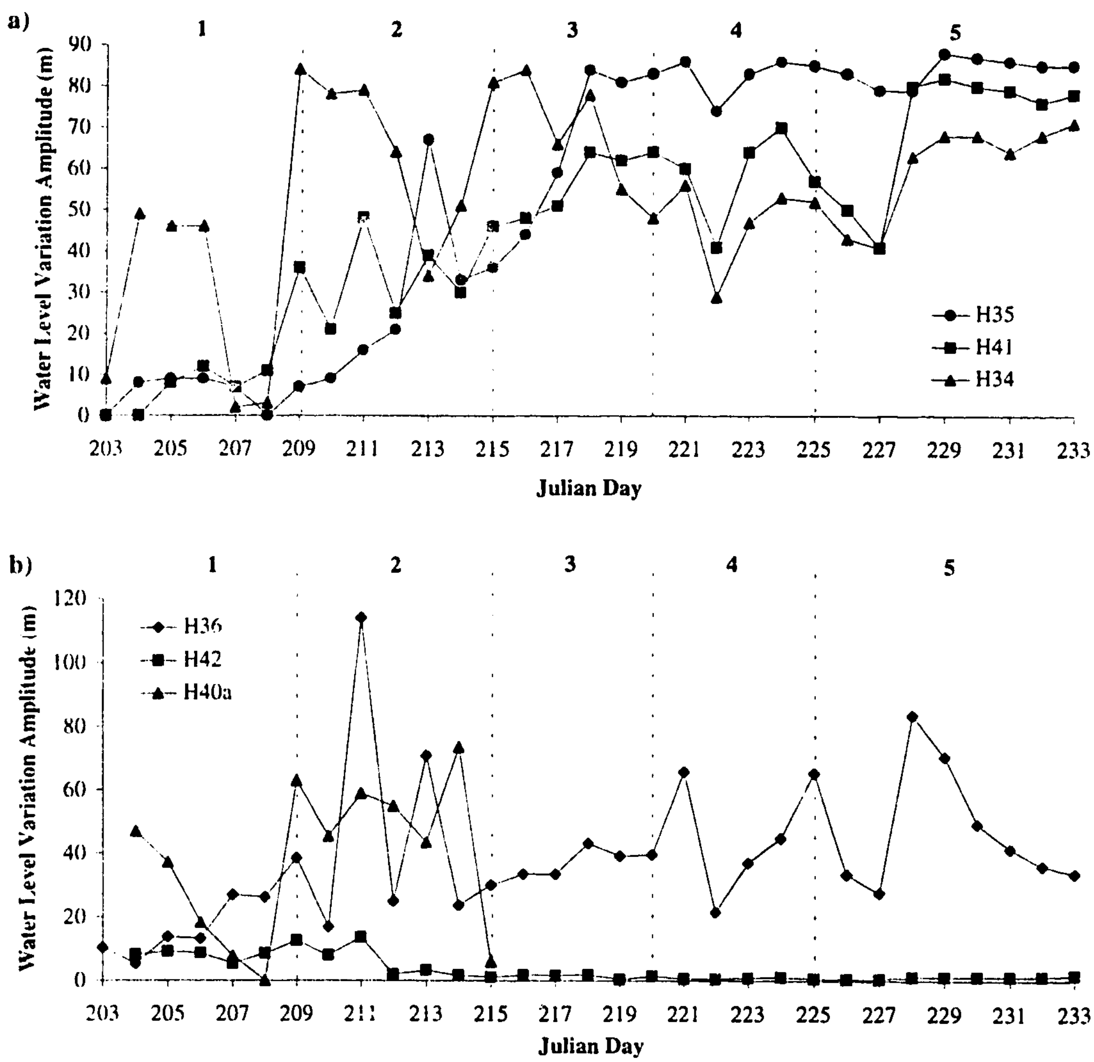

Figure 4.8: Water level variation amplitudes in a) H35, H41 and H34 and b) H36, H42 and H40a from JD 203 to JD 233.

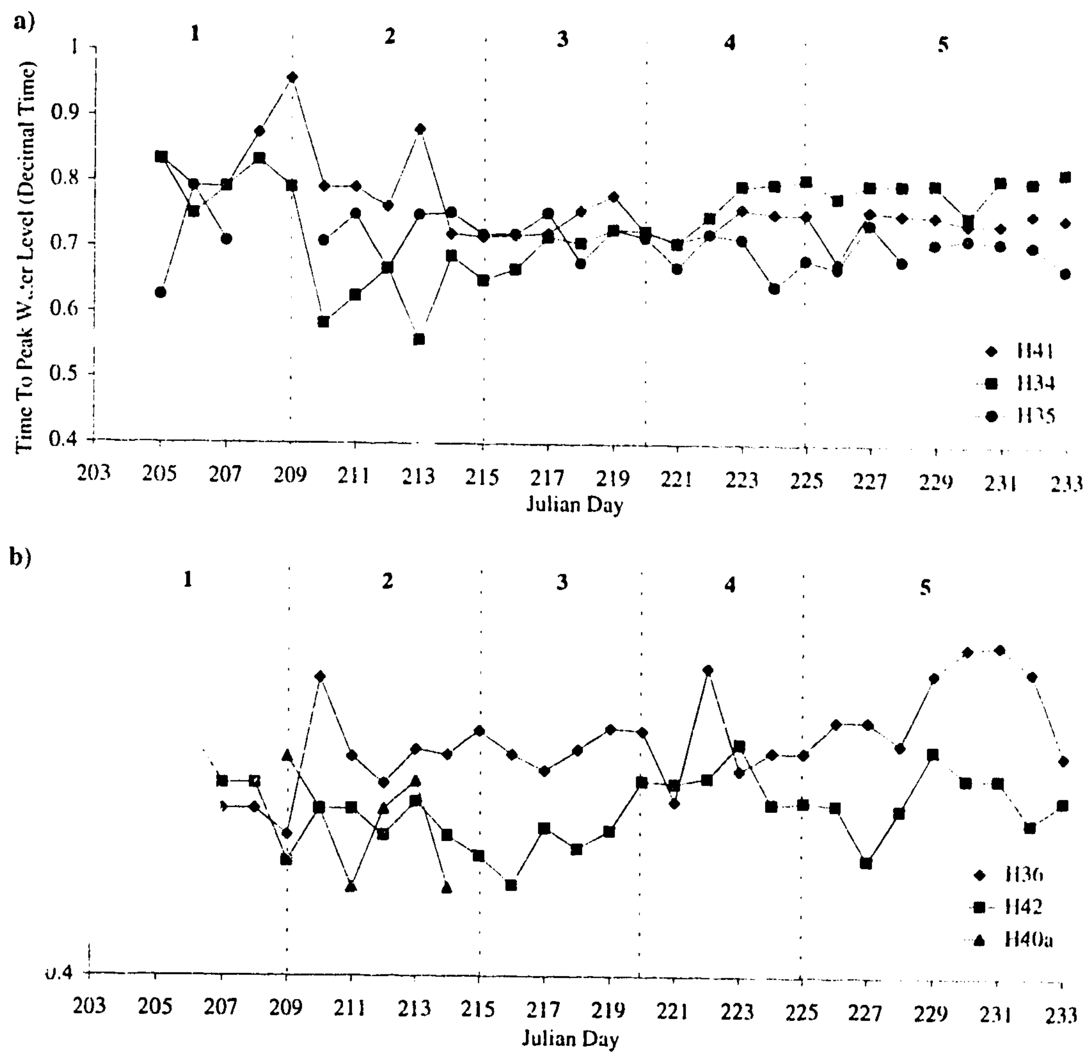

Figure 4.9: Time (in decimal fractions of a day) at which daily peak WL was reached in a) H35, H41 and H34, and b) H36, H42 and H40a from JD 203 to JD 233.