HYDROECOLOGICAL RESPONSE OF ALPINE STREAMS TO DYNAMIC WATER SOURCE CONTRIBUTIONS

By

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TEXT BOUND CLOSE TO THE SPINE IN THE ORIGINAL THESIS

ABSTRACT

Hydroecological relationships in alpine catchments are poorly understood. Glacial icemelt, snowmelt and groundwater sources each produce a distinctive suite of physico-chemical stream habitat characteristics in alpine streams. These spatially and temporally dynamic habitat conditions influence stream benthic community composition. An interdisciplinary approach (hydrology-hydrochemistry-ecology) was adopted to examine hydroecological responses to dynamic alpine water source contributions, involving development and testing of a new conceptual model of alpine stream habitat classification. Fieldwork was undertaken over two summer melt seasons (2002 and 2003) within the Taillon-Gabiétous catchment, French Pyrénées. Hydrochemical separation methods demonstrated differences in meltwater and groundwater contributions to streamflow both spatially and at diurnal, seasonal and inter-annual time-scales. Suspended sediment concentration was lowest when groundwater contributions to streamflow were dominant. Water column temperatures were lowest where snow and ice meltwaters dominated streamflow. Higher Si, Ca^{2+} and HCO_3^- concentrations were found in groundwater sources. Benthic macroinvertebrate communities varied markedly throughout the summer melt season. Total macroinvertebrate abundance, number of macroinvertebrate taxa, number of EPT taxa, and community stability and persistence were higher when groundwater contributions dominated streamflow. Most taxa showed positive relationships with the proportion of groundwater but *Rhyacophila* were absent where the proportion was >0.5. Hydroecological patterns and processes in this alpine catchment are summarized in conceptual models to present key findings, and as a template for hydroecological research in other alpine glacierized basins.

Dedicated to the
macroinvertebrates who gave
their lives in the name of science

Deep in the human unconscious is a pervasive need for a logical universe that makes sense. But the real universe is always one step beyond logic.

-From 'The Sayings of Muad'Dib' by the Princess Irulan

(Frank Herbert, 1965. *Dune*)

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CHAPTER 1
INTRODUCTION

1.1. THESIS OVERVIEW

"Glacial flood plain[s] *shift from a monotonous physico-chemical riverscape in winter to a complex mosaic in summer, this seasonal pattern being clearly driven by hydrological factors operating at the catchment scale"* (Malard *et al.*, 2000)

"Different stream sections have characteristics that reflect the relative proportions of the different runoff sources: glacier melt, snowmelt, rainfall and springflow. Each of these sources generates a hydrological signature and runoff of different physical and chemical quality" (McGregor *et al.*, 1995a)

"[This] *spatio-temporal pattern of widely contrasting environmental conditions makes glacier-fed rivers unique. Macroinvertebrate community structure shifts in response to these changes in environmental conditions".* (Milner *et al.*, 2001, p. 1845)

Despite the above observations, understanding the response of alpine stream communities to water source variability is currently limited by a paucity of data quantifying hydroecological relationships in alpine catchments. Previous research by Smith (1999) and Snook (2000) as part of the EU funded Arctic and Alpine Stream Ecosystem Research (AASER) programme indicated that the confluence of the Taillon and Tourettes streams (Les Crampettes), Taillon-Gabiétous catchment, French Pyrénées, is an area where stream habitat and associated benthic communities are highly dynamic. Therefore, the research in this thesis builds upon this foundation by taking an interdisciplinary approach to increase our understanding of the links between stream hydrological and ecological sciences, and aims to:

1. improve understanding of alpine stream water source dynamics and associated stream physico-chemical habitat variability,

2. further knowledge of benthic macroinvertebrate strategies for response to habitat dynamics, and;

3. provide an insight into the implications of changes in the timing and magnitude of alpine water source contributions for stream macroinvertebrate communities.

1.2. RESEARCH AIMS AND THESIS STRUCTURE

1.2.1. Research aims

Although the structure of benthic communities is relatively well understood in alpine glacier-fed streams, their response to dynamic water source contributions is not. Given the potential for significant changes in alpine catchment hydrological functioning under scenarios of future climate change (McGregor *et al.*, 1995a), it is important that ecological response can be predicted. Hence, this research was undertaken to investigate the role of dynamic water source contributions (from glacier icemelt, snowmelt and groundwater) in determining stream physico-chemical habitat variability within alpine streams, and, in turn, ecological response. To address this broad research gap, fieldwork was undertaken during two consecutive summer melt seasons (June-September, 2002 and 2003) in the Taillon-Gabiétous catchment, Cirque de Gavarnie, French Pyrénées, with the aim of:

1. developing and testing an alternative approach to alpine stream classification that recognises the dynamic nature of water source contributions, and building upon traditional classification methods (e.g. kryal, krenal, rhithral; Ward, 1994) based predominantly on water temperature,

2. examining spatial and temporal variability in water column and streambed temperatures,

3. investigating water source contributions to streamflow, and identifying how they vary both spatially and temporally,

4. quantifying stream physico-chemical habitat dynamics in relation to water source variations identified by (3),

5. investigating short-term temporal ecological community dynamics within streams sourced from different water stores, in relation to physico-chemical habitat dynamics, and;

6. producing an integrated model of alpine stream hydroecological relationships.

1.2.2. Thesis structure

The research in this thesis is reported is summarised in Figure 1.1. Chapter 2 reviews the literature on alpine streams and uses specific examples to demonstrate the need for an alternative approach to describe the dynamic functioning of alpine stream physico-chemical habitat and ecological communities. Problems with traditional alpine stream classifications are identified before an alternative method is proposed. A brief overview of its application for identifying spatial and temporal variability in water source contributions is provided. Chapter 3 outlines the study area and general methods (e.g. sampling design, field instrumentation). More specific methods are described within respective results-based chapters. A field-based assessment of traditional temperature based approaches to alpine stream classifications is summarised in Chapter 4, with emphasis on the implications of thermal variability for stream ecological communities and traditional alpine stream classifications. Stream hydrochemistry is examined in Chapter 5 to inform investigations of dynamic water source contributions (snowmelt, glacial icemelt and groundwater). The role of water source dynamics upon stream physico-chemical variability is investigated in Chapter 6. Chapter 7 describes variability within stream benthic communities over two summer melt-seasons, and Chapter 8 further considers benthic macroinvertebrate community composition in relation to stream environmental conditions by examining community stability and persistence. The final chapter synthesises stream environment variability and benthic community distributions in relation to water source contributions to provide an overall integrated hydroecological understanding of alpine stream dynamics. This concluding chapter also proposes refined models of the hydroecological functioning of the Taillon-Gabiétous catchment, and glacier-fed alpine streams more generally, and identifies potential future research directions.

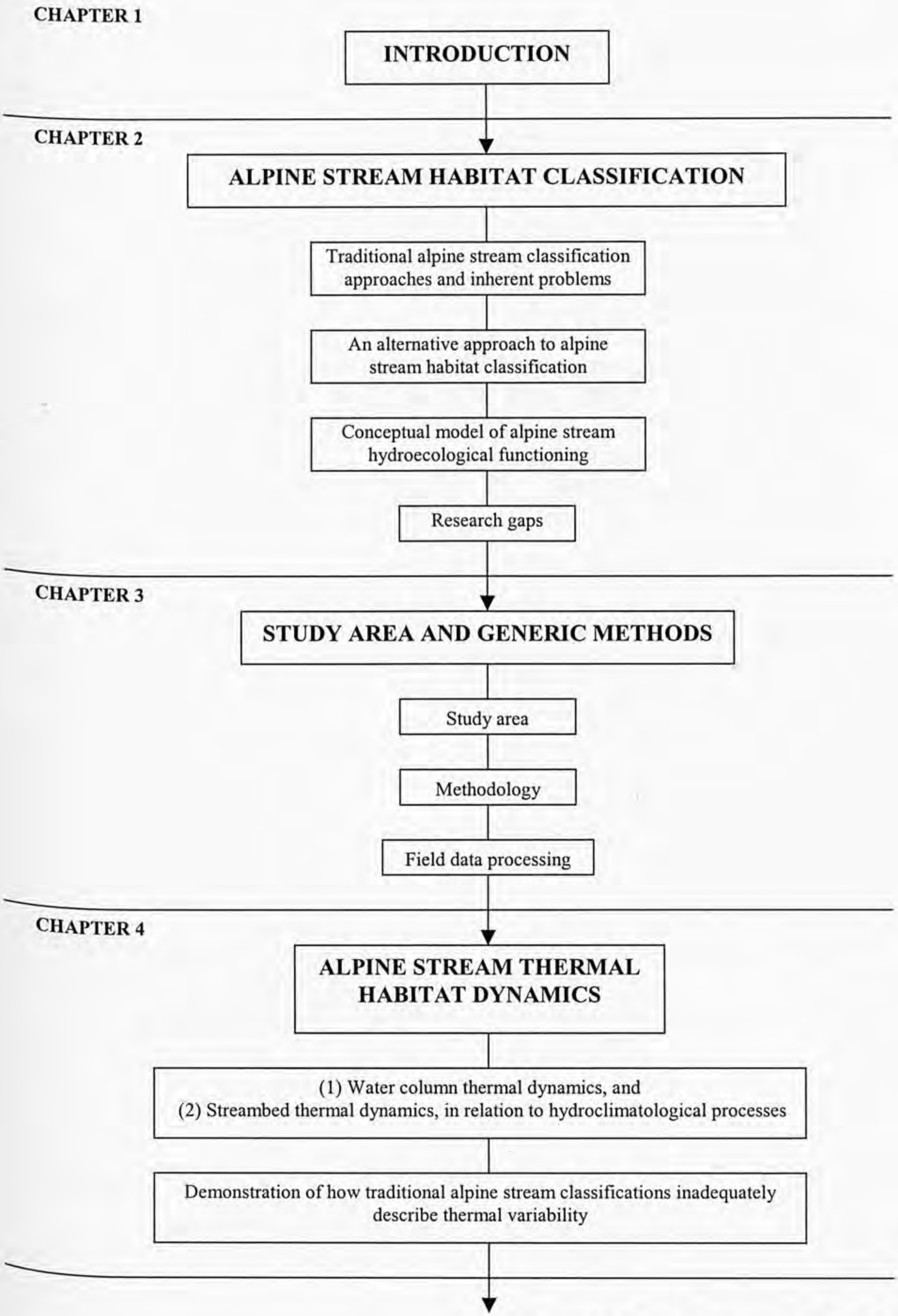


Figure 1.1. Flow diagram outlining thesis structure

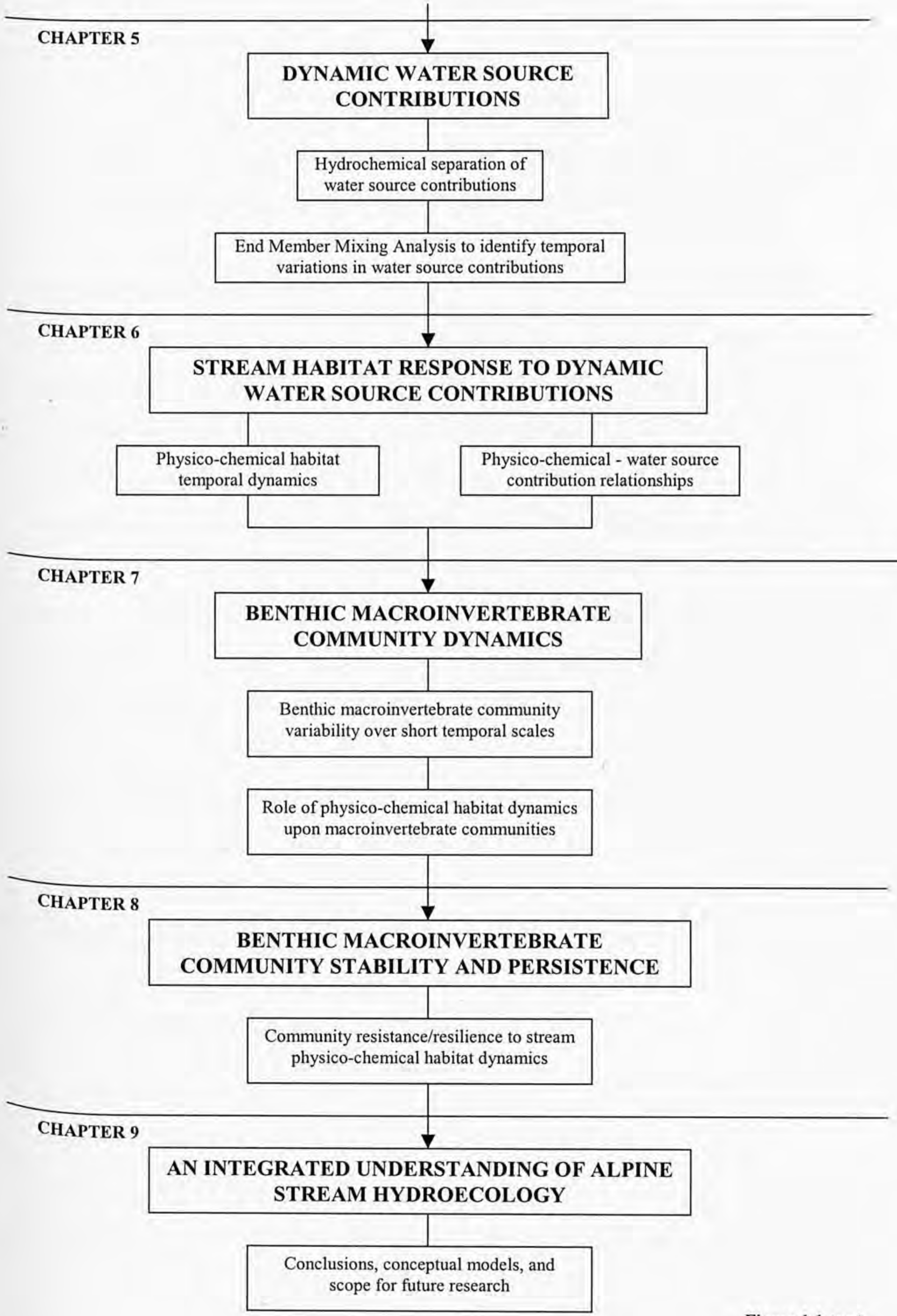


Figure 1.1.cont.

CHAPTER 2

LITERATURE REVIEW

Alpine stream habitat classification: an alternative approach incorporating the role of dynamic water source contributions

2.1. CHAPTER INTRODUCTION

This chapter provides an integrated overview of hydrological, stream physico-chemical habitat and ecological research within alpine glacierized catchments. This literature review is not intended to be comprehensive as more specific detailed reviews are provided within each individual chapter. The chapter begins by detailing the overall context for the thesis, by considering recent advances in understanding the dynamic functioning of alpine water sources, and the interrelationships between environmental variables and their roles in determining benthic communities (Section 2.2). Traditional classifications of alpine streams into 'glacial,' 'snowmelt,' and 'groundwater' categories based upon water temperatures are examined (Section 2.3) and the suitability of this classification approach critically evaluated (Section 2.4). The central theme of habitat complexity is developed with the major links between environmental variables and benthic communities highlighted through a conceptual model. A new alternative classification scheme is proposed, with the aim of providing a basis for a more complete understanding of the dynamic nature of water store contributions, along with the physical and chemical properties they impart upon stream communities (Section 2.6). A brief summary of the key findings of the literature review (Section 2.7) precedes the research gaps that will be addressed in the thesis (Section 2.8).

2.2. CONTEXT

Alpine river systems are fed by glacial icemelt, snowmelt and groundwater (Milner and Petts, 1994; Ward, 1994; Malard *et al.*, 1999; Ward *et al.*, 1999; Füreder *et al.*, 2001). Although streams originating from these water sources share common features, such as steep gradients, high flow velocities, and high dissolved oxygen concentrations, each source produces a characteristic discharge regime and a distinctive suite of physical and chemical characteristics (Milner and Petts, 1994; Ward, 1994; Tockner *et al.*, 1997; Friberg *et al.*, 2001; Milner *et al.*, 2001; Füreder *et al.*, 2002; Tockner *et al.*, 2002). Furthermore, the distribution of snow, ice and groundwater springs varies spatially from stream-reach to catchment scale, resulting in stream segments with characteristics reflecting the different proportions of runoff sources (Brittain *et al.*, 2001a). Physico-chemical variables (e.g., discharge, water temperature, channel stability, suspended sediment concentration, hydrochemistry) influence streams over time-scales ranging from diurnal to millennial (Smith *et al.*, 2001), adding further complexity to abiotic mechanisms controlling ecological processes in alpine streams.

Many aspects of the hydrology and physico-chemical features of glacier-fed streams are relatively well studied, especially in Europe (Milner and Petts, 1994); in contrast, knowledge of the ecology of these systems has been relatively poor until recently (e.g. Brittain and Milner, 2001; Lods-Crozet *et al.*, 2001; Snook and Milner, 2001b; Zah *et al.*, 2001). Recent work undertaken within a number of glaciated catchments in Europe as part of a coordinated project (Arctic and Alpine Stream Ecosystem Research [AASER]) has greatly enhanced understanding of alpine stream ecology (see Brittain *et al.*, 2001a; Milner *et al.*, 2001). Importantly, this work illustrated that a range of spatio-temporal patterns in environmental conditions markedly affect the composition of benthic stream communities. Currently, the classification of alpine streams is predominantly based upon water source and temperature (e.g. Steffan, 1971; Ward, 1994), although some studies refer to habitat conditions, including turbidity and flow regimes (Ward, 1994). However, the dynamic nature of water source contributions in alpine catchments results in a greater amount of stream physico-chemical habitat variation than these traditional classifications account for. A fuller understanding of the cascade of environmental processes involved in determining benthic community assemblages is required if these unique alpine ecosystems are to be utilized as indicators of climate change (McGregor *et al.*, 1995a).

2.3. TRADITIONAL CLASSIFICATION AND ZONATION SCHEMES FOR ALPINE STREAMS

As stream character in alpine catchments is strongly influenced by local water source and the origin of major tributaries (Füreder, 1999), three general stream biotypes (kryal, rhithral, and krenal) have been designated based upon their water source, which determines characteristic stream temperature ranges for these biotopes. These temperature ranges play a major role in defining faunal distributions (e.g. Steffan, 1971; Ward, 1994). Glacier-melt-dominated (kryal) streams occur at high altitude close to the glacier terminus and have low water temperatures. Kryal streams are usually subdivided into an upper metakryal and lower hypokryal, reflecting contrasting faunal compositions: *Diamesa* dominated and predominantly Diamesinae/Orthocladiinae, respectively (Steffan, 1971). Groundwater (krenal) streams are typified by relatively constant water temperature. Rhithral (snowmelt-fed) streams are characterized by conditions intermediate between kryal and krenal (Ward, 1994).

In alpine regions, these zonations are generally applied to headwater streams that lie between the permanent snowline and the treeline (Brittain *et al.*, 2001a). In undisturbed environments, the treeline, which forms the divide between subalpine/subarctic woodland and treeless alpine/tundra areas, approximates to the 10°C July isotherm (Remmert, 1980). Snowfields may be present year-round at higher altitudes. In some areas, glaciers (e.g. Brittain *et al.*, 2001b; Robinson *et al.*, 2001) and glacier-melt-dominated streams (Burgherr and Ward, 2001; Zah *et al.*, 2001) extend through the treeline, but in such situations, the stream classifications are usually still applied.

Alpine drainage basins containing water from multiple sources are complex systems. Water sources such as glaciers, snow and groundwater act as hydrological stores within which flows are attenuated. Sediment can be eroded, transported and deposited, energy exchanges can affect water temperature, and physico-chemical reactions and the mixing of water from different sources can result in water quality variations (Smith *et al.*, 2001). Consequently, stream communities have to exist within, and respond to, a range of dynamic physico-chemical processes within alpine stream systems. These physico-chemical variables control both the structure and functioning of alpine stream communities. A summary of the environmental variables that contribute to the dynamic nature of alpine streams and their effect upon benthic stream communities is provided in Table 2.1.

2.3.1. Kryal (glacial streams)

Glacial streams are characteristically very cold with stream temperatures close to 0°C where meltwater emerges from the glacier snout (Milner and Petts, 1994; Ward, 1994). Water temperature ranges are only a few degrees Celsius in kryal reaches due to proximity to glaciers (reaching a maximum of 4°C; Füreder, 1999), but typically show diurnal and seasonal fluctuations largely as a result of snowpack retreat and solar heating. The discharge from glaciers reaches a peak in summer, when energy input is at a maximum (Hannah *et al.*, 1999a). Diurnal flow variations of glacial rivers, with peak flow in late afternoon, are a characteristic feature during the ablation season reflecting cycles of atmospheric energy supply, and, in turn, glacier melt (Röthlisberger and Lang, 1985; Church, 1987; Hannah *et al.*, 2000b).

During summer melt periods glacial rivers often carry high concentrations of fine sediment that can reach over 500mg L^{-1} at peak flows (Gurnell, 1987). Proglacial river channels are usually highly unstable and characterized by frequent channel-shifting disturbances (Milner and Petts, 1994). Over a range of time scales, interactions between glacier mass-balance, sediment load, and riparian vegetation result in a wide variety of proglacial river channel forms (Hickin, 1993; Gurnell *et al.*, 1999). Ca^{2+}, HCO_3^- and SO_4^{2-} usually dominate bulk glacial outflow chemistry in varying proportions (Raiswell, 1984; Tranter *et al.*, 1993; Hodson *et al.*, 2002) along with lesser quantities of Mg^{2+}, Na^+, and K^+ (Füreder *et al.*, 2001). This dominance is due predominantly to subglacial drainage processes and bedrock type acting as key controls on weathering (Brown *et al.*, 1996a).

Table 2.1. Physico-chemical variables contributing to the dynamic nature of alpine stream environments, with summaries of their influence on benthic communities (modified after Milner and Petts, 1994)

Variables	Kryal	Rithral	Krenal	Effects on benthic communities
Water temperature	Relatively low; <2°C close to glacial margins increases with distance from glacier (Smith *et al.*, 2001)	High in summer, range from 0 - 12°C. Large diurnal variation (Ward, 1994)	Related to air temperature at source, typically low diurnal and seasonal variation (Ward, 1994)	Control on primary productivity and growth/ life cycles of macroinvertebrates (Milner and Petts, 1994)
Channel form/ stability	Frequently unstable, braided or wandering. Stability a function of distance from glacier and time since deglaciation (Gurnell *et al.*, 2000)	Typically more stable and less braided (Milner and Petts, 1994)	Stable, single thread (Ward, 1994)	Affects algal/invertebrate attachment to substrate (Milner and Petts, 1994)
Discharge	Summer peak, diel variations sustained through melt season (Röthlisberger and Lang, 1985; Hannah *et al.*, 2000)	Spring snowmelt causes peak flow. Also peak following rainfall events (Milner and Petts, 1994)	Relatively constant but attenuated peaks following precipitation events (Ward, 1994)	May affect emergence of some taxa. Control on macroinvertebrate drift. Species with adaptive traits favoured (Milner and Petts, 1994; Saltveit *et al.*, 2001)
Turbidity/ suspended sediment	Typically >30NTU except during winter low flows (Milner and Petts, 1994) High suspended sediment concentrations (>20mg/l^{-1}) with peaks over 200mgl^{-1} (Gurnell, 1985, 1987)	May be elevated during high flows, but much lower than kryal (Ward, 1994).	Low (Füreder, 1999)	Control on primary productivity in deeper streams, restricts benthic macroinvertebrate filter feeders. Affects algal/invertebrate attachment to substrate. (Milner and Petts, 1994)
Hydro-chemistry	Conductivity usually low (<10µs/cm^{-1}) (Fenn, 1987)	Ionic enrichment related to snowpack concentrations of solutes Intermediate between kryal and krenal (Malard *et al.*, 1999)	Generally high conductivity. Chemistry related to geology of groundwater store (Fenn, 1987)	May affect primary productivity and distribution of various invertebrate taxa (Robinson *et al.*, 2001) Silica levels determine diatom growth (Sabater and Roca, 1990)

2.3.2. Rhithral (snowmelt streams)

In the Northern Hemisphere, snowmelt-dominated regimes generally show peak discharge in spring before maximum glacial runoff occurs, although at high altitudes, the peak may be delayed until as late as July (Milner and Petts, 1994). A receding snowline and shrinking snowpacks through late spring and early summer reduce the influence of snowmelt on alpine stream hydrology (Smith *et al.*, 2001). Snowmelt streams typically exhibit the widest temperature range of all alpine stream types, with maximum temperatures reaching between 5-10°C (Ward, 1994). As snow cover and snowmelt generation can differ markedly over small spatial scales (Marsh, 1999), the influence of meltwater on different stream sections will vary accordingly. Normally, snowmelt-dominated streams are very clear and transport little sediment. However, during high flows they may have elevated turbidity due to re-suspension of fine sediments from the streambed (Milner and Petts, 1994).

Peaks in concentration of some stream solutes occurs during snowmelt as a result of preferential elution of ions from snowpacks (Johannessen and Henriksen, 1978; Tranter *et al.*, 1987; Helliwell *et al.*, 1998). High concentrations of nitrogen (as nitrate-N) and SO_4^{2-} characterize spring snowmelt runoff (Robinson *et al.*, 2001; Hodson *et al.*, 2002). The ionic composition of snowmelt also varies throughout the year, with winter samples being relatively dilute compared with samples collected in spring that may be enriched with Ca^{2+} and HCO_3^- (Malard *et al.*, 1999).

2.3.3. Krenal (groundwater streams)

Water temperatures at the sources of high altitude groundwater streams are related to annual mean air temperature and typically vary by only 1–2°C over an annual cycle (Ward, 1994; Füreder, 1999). However, Füreder *et al.* (2001) found that seasonal mean water temperature varied from <0.1–4.6°C in the groundwater spring-fed Königsbach stream, Austrian Central Alps. Increased discharge from groundwater springs is thought to result in lower daily temperature fluctuations downstream while also extending the distance of the groundwater's stabilising influence.

In contrast to kryal and rhithral streams, spring-fed streams do not exhibit marked diurnal and seasonal flow fluctuations (Ward, 1994). However, in karstic limestone systems, spring discharge may respond quickly to extreme precipitation events due to the relatively short residence time of water in the aquifer (Ford, 1993). Some groundwater streams in the French Pyrénées flowed intermittently toward the end of the melt season (Smith, 1999), following groundwater recharge by meltwaters. Thus, all alpine groundwater streams may not be characterized by predictable flow regimes.

Ionic enrichment and specific conductance of groundwater is often much greater than in either rhithral or kryal streams (e.g. Milner and Petts, 1994; Ward, 1994; Ward *et al.*, 1999), with relatively high concentrations of silica being characteristic of spring-fed streams (e.g. Malard *et al.*, 1999; Smith, 1999; Ward *et al.*, 1999). Annual variability in water chemistry of spring-fed streams is also much lower than in rhithral or krenal streams (Füreder *et al.*, 2001). Nevertheless, large differences may exist in the chemical composition of different groundwater streams both within (Malard *et al.*, 1999; Ward *et al.*, 1999) and between catchments (e.g. Sabater and Roca, 1990) due to variations in rock-weathering reactions brought about by differences in geology and groundwater residence time.

2.4. APPLICABILITY OF TRADITIONAL ALPINE STREAM ZONATION

Wide spatio-temporal variability in water store inputs contributes to the uniqueness of alpine stream systems (Smith *et al.*, 2001). To understand how this variability may affect the physico-chemical characteristics of streams, and how these characteristics interact to determine the structure of benthic communities, it is essential to consider the range and scales of linkages within stream ecosystems. A conceptual model summarising these interactions is presented in Figure 2.1. It is apparent that a range of environmental variables may shape the characteristics of alpine streams, interacting to produce a variety of habitats within which benthic communities exist.

Regional climatic influences play a major role in alpine stream dynamics by supplying and removing mass and energy at the glacier and snowpack surface, thereby determining accumulation and ablation rates of snow and ice (Hannah *et al.*, 1999b). This process drives variation in snow and ice meltwater inputs to glacial streams throughout the year. The timing and volume of bulk meltwater production (Hannah and Gurnell, 2001), along with inputs of groundwater from springs, seeps, and upwellings (Ward *et al.*, 1999; Füreder *et al.*, 2001; Lafont and Malard, 2001; Malard *et al.*, 2001) result in wide spatio-temporal variation in the physico-chemical properties of streams. The dynamic nature of inputs from all these sources may have a significant impact on benthic communities in alpine streams at the stream-reach scale (Snook and Milner, 2001b).

Water temperature has long been recognized as a major contributor to stream community structure and functioning (Hynes, 1970; Vannote *et al.*, 1980; Vannote and Sweeney, 1980; Ward, 1985). In glacial streams, water temperature plays a primary role in structuring benthic communities (Milner and Petts, 1994; Milner *et al.*, 2001). At the level of individual organisms, water temperature controls growth rates, the timing of life cycles, and rates of primary and secondary production (Hynes, 1970; Allan, 1995). In alpine streams, water sources are the primary influence on water temperature, although climatic influences such as solar radiation input can also play an important role. Because stream water temperature may be influenced by factors other than the source, classifying streams on the basis of water temperature alone is problematic. In addition, water sources impart a range of other physical and chemical properties that are discussed by current classification approaches (e.g. Ward, 1994) but rarely used in practice.

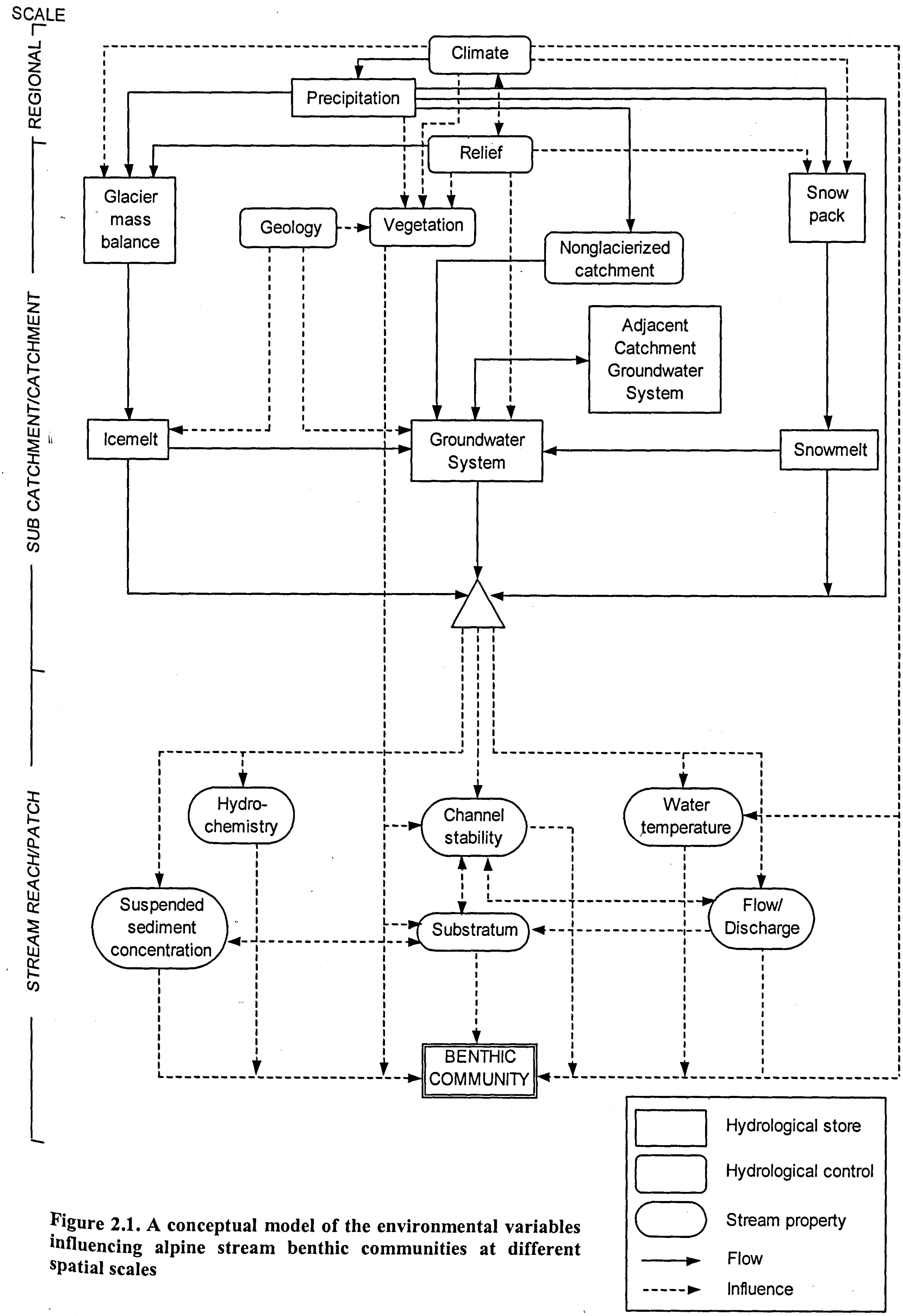


Figure 2.1. A conceptual model of the environmental variables influencing alpine stream benthic communities at different spatial scales

Even where water temperature is suitable, channel and bed stability may still inhibit colonisation of certain taxa (Milner and Petts, 1994). For this reason, stability must be considered in conjunction with water temperature when evaluating community composition of glacial rivers (Milner and Petts, 1994; Milner *et al.*, 2001). Channel stability is related to channel slope, substratum composition and stream power (Resh *et al.*, 1988). The increased sediment loads that accompany high flows, and that are characteristic of glacial streams (Gurnell, 1985, 1987), may directly affect stream communities through abrasion and reduced light penetration (Gíslason *et al.*, 1998; Castella *et al.*, 2001; Milner *et al.*, 2001). Stream communities are also affected indirectly by the reworking of channel profiles (Statzner *et al.*, 1988), and riparian vegetation can indirectly affect stream communities by restricting local morphological and sedimentological change (Gurnell *et al.*, 1999).

Inputs of allochthonous organic matter to streams (delivered by aerial inputs, erosion, or exfiltrating groundwater; e.g. Zah *et al.*, 2001) act as an important energy source for benthic macroinvertebrates (Cummins *et al.*, 1973; Anderson and Sedell, 1979; Bird and Kaushik, 1981), and can influence their distribution and abundance (Vannote *et al.*, 1980; Ward, 1992; Allan, 1995). Although inputs of vegetation to streams act primarily as a food source, they also contribute to the nature of the substratum (Minshall, 1984). The substratum consists of both inorganic (microscopic silts to boulders) and organic materials (bryophytes and land-derived vegetation) and forms the stage upon which aquatic insects move, rest, find shelter and seek food (Minshall, 1984). In alpine streams, deposits of suspended sediment affect the nature of the substratum. The substratum is also a key control on channel and bed stability (Pfankuch, 1975). The ability of an insect to adhere, cling, burrow, or build cases is directly affected by the nature of the substratum (Mackay, 1977; Minshall, 1984). The substratum may indirectly affect the composition of benthic communities through alteration of the direction, force, and turbulence of water flows (Newbury, 1984). These flow characteristics influence the metabolism, feeding and behaviour of lotic organisms (Statzner *et al.*, 1988).

The availability of ions from the weathering of rocks and soils along with atmospheric inputs influences the water chemistry of streams, which, in turn, may play an important role in determining benthic community composition (Hynes, 1970; Sabater and Roca, 1990). In alpine catchments, little research has been undertaken to determine specifically the influence of water chemistry on stream communities (Kownacka and Kownacki, 1972; Sabater and Roca, 1990; Robinson *et al.*, 2001). Water quality analyses have confirmed that some groundwater streams have distinctive chemical characteristics that vary spatially and temporally (Sabater and Roca, 1990; Robinson *et al.*, 2001). Such chemical variability is likely to result in habitat differences and, thus, have an effect on benthic community composition (Sabater and Roca, 1990; Robinson *et al.*, 2001).

Given the occurrence of high spatio-temporal variability in physico-chemical habitat in alpine streams, the traditional classification system using water temperature alone to indicate water source is misleading. For example, a stream fed only by glacial meltwater is classified as kryal in its uppermost reaches (Ward, 1994). As water flows downstream, increases in temperature occur as a result of a range of energy fluxes (Füreder, 1999), leading to a thermal classification of the stream as rhithral, even though it may have no true snowmelt influence. As such, the current classification system of kryal, rhithral, and krenal may be misleading due to the conflation of water *source* and water *temperature*. Figure 2.2 highlights the problem of using stream temperature to classify stream reaches. These data were collected on a glacial stream in the French Pyrénées over the 1997 melt season (see Smith *et al.*, 2001 for details of methodology). Water temperature was consistently <4°C (kryal) at the beginning of the melt season, when snowmelt was the major contributor to stream flow. As the melt season progressed, the temperature range increased due to a greater receipt of solar radiation input, so that use of the traditional classification method would result in a rhithral classification despite the fact that snowmelt contribution was decreasing and glacial icemelt increasing (Smith, 1999).

The term 'kryal' was used in a study of streams fed by a permanent snowfield but no glacier (Elgmork and Saether, 1970). In this study, five stream reaches were investigated in the Colorado Rocky Mountains between a snowfield and the first of a series of lakes. All five study sites had mid-summer temperatures of approximately 1°C, and as such were deemed to be an example of kryal streams (after Ward, 1994). In this situation, streams fed completely by snowmelt should be placed into a modified rhithral category, which would correctly reflect the origin and physico-chemical characteristics of these meltwaters.

A further example of the way in which traditional alpine stream categories are problematic is that outlets from cirque lakes have been classified as rhithral (e.g. Elgmork and Saether, 1970). Lakes may significantly alter the nature of headwaters by increasing channel stability downstream, modifying chemical characteristics and/or increasing water temperature (Milner and Petts, 1994) to such an extent that the streams draining them are markedly different from inflows. Even though the water temperature of snowmelt streams may be similar to those of lake outlets, other physico-chemical characteristics may be markedly different enough to require a separate classification.

The use of the term 'rhithral' has also been questioned with reference to its application to precipitation as well as snowmelt-fed streams (Illies, 1961; Illies and Botosaneanu, 1963; Ward, 1994). More recently, the terms 'ombral' and 'chial' have been proposed to describe rainfall- and snowmelt-fed streams, respectively (Schutz, 1999; Lencioni, 2000). However, even this division is problematic because streams are rarely influenced by a single water source. Snowmelt may flow overland into glacial- or groundwater-fed streams; precipitation may also fall directly (typically <1% contribution) or flow overland or through hillslopes into streams. In these situations, the stream would still be classified by water temperature. In a similar manner, spring-fed tributaries may markedly increase the temperature of kryal streams below confluences (e.g. Ward, 1994). Therefore, a stream reach downstream of a groundwater input to a glacial stream could be classified as rhithral, if thermal conditions were substantially altered regardless of the absence of meltwater from snowpacks.

In streams close to glacial margins, the subdivision of the kryal into an upper 'metakryal' and lower 'hypokryal' is also problematic. Snowpacks cover the ablation zone of glaciers, melting up-glacier over the summer (Hannah *et al.*, 2000a), and their meltwaters may flow into the proglacial zone, resulting in a mixed water source. However, as temperature is the principal habitat variable used as a classification criterion, little account is taken of the influence of the snowmelt contributions.

The quantity and quality of water source inputs to alpine streams may also vary over a number of temporal scales from diurnal to inter-annual (Figure 2.3). This can result in changes in stream classification over an annual cycle. For example, springtime flows may be predominantly snowmelt driven. In summer, glacial melt often dominates, while toward the end of the melt season and through winter, groundwater inputs may be the principal water source for streams (Malard *et al.*, 1999). Similarly, changes in water routing can occur diurnally. Groundwater sources may dominate stream channels at low flows through the late evening and night, when glacial icemelt or snowmelt is minimal. As solar radiation increases toward an afternoon peak, the proportion of snow- and ice-melt increases, and streams shift to be either snowmelt or glacial icemelt dominated. The current system does not take these temporal shifts into account unless they are accompanied by marked changes in water temperature.

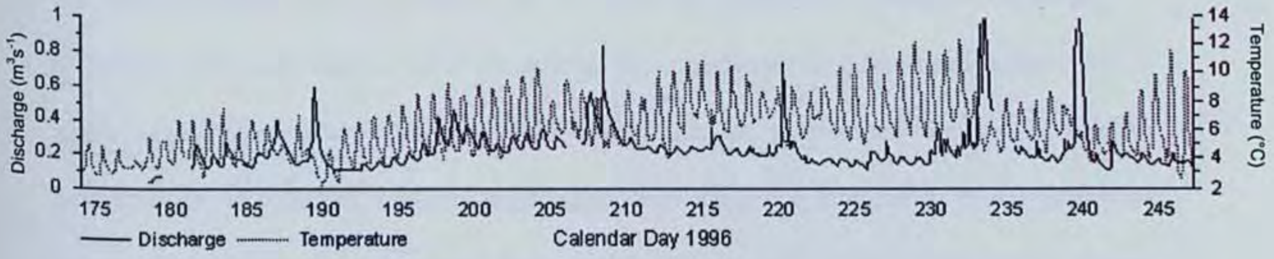


Figure 2.2. Time series of stream water temperature and discharge approximately 1 km downstream of the Taillon Glacier snout, French Pyrénées, for the 1996 ablation season (Smith *et al.*, 2001)

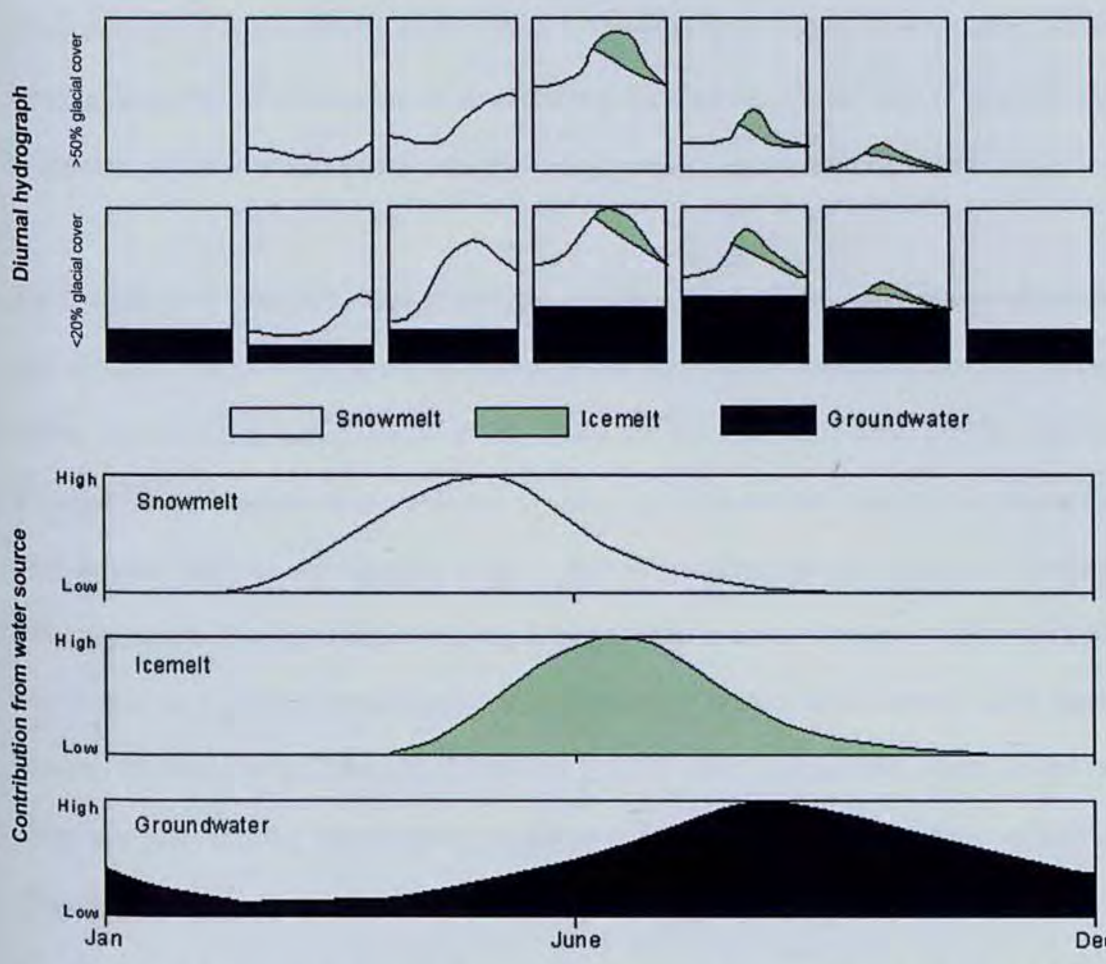


Figure 2.3. A conceptual model of spatial and temporal variations in daily bulk runoff hydrographs and water source contributions in alpine glacierized catchments over an annual cycle (modified from Smith *et al.*, 2001).

2.5. AN ALTERNATIVE APPROACH TO ALPINE STREAM CLASSIFICATION

Given the level of inconsistency in classifying alpine streams using traditional approaches, it would appear that future studies should concentrate on determining the actual relative contributions of different water sources rather than assigning streams to broad categories based upon their perceived dominant water source and associated temperature regime. Hence, nine new categories for classification are proposed based upon the relative proportions of glacial meltwater (kryal), snowmelt (nival), and groundwater (krenal) present (Table 2.2). A greater number of categories, giving qualitative explanations of the stream type as determined by source waters alone, may improve comparisons of stream reaches between studies and allow changes in source waters within alpine catchments to be tracked over temporal scales ranging from diurnal to seasonal. A simple triangular diagram (Figure 2.4) to illustrate the proportion of source waters to a stream reach allows ease of classification.

The classification principally aims to categorise streams based on their relative proportions of source waters. Variations in environmental characteristics can be predicted based upon water source contributions (e.g. Gíslason *et al.*, 2000) for the nine categories, providing fuller physico-chemical habitat characterisation (Table 2.3). Characteristic temperature ranges for each category are not included due to the complicating influences of climate and distance from the source. The important role of water temperature in alpine streams is acknowledged, but its use as a primary classification tool is severely limited when equated with water sources. However, to aid comparison between studies, water temperature ranges should be stated alongside the new classification categories to facilitate proper interpretation of habitat characteristics within a stream reach and so enable comparison between studies.

Table 2.2. Summary of alternative alpine stream classifications based on proportions of water sources (refer to Figure 2.4 for water source classifications)

Reference	Classification	Water source contributions
A	Krenal	High proportion of groundwater (>70%). Combined glacial meltwater and snowmelt total <30%
B	Kreno-nival	Groundwater sources dominate (35 - 70%). Snowmelt contribution > glacial
C	Kreno-kryal	Groundwater sources dominate (35 – 70%). Glacial meltwater contribution > snowmelt
D	Nivo-krenal	Snowmelt sources dominate (35 – 70%). Groundwater contribution > glacial
E	Kryo-krenal	Glacial meltwater sources dominate (35 – 70%). Groundwater contribution > snowmelt
F	Nival	High proportion of snowmelt (>70%). Combined glacial meltwater and groundwater total <30%
G	Nivo-kryal	Snowmelt sources dominate (35 – 70%). Glacial meltwater contribution > groundwater
H	Kryo-nival	Glacial meltwater sources dominate (35 – 70%). Snowmelt contribution > groundwater
I	Kryal	High proportion of glacial meltwater (>70%). Combined snowmelt and groundwater total <30%

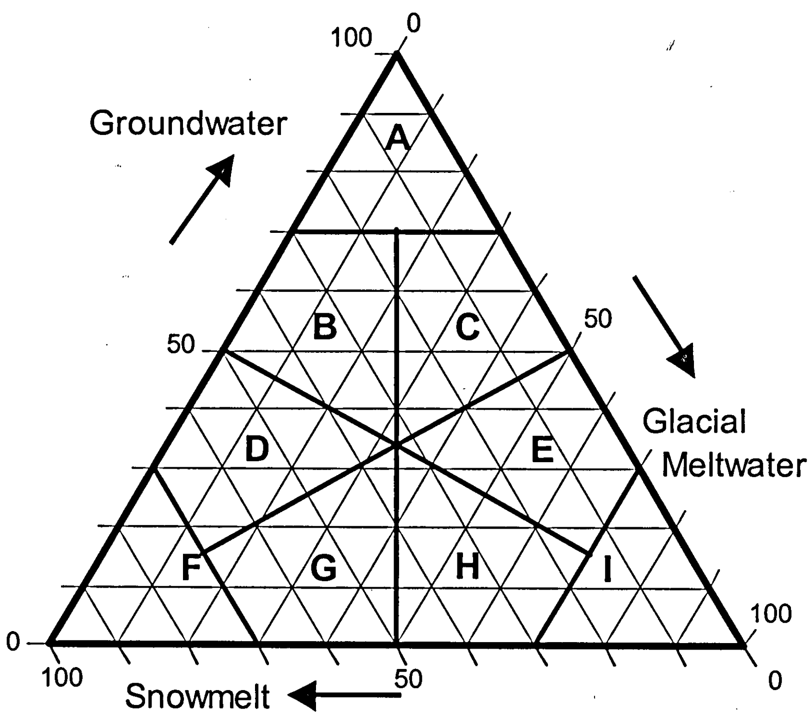


Figure 2.4. Classification of alpine streams based on percentage contribution of source water inputs (refer to Table 2.2 for stream categories A–I).

Table 2.3. Characteristic physico-chemical variables expected for alpine stream categories based on relative proportions of source water contributions

Category	Suspended Sediment Concentration	Hydrochemistry	Channel Stability	Flow Variation
Krenal	Constantly very low (Füreder, 1999). <10mg/L (L.E. Brown, *unpublished data.*)	High silica, bicarbonate and sulphate (Malard *et al.*, 1999; Ward *et al.*, 1999)	Very stable, straight or gentle meanders, single thread (Ward, 1994)	Constant flow with little diurnal variation (Ward, 1994)
Kreno-nival	Low but >krenal as snowmelt may contribute a small amount	High silica (<krenal) and relatively high chloride (<nival)	Stable, single thread and meandering or straight	Relatively constant flow, small diurnal variation from snowmelt input
Kreno-kryal	Low concentration due to groundwater dilution. Small diurnal variation likely	High silica (<krenal) and relatively high calcium and sulphate (<kryal)	Relatively stable but glacial sediment inputs may result in some braiding	Baseflow relatively constant but glacial influence may cause diurnal variation
Nivo-krenal	Low but slightly > kreno-nival due to greater proportion of snowmelt	High chloride (<nival) and relatively high silica (<krenal)	Stable as low sediment inputs and low discharge variation	Diurnal variations due to snow input (>kreno-nival)
Kryo-krenal	Relatively high as glacial source dominant. <kryal	High sulphate (<kryal) and silica (<krenal)	Relatively low channel stability due to dominance of glacial source	Glacial source dominant so fairly pronounced diurnal variation
Nival	Low but > krenal. Very low diurnal variation. Possible increase when high flows (Milner and Petts, 1994)	High chloride and nitrate from snowpack elution, low silica (Malard *et al.*, 1999)	Typically more stable than kryal (Milner and Petts, 1994)	Diurnal cycle <kryal. Building towards late afternoon/early evening.
Nivo-kryal	Elevated levels compared to nival due to glacial influence. Diurnal variations	High chloride as snow dominant (<nival) Relatively high sulphate. Low silica.	Relatively stable but glacial sediment inputs may result in some braiding	Diurnal peak intermediate between nival and kryal. <kryo-nival as snow dominant
Kryo-nival	High but < kryal. Pronounced diurnal variations	High sulphate as glacial meltwater source dominates Relatively high chloride and nitrate	Unstable channel. Variety of channel forms as glacial input dominant	Pronounced diurnal peak intermediate between nivo-kryal and kryal
Kryal	Very high during peak flows with large diurnal range (Gurnell, 1987)	High sulphate and calcium, low chloride and silica. ((Tranter *et al.*, 1993)	Very low channel stability. Frequently braided or wandering (Gurnell *et al.*, 1999)	Large diurnal cycle related to solar radiation input. Peak late afternoon (Hannah *et al.*, 2000b)

The new classification system accounts only for stream conditions between precipitation events, which is a limitation. However, given that precipitation events often provide volumes of water that exceed those from other sources (Matthaei *et al.*, 1997), their contribution should be evident from the examination of stream hydrographs (Hannah *et al.*, 1999a; Hannah *et al.*, 2000b). Nevertheless, because precipitation events are usually episodic, they are likely to result in relatively short-term deviations from the conditions described by a classification, although these may be ecologically important disturbance events. It is important to acknowledge these short-term deviations because peak flows caused by precipitation events are likely to have an effect on stream communities (e.g. Matthaei *et al.*, 1997).

2.6. ALTERNATIVE ALPINE STREAM CLASSIFICATION APPLICATIONS: A PRELIMINARY ASSESSMENT

Potential applications of the new classification (proposed in Section 2.3) can be demonstrated using data collected from the Taillon-Gabiétous catchment during 1996 and 1997 (Smith, 1999; Snook, 2000). Temporal changes in the percentage of water source contributions to stream flow for the Taillon-Gabiétous catchment, 1997 ablation season (Smith, 1999), are shown in Figure 2.5. Close to the Taillon Glacier margin, the stream is predominantly classified as Nivo-kryal, reflecting the large input of snow and glacial meltwaters to the proglacial stream. Toward the end of the ablation season, snowmelt input to the stream decreases to less than 20%, icemelt waters become dominant, and the classification becomes Kryo-nival. These subtle changes, which may be of importance to benthic communities, have not been documented previously since water temperature was always <2°C and the stream reach was classified simply as kryal throughout the melt season (Snook and Milner, 2001b). Other physical habitat variables, notably diurnal discharge fluctuations and suspended sediment concentration also varied as water sources changed (Smith *et al.*, 2001). Classification approaches based principally upon temperature do not adequately describe this variability.

The classification may also be used to describe changes in streams with distance from glacial margins. Figure 2.6 shows proportions of source water contributions to the Taillon Glacier stream, averaged over the 1997 ablation season (for site descriptions, refer to Snook and Milner, 2001). At the glacier margin (Site 1) and at Site 2, the stream is classified as Kryo-nival, highlighting the mix of waters from the snow-covered glacier. The classification changes to Nivo-kryal as distance from the glacier increases, reflecting the increased proportion of snowmelt input as the catchment area upstream of the stream reach increases and the percentage covered by glacier decreases. Between Sites 3 and 5 (Site 4 was located on a side tributary), approximately 1 km downstream of the Taillon Glacier, a number of groundwater springs enter the Taillon stream accounting for the change in classification to Kreno-nival.

These two examples illustrate the spatio-temporal variability in water source contributions that may be identified using the alternative classification. In comparison, traditional classification approaches would not identify this dynamism. Although this classification approach has apparent potential for more accurately describing alpine stream water source and habitat dynamics, further evaluation is required to determine its effectiveness under a range of spatio-temporal conditions. Testing is also required to establish whether the approach adequately describes variations in source water inputs and the physico-chemical characteristics of other alpine glacierized catchment streams.

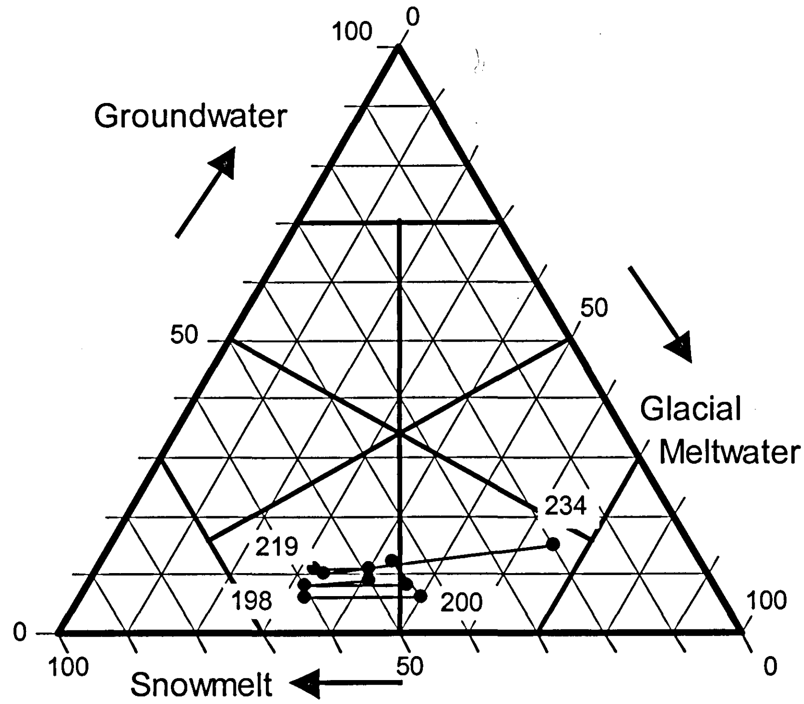


Figure 2.5. Temporal variations in water source contributions to stream flow at the Taillon Glacier snout throughout the 1997 ablation season. Proportions of each source were estimated using End-Member Mixing Analysis (Smith, 1999). Numbers refer to Julian Day, 1997.

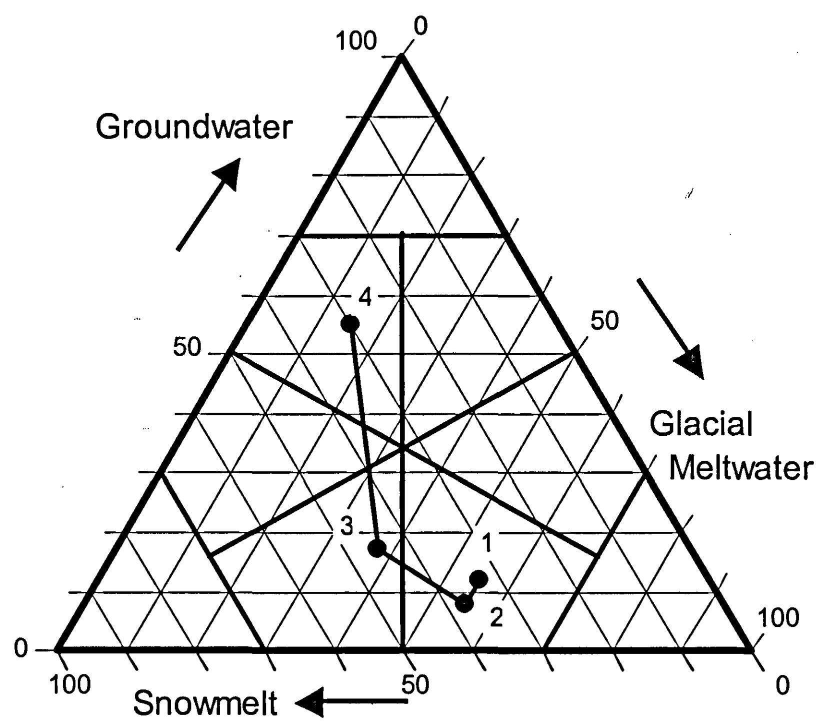


Figure 2.6. Longitudinal variations in water source contributions to stream flow downstream of the Taillon Glacier throughout the 1997 ablation season. Proportions of each source were estimated using End-Member Mixing Analysis and averaged over the ablation season (Snook, 2000). Numbers refer to sampling locations (see text).

2.7. SUMMARY

Based upon a review of the literature, the following key points can be identified:

1. Stream-reach characteristics in alpine catchments are strongly influenced by water source. Classifications based predominantly upon water temperature are problematic because the conflation of water source and water temperature is often inaccurate. Furthermore, alpine streams exhibit wide spatial and temporal variation in a range of physical and chemical characteristics, both within and between streams, which is largely unaccounted for by current classification approaches.

2. Even within the Taillon-Gabiétous catchment, temporal and spatial changes in water sources are evident throughout the melt season, and therefore, alternative stream classifications occur. In a much larger catchment (Val Roseg, Switzerland), groundwater contributions have been shown to vary from <10% to >70% over the course of an ablation season (Tockner *et al.*, 2002). The proportion of glacial melt in an Icelandic river system was estimated to be ~50% in the uppermost reaches, but declined to ~20% 42 km downstream (Adalsteinsson *et al.*, 2000). These examples demonstrate the potential for much greater variability in stream classification than shown in the two examples above for the headwater Taillon-Gabiétous catchment.

3. Further examination of temporal changes in stream classification may yield important information on associated changes in stream physical and chemical characteristics, which, in turn, may be important determinants in the timing of life cycles of aquatic insects and benthic macroinvertebrate community structure. Water temperature and channel stability are recognized as fundamental stream characteristics influencing benthic communities of alpine streams at the reach scale (Milner and Petts, 1994; Milner *et al.*, 2001). However, recent work has highlighted the roles of other environmental variables, such as hydrochemistry and suspended sediments in determining alpine stream community structure (e.g. Castella *et al.*,

2001; Lods-Crozet *et al.*, 2001; Milner *et al.*, 2001). This classification provides a framework for future research that should provide a more refined resolution for understanding dynamic changes in alpine stream habitat characteristics and benthic communities.

2.8. RESEARCH GAPS

The research gaps identified in this chapter, and which will be addressed in subsequent chapters, are summarised below. These research gaps are elaborated upon in the context of previous research within the introduction sections of individual chapters.

1. Traditional classifications of alpine streams based upon water temperatures may be unsuitable where streams are strongly influenced by atmospheric energy inputs and dynamic water source contributions. Despite the strong emphasis on temperature in these stream classifications, there is a clear need for detailed studies of alpine stream thermal variability to address the role of hydroclimatological influences on alpine stream water temperature.

2. Alpine water source contributions to streamflow can be highly dynamic but few studies have addressed water source dynamics at the catchment scale. These water source dynamics may result in a greater amount of stream physico-chemical habitat variation than traditional stream classifications account for. An integrated understanding of the effects of water source dynamics upon stream physico-chemical habitat is required to inform alpine stream ecological studies.

3. Despite the recent increase in alpine stream ecological research, little is known of how community structure varies temporally over the summer melt season, particularly with respect to links with habitat dynamics. Further studies of alpine stream community temporal variability are required to increase understanding of the strategies employed by macroinvertebrate populations in response to physico-chemical habitat variability.

4. Alpine stream water source contributions, and, thus, physico-chemical habitat characteristics may vary over diurnal to sub-monthly time-scales, and in turn, influence stream community structure. To accurately predict alpine stream community response to water source changes under scenarios of potential climate change, there is a clear need for an integrated hydroecological approach linking water source-habitat-ecological dynamics.

The thesis addresses these issues by adopting a holistic hydroecological approach, first examining water column and streambed thermal variability, and relating the findings to the problems with traditional alpine stream habitat classifications (Chapter 4). The thesis structure then follows a cascade linking water source (described using hydrochemical methods; Chapter 5), stream physico-chemical habitat (hydrological methods; Chapter 6), and ecological variability (Chapters 7 and 8). By doing so, the research contained herein is used to address the above research gaps, and validate glacial icemelt, snowmelt and groundwater contributions at the catchment/sub-catchment scale, to stream physico-chemical habitat and ecological variability at the reach scale (Figure 2.1).

CHAPTER 3
STUDY AREA AND GENERAL METHODS

3.1. CHAPTER INTRODUCTION

This chapter describes the design and implementation of the fieldwork programme undertaken in the Taillon-Gabiétous catchment during the 2002 and 2003 summer melt seasons. The chapter describes catchment selection, research design and methods used to collect field data and process samples in the laboratory, which allow the wider research aims outlined in Chapter 1 to be addressed. A justification of catchment selection is provided (Section 3.2.1), followed by an overview of the study area (Section 3.2.2), and reviews of catchment geology (Section 3.2.3), glaciology and hydrology (Section 3.2.4). Sampling design and general methods used in investigations detailed in subsequent chapters are outlined (Section 3.3). Following an evaluation of field data quality (Section 3.6.1 and 3.6.2), techniques used to prepare field data for analysis in subsequent chapters are discussed (Section 3.6.3 to 3.6.5). More specific methods (e.g. statistical methods, data analyses) are described within relevant chapters.

3.2. STUDY AREA

3.2.1. Catchment selection criteria

To address the overall aim of understanding how dynamic water store contributions influence stream benthic communities, it was necessary to work within an alpine catchment with glacial, snowmelt and groundwater sources that varied spatially and temporally. The Taillon-Gabiétous catchment, Cirque de Gavarnie, French Pyrénées (Figure 3.1; Plate 3.1) was selected as being particularly suitable for such a hydroecological investigation because:

- The catchment is relatively small (7.7 km^2) facilitating intensive study by a small team. The catchment can be accessed on foot (from the north via the nearby town of Gavarnie), or by road (to the head of the Vallée des Pouey Aspé).

- The catchment is well defined and contains a number of different water sources including glaciers, snowpacks, and hillslope/karstic groundwaters. The catchment can be divided into nested sub-catchments, each of which contains variations in glacierized area (2%-41%), snowpack cover, and permeable rock formations storing groundwater.
- Much recent work has been undertaken in the catchment (especially by University of Birmingham researchers), including studies of geological characteristics and karstic groundwater pathways (Parc-National-des-Pyrénées, 1991), glacial retreat (Gellatly *et al.*, 1995; McGregor *et al.*, 1995b), hydroclimatology (McGregor and Gellatly, 1996; Hannah, 1997; Hannah *et al.*, 1999a, b; Smith, 1999; Hannah *et al.*, 2000a; Hannah *et al.*, 2000b; Hannah and Gurnell, 2001; Smith *et al.*, 2001) and stream ecology (Snook, 2000; Snook and Milner, 2001a, b, 2002). This work provides a context and baseline understanding for the research in this thesis to build upon.

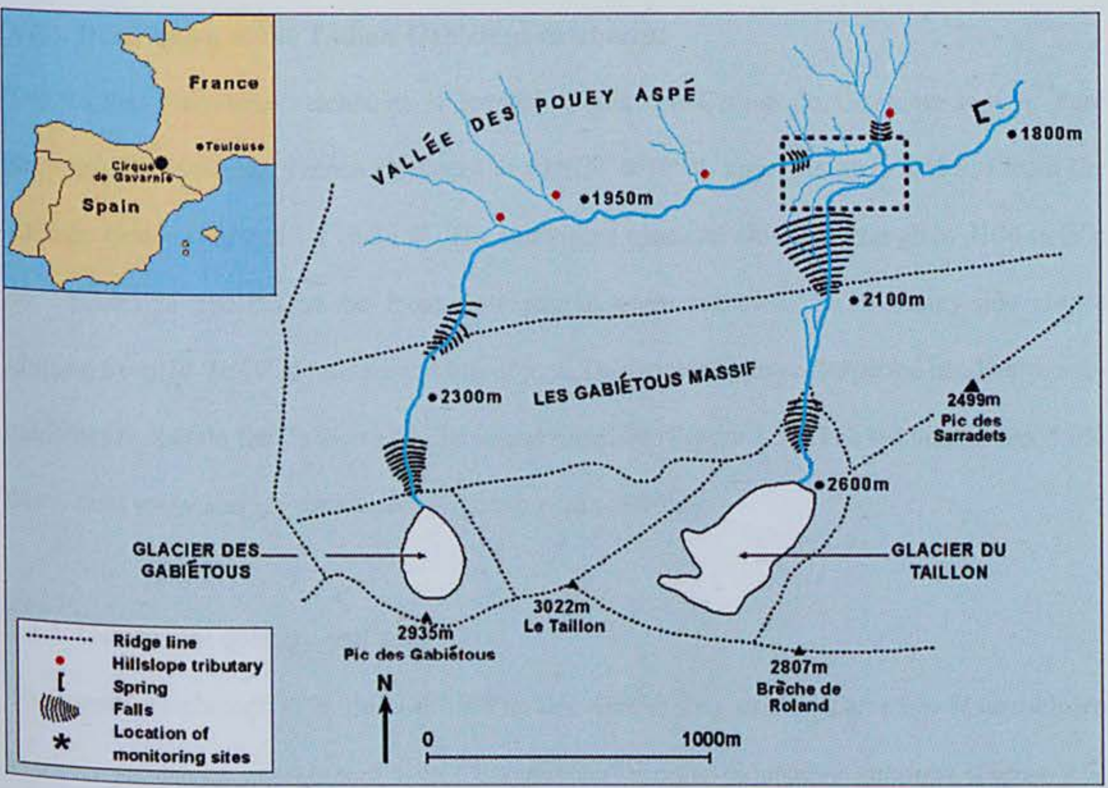


Figure 3.1. Map of the Taillon-Gabiétous catchment showing the location of the study site in the French Pyrénées (inset), and locations of the Taillon and Gabiétous Glaciers in relation to the main study area (hatched box) in the lower Vallée des Pouey Aspé.

Plate 3.1. The Taillon-Gabiétous catchment photographed from the Refuge des Espugettes, looking approximately west-southwest.

3.2.2. Description of the Taillon-Gabiétous catchment

The Taillon-Gabiétous catchment is located within the Cirque de Gavarnie region, Parc National des Pyrénées, French Pyrénées at 43°6'N, 0°10'W, approximately 145 km from the Atlantic Ocean (Figures 3.1 and 3.2). The catchment spans an altitudinal range of 3144 m (Pic du Taillon) to 1850 m at the most downstream point sampled. Steep valley-side slopes ranging from 30° to 70° dominate the catchment. Two glacially over-deepened headwater sub-catchments contain the Taillon and Gabiétous Glaciers (Figure 3.2). The catchment has 5.0% permanent snow and ice pack cover (Hannah *et al.*, 2000b).

3.2.3. Catchment geology and soils

The upper catchment (Pic du Taillon/Pic des Gabiétous) drains Campano-Maastrichtien Marboré sandstone interspersed with Cenomanian/Turonian limestone outcrops (Figure 3.3; Flachére, 1977). An area of calcareous/dolomitic sandy limestone of the Santonien and Conacien series underlies the north-facing catchment slopes (Les Gabiétous Massif; Plate 3.2). The lower catchment (Vallée des Pouey Aspé) is a wide gentle gradient valley composed mainly of Cenomanian/Turonian limestone (Parc-National-des-Pyrénées, 1991). Small areas of carboniferous shale are also found on parts of the south facing slopes. The valley bottom contains deposits of alluvium and glacial debris/fill (Figure 3.3). Shallows soils (<0.2 m) are scarce on the north facing slopes of Les Gabiétous massif, but are widespread on south facing slopes of the Vallée des Pouey Aspé, possibly reaching depths of ~0.5 m at lower elevations (*L.E. Brown; personal observation*).

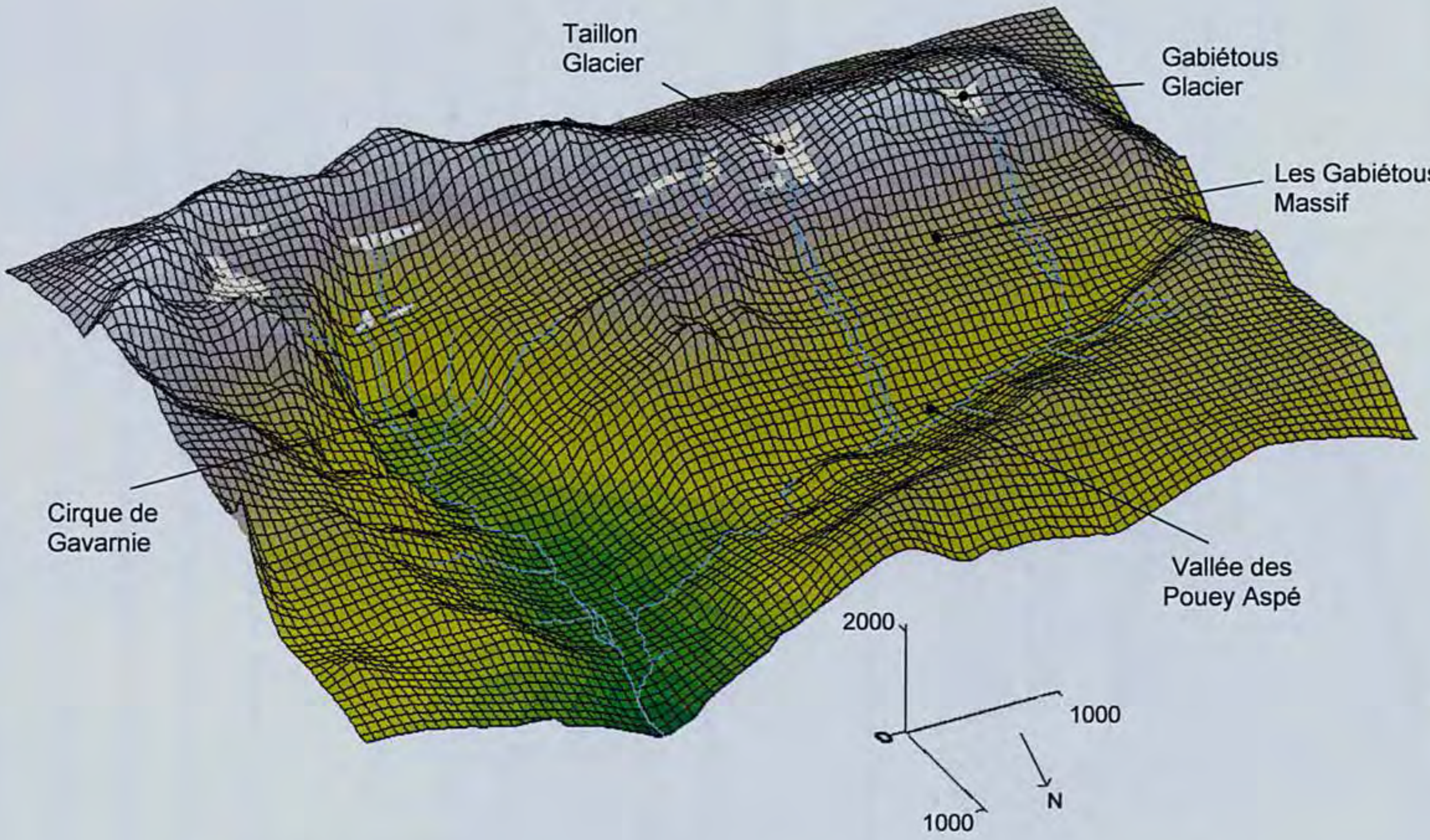


Figure 3.2. The Taillon-Gabiétous catchment (right), which drains into the Cirque de Gavarnie

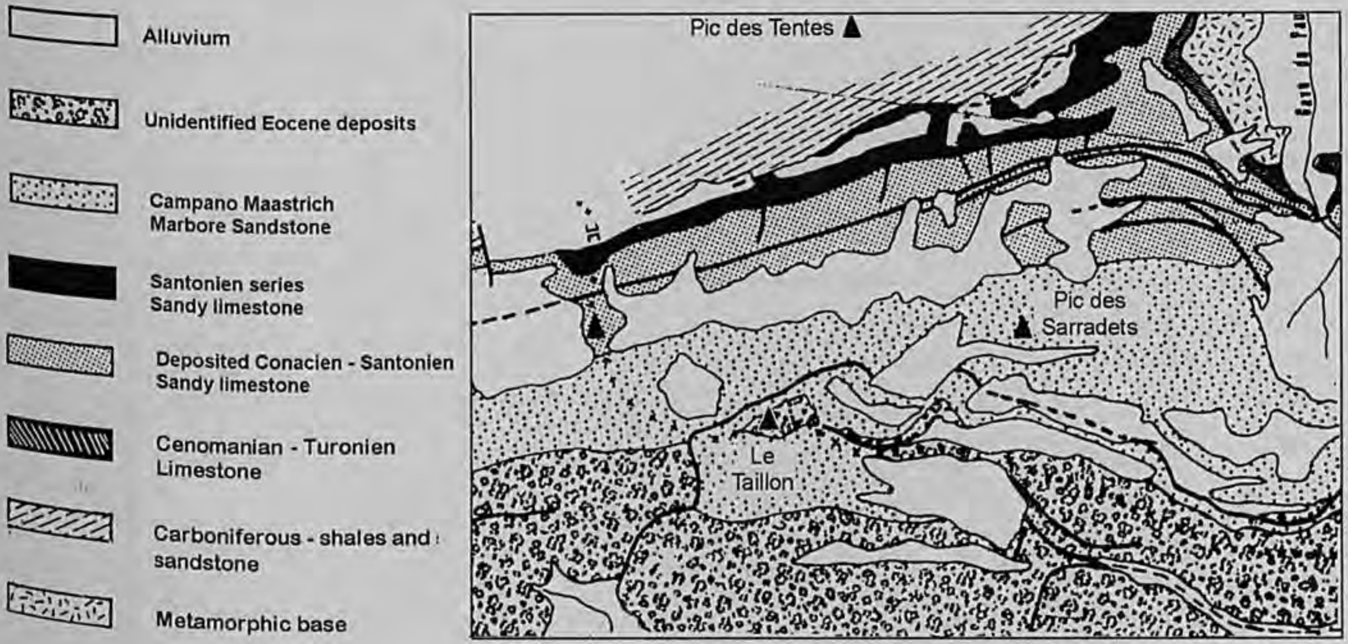


Figure 3.3. Geological map of the Taillon-Gabiétous catchment (modified from Flachére, 1977)

3.2.4. Catchment water sources

The catchment contains four distinct and highly dynamic hydrological stores: (1) the Taillon (Plates 3.2-3.3) and Gabiétous Glaciers (Plate 3.3), (2) seasonal snowpacks below 2700 m, (3) a karst groundwater system (Plate 3.4) and (4) hillslope aquifers (Plate 3.5). These water sources feed a large number of streams, many of which are confluent at the lower end of the Vallée des Pouey Aspé (Figure 3.2). Relative proportions of water from each source can vary at diurnal to seasonal time-scales (Hannah and Gurnell, 2001; Smith *et al.*, 2001).

The eastside of the upper part of the catchment contains the Taillon Glacier, located within a well-defined northeast-facing cirque. The glacier descends from the cirque wall at an altitude of 2790 m to the terminus at 2550 m, covering an altitudinal range of 240 m. It is the third largest of the fifty remaining Pyrénéan glaciers (McGregor and Gellatly, 1996). Glacier extent has fluctuated markedly over the last 150 years as illustrated by the position of its snout (Figure 3.4). However, some periods of glacial advance can be identified (1906-1911, 1926-1928 and 1963-1964), associated with above average winter precipitation and below average seasonal temperatures (Gellatly *et al.*, 1995; McGregor *et al.*, 1995b; Association-Moraine-Pyrénéenne-de-Glaciologie, 2003).

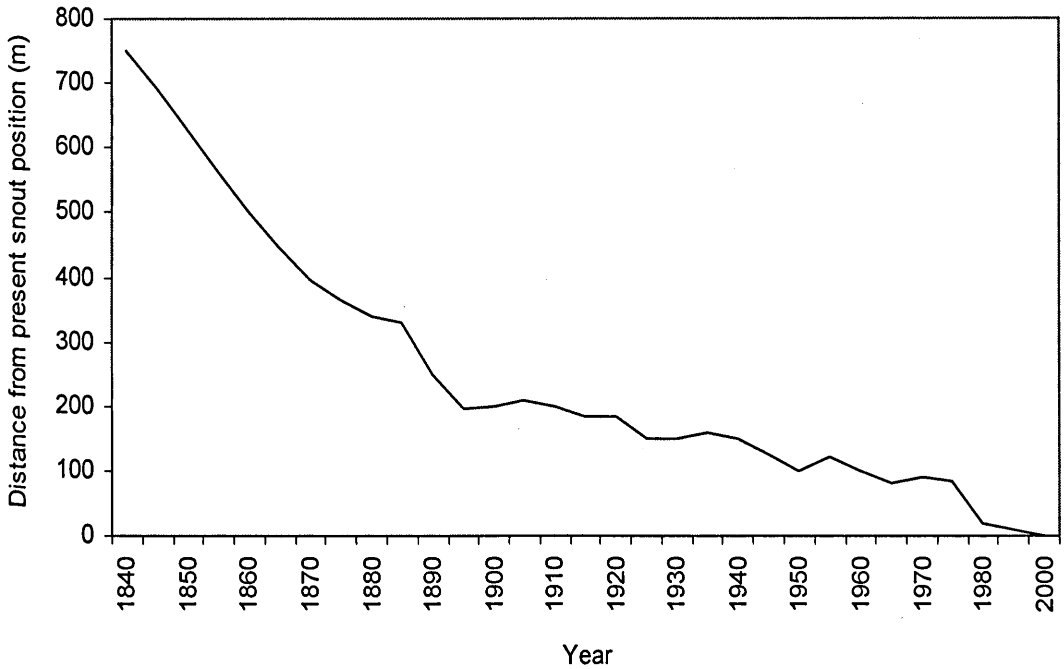


Figure 3.4. Variations in the position of the Taillon Glacier snout in relation to its present position (1840-2004). Modified from Gellatly et al. (1995), McGregor et al. (1995b) and Association Moraine Pyrénéenne de Glaciologie (2003).

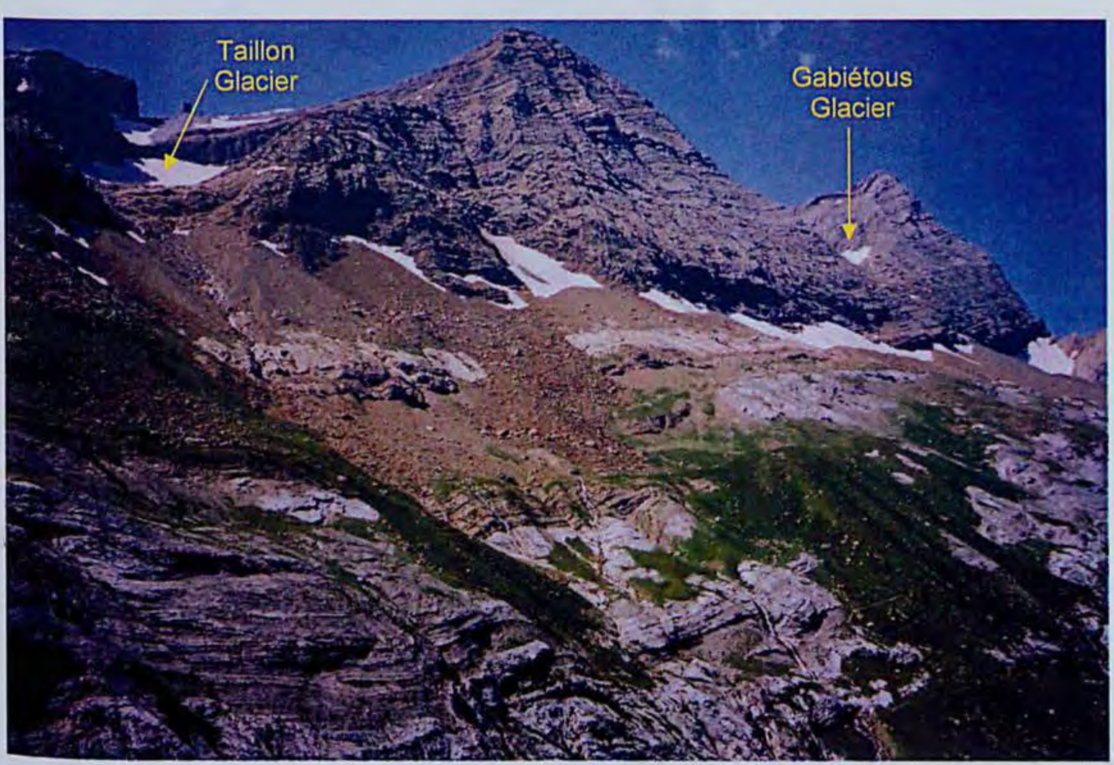


Plate 3.2. Les Gabiétous Massif (photographed from the northeast) with seasonal snowpacks below 2500m, le Taillon (3144m; centre) and the Pic des Gabiétous (2935m; right). The Taillon and Gabiétous Glaciers are highlighted

Plate 3.3. The Taillon Glacier exposed following transient snowline retreat (21/07/02; day 202)

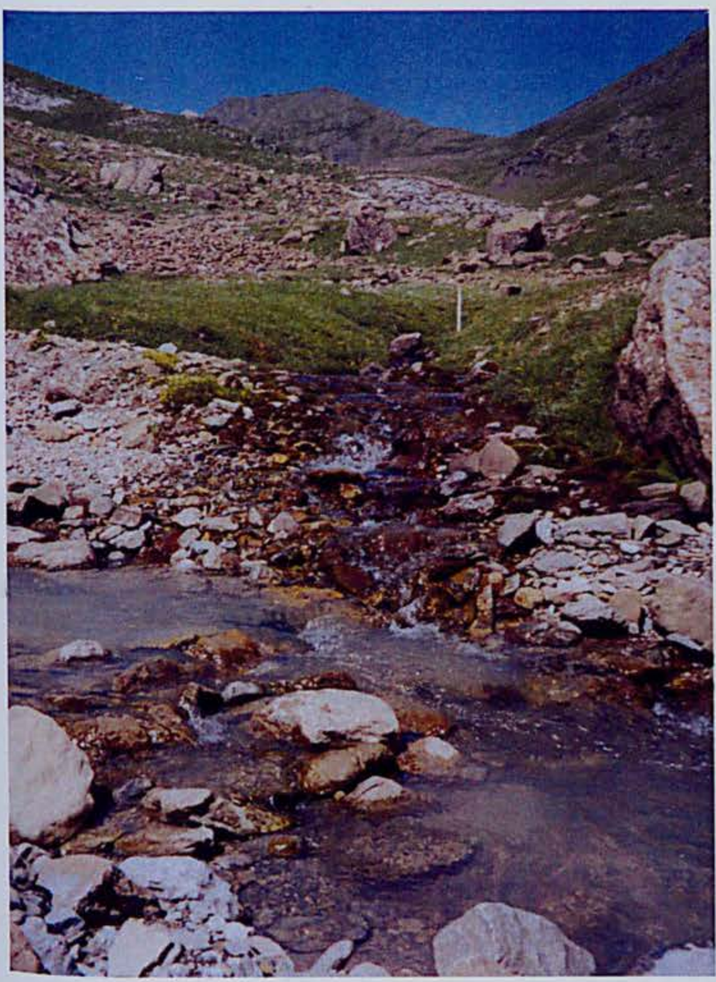


Plate 3.4. The Resurgence des Crampettes, a karstic spring that emerges in the lower Vallée des Pouey Aspé and flows into the Taillon Glacier stream

Plate 3.5. Hillslope groundwater streams draining aquifers on the south-facing slopes of the catchment

The Taillon Glacier now covers 15 ha (41% of its 36.5 ha catchment). It is currently retreating by 5.0-5.5 m per year (Association-Moraine-Pyrénéenne-de-Glaciologie, 2003). Meltwaters flow out of the Taillon Glacier's sub-catchment via a bedrock-confined reach and descend into the lower eastern part of the catchment (≤1900 m), an altitudinal drop of 700 m over approximately 1 km distance.

The Gabiétous Glacier is a small hanging glacier, which provides the source of the Tourettes stream in the Vallée des Pouey Aspé. It covers an area of 9 ha and has retreated by approximately 11 m since 1989 (Association-Moraine-Pyrénéenne-de-Glaciologie, 2003). The Gabiétous Glacier covers an altitudinal range of 250 m, descending from the cirque headwall at 2935 m to the terminus at 2685 m. Meltwaters issuing from the glacier flow into the western end of the Vallée des Pouey Aspé.

As a result of the high-altitude alpine location, snowpacks cover parts of the Taillon-Gabiétous catchment for much of the year below 2500 m. During the ablation season from May to October, the snowline generally recedes and exposes glacial ice on the two glaciers (Hannah and Gurnell, 2001). Small remnant snowpacks often remain on the highest peaks throughout the melt season. Permanent snow and ice comprise approximately 5.0% of the catchment area (Hannah *et al.*, 2000b).

On south facing catchment slopes there are several major hillslope tributaries (Plate 3.5) because much of this part of the catchment is underlain by permeable rock formations (Souquet, 1967; Flachére, 1977). A small limestone area exists on the north facing side of the catchment routing meltwaters to karstic springs and seeps in the lower catchment (Les Crampettes and the Vallée des Pouey Aspé; Parc-National-des-Pyrénées, 1991). Some of the subterranean caverns are up to 250 m deep, and dye tracing studies have revealed through flow times range from 4-47 h at peak flow and low flow conditions, respectively (Parc-National-des-Pyrénées, 1991).

3.2.3. The climate of the Midi-Pyrénées

Meteorological data have been collected at the Pic du Midi climate station (2877 m), 10km north of the Taillon-Gabiétous catchment from 1882–1988, then from 1994 onwards (Hannah, 1997). Mean air temperatures for the region are 7.0°C in July and -7.5°C in January. Mean annual precipitation for the region is 925 mm (McGregor and Gellatly, 1996). Detailed discussion of recent climatic fluctuations in the Midi-Pyrénées can be found in Bücher and Dessens, (1991); Dessens and Bücher, (1995; 1997), McGregor *et al.* (1995b), Hannah (1997) and Smith *et al.* (2001).

3.3. GENERAL METHODS

This section describes methods used throughout the thesis. Monitoring of climate variables is discussed first (Section 3.5.1) as these are used to characterise hydroclimatological conditions influencing stream water column and bed temperature variability (Chapter 4). Information about stream gauging stations is provided in Section 3.3.2 onwards; hydrometric and water quality data are used in a number of chapters (Chapters 4-8). Methods and equipment for the collection of water column and streambed temperatures, stream discharge, suspended sediment and electrical conductivity are discussed in turn. Data logging protocols are also outlined. The collection of hydrochemical data during spatial surveys is detailed in Section 3.3.3; these data are used to separate water source contributions in Chapter 5 and 6. Methods for transient snowline monitoring are summarised in Section 3.3.4. Finally, benthic macroinvertebrate field collection methods used in Chapters 7 and 8 are discussed in Section 3.3.5.

3.3.1. Monitoring of meteorological variables

An Automatic Weather Station (AWS) was used to collect air temperature, incoming short-wave radiation and precipitation data, so that hydroclimatological conditions could be determined, and compared between the two melt seasons. Meteorological variables were continuously recorded by equipment located over the Taillon stream (Figure 3.5; Plate 3.6). Air temperature (°C) was measured using a Campbell HMP35AC temperature and relative humidity probe. Incoming short-wave radiation was measured with a Campbell SP1110 pyranometer. Instantaneous short-wave radiative fluxes were measured in Wm^{-2} from which daily totals were estimated in $MJm^{-2}d^{-1}$. Precipitation was measured with a Campbell ARG100 tipping bucket rain gauge.

3.3.2. Stream gauging stations

Stream gauging equipment was installed during the two summer melt seasons at three sites (Figure 3.5; Plate 3.7). At each gauging site, water column temperature, streambed temperatures at 0.05, 0.20 and 0.40 m depth, stream stage (water depth), electrical conductivity and turbidity were recorded. The gauging stations were located as follows:

- On the Taillon glacial stream (Site A), upstream of its confluence with the Resurgence des Crampettes, to estimate runoff from the Taillon Glacier sub-catchment (catchment area = 2.4 km^2; glacierized area = 6%; Plate 3.8).
- A second gauge was located on the Tourettes stream (Site B) to monitor runoff that predominantly originated from the Vallée des Pouey Aspé, with limited glacial influence (catchment area = 3.9 km^2; glacierized area = 2%; Plate 3.9).
- A third gauge was situated after the confluence of the Taillon and Tourettes streams (Site C), to monitor runoff from the Taillon and Gabiétous Glaciers, snowpacks and hillslope/karstic groundwater systems (catchment area = 6.9 km^2; glacierized area = 4%; Plate 3.10).

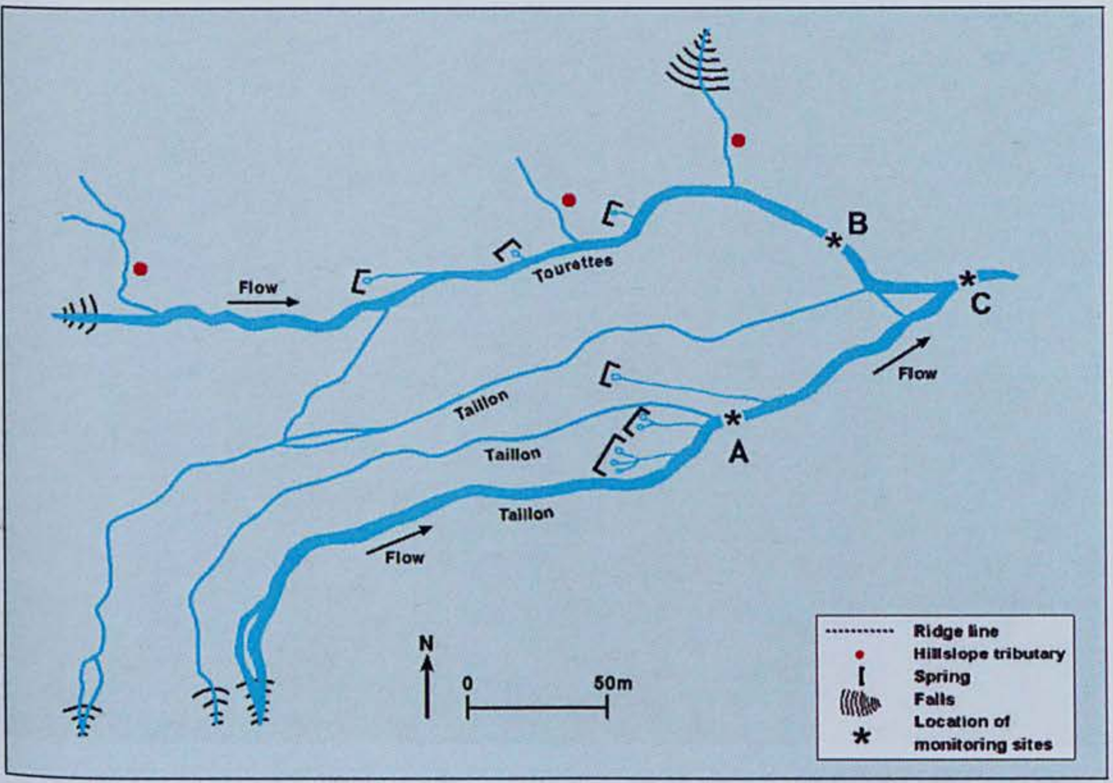


Figure 3.5. Map of the main study site at the confluence of the Taillon and Tourettes streams, showing locations of stream gauging sites and automatic weather station.

Plate 3.6. Automatic Weather Station located next to the Taillon glacial stream (facing downstream). Stream water is relatively clear as the photograph was taken during the morning prior to peak snow- and ice-melt.

Plate 3.7. The confluence area of the Taillon and Tourettes streams showing locations of stream gauging sites. T^1 and T^2 contribute to stream discharge at Site A. T^3 bypasses Site A and enters the Tourettes stream downstream of Site B. T^4 is a small glacial stream contributing to flow at Site B. RDC is the Resurgence des Crampettes.

Plate 3.8. Stream gauging station Site A located on the Taillon Glacier stream (facing downstream)

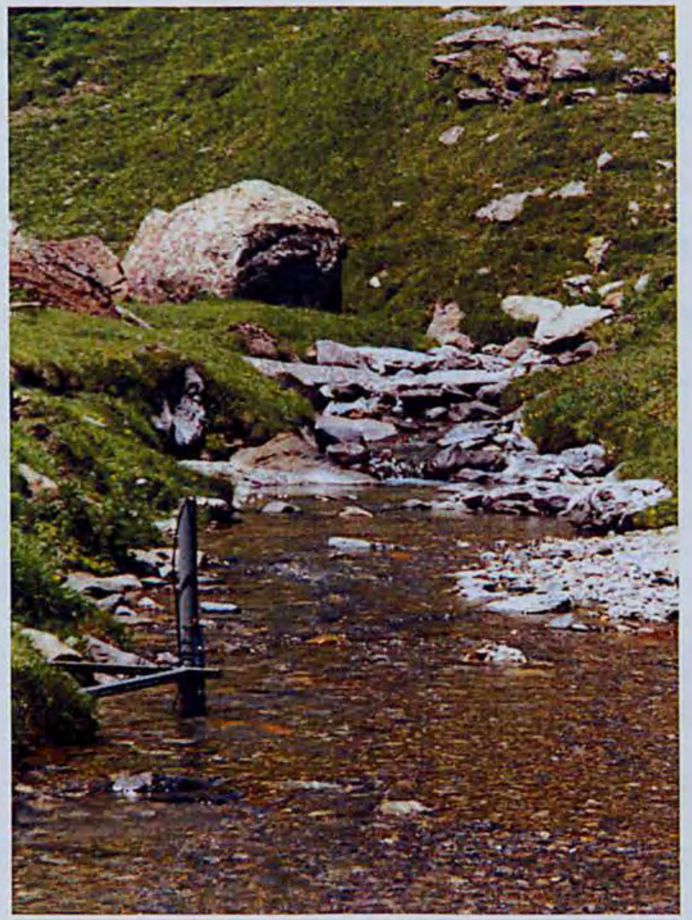


Plate 3.9. Stream gauging station Site B located on the Tourettes stream (facing upstream)

Plate 3.10. Stream gauging station Site C located below the confluence of the Taillon (left) and Tourettes (right) streams (facing upstream).

Water column and streambed temperatures

Water temperature was recorded continuously at the stream gauging stations using Campbell Scientific 247 temperature-electrical conductivity probes. Streambed temperatures were recorded using Campbell Scientific 107T thermistors. Streambed temperatures were also measured at the AWS. Water column temperatures were recorded at a number of additional sites throughout the catchment using Gemini TinyTag Plus temperature dataloggers (for further details see Chapter 4). All instruments measuring water column temperatures were housed within radiation shields (0.05-0.10 m above the streambed) that permitted free circulation of water around the sensors. All temperature sensors were cross-calibrated (Stevens *et al.*, 1975) in a water bath before and after field deployment, across and beyond the temperature range experienced in the field. Correction factors were obtained using the method of Evans and Petts (1997), which were within the manufacturers overall accuracy range (i.e. thermistors and TinyTag dataloggers = ±0.20°C).

Stream discharge estimation

Water stage was monitored using Druck PDCR-1830 pressure transducers mounted in stilling wells. Discharge (Q) was calculated for the range of observed flows using the velocity-area method (Herschy, 1985). Stage-discharge rating curves were constructed to provide continuous estimates of riverflow (see Section 3.4.3).

Discharge estimates (m^3s^{-1}) were obtained from stream transects divided into a minimum of 10 equally spaced segments (0.2 m width). Stream velocity was recorded at 0.6 depth at the centre of each segment using a Sensa RC2 electromagnetic current meter, with 2 sec readings averaged over 30 secs. Discharge was calculated using the sum of the product of cross-section width (w), depth (d) and velocity (v) measured for each segment using Equation 3.1 (Gordon *et al.*, 1992).

$$Q = (w_1 d_1 v_1) + (w_2 d_2 v_2) + ...(w_n d_n v_n) \qquad \textbf{(Equation 3.1)}$$

Turbidity and suspended sediment concentration

Continuous turbidity measurements at the three gauging sites were made using Partech IR40 infrared turbidity probes. Probes were located at approximately 0.3 flow depth, and adjusted regularly to prevent sensor exposure at low flows. Sensor heads were cleaned twice weekly to remove fine sediment deposits and algal growth. Turbidity-Suspended Sediment Concentration [SSC] rating curves were constructed to provide continuous estimates of [SSC]. These rating curves enabled comparison between the three gauging sites, as turbidity measurements were made in millivolts (mV), thus, outputs were not directly comparable due to slight differences in electronic circuit board configuration. Between site comparisons of turbidity measured simply as mV would be misleading due to the effect of suspended sediment particle size, shape and colour effects on turbidity measurements (Gippel, 1989).

Stream water samples for suspended sediment analysis were collected at the gauging sites over the range of turbidity measurements by submerging a pre-rinsed 500ml sample bottle to a depth of 10 cm until filled. All samples were taken from well-mixed stream sections close to the turbidity probes, although variation in suspended sediment concentration has been shown to be minimal across the proglacial stream cross-section (Gurnell *et al.*, 1992). In addition, two automated ISCO 2900 pump samplers were alternated between the gauging sites. Pump samplers were programmed to collect 500 ml of stream water to provide additional background samples and sample during storm events. Automated sampling was particularly useful given time constraints and safety considerations, because many storm generated high flows were accompanied by lightening.

All samples were filtered in the field through pre-weighed 0.45μm Whatman cellulose nitrate filters using Nalgene hand-operated vacuum pumps. Filter papers were air dried to remove excess moisture, then stored in sealed bags prior to laboratory analysis. On return from the field, filter papers were dried for 24 h at room temperature and reweighed to determine suspended sediment weight. Every fiftieth paper was retained unused to control for any weighing balance drift. Suspended sediment concentration was estimated in mgL^{-1}.

Electrical conductivity

Electrical conductivity was recorded continuously at the three gauging sites using Campbell Scientific 247 temperature-electrical conductivity probes located at the three gauging stations. Sensors were cleaned regularly to remove deposits of fine sediment within the measuring chamber. These probes measure electrical conductivity over the range 0.005 to 7.5 $mScm^{-1}$, with an accuracy of ±5% over the range 0.44 to 7.0 $mScm^{-1}$. All field observations were within this range.

Data logging and sensor scanning frequency

All AWS and gauging stations sensors were scanned every 10 s, from which 15 min averages (totals for precipitation) were computed. Data were stored on either Campbell Scientific CR10X or CR21X dataloggers. TinyTag temperature dataloggers recorded water temperature data at 15 min intervals. All dataloggers and TinyTags were synchronised prior to installation and internal clocks (set to GMT) checked regularly throughout both monitoring periods.

3.3.3. Hydrochemical sampling regime

This section details the sampling regime undertaken: (1) to characterise spatial and temporal hydrochemical dynamics of water sources (snowmelt, icemelt and groundwater), and; (2) to estimate the proportions of these different sources contributing to streamflow over the course of the two melt seasons (Chapter 5). Snowpack sampling methods and stream water sampling methods are detailed in turn.

Snowpack sampling

At the beginning of each field season, lower valley snowpacks had largely melted with the exception of a few small patches of 'old' snow. Therefore, snow samples were collected from snowpits dug on the Taillon Glacier. Three pits were excavated at the beginning of each field season along an altitudinal transect from the glacier snout (2550 m) to the lower accumulation zone (2700 m). Snowpits were dug using aluminium spades to a maximum depth of 4 m, or until glacier ice was encountered. Two samples were taken from each different snow layer; these were identified visually as bands of ice and snow of variable density represented consecutive melt and fresh snowfall episodes. Unused 125 ml HDPE bottles were pressed into the snowpack then snow samples were allowed to melt and filtered as for stream water samples (below). In 2002, additional snow samples were also collected one week into the field season to give an indication of the rate and extent of snowpack ion elution from the time of initial snow sample collection.

Stream water sampling

A hydrochemical sampling programme was carried out on a weekly basis at the three stream gauging locations. Additional samples were collected on the same day at a fourth site (Upper Site) 100 m downstream from the Taillon Glacier snout (Figure 3.2) to characterise stream hydrochemistry as a result of snow- and ice-melt in the upper catchment. Samples were collected twice daily at low (06:00-09:00 h) and high flow (14:00-16:00 h) to characterise diurnal variability in stream hydrochemistry as a result of daily cycles of meltwater generation. This sampling framework involved collecting samples in the lower Vallée des Pouey Aspé at daybreak (06:00-06:30 h), then climbing ~700 m to the Taillon Glacier before snow and ice melt began to contribute a significant amount of flow (08:30-09:00 h). Late afternoon peak-flow samples were collected first at the Taillon Glacier (15:00 h), before descending back into the Vallée to collect samples at the main gauging sites (16:00-16:30 h). After this +10 h sampling day, samples were carried back to base camp (1200 masl; a further 2 hrs walk) to allow samples to be frozen! Catchment wide sampling was undertaken monthly at several hillslope streams and karstic groundwater springs (Figures 3.2 and 3.5) throughout the Vallée des Pouey Aspé to characterise spatial and temporal variations in groundwater hydrochemistry.

A manual sampling technique was undertaken for all samples as immediate filtration was necessary to avoid post-sampling changes in water chemistry due to the high concentrations of suspended sediment in stream water (e.g. Brown *et al.*, 1994). Individual samples were collected in 500 ml bottles that were rinsed with stream water three times before the sample for analysis was collected. Sample was taken from this 500 ml bottle using a 30 ml syringe. After rinsing the syringe three times, 30 ml of stream water were passed through a filter unit (pre-rinsed with distilled water) housing a 0.45μm Whatman cellulose-nitrate paper, ensuring all inside surfaces were wetted. This initial filtrate was discarded. Sample bottles (60 ml HDPE) were then rinsed three times with 10 ml of filtrate, by replacing the cap each time and shaking vigorously for 10 s. Bottles were then filled with 55 ml of filtrate, leaving space for sample expansion during freeze storage. Samples were frozen to minimise any changes in hydrochemical composition before analysis at the end of the summer. Electrical conductivity was measured in the field for unfiltered aliquots of stream water with a portable WPA 35 electrical conductivity meter, and the pH of all samples was measured using a Jenway 3150 meter. Electrical conductivity and pH measurements were made on unfiltered aliquots of stream water. Details of laboratory techniques for hydrochemical analysis are provided in Section 3.5.5.

3.3.4. Transient snowline monitoring

Transient snowline altitudes were determined from weekly photographs of the upper catchment taken from an elevated bedrock terrace vantage point at approximately 2500 m. These data were collected to provide additional background information on snowline retreat and, thus, decreasing snowpack and increasing icemelt contributions to streamflow over the summer melt seasons. With the exception of the first week of monitoring in both melt seasons, the transient snowline was at or above the altitude of the Taillon Glacier snout. Photographs were compared with an Institut Géographique National 1748OT map (1:25000) to determine snowline altitude.

3.3.5. Benthic macroinvertebrate sampling

Benthic macroinvertebrate samples were collected at the three gauging sites at approximately fortnightly (bi-weekly) intervals during both melt seasons, so that community responses and life history variability could be established in relation to dynamic water source contributions. The three sites were sampled six times during both field seasons (Table 3.1). Samples were collected on the same day at each site, and on approximately the same dates each year. Benthic macroinvertebrate samples were collected on different dates at the beginning of the 2002 field season due to time restrictions as a result of installing stream gauging equipment. Hereafter, samples are coded by site/year/date (i.e. sample C/02/1 represents samples collected at Site C in 2002 on sampling date 1). Sampling dates are listed in Table 3.1.

Five replicate 0.1 m^2 Surber samples were collected randomly from 15 m reaches using a 250-µm mesh net. All samples were collected downstream of stream gauges to prevent sampling disturbance influencing stream gauging equipment. Samples were collected prior to peak daily flow conditions to avoid sampling areas wetted only at high flow. All samples were preserved in 4% formaldehyde until they were transported back to the laboratory for sorting and identification.

Water depth was measured at the same position as each benthic macroinvertebrate sample. Current velocities (0.6 depth) scanned every two seconds and averaged over 30 secs were measured using an electromagnetic current meter. Substrata size was assessed for each site by measuring b-axis lengths of 100 randomly selected stones, and substrate diversity was calculated using Simpson's index (Zar, 1999). Percentage substrata composition was assessed visually for each 0.1m^2 area immediately prior to Surber samples being collected. Five substrata categories were defined: particles (1) < 0.0001m diameter (very fine sediment), (2) 0.0001 – 0.002m diameter (silt), (3) 0.002 – 0.05m diameter (gravel), (4) 0.05 – 0.2m diameter (cobbles), and (5) >0.2m diameter and bedrock. Channel stability was evaluated using the bottom component of the Pfankuch (PFAN) index (Pfankuch, 1975) on each sampling date. PFAN assesses the stability of the streambed by generating a score based on rock angularity, substrata brightness (in terms of algal staining), substrate consolidation (packing/bed armouring), scour and deposition, and aquatic vegetation presence/absence.

3.4. FIELD DATA PROCESSING

3.4.1 Error Sources in data collection

Whilst undertaking fieldwork, methodical (at least twice-daily) checking of automated data output from dataloggers (coupled with at least twice weekly probe maintenance), resulted in very few errors within the time-series. Errors may result from observational, environmental, instrumentation and/or practical problems. Errors associated with instrument measuring accuracy are detailed in Table 3.2. These accuracy ranges should be considered alongside discussion of results in subsequent chapters. Foreseeable observer, environmental and practical errors, with their mitigation techniques, are summarised in Table 3.3.

3.4.2 Field data evaluation and quality control

Logged 'raw' field data were evaluated on a twice-weekly basis following downloading. Therefore, potentially unreliable runs of data could be recognised and problems remedied without delay. However, most unreliable data were single 15 min data points, most likely caused by momentary interference of the sensors or corruption in logger storage. These erroneous data were corrected by linear interpolation between previous and subsequent data points. Longer periods of erroneous data were very rare and never exceeded 3 h. None of these invalid measurements occurred during extreme hydrological events, therefore, 'missing' or erroneous data could easily be corrected through a combination of correlation with data recorded by other probes at the same gauging station, and correlation with the same variable

Table 3.1. Dates on which macroinverebrate samples were collected, with calendar days in parentheses

Year/ Sampling Date	Site A	Site B	Site C
2002			
1	01/07 (182)	26/06 (177)	02/07 (183)
2	11/07 (192)	11/07 (192)	11/07 (192)
3	24/07 (205)	24/07 (205)	24/07 (205)
4	07/08 (219)	07/08 (219)	07/08 (219)
5	21/08 (233)	21/08 (233)	21/08 (233)
6	03/09 (246)	03/09 (246)	03/09 (246)
2003			
1	27/06 (178)	27/06 (178)	27/06 (178)
2	10/07 (191)	10/07 (191)	10/07 (191)
3	24/07 (205)	24/07 (205)	24/07 (205)
4	06/08 (218)	06/08 (218)	06/08 (218)
5	20/08 (232)	20/08 (232)	20/08 (232)
6	03/09 (246)	03/09 (246)	03/09 (246)

Table 3.2. Electronic sensors used at stream gauges and automatic weather station (AWS), with output accuracies and measurement ranges

Variable	Instrument	Instrument Error (range)
Stream gauges		
Stream velocity	Sensa-RC2 electromagnetic current meter	0.005 ms^{-1}
River stage	Druck PDCR-1830 pressure transducer	±0.1%
Electrical conductivity	Campbell 247 conductivity and temperature probe	±5% (0.44 to 7.0 $mScm^{-1}$)
Water temperature	Campbell 247 conductivity and temperature probe	±0.2°C (-35 to +48°C)
	Gemini TinyTag Plus temperature datalogger	±0.2°C (–30°C to +50°C)
Streambed temperature	Campbell 107T thermistor	±0.2°C (-40 to +56°C)
Turbidity	Partech IR40C	(0-1500 mgL^{-1})
AWS		
Air temperature	Vaisala HMP35AC temperature and humidity probe	±0.2°C (-39.2 to +60°C)
Incoming short-wave	Campbell SP1110 pyranometer	±1.5%
Precipitation	Campbell ARG100 tipping bucket rain gauge	0.05 mm

Table 3.3. Potential sources of error in data collection and summaries of rectification procedures

Instrumentation	Problem	Solution
Hydrological Variables		
Stream gauging stations	Animals eating cables	Bury under rocks, or encase in plastic tubing
	Drifting vegetation covering sensors	Clean regularly
	Sediment/Biofilm affecting turbidity readings	Clean at least twice weekly with a toothbrush
	Sediment/small invertebrates affecting conductivity probe readings	Clean twice-weekly with a small brush
	Exposure of turbidity/conductivity probes	Adjust sensors height at extreme low flows
	Logger failure	Download regularly Leave storage module connected to CR21X
	Power supply failure	Check battery voltage daily Rotate solar panels between batteries to ensure trickle charging
	Random instrument error	None
	Condensation within housing	Silica gel desiccant
	Sensor calibration	Cross calibrate before and after field season
Stream gauging/ rating curves	Uneven bed affecting depth measurements	Re-survey frequently
	Difficulty holding current meter straight in high flows	Brace against body
	Turbulence affecting readings	Clear large material from cross section before starting stream gauging Average velocities over 30 s
	Sagging tape measure affecting width measures	Pull tape measure taught before each gauging
	Scour and fill changing stage: stream cross sectional area relationship	Check regularly Manually record stage regularly Multiple ratings
	Turbulence around pressure transducer	High temporal resolution scanning (10 s) Stilling well
	Sediment blocking pressure transducer heads	Clean weekly
Automatic Weather Station		
Precipitation	Dead ants blocking water intake	Shield intake with 500μm mesh Clean regularly
	Rain splash	Shield
	Water retained in bucket after tipping	Check gauge is level
	Cattle kicking gauge over	Shield with heavy rocks
AWS general	Bird damage to sensors	Wire guards
	Lightening strike	Sensors and data logger earthed
	Direct insolation on thermistors	Shield using temperature screens
	Shading of sensors by mast or other instruments	Mount sensors on cross arms

at another gauging station. The maximum amount of data replaced by these methods totalled 3.8% for Site B in 2003.

3.4.3 Stage-discharge relationships

All river stage time-series were converted to 15 min discharge estimates using stage-discharge rating curves (Figures 3.6 and 3.7; Table 3.4). Rating equations were determined following the procedure of Smith (1999). Multiple rating curves (Figure 3.7) were required in 2003 following channel scour during peak flows. An incremental change from pre-peakflow to post-peakflow rating equations was undertaken to account for the changing channel bed during these erosive flows.

3.4.4 Turbidity-suspended sediment concentration relationships

Rating equations were developed to estimate continuous time-series of suspended sediment concentration from turbidity measurements (Figures 3.8 and 3.9; Table 3.5), using a similar procedure as for stage-discharge relationships. SSC-turbidity relationships often vary in their form as the melt season progresses as sediment source areas and, thus, sediment character change (Gurnell *et al.*, 1992). Relatively strong relationships were found between SSC and turbidity, despite the wide detection range of the sensors and potentially large errors introduced by the filtration method of calibration (Gippel, 1989). In 2002, the sensor located at the gauge on the Taillon glacial stream produced a two-phase response when turbidity exceeded ~1900 mV. Therefore, two individual linear regressions were applied to these data to better describe suspended sediment concentrations at high turbidity (Figure 3.8a).

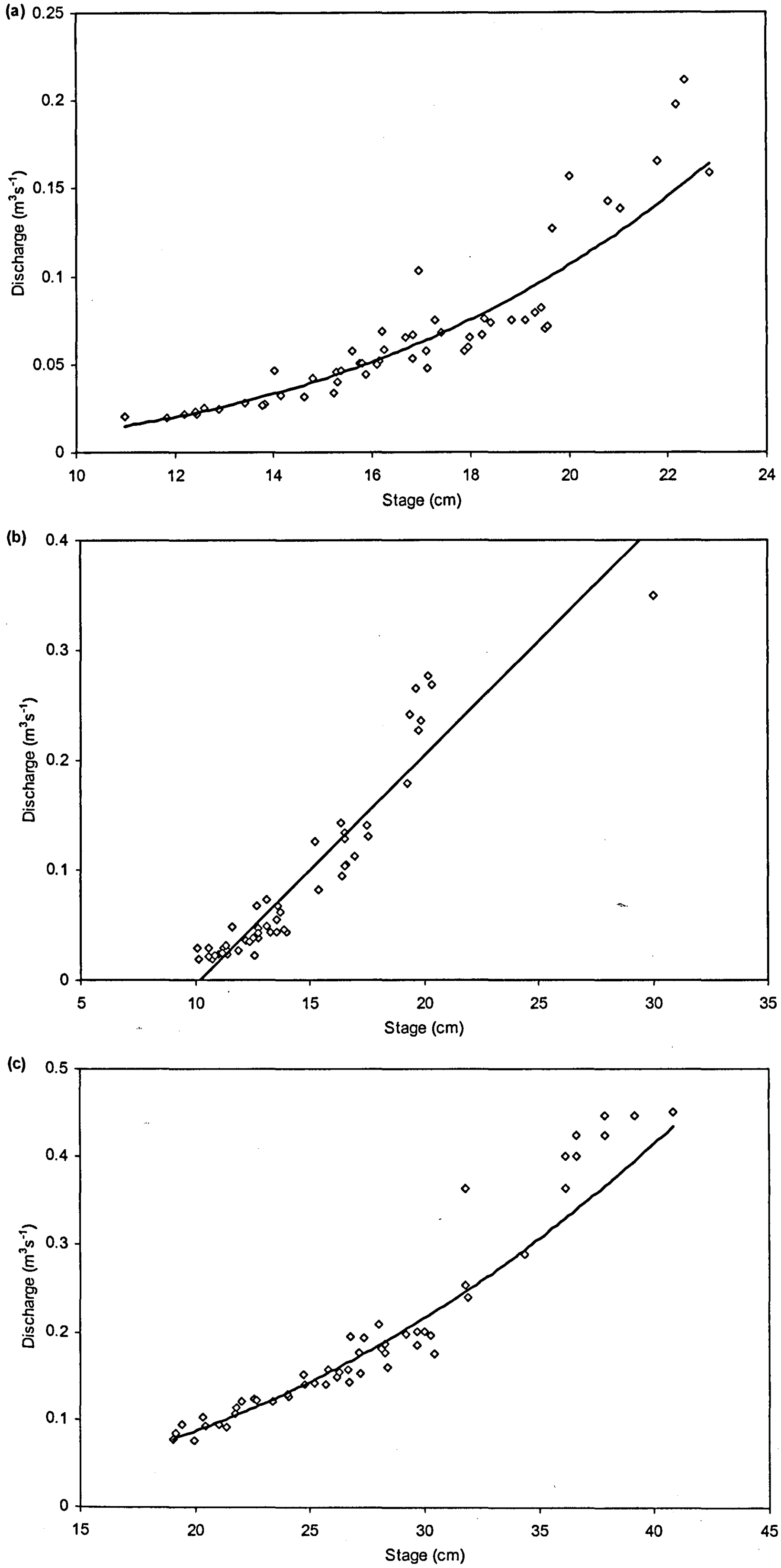


Figure 3.6. Stage-discharge rating curves for the 2002 field season at (a) Site A, (b) Site B, and (c) Site C.

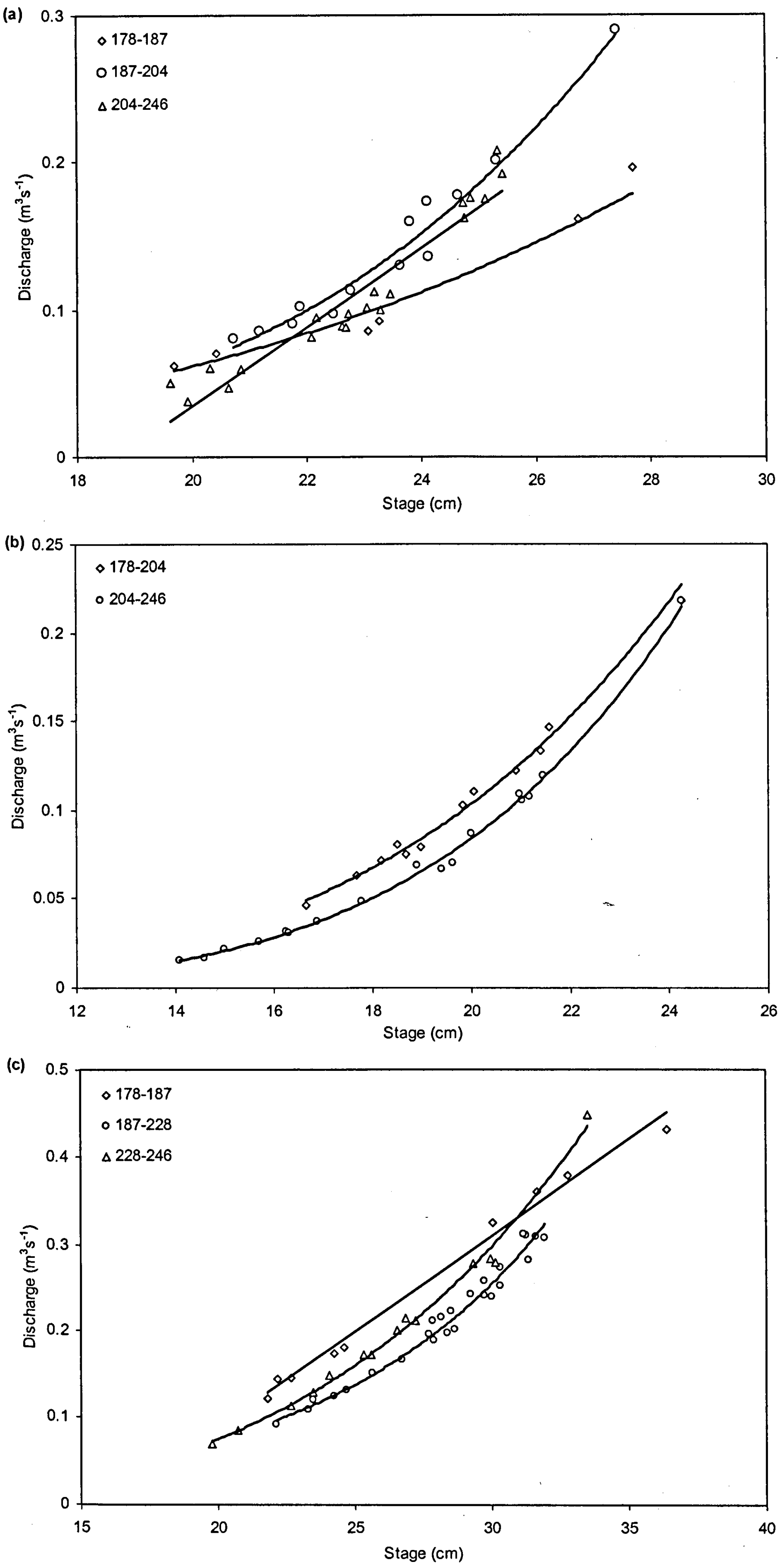


Figure 3.7. Stage-discharge rating curves for the 2003 field season at (a) Site A, (b) Site B, and (c) Site C.

Table 3.4. Stage-discharge rating equations for the three stream gauging stations

Melt Season	Site	Dates	Stage-discharge relationship	r^2
2002	A	All	$Q=0.000006S^{3.2589}$	0.902
	B	All	$Q=0.0208S-0.2123$	0.898
	C	All	$Q=0.0001S^{2.2589}$	0.954
2003	A	178-187	$Q=0.0038\exp^{0.1397S}$	0.972
		187-204	$Q=0.0317S-0.595$	0.966
		204-246	$Q=0.0005\exp^{0.2318S}$	0.977
	B	187-204	$Q=0.0000005S^{4.0713}$	0.989
		204-246	$Q=0.00000004S^{4.855}$	0.996
	C	178-187	$Q=0.0221S-0.3549$	0.991
		187-228	$Q=0.0063\exp^{0.1232S}$	0.982
		228-246	$Q=0.000003S^{3.4023}$	0.994

Table 3.5. Turbidity-SSC rating equations for the three stream gauging stations

Melt Season	Site	Turbidity Range	Turbidity-SSC relationship	r^2
2002	A	<1900	SSC=0.473T-0.6011	0.902
		>1900	SSC=28.091T-52590	0.777
	B	All	SSC=0.468T-46.772	0.741
	C	All	SSC=0.3828T-0.9158	0.881
2003	A	All	SSC=0.6165T-66.342	0.974
	B	All	SSC=0.3402T-58.778	0.987
	C	All	SSC=0.737T-69.875	0.830

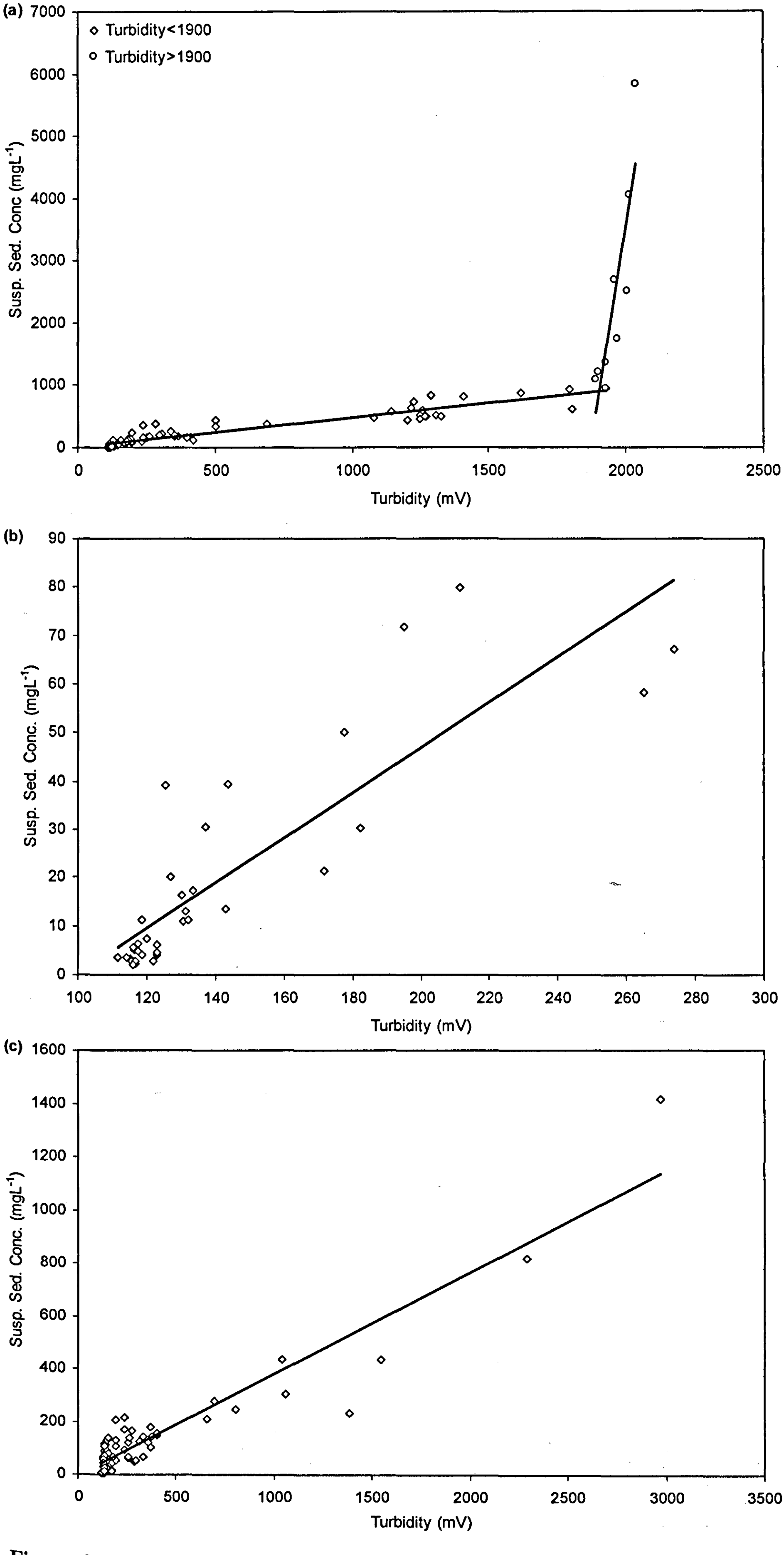


Figure 3.8. SSC-turbidity rating curves for the 2002 field season at (a) Site A, (b) Site B, and (c) Site C.

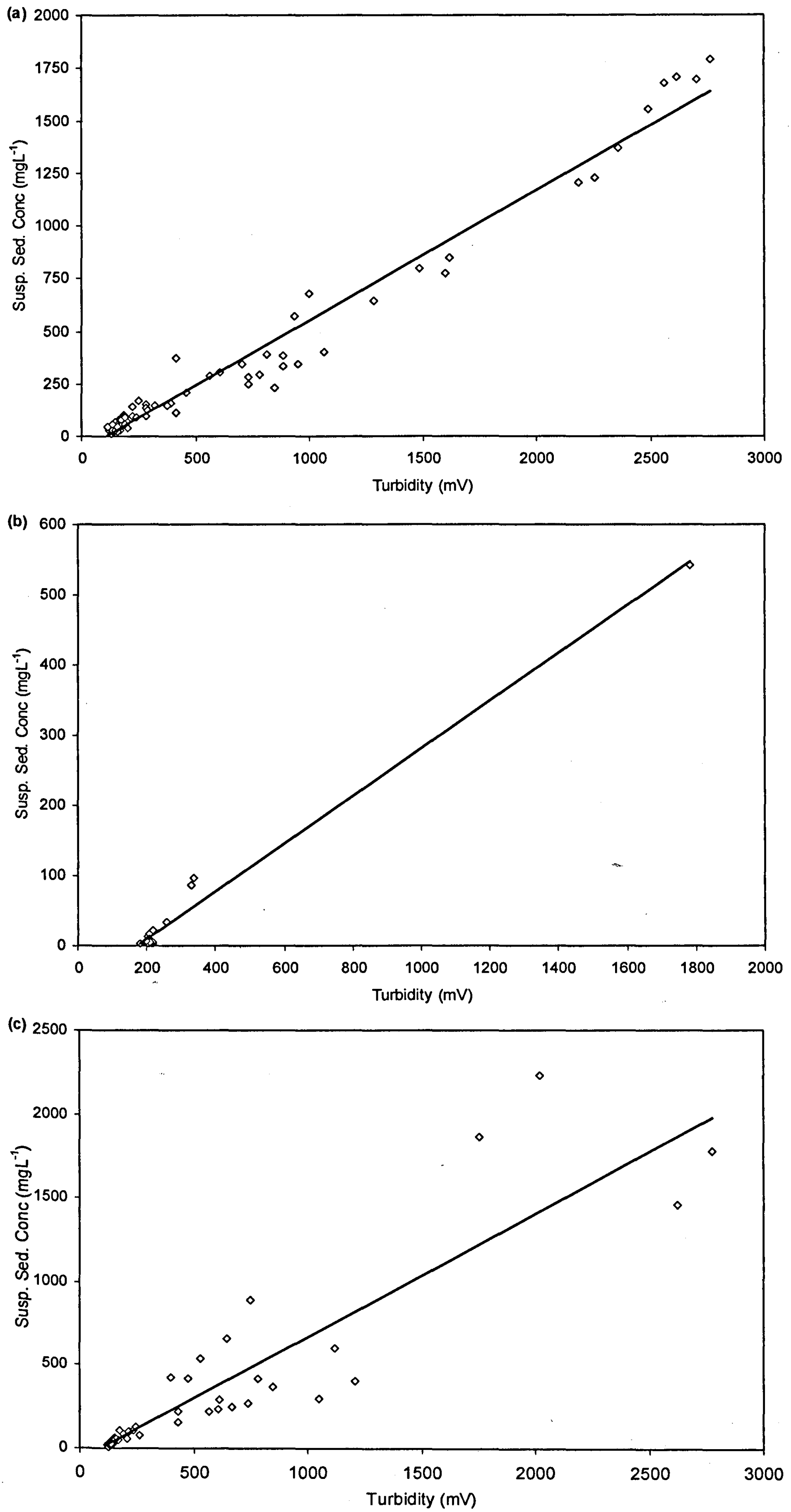


Figure 3.9 SSC-turbidity rating curves for the 2003 field season at (a) Site A, (b) Site B, and (c) Site C.

3.4.5. Laboratory analysis of hydrochemistry samples

Concentrations of major ions were determined using a Dionex 4000i ion chromatograph in conjunction with an automatic sampler. Concentrations of major cations (Sodium, Potassium, Magnesium and Calcium) were determined using an IonPac CS12 cation exchange column. Major anion concentrations (Chloride, Nitrate and Sulphate) were determined using an IonPac Fast Anion exchange column. Silica concentrations were determined using a FIAStar 5023 spectrophotometer and the molybdosilic acid method (Foss Tecator, 2001). Bicarbonate concentrations were estimated from charge-balance deficits. Calibration standards (0.05-10 ppm) were prepared using reagent grade compounds and deionised distilled water. Blank samples (deionised distilled water) were evaluated every 10 samples. Previous studies have shown these methods introduce an average analytical error of <5% for alpine glacierized catchments (Brown, 1991; Hodson, 1994). Analysis of replicate samples by these authors suggests overall precision of Ca^{2+}, Mg^{2+} and Na^{+} to be ±2.5% and K^{+} to be approximately ±10%. Precision errors of SO_4^{2-} and Cl^{-} have been shown to be <4%, and NO_3^{-} precision errors to be up to 20% (Hodson *et al.*, 2002). Precision error estimates for dissolved Si concentrations are ≤5% (Hodson *et al.*, 2002).

3.4.6. Benthic macroinvertebrate sorting and identification

Organisms were sorted under a light microscope (x10 magnification) then stored in 70% ethanol. Coarse benthic organic matter (CBOM) was separated from macroinvertebrates. After drying and weighing, CBOM was ashed at 500°C for 1 h to determine ash free dry weight. Wherever possible, Chironomidae, Ephemeroptera, Plecoptera, Trichoptera were identified to species, but other taxa could only be confidently identified to genus/family. Very few recent specific identification keys exist for French benthic macroinvertebrates, and published material on the identification of larval stages of many endemic Pyrénéan taxa are unavailable. A list of European publications used and taxonomic experts consulted is provided in Appendix A.

To achieve quantitative estimates of Chironomidae (due to extremely high abundances), a fixed count sub-sample was taken from each sample. Individuals were agitated in a delineated tray, and then all individuals removed from randomly selected compartments. This process was repeated until a minimum number of 50 individuals were obtained. If this target number of 50 was exceeded by more than 20%, the sub-sample was further divided until between 50 and 60 individuals were sampled (Barbour and Gerritsen, 1996). The lowest percentage of sub-sampled individuals from a sample was 3% in 2002, and 6% in 2003. For samples containing <50 Chironomidae, all individuals were identified. Chironomidae were cleared in a hot solution of 10% KOH for 2-10 minutes, rinsed in distilled water and mounted in dimethyl hydantoin formaldehyde solution. Specimens were mounted with head capsules ventrally and identified at x600-1000 magnification.

3.5. SUMMARY

This chapter has discussed the investigative design and methodology utilised over the 2002 and 2003 melt seasons, in addition to post-fieldwork data processing and laboratory techniques. The data collected enable the analysis and interpretation of water column and streambed temperature dynamics (Chapter 4), hydrochemical characterisation of spatial and temporal water source contributions to streamflow (Chapter 5), stream physico-chemical habitat variability in relation to water sourcing (Chapter 6), benthic macroinvertebrate community responses to physico-chemical habitat dynamics (Chapters 7 and 8), and an integrated hydroecological understanding of alpine streams (Chapter 9).

CHAPTER 4
WATER COLUMN AND STREAMBED TEMPERATURE DYNAMICS WITHIN THE TAILLON-GABIÉTOUS CATCHMENT

A field-based assessment of traditional temperature based alpine stream habitat classifications

4.1. CHAPTER OVERVIEW

This chapter examines thermal variability at eight sites within the Taillon-Gabiétous catchment, in order to provide a field-based assessment of temperature based alpine stream classifications discussed in Chapter 2. The chapter develops melt-season (Section 4.4.1) and sub-seasonal (Section 4.4.2) hydroclimatological contexts, to understand the key variables driving seasonal and sub-seasonal water column (Section 4.4.3) and streambed (Section 4.4.4) temperature dynamics. A general discussion of thermal variability in the catchment within the context of previous research (Section 4.5) is followed by a consideration of the implications for alpine stream classifications and ecological communities (Section 4.6).

4.2. INTRODUCTION

Alpine glacierized catchments are characterised by water source contributions that vary markedly in space and over time-scales from diurnal to inter-annual (Smith *et al.*, 2001; Brown *et al.*, 2003). This hydrological dynamism may be responsible for much of the thermal heterogeneity found in alpine proglacial floodplains (Ward *et al.*, 1999; Malard *et al.*, 2001; Uehlinger *et al.*, 2003). Water temperature is one of the primary physical habitat factors influencing the distribution and diversity of macroinvertebrate taxa in lotic ecosystems (Vannote and Sweeney, 1980; Ward and Stanford, 1982; Ward, 1985; Petts, 2000) especially in alpine environments (Ward, 1994; Milner *et al.*, 2001). It is hypothesised that as water temperature increases downstream along glacial rivers, more diverse benthic communities become established (Milner and Petts, 1994; Milner *et al.*, 2001).

Traditionally, ecological alpine stream classifications have relied primarily upon temperature variations to explain the characteristic benthic communities found in different streams (Steffan, 1971; Ward, 1994; see also Chapter 2). Kryal (glacier-fed) streams are classified as being between 0-4°C and relatively stable. Rhithral (snowmelt) streams have maximum temperatures of 5-10°C and generally fluctuate diurnally. Krenal (groundwater) streams are thermally stable, with only a 1-2°C range over an annual cycle (Ward, 1994). However, the dynamic nature of climate and water source contributions in alpine catchments may result in a greater amount of thermal variation than these traditional classifications indicate, making such divisions somewhat arbitrary (Brown *et al.*, 2003; see also Chapter 2). Therefore, an understanding of the physical processes driving thermal habitat gradients is fundamental for accurate stream classification, and, thus, assessment of ecological response. However, few studies have determined temperature variations in non-glacial alpine streams (Ward *et al.*, 1999; Malard *et al.*, 2001).

Distinct annual, seasonal and diurnal fluctuations in alpine stream water column temperatures are related to variable source water inputs and changes in incoming solar radiation and air temperature (Constantz, 1998; Füreder, 1999; Ward *et al.*, 1999; Malard *et al.*, 2001) and may be enhanced by the large surface-area to volume ratios that often characterise upland streams (Webb and Walling, 1993). However, heat gains/losses and transfers within river systems are complex, occurring by a combination of radiation, conduction, convection and advection (Hondzo and Steffan, 1994; Silliman *et al.*, 1995; Hannah *et al.*, 2004). These energy exchanges add and remove heat to and from the stream. Inputs may occur by: incident short-wave (solar) and long-wave (downward atmospheric) radiation, condensation, friction at the channel beds and banks, and chemical and biological processes. Losses may include reflection of solar radiation, emission of long-wave (back) radiation and evaporation. Sensible heat and water column-bed energy transfers may cause gains or losses. In addition to these exchanges, energy may be advected by: in/out flowing stream discharge, evaporated water, groundwater up/downwelling, tributary inflows and precipitation.

Recently, the riverbed has been identified as an important heat source and sink affecting overlying channel water temperatures in humid-temperate environments (Evans *et al.*, 1998; Hannah *et al.*, 2004). Temperature gradients within the ecologically active surface bed layer where surface (stream channel) water and groundwater interact (termed the hyporheic zone; (termed the hyporheic zone; Stanford and Ward, 1988; Harvey and Bencala, 1993; White, 1993), are controlled by fluxes of water passing through it (convection and advection; Vaux, 1968) and bed conduction resulting from solar radiation and contact between water and substrate (Comer and Grenney, 1977). Streambed temperatures have been found to be highly spatially and temporally variable due to climatological, hydrological (hydraulic), sedimentary and geomorphological factors in temperate, humid and desert environments (e.g. White *et al.*, 1987; Crisp, 1990; Evans *et al.*, 1995; Webb and Zhang, 1999; Hannah *et al.*, 2004). In comparison, there is a paucity of research on alpine streambed thermal behaviour, with only Malard *et al.* (2001) examining the role of hydrological (hydraulic) influences.

Diurnal temperature patterns of surface waters have been shown to be similar to those of the streambed (0.30 m) in glacial streams (Malard *et al.*, 2001) but little is known of the hydrological, climatological, or sedimentological controls. One of the most salient features of glacier-fed streams is marked diurnal and annual discharge variations (Röthlisberger and Lang, 1985). Although raised hydraulic head and interstitial flow velocities at high flows may affect streambed temperatures (Malcolm *et al.*, 2004), the influence of discharge fluctuations upon water column and streambed temperatures in alpine catchments has not been studied. Moreover, although Uehlinger *et al.* (2003) relate air temperatures and incoming solar radiation (measured at weather stations 4 km and 10 km away) to water temperatures in glacial streams, no studies have examined the role of local valley climate in influencing temperature fluctuations. Non site-specific data may provide general information about trends, but they are insufficient for understanding processes operating at sub-catchment scale (Johnson, 2003).

This chapter reports upon a detailed, high-resolution (15 min) study of water column and streambed temperatures at eight sites over two consecutive melt-seasons. The aims are: (1) to characterise the nature and dynamics of water column and streambed thermal patterns for streams draining alpine water sources, (2) to investigate stream thermal variability under a range of hydroclimatological conditions to improve understanding of the key controls on alpine stream thermal variability, and (3) use the findings of (1) and (2) to demonstrate how stream thermal variability within the Taillon-Gabiétous catchment renders traditional (principally temperature based) alpine stream classifications problematic.

4.3. METHODOLOGY

4.3.1. Sampling framework

Field observations made between 1 July (day 182) and 2 September (day 245) 2002 and 2003 are presented for analysis of data over the same time frames. Hereafter, dates are referred to using the calendar day and time is quoted in Greenwich Mean Time (GMT). To characterise atmospheric conditions, air temperature, incoming short-wave radiation and rainfall were monitored using an Automatic Weather Station (AWS; Figure 4.1). Air temperatures were also measured at the Taillon Glacier snout ($T_{a(Taillon)}$) using a Gemini TinyTag temperature datalogger housed in a radiation shield.

Water column temperatures were monitored continuously at eight locations within the catchment (Figure 4.1; Table 4.1): Sites A, B (Gauging station Site A), D and F (Gauging station Site C) were located on the Taillon glacial stream; Sites C (karstic), G (hillslope) and H (karstic) were groundwater springs and tributaries along the lower Vallée des Pouey Aspé. Site E on the Tourettes stream (Gauging station Site B) is predominantly groundwater-fed, with a small glacial input (Smith *et al.*, 2001). Sites were lettered consecutively with distance away from the Taillon Glacier snout. In addition at Sites D, E and F, streambed temperatures were measured at 0.05 m ($T_{b0.05}$), 0.20 m ($T_{b0.2}$) and 0.40 m ($T_{b0.4}$) depth. At Site D in 2002, the thermistor at 0.05 m depth developed a recurrent fault; therefore, data were deemed unreliable and are not presented. Stream discharge was measured at Sites B, E and F. Surface bed sediments for Sites D, E and F were characterised by b-axis lengths for 100 randomly selected clasts (Table 4.1). Bed surface sediments were coarsest at Site D (D_{50} = 89 mm), similarly coarse at Site F (D_{50} = 85 mm) but fine skewed at Site E (D_{50} = 58 mm).

4.3.2. Data analysis

Temperature-duration curves were constructed for water column temperatures at all eight sites, and streambed temperatures at Sites D, E and F, to illustrate the percentage time a temperature is equalled or exceeded at each sampling location. The form of these curves depicts the nature of thermal characteristics as steep (low) gradient curves reflect high variability (thermal constancy).

Pearson's Product Moment Correlation co-efficients (r) were used as a measure of association between air temperatures, discharge, incoming short-wave radiation, and water column and streambed temperatures at 15 min resolution. For air temperature-water column relationships at Site A, air temperatures measured at the Taillon Glacier snout were used. Correlations between air temperature and water column temperatures elsewhere used air temperatures recorded in the Vallée. Cross-correlation functions (Norusis, 2003) were computed to assess lags and leads in the maximum correlation between air, water column and streambed temperatures up to ±24 hours. Correlations were considered significant for $p<0.05$.

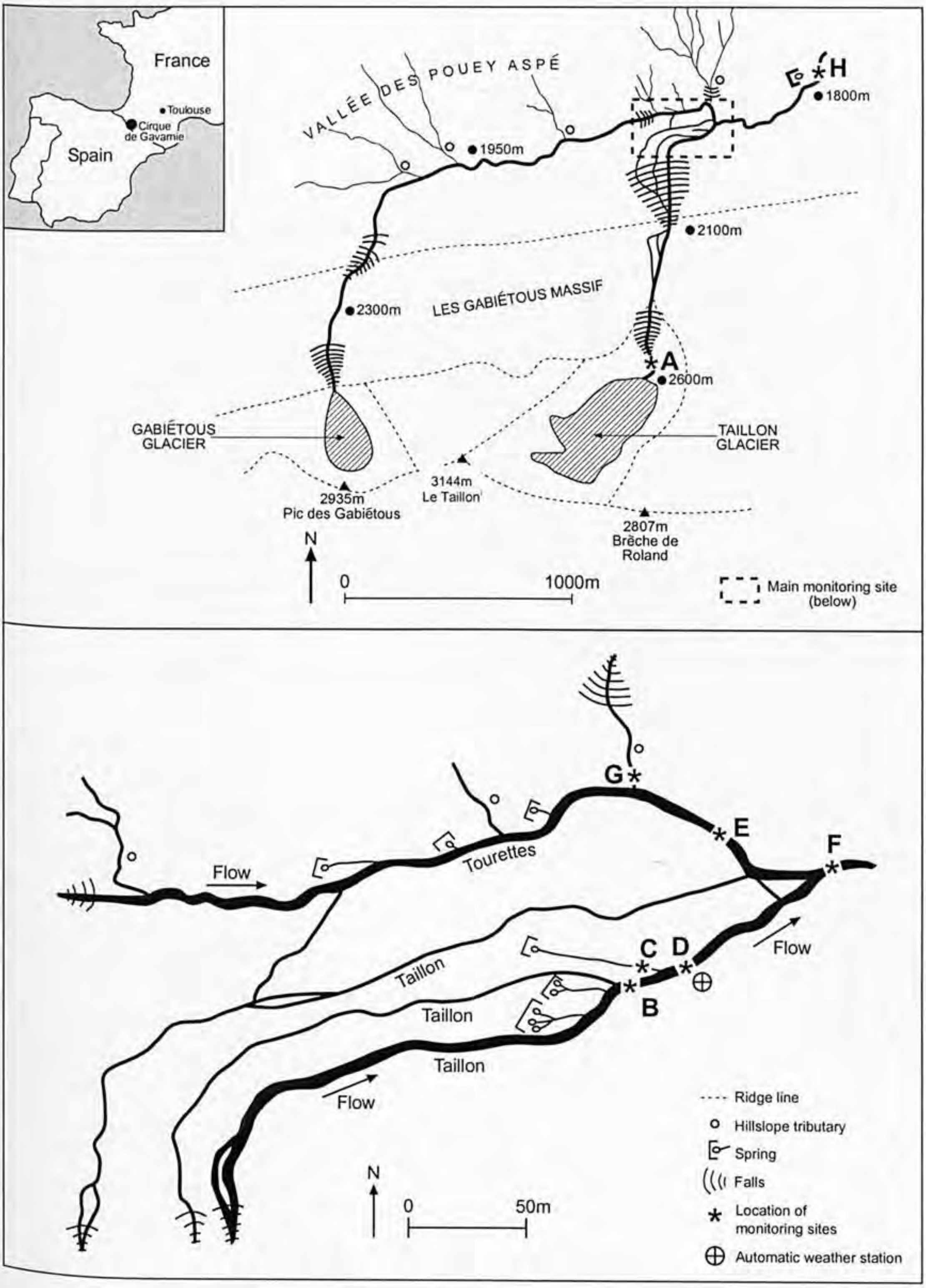


Figure 4.1. Map of study area showing location of additional water column temperature monitoring sites

Table 4.1. Water column and streambed temperature monitoring site descriptions

Site	Stream	Altitude (m)	Source(s)	Distance from Taillon Glacier (m)	Approx length of groundwater channels (m)	Width:depth ratio	Aspect (Facing)	B-axis (D_{50})
A	Taillon	2570	Taillon Glacier	100	N/A	10:1	N	No data
B	Taillon **(Gauging Site A)**	1850	Taillon Glacier	980	N/A	16:1	E	No data
C	Resurgence des Crampettes	1847	Karstic groundwater	N/A	30	11:1	E	No data
D	Taillon	1847	Taillon Glacier/Crampettes	1000	N/A	16:1	NE	89
E	Tourettes **(Gauging Site B)**	1843	Groundwater with very limited glacial input	N/A	Multiple groundwater channel inputs (see Figure 1)	36:1	SE	58
F	Taillon **(Gauging Site C)**	1840	Mix of Site D and Site E	1080	N/A	24:1	NE	85
G	Hillslope	1848	Hillslope groundwater	N/A	100+	16:1	S	No data
H	Peyre Blanque	1780	Karstic groundwater	N/A	10	5:1	N	No data

4.4. RESULTS

4.4.1. Melt season hydroclimatological context

In both field seasons, snow cover <2400 m was limited to isolated patches that melted by approximately day 190. The transient snowline on north-facing slopes retreated rapidly so by day 197 (2002) and day 200 (2003), ice was exposed on the Taillon Glacier at ~2600m (Figure 4.2a and b). In 2002, the snowline retreated to a maximum altitude of ~2710 m by day 220. In 2003, the snowline receded more quickly than the previous year after day 200, reaching ~2750 m by the end of the field season (Figure 4.2b). South-facing slopes were devoid of snow cover throughout both monitoring periods.

During both field seasons, daily incoming short-wave radiation varied markedly due to variable cloud cover, although a broad decline occurred over the monitoring period (Figure 4.2a) as days shortened with time from the summer solstice (day 173). Mean total daily insolation was slightly higher in 2002 (15.96 MJm^2d^{-1}) than 2003 (17.77 MJm^2d^{-1}), although daily totals ranged widely in both years (Table 4.2). The 2002 field season was wetter (Table 4.2) with frequent rainfall events after day 189 (Figure 4.2c), but most events were of low intensity and interspersed by dry periods (days 197-201, 205-208 and 223-225). The wettest four-day period occurred from day 228-231 when 85.4 mm of rain fell (Table 4.2). In 2003, precipitation events were also common, although drier periods were generally longer (days 190-195, 197-204 and 209-217; Figure 4.2d). However, storms were more intense (e.g. days 187 and 225) and maximum daily precipitation total was 10 mm greater than the previous year.

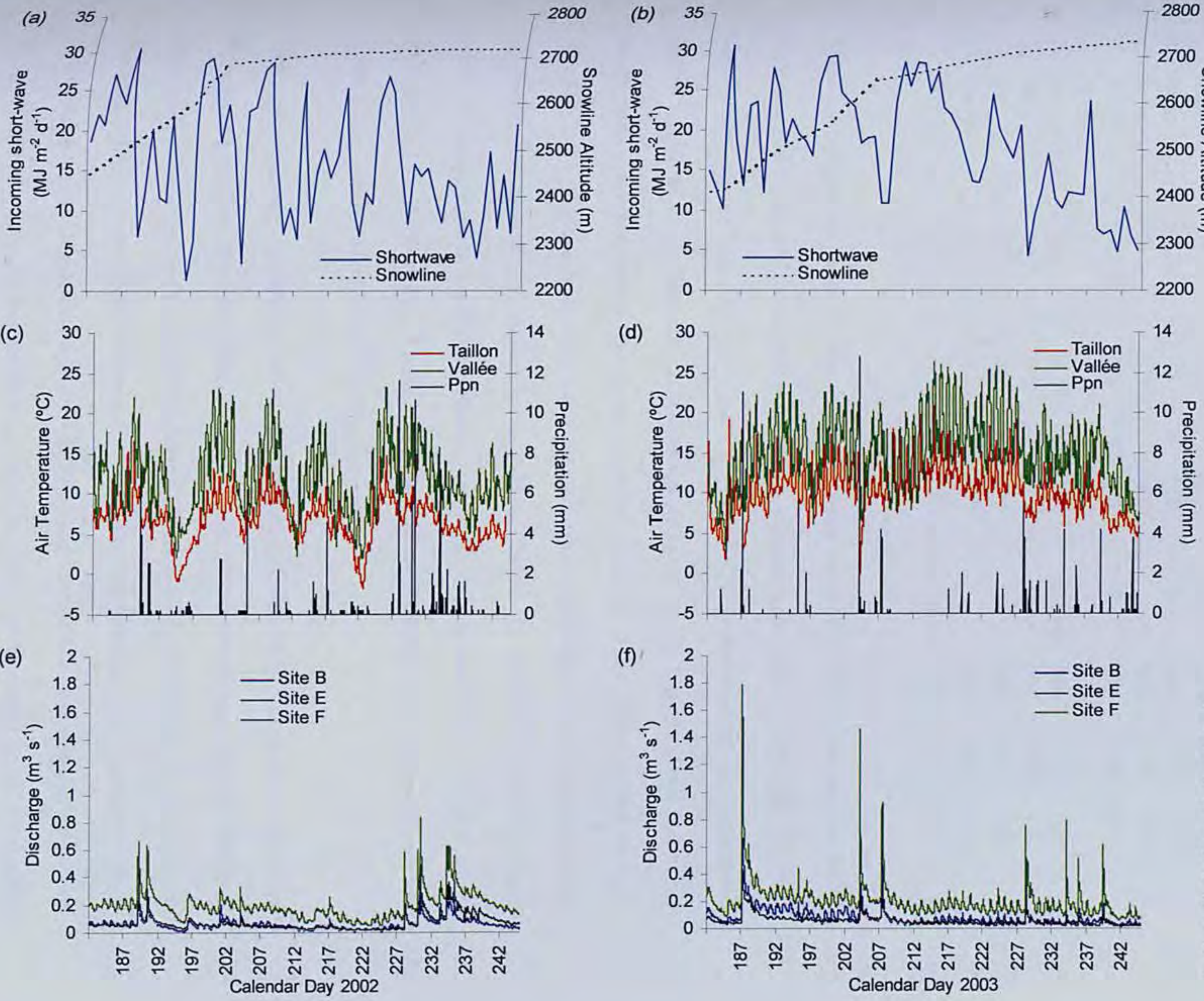


Figure 4.2. (a) and (b) Incoming short-wave radiation and snowline altitude, (c) and (d) air temperatures and precipitation, and (e) and (f) gauging station discharges. (a), (c) and (e) are data for the 2002 monitoring period, (b), (d) and (f) are data for the 2003 monitoring period

Table 4.2. Descriptive statistics for melt season air temperatures, incoming short-wave radiation, precipitation (Ppn) and stream discharge (Sites B, E and F) over the 2002 and 2003 monitoring periods. Parentheses denote daily totals for precipitation sum.

	$T_{a(Taillon)}$ (°C)	$T_{a(Vallée)}$ (°C)	K↓ ($MJm^{-2}d^{-1}$)	Ppn (mm)	Q (m^3s^{-1}) Site B	Site E	Site F
2002							
Mean (Sum)	6.7	11.7	15.96	(297.4)	0.07	0.07	0.20
Max	16.7	23.3	30.41	44.2	0.34	0.49	0.83
Min	-1. 8	1.9	1.32	0.0	0.01	0.01	0.05
Range	18.5	21.4	29.09	-	0.33	0.48	0.78
St.Dev.	2.7	4.3	7.65	9.0	0.04	0.06	0.10
2003							
Mean (Sum)	10.1	15.1	17.77	(252.6)	0.09	0.06	0.20
Max	22.7	26.4	30.58	54.2	0.67	0.69	1.79
Min	-0.2	2.6	4.27	0	0.02	0.01	0.06
Range	22.9	23.8	26.31	-	0.65	0.68	1.73
St.Dev.	3.0	4.2	7.11	9.8	0.06	0.05	0.12

Mean air temperature in the Vallée des Pouey Aspé and at the Taillon Glacier was 3.4°C higher in 2003 than 2002, with greater minimum and maximum values (Table 4.2). In 2002, three cooler periods (days 195, 213 and 223; Figure 4.2c) punctuated the air temperature time-series, whereas in 2003, the coolest periods occurred at the beginning and end of the study period. Air temperature was almost invariably warmest in the Vallée, except for days 209-211, 2002 (Figure 4.2c-d) when low-level valley cloud resulted in reduced radiative input compared with clear-sky conditions at the Taillon Glacier. As expected at higher altitude, mean air temperature at the Taillon Glacier was lower than in the Vallée over both study periods (Table 4.2). However, air temperature patterns were similar at the Taillon Glacier and in the Vallée within years (Figure 4.2c-d).

Although discharge magnitude varied between sites (Table 4.2), the streams displayed broadly similar flow patterns (Figure 4.2e-f). The classical mid-summer glacial discharge flow peak previously observed in the catchment (Hannah *et al.*, 2000b) did not occur due to variable climatic conditions influencing meltwater generation, and episodic, major precipitation inputs. Mean discharge over the two field seasons at Site B was slightly greater in 2003; Site E discharge was marginally higher in 2002, whilst Site F showed the same average discharge in both years (Table 4.2). Although mean discharge was not markedly different between years at each site, maximum flows were much higher in 2003 (approximately double 2002). The difference between the sum of discharges for Site B plus E, and the discharge at Site F, was due to a karstic tributary inflow to the Taillon stream, and a glacial/snowmelt-fed tributary discharging into the Tourettes stream downstream of Site E (Figure 4.1). Flows at Site E showed less diurnal variation than Sites B and F, as the Tourettes stream is largely fed by groundwaters with limited connectivity to glacial/snowmelt streams.

These hydroclimatological data, supplemented by field observations, permit identification of seven sub-seasonal periods across the two summer melt-seasons (below). Through detailed examination of these periods, the relationships between snowline altitude (i.e. exposure of glacial ice and the upper catchment stream network to the atmosphere), air temperature, incident short-wave radiation, precipitation, discharge and water column and bed temperatures may be assessed at the diurnal scale. Periods were not necessarily chosen to represent extreme water column and streambed temperature conditions, but to reflect a range of hydroclimatological conditions that may influence thermal variation. Five periods were examined in detail for 2002, and two periods for 2003. This is not intended as a reflection of the level of hydroclimatological variability in each year, but merely to avoid repeated analysis of similar hydroclimatological conditions and stream temperature patterns between years.

4.4.2. Sub-seasonal hydroclimatological periods

Period 1: Early season snowmelt (day 185-188; 4-7 July, 2002)

During this period, the snowline was at the altitude of Site A. Mean air temperature in the Vallée was 12.1°C and 8.7°C at the Taillon Glacier, with relatively large mean diurnal ranges of 16.5°C and 12.4°C, respectively. Mean total daily short-wave radiation receipt was the highest of the seven selected periods (Table 4.3) while total precipitation was minimal (0.4 mm). Mean discharge for Sites B, E and F were 0.07, 0.05 and 0.2 m^3s^{-1} respectively, with clear diurnal melt-cycles.

Period 2: Cold Period (day 195-198; 14-17 July, 2002)

This sustained cold period occurred due to persistent valley and ridge-top cloud cover as shown by much reduced mean total incoming solar radiation (11.84 MJm^2d^{-1}). Air temperature was warmer on average in the Vallée than at the Taillon Glacier, with the lowest diurnal air temperature ranges (Vallée = 1.9°C; Taillon Glacier = 1.8°C) on days 195 and 196 (Table 4.3). Rainfall was low from day 195 until 1300 h on day 196 (1.2 mm), when a prolonged (13 h) low intensity precipitation episode occurred (Figure 4.2c). The lowest recorded discharges of the field season were experienced, with mean discharge at Site D on the glacial stream less than at Site E. The lowest diurnal ranges of the melt season were recorded on day 195 (B = 0.01, E = 0.01 and F = 0.02 m^2s^{-1}).

Period 3: Glacier-melt dominated, warm atmospheric conditions (day 224-227; 12-15 August, 2002)

Maximum snowline altitude coincided with relatively warm weather so that flows were dominated by ice-melt contributions. These dates were chosen to represent glacial melt later in the melt season (days 224-227) as ice exposure was at a maximum, and large diurnal fluctuations in discharge and high suspended sediment concentrations were observed. Diurnal discharge ranges were greater at Site B (0.03 m^2s^{-1}) than Site E (0.01 m^2s^{-1}) reflecting the role of ice-melt in driving runoff fluctuations. Mean air temperature was 14.8°C and 8.7°C at the Taillon Glacier. The maximum air temperature for the entire monitoring period was recorded at the Vallée on day 226 (23.3°C; Table 4.3). Total daily incoming short-wave radiation averaged 22.69 MJm^2d^{-1} and precipitation was low (3.4 mm).

Period 4: Precipitation-dominated period (day 228-231; 16-19 August, 2002)

Vallée air temperature was similar to that for Period 2, although incoming short-wave radiation was considerably lower and (Table 4.3) precipitation was very much greater. The largest rainstorms of the melt season occurred on day 228 (maximum 15 min total = 11.6 mm) and day 230 (maximum 15 min total = 11.4 mm). Mean discharge was 0.11, 0.13 and 0.28 m^2s^{-1}, but fluctuated by 0.32, 0.47 and 0.74 m^2s^{-1}, at Sites B, E and F, respectively.

Period 5: Late melt season, cooling air temperatures (day 241-244; 29 August-1 September)

Air temperatures were relatively low (10.3°C and 5.3°C, Vallée and Taillon Glacier, respectively) and short-wave radiative inputs low compared with earlier periods (12.48 MJm^2d^{-1}; except for Period 2). Total precipitation was low (2.4 mm) but discharge was relatively high at all sites due to streamflow recession from heavy rainstorms on preceding days (Figure 4.2). Site E (draining hillslopes and other groundwater stores) had a greater mean discharge than the glacial Site B, although ranges were similarly low (Table 4.3).

Period 6. Mid-summer extreme precipitation event (day 203-206; 22-25 July, 2003)

A heavy hail/rainstorm occurred during an otherwise warm period; Maximum air temperature for the period was 21.5°C but during the storm, air temperature reached a minimum of 6.1°C in the Vallée and 0°C at the Taillon Glacier. Precipitation totalled 53 mm, with a 15 min maximum of 12.8 mm and daily total of 49.6mm on day 204. Maximum discharges were extremely high for the basin, reaching 1.46 m^3s^{-1} at Site C (Table 4.3). Discharge from Site E was higher than Site B, indicating that most runoff was sourced from the larger Vallée des Pouey Aspé rather than the Taillon Glacier sub-catchment.

Period 7. Glacial icemelt dominated, very warm atmospheric conditions (day 214-217; 2-5 August, 2003)

In early August 2003, an anti-cyclonic (high pressure) system prevailed over southern France, giving an extended period of very warm weather. Air temperatures were the highest recorded over the two melt seasons, reaching a maximum of 26.4°C in the Vallée and 22.7°C at the Taillon Glacier (Table 4.3). Total precipitation was low at 2.4 mm. The snowline altitude was relatively high; therefore, the upper catchment stream network was uncovered and glacial meltwater dominated runoff. Hence, discharge in the Taillon Glacier stream (Site B) was greater and more variable than the predominantly groundwater-fed Tourettes stream (Site E; Table 4.3).

Table 4.3. Descriptive statistics for air temperatures, incoming short-wave radiation, precipitation and discharge (Sites B, E and F) during the selected sub-seasonal periods. Parentheses denote precipitation sum.

	$T_{a(Taillon)}$ (°C)	$T_{a(Vallée)}$ (°C)	K↓ ($MJm^{-2}d^{-1}$)	Ppn (mm)	Q (m^3s^{-1}) Site B	Site E	Site F
Period 1 (day 185-188, 2002)							
Mean (Sum)	8.7	12.1	26.47	(0.4)	0.07	0.05	0.21
Max	16.7	22.0	30.41	0.2	0.10	0.07	0.26
Min	4.3	5.5	23.35	0.0	0.04	0.04	0.16
Range	12.4	16.5	7.06	0.2	0.05	0.02	0.10
St.Dev.	2.4	4.1	3.68	0.01	0.02	0.01	0.03
Period 2 (day 195-198, 2002)							
Mean (Sum)	2.8	7.6	11.84	(16.0)	0.04	0.06	0.17
Max	8.4	15.9	28.33	11.4	0.10	0.11	0.28
Min	-0.8	2.2	1.32	0.8	0.01	0.03	0.08
Range	9.2	13.7	27.01	10.6	0.08	0.08	0.20
St.Dev.	2.3	3.0	14.37	5.2	0.03	0.02	0.07
Period 3 (day 224-227, 2002)							
Mean (Sum)	8.7	14.8	22.69	(3.4)	0.04	0.02	0.11
Max	14.7	23.3	26.76	3.2	0.07	0.04	0.17
Min	3.0	6.0	15.86	0.0	0.01	0.01	0.05
Range	11.7	17.3	10.90	3.2	0.05	0.02	0.12
St.Dev.	2.6	4.5	5.80	1. 6	0.01	0.01	0.03
Period 4 (day 228-231, 2002)							
Mean (Sum)	8.2	14.8	13.37	(85.4)	0.11	0.13	0.28
Max	10.8	21.1	15.76	44.2	0.34	0.49	0.83
Min	4.0	7.9	8.35	0.2	0.03	0.02	0.09
Range	6.8	13.2	7.41	44.0	0.32	0.47	0.74
St.Dev.	1.3	3.3	0.83	24.5	0.07	0.10	0.15
Period 5 (day 241-244, 2002)							
Mean (Sum)	5.3	10.9	12.48	(2.4)	0.05	0.08	0.18
Max	7.4	16.4	20.65	0.6	0.07	0.11	0.22
Min	3.5	7.8	7.03	0.0	0.03	0.04	0.14
Range	3.9	8.5	13.62	0.6	0.03	0.07	0.08
St.Dev.	0.9	2.1	6.82	0.05	0.01	0.02	0.02
Period 6 (day 203-206, 2003)							
Mean (Sum)	9.9	14.2	19.74	(53.0)	0.12	0.09	0.26
Max	18.9	21.5	22.75	49.6	0.39	0.69	1.46
Min	-0.2	6.1	18.18	0	0.05	0.04	0.15
Range	19.1	15.4	4.57	12.8	0.34	0.64	1.31
St.Dev.	3.5	4.0	2.05	24.3	0.07	0.07	0.15
Period 7 (day 214-217, 2003)							
Mean (Sum)	13.4	19.5	24.06	(2.4)	0.06	0.04	0.16
Max	22.7	26.4	27.18	2.4	0.11	0.06	0.28
Min	9.6	11.4	21.88	0	0.03	0.03	0.11
Range	13.1	15.0	5.30	2.4	0.08	0.03	0.17
St.Dev.	2.4	4.2	2.36	1.2	0.02	0.01	0.04

4.4.3. Water column temperatures

Melt season averaged patterns

Water column temperatures varied markedly between different streams and years (Table 4.4; Figures 4.3 and 4.4), although most sites experienced warmer mean water temperatures in 2003. In both field seasons, the coldest water column temperatures were recorded at Site A close to the Taillon Glacier snout. Warmest water column temperatures were found at Site G, which is sourced from south-facing hillslope groundwater stores. Karstic (Sites C and H) groundwater stream temperatures were generally colder than the glacial stream with the exception of Site A (Table 4.4). Site H temperatures were on average ~1°C warmer than Site C (Figure 4.3a and c), but both sites had similar mean temperatures in both years. Water column temperatures in the Taillon stream increased consistently downstream (Table 4.4; Figure 4.3b and d; i.e. Site A to B), by 7°C and 8.6°C in 2002 and 2003, respectively, over a distance of approximately 1 km. Seasonally averaged water column temperatures decreased by 0.4°C from Site B to D in both years due to cold water inputs from the Crampettes spring (Site C), but subsequently increased between Sites D and F by 1.8°C (1.7°C) in 2002 (2003) after the confluence with the warmer Tourettes stream (Table 4.4).

Relatively flat temperature-duration curves for Sites A, C and H in both years shows thermally constant conditions at sites in close proximity to their source (Figure 4.4a-b). Steeper curves for Sites B, D, F and G reflect more variable thermal regimes. The temperature-duration curve for Site E is intermediate between the two main groupings (Sites A, C and H and Sites B, D, F and G), but more variable in 2003. Correlation of air and water column temperature at Sites A, C and H for both monitoring-period are poor (as in other groundwater stream studies: (Smith, 1981; Mackey and Berrie, 1991; Webb and Zhang, 1999), compared with *r*-values >0.700 for the other sites (Table 4.5). Correlations for all sites are stronger in 2003. Below Site A on the Taillon stream, correlations increase successively between sites indicating more similar patterns to air temperature at downstream sites (Table 4.4).

Sub-seasonal patterns

During Period 1, water column temperature at Site A was very low and relatively constant (Table 4.6) as snow cover prevented direct exposure to the atmosphere. Thus, correlations with air temperature were very weak (Table 4.5; c.f. Smith and Lavis, 1975; Kobayashi, 1985; Webb and Nobilis, 1997 for snowmelt-fed streams). Karstic groundwater temperatures at Sites C and H also remained relatively constant but were considerably (4-5°C) warmer than at the Taillon Glacier snout (Table 4.6). All other sites were characterised by large diurnal temperature fluctuations (Figure 4.3). Water temperatures at Site G were warmest (Table 4.6) and yielded the highest correlation with air temperature, although this was only marginally higher than those for Sites B-F (Table 4.5). Site E was also relatively warm probably due to its upstream connection with the hillslope tributary (Table 4.3).

Averaged water temperatures for Period 2 in the Taillon stream (except Site A) were approximately 1.7°C cooler than Period 1 (Table 4.6). Furthermore, this was the only period in 2002 when minimum temperatures recorded at Sites B and D dropped below minimum temperatures at Site C (Table 4.6). Correlations of air and water column temperatures were strongest for the Taillon stream (Sites B, D and F) compared with other sites, and also much higher than seasonal correlations (Table 4.5). Groundwater-fed Sites C, E and G yielded relatively strong correlations with air temperature. However, Site H experienced constant water temperature, thus, no correlation with air temperature. Water column temperatures were warmest at Site G, although these were ~2.8°C cooler than seasonal averages (Table 4.6).

Table 4.4. Descriptive statistics for water column temperatures over the 2002 and 2003 monitoring periods.

	Site							
	A	B	C	D	E	F	G	H
Melt season 2002								
Mean	0.4	7.4	4.5	7.0	9.7	8.8	11.3	5.5
Max	2.3	15.0	5.6	14.0	13.4	15.4	19.6	6.3
Min	-0.3	3.8	3.6	3.6	7.1	5.2	5.5	4.7
Range	2.6	11.2	2.0	10.4	6.3	10.2	14.1	1.6
St.Dev	0.4	2.2	0.4	2.1	1.2	1.9	2.7	0.4
Melt season 2003								
Mean	0.4	9.0	4.5	8.6	11.1	10.3	13.2	5.2
Max	2.1	16.1	5.7	15.7	16.5	17.0	21.5	6.0
Min	-0.4	0.0	2.2	0.0	2.3	1.9	1.3	4.3
Range	2.5	16.0	3.5	15.7	14.2	15.1	20.2	1.7
St.Dev	0.4	2.4	0.5	2.4	1.8	2.3	2.9	0.5

Table 4.5. Correlation co-efficients for air-water column relationships over the 2002 and 2003 monitoring periods. Correlations are significant at $p<0.01$ except for * ($p<0.05$), ^(insignificant), and – (no correlation as T_w constant).

	Site							
	A	B	C	D	E	F	G	H
Season 2002	0.083	0.729	0.173	0.740	0.727	0.769	0.801	0.109
Season 2003	0.163	0.813	0.514	0.815	0.720	0.817	0.825	0.116
Period 1	0.117*	0.619	0.604	0.626	0.642	0.631	0.677	0.075^
Period 2	-0.085^	0.949	0.606	0.944	0.821	0.914	0.741	-
Period 3	0.243	0.746	0.591	0.748	0.766	0.727	0.729	0.420
Period 4	0.701	0.653	0.228	0.671	0.776	0.802	0.670	-0.474
Period 5	0.464	0.843	0.558	0.866	0.803	0.857	0.634	-0.112*
Period 6	0.228	0.822	0.625	0.812	0.696	0.768	0.862	-0.033^
Period 7	0.522	0.884	0.836	0.878	0.694	0.891	0.743	0.439

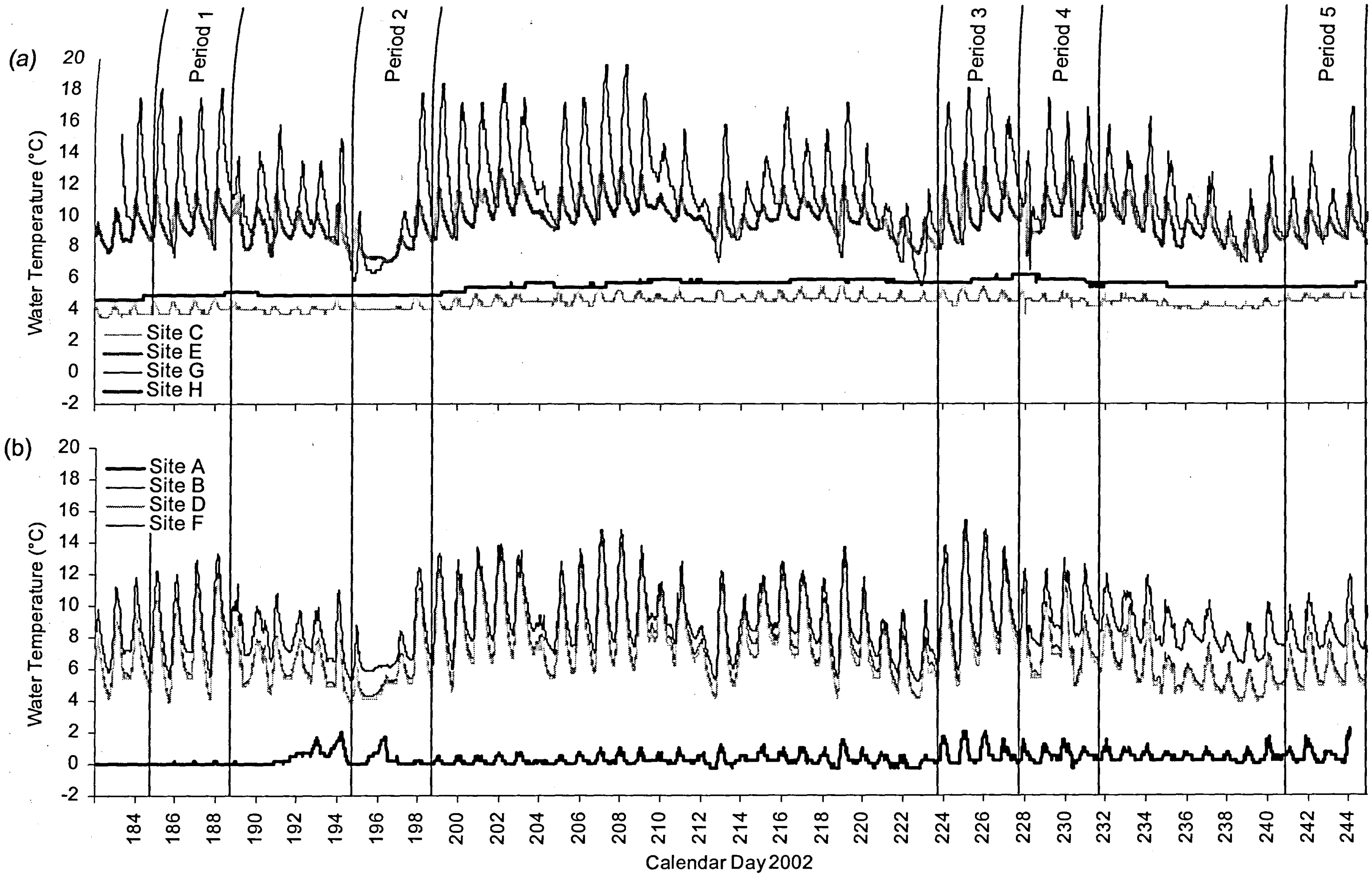


Figure 4.3. Water column temperatures for (a) the Tourettes stream and groundwater-fed sites and (b) sites on the Taillon stream, for the 2002 melt season

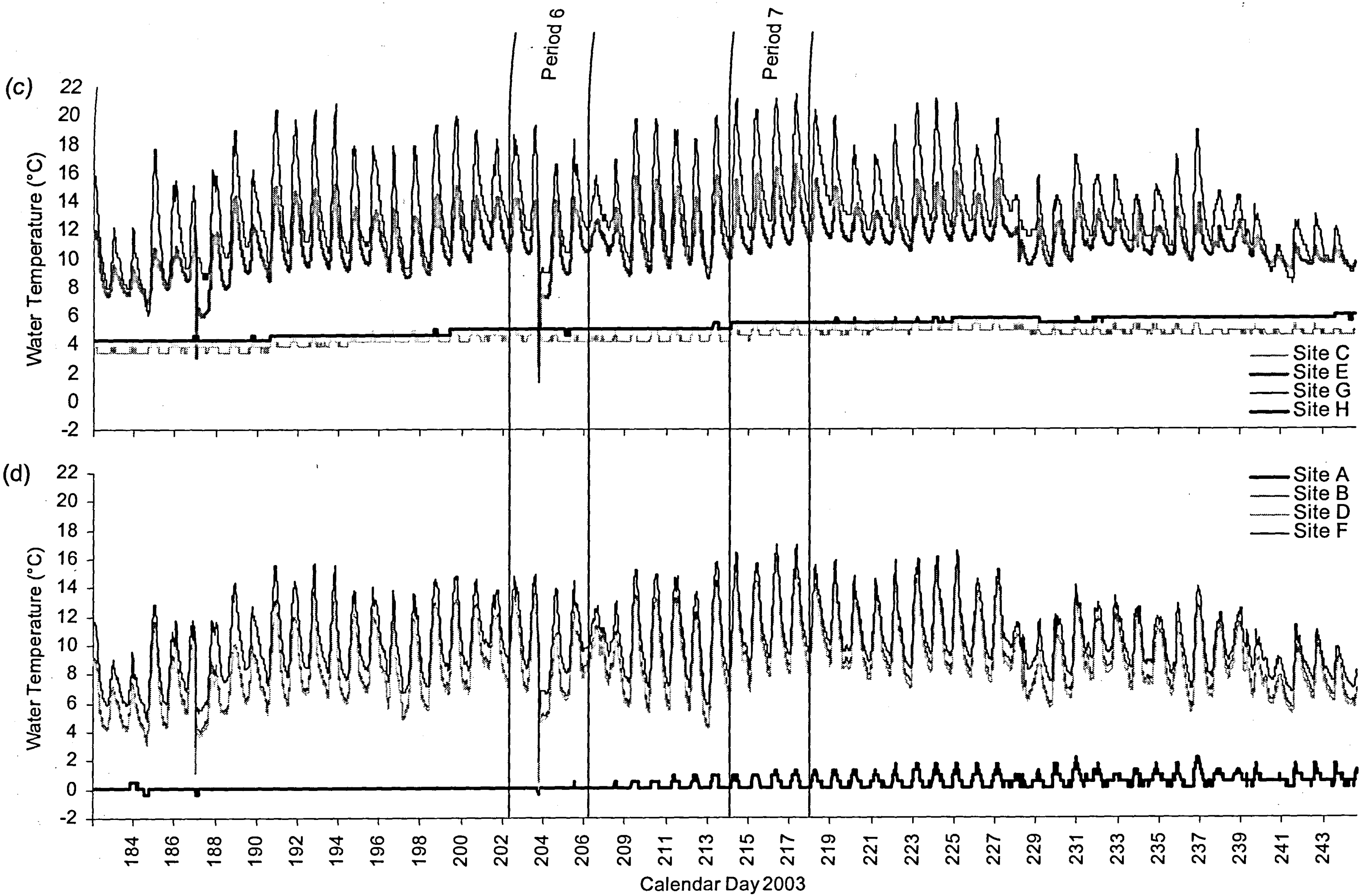
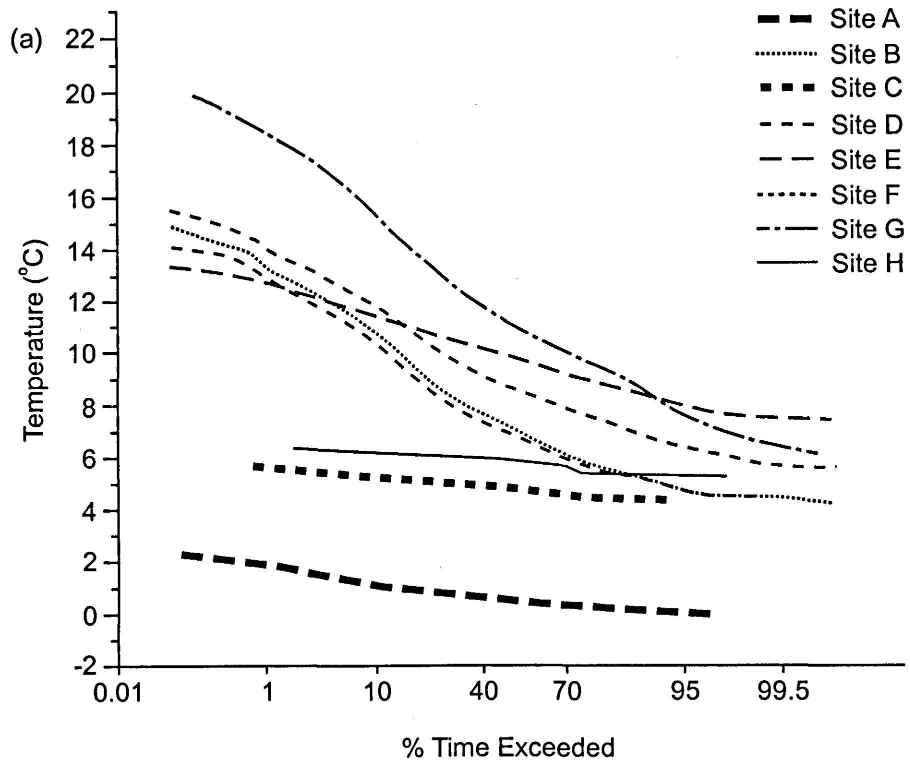


Figure 4.3.cont. Water column temperatures for (c) the Tourettes stream and groundwater-fed sites and (d) sites on the Taillon stream, for the 2003 melt season



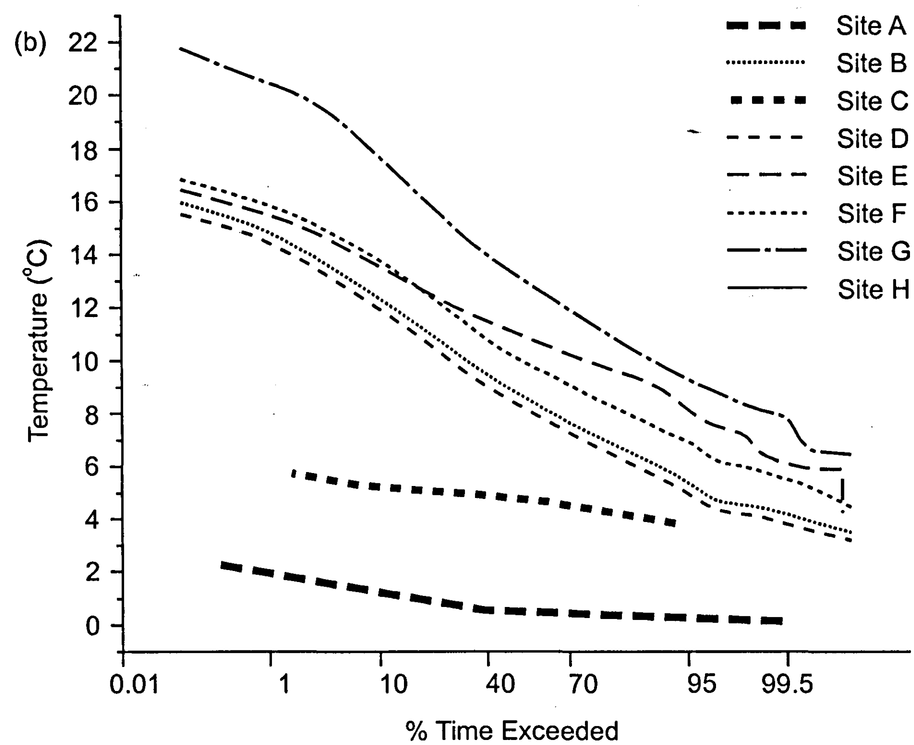


Figure 4.4. Water column temperature-duration curves for (a) the 2002 melt season, and (b) the 2003 melt season

In Period 3, the highest mean water column temperatures at all sites (except E and H; Table 4.6) coincided with the warmest air temperatures and highest incoming short-wave radiation during the 2002 field season. Temperature variability (range and standard deviation) for glacial stream Sites B, D and F was high (Table 4.6). Air and water temperatures at Site A were not well correlated (Table 4.5) despite exposure of most of the upper stream network to the atmosphere following snowline recession. Downstream increases in temperature between Sites A and B were relatively large (averaging 8.9°C; Table 4.6) but the temperature difference between Sites D and F (1.3°C) was one of the lowest for any of the selected periods. Site G was warmer on average and experienced higher maximum temperatures than for any other period in 2002, although warmer minimum temperatures meant variability was reduced.

For Period 4, maximum mean water column temperatures were recorded at Site G (Table 4.6). At Site E, maximum mean temperatures of the selected periods for 2003 were recorded. Correlations of air and water temperature were relatively high at Site A, but a spurious inverse relationship was found at karstic Site H. For the precipitation episodes on days 228 and 230, temperatures decreased rapidly, especially at Sites E and G (Figure 4.3). Lowest minimum temperatures at Sites A (-0.3°C) and C (3.6°C) for 2002 were also recorded during these rainstorms.

Table 4.6. Descriptive statistics for water column temperatures during the sub-seasonal periods.

	Site							
	A	B	C	D	E	F	G	H
Period 1 (day 185-188, 2002)								
Mean	0.1	7.4	4.1	7.2	9.7	8.8	12.1	5.0
Max	0.3	12.1	4.8	11.7	11.7	13.3	18.1	5.2
Min	0.1	4.0	3.8	3.9	8.1	5.4	7.3	5.0
Range	0.2	8.1	1.0	7.8	3.6	7.9	10.8	0.2
St.Dev	0.1	2.2	0.3	2.1	1.0	2.2	3.0	0.0
Period 2 (day 195-198, 2002)								
Mean	0.3	5.7	4.1	5.6	8.0	7.1	8.5	5.0
Max	1.8	11.1	4.8	10.9	11.0	12.4	17.8	5.0
Min	0.1	3.8	4.1	3.6	7.1	5.3	5.8	5.0
Range	1.7	7.3	0.7	7.3	3.9	7.1	12.0	0.0
St.Dev	0.4	1.7	0.2	1.7	1.0	1.7	2.8	0.0
Period 3 (day 224-227, 2002)								
Mean	0.7	9.6	4.8	8.8	10.2	10.1	12.7	5.9
Max	2.1	15.0	5.6	14.0	13.4	15.4	18.1	6.3
Min	0.1	5.2	4.3	4.9	7.9	5.9	7.8	5.8
Range	2.0	9.8	1.3	9.1	5.5	9.5	10.3	0.5
St.Dev	0.6	2.6	0.4	2.5	1.4	2.6	3.0	0.1
Period 4 (day 228-231, 2002)								
Mean	0.6	7.7	4.7	7.3	10.3	9.5	11.9	6.0
Max	1.6	12.0	5.3	11.5	13.3	13.0	17.5	6.3
Min	-0.3	5.0	3.8	4.9	7.4	7.4	6.5	5.5
Range	1.9	7.0	1.5	6.6	5.9	5.6	11.0	0.8
St.Dev	0.4	1.7	0.2	1.6	1.2	1.5	2.1	0.2
Period 5 (day 241-244, 2002)								
Mean	0.6	6.2	4.8	5.9	9.3	8.4	10.2	5.5
Max	2.3	9.8	5.6	9.3	11.5	11.9	16.9	5.8
Min	0.1	4.8	4.3	4.6	8.2	7.0	7.8	5.5
Range	2.2	5.0	1.3	4.7	3.3	4.9	9.1	0.3
St.Dev	0.5	1.2	0.2	1.1	0.7	1.1	2.1	0.1
Period 6 (day 203-206, 2003)								
Mean	0.1	8.7	4.4	8.4	10.9	10.4	13.1	5.0
Max	0.5	13.7	5.3	13.5	14.2	14.9	19.3	5.4
Min	-0.4	0.0	2.2	0.0	2.3	1.9	1.3	4.6
Range	0.9	13.7	3.1	13.4	11.9	13.0	18.0	0.8
St.Dev	0.1	2.5	0.3	2.5	2.3	2.6	3.0	0.1
Period 7 (day 214-217, 2003)								
Mean	0.4	11.1	4.8	10.6	12.5	12.0	15.6	5.4
Max	1.3	16.1	5.7	15.7	16.5	17.0	21.4	5.4
Min	0.1	6.5	4.2	6.0	9.9	7.7	10.8	5.0
Range	1.2	9.6	1.5	9.7	6.6	9.3	10.7	0.4
St.Dev	0.4	2.6	0.3	2.6	1.8	2.6	3.0	0.1

With the exception of Site A and for Period 2, temperatures for Taillon stream sites were coolest in Period 5 (Table 4.6). However, correlations of air and water temperatures at Taillon stream Sites B, D and F were strong, and the maximum temperature difference between Sites D and F (2.5°C) was also observed. At Site A, mean temperature was greater than the seasonal average (Table 4.3). In addition, maximum temperatures for the study period and a relatively strong correlation compared to the seasonal r-values were recorded at Site A (Table 4.5). Groundwater-fed Sites C, E and G were coolest at this time (with the exception of Period 2), but temperature ranges were relatively large (Table 4.6).

For Period 6, maximum mean water column temperatures were recorded at Site G (Table 4.6). The lowest minimum temperatures at all sites for any period were recorded at every site, coinciding with the intense hail and rainstorm that characterised this period. Groundwater Sites C and E also experienced very low minimum temperatures (2.2-2.3°C), but Site H remained relatively warm despite the cold precipitation inputs (minimum = 4.6°C; Table 4.6). Outwith this major precipitation event, maximum temperatures at most sites were relatively high, which resulted in the largest ranges recorded in any sub-seasonal period (except Site A; Table 4.6). Correlations with air temperatures decreased downstream from Site B to F, whereas for Site G, water column temperature and air temperatures were more strongly correlated than for any other period (Table 4.5).

In Period 7, the largest increase in temperature between Site A and B (10.7°C) for any period was recorded (Table 4.6). Furthermore, all sites (except A and H) experienced the warmest maximum temperatures compared to any other period. Correlations with air temperature were very strong at all sites, but the strongest correlations of any period were found for karstic groundwater Sites C and H (Table 4.5). Temperature range was relatively high at Site C compared with other periods, but at Site H, temperatures remained almost constant.

4.4.4. Water column and streambed temperature patterns

Melt season averaged patterns

Contrasting bed temperature profiles were evident between Sites D, E and F in both years, although for 2003, all sites experienced warmer average and maximum temperatures and greater thermal variability at all depths (Figure 4.5; Table 4.7). Bed temperatures at all depths were coldest (warmest) and most (least) variable for the Taillon (Tourettes) stream. At Site F, below the confluence of these two streams, bed temperatures and variability were consistently intermediate of Sites D and E (Figure 4.5). Temperature-duration plots support these findings (Figure 4.6), showing streambed temperatures at Site D to be most variable with very little vertical thermal attenuation except for temperatures above 10°C in 2002, and 12°C in 2003 (both exceeded ~10% of the time; Figures 4.6a and d). At Sites E and F, curve slope decreases with depth (i.e. increasing thermal attenuation into the streambed; Figure 4.6b-c and e-f), but both were steeper for 2003, with a steep drop at the lower end of the temperature duration curve (Figures 4.6e-f) due to short duration cold precipitation events (see below). In 2002, curves for all depths diverge above 10°C at Sites D and E, and above 8°C at Site F, as vertical gradients become steeper. However, in 2003, divergence occurs at higher temperatures for Sites E and F (~11°C; Figure 4.6).

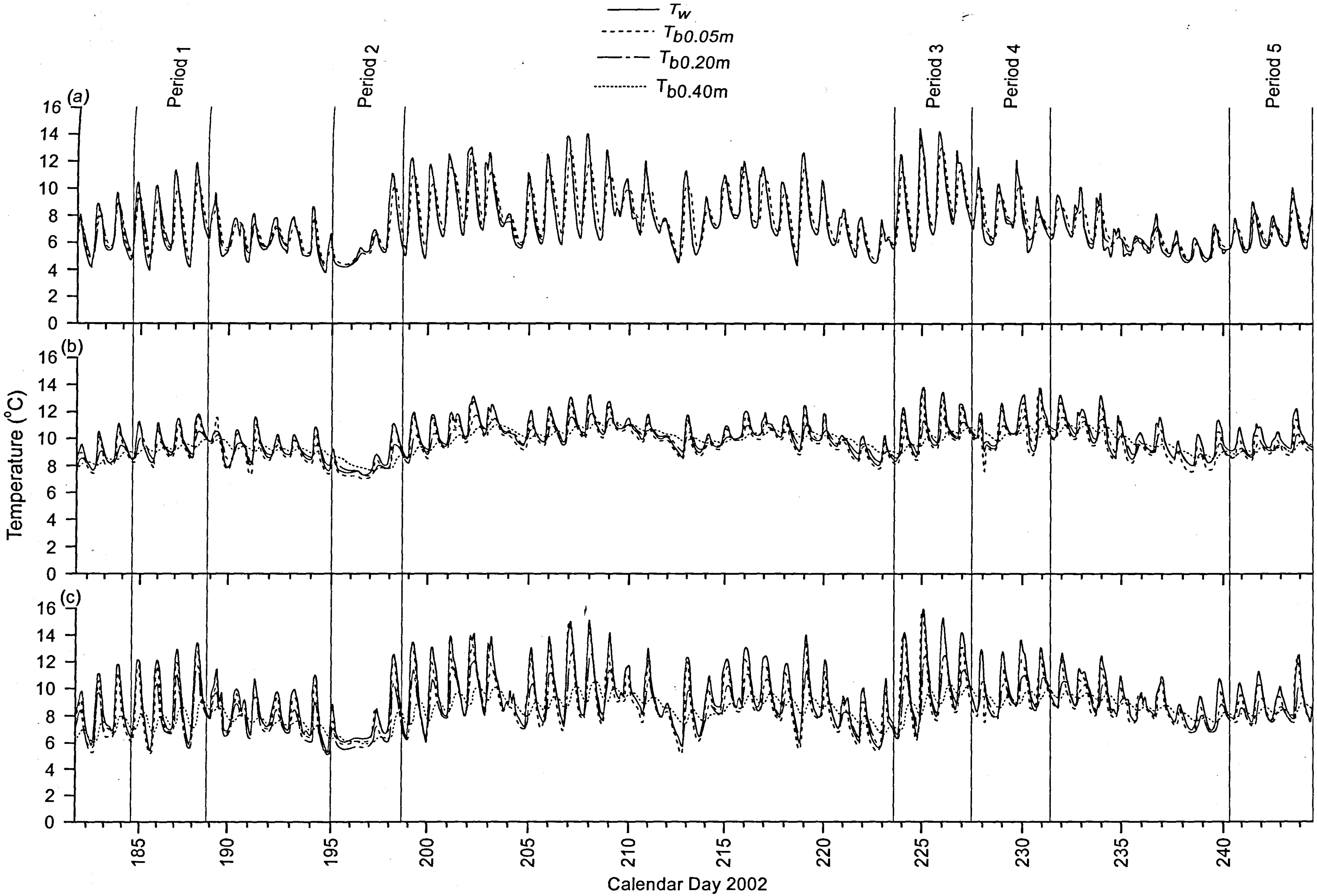


Figure 4.5. Water column and streambed temperatures recorded at (a) Site D (b) Site E and (c) Site F over the 2002 melt season

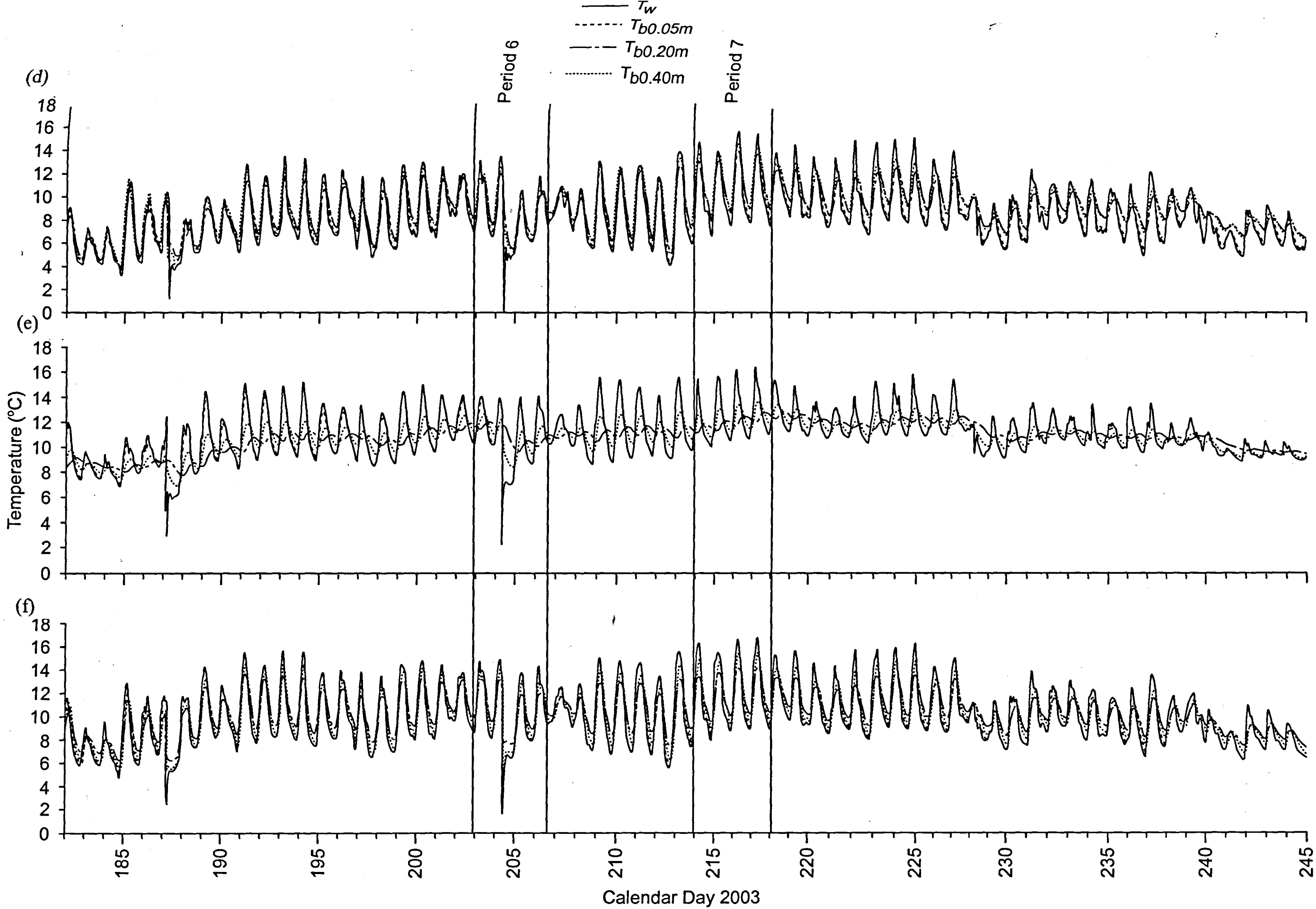


Figure 4.5.cont. Water column and streambed temperatures recorded at (d) Site D (e) Site E and (f) Site F over the 2003 melt season

In both years, seasonally averaged bed temperatures at Site D were extremely similar to the water column (within 0.1°C in 2003; c.f. 0.2°C thermistor accuracy, and by only 0.4°C in 2003), although temperature range and standard deviation decreased with depth into the streambed (Figure 4.5a; Table 4.7). Air-streambed temperature relationships were lagged with increasing depth (Table 4.8). Lag times between water column and streambed thermal responses were short but slightly longer at 0.20 m depth in 2003 (Table 4.8). Cross-correlation functions incorporating a time lag were always stronger than Pearson's correlations (c.f. Webb *et al.*, 2003) and correlation strength generally decreased into the streambed.

At Site E, bed temperature fluctuations were more damped and lagged with depth compared with Site D (Table 4.8; Figure 4.5b). Correlations were also weaker, depth for depth, compared with Site D. Streambed temperatures at 0.05 m depth were 0.3°C cooler on average than the water column in 2002, but in 2003 were the same (Table 4.7). Mean bed temperatures at all depths were identical, although with increasing depth variability decreased and minimum (maximum) temperatures were warmer (cooler). Air temperature yields successively weaker relationships and longer lag times with bed temperatures as depth increases (Table 4.8). Similarly, water column and streambed temperature variations were also less well correlated and increasingly lagged with depth (Table 4.8).

Streambed temperatures at Site F were intermediate to those at the two other sites (Table 4.7; Figure 4.5c). In 2002, temperatures were cooler with depth into the streambed, whereas in 2003, temperatures were identical at all depths (i.e. within 0.2°C thermistor accuracy; Table 4.7). Lag times of air and streambed temperatures were generally intermediate of Sites D and E and successively longer with depth (Table 4.8). Water column and 0.05 m depth temperature fluctuations were synchronous but streambed temperatures were increasingly lagged with depth, but to a lesser extent in 2003.

Table 4.7. Descriptive statistics for melt season water column and streambed temperatures

	Site D				Site E				Site F			
	T_w	$T_{b0.05}$	$T_{b0.20}$	$T_{b0.40}$	T_w	$T_{b0.05}$	$T_{b0.20}$	$T_{b0.40}$	T_w	$T_{b0.05}$	$T_{b0.20}$	$T_{b0.40}$
Melt Season 2002												
Mean	7.0	-	7.1	7.2	9.7	9.4	9.4	9.4	8.8	8.5	8.2	8.1
Max	14.0	-	13.1	12.7	13.4	13.0	11.7	11.0	15.4	15.1	12.5	10.4
Min	3.6	-	3.9	4.1	7.1	6.8	7.1	7.4	5.2	4.9	4.9	5.7
Range	10.4	-	9.2	8.6	6.3	6.2	4.6	3.6	10.3	10.2	7.6	4.7
St. Dev.	2.1	-	1.9	1.9	1.2	1.2	1.0	0.8	1.9	1.9	1.5	1.0
Melt Season 2003												
Mean	8.6	8.7	9.2	9.0	11.1	11.1	11.0	11.0	10.3	10.2	10.3	10.5
Max	15.7	15.5	14.8	14.2	16.5	16.3	13.9	13.0	17.0	16.5	15.7	14.4
Min	0.0	1.1	3.5	3.6	2.3	3.6	6.9	7.7	1.9	2.6	5.1	6.2
Range	15.7	14.4	11.2	10.6	14.2	12.7	6.9	5.2	15.1	14.0	10.6	8.3
St. Dev.	2.4	2.3	2.0	1.9	1.8	1.8	1.3	1.1	2.3	2.3	2.0	1.6

Table 4.8. Correlation and Cross-Correlation Function (CCF) co-efficients with lag times, for melt season air-streambed and water column-streambed temperature relationships

		Air-Streambed				Water Column-Streambed			
Melt Season	Site	Depth (m)	*r*	*r* (CCF)	Lag (hrs)	Depth (m)	*r*	*r* (CCF)	Lag (hrs)
2002	D	0.20	0.688	0.773	2.50	0.20	0.959	0.989	1.00
		0.40	0.541	0.770	4.00	0.40	0.843	0.973	2.75
	E	0.05	0.720	0.747	1.50	0.05	0.995	0.995	0
		0.20	0.557	0.689	4.00	0.20	0.848	0.924	2.25
		0.40	0.332	0.553	10.50	0.40	0.573	0.776	7.75
	F	0.05	0.777	0.787	0.75	0.05	0.995	0.999	0
		0.20	0.686	0.800	3.00	0.20	0.874	0.947	1.75
		0.40	0.431	0.738	8.25	0.40	0.403	0.773	6.50
2003	D	0.05	0.801	0.847	1.50	0.05	0.996	0.998	0.25
		0.20	0.651	0.825	3.25	0.20	0.864	0.951	2.00
		0.40	0.585	0.814	4.25	0.40	0.783	0.927	2.75
	E	0.05	0.696	0.804	2.75	0.05	0.994	0.997	0.25
		0.20	0.470	0.751	6.25	0.20	0.711	0.881	3.75
		0.40	0.394	0.601	11.50	0.40	0.481	0.704	9.25
	F	0.05	0.785	0.852	1.75	0.05	0.983	0.994	0
		0.20	0.701	0.857	3.00	0.20	0.902	0.977	1.50
		0.40	0.550	0.859	4.75	0.40	0.691	0.941	3.25

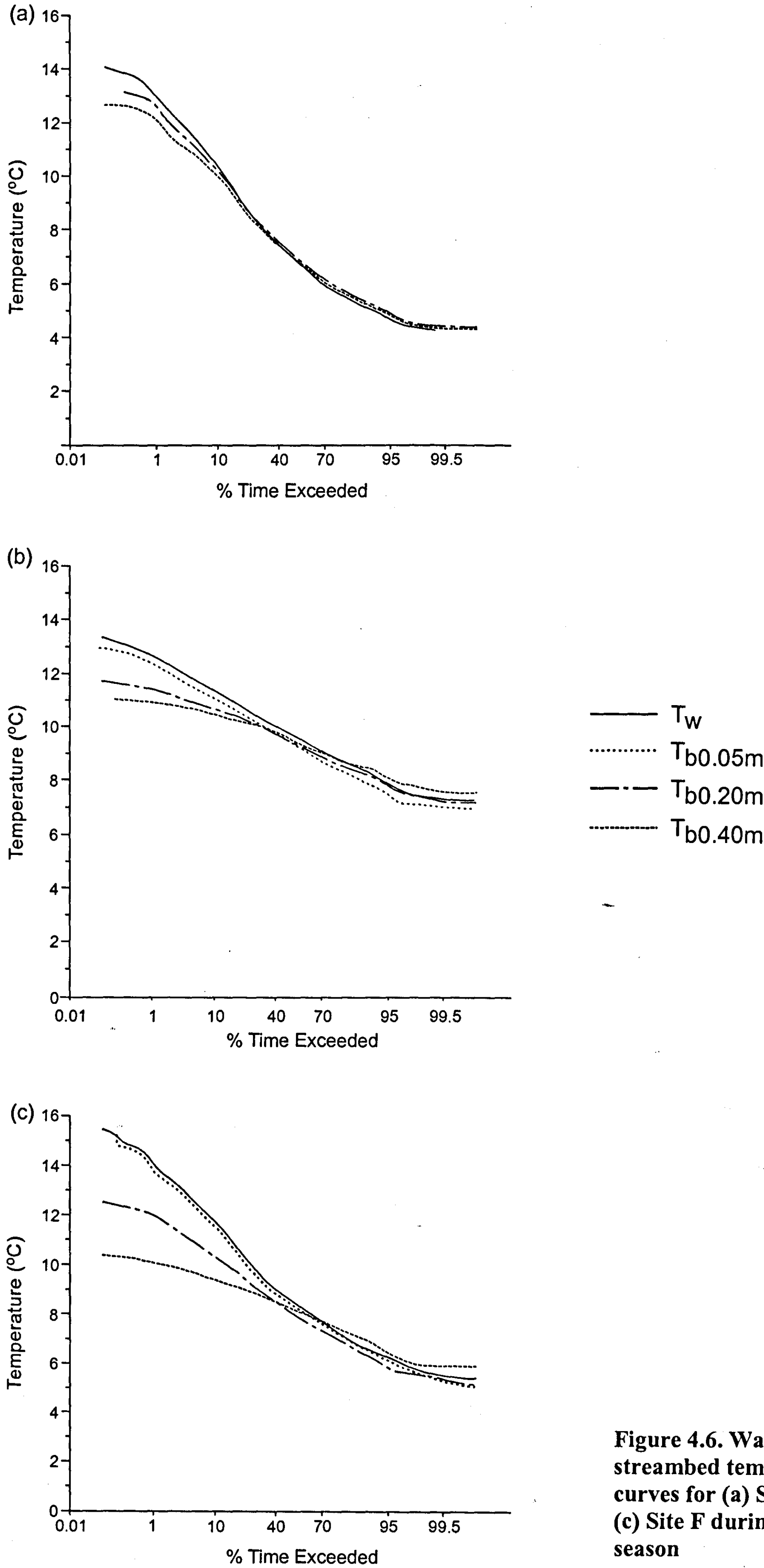
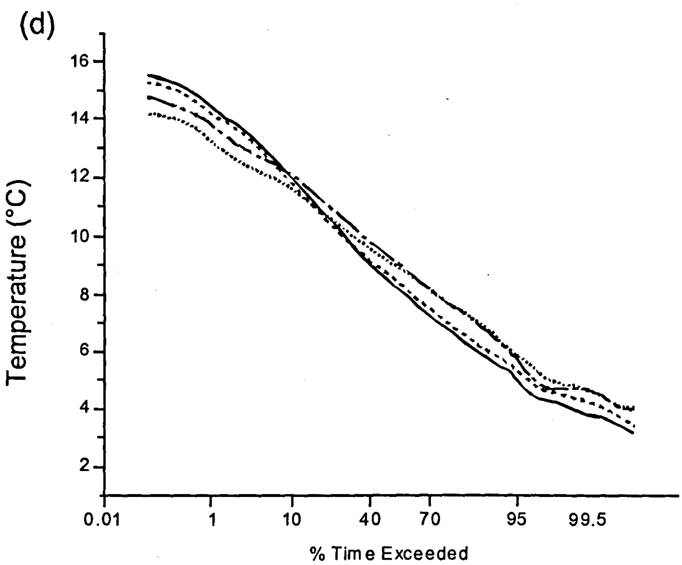
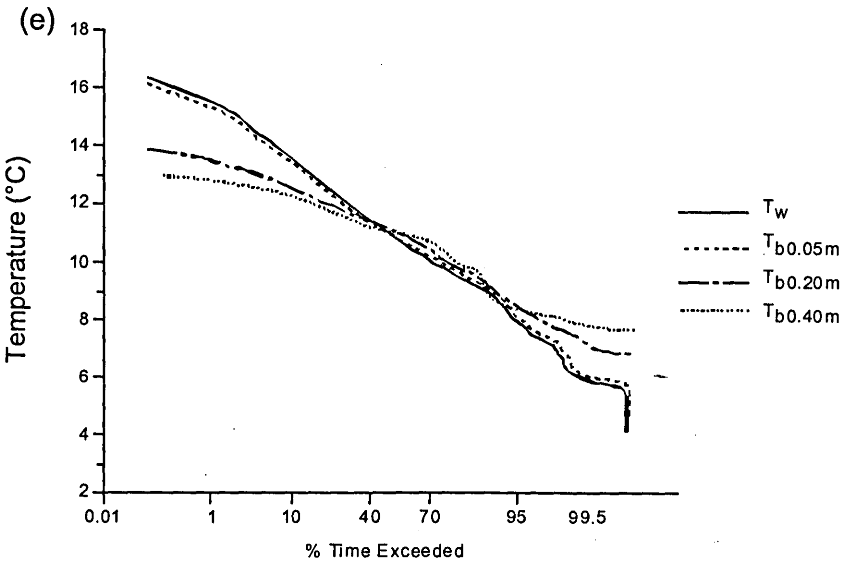


Figure 4.6. Water column and streambed temperature duration curves for (a) Site D, (b) Site E, and (c) Site F during the 2002 melt season





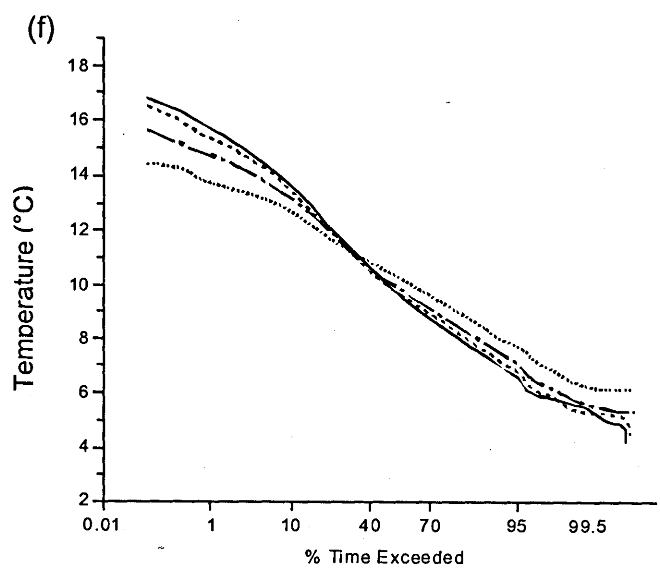


Figure 4.6.cont. Water column and streambed temperature duration curves for (d) Site D, (e) Site E, and (f) Site F during the 2003 melt season

At Site D, discharge and water column temperatures were weakly inversely correlated in both years (Table 4.9). In 2002, discharge was not significantly correlated with streambed temperatures at 0.20 m depth, and was weakly correlated with temperatures at 0.40 m depth. In 2003, discharge was weakly negatively correlated with streambed temperatures at all depths (Table 4.9). Discharge at Site E yielded very weak negative correlations with both water column and bed temperatures at all depths although these associations were slightly stronger in 2003 (Table 4.9). Site F discharge was not significantly correlated with water column or 0.05 m depth temperatures in 2002. Weak positive relationships were found between discharge and streambed temperatures at 0.20 m and 0.40 m depth in 2002, but no relationships were found for these depths in 2003.

Table 4.9. Correlation co-efficients for discharge and water column-streambed temperatures over the 2002 and 2003 monitoring periods. Correlations are significant at $p<0.01$ except for ^(insignificant), and – (no data)

Melt Season	Depth	Site D	Site E	Site F
2002	T_w	-0.085	-0.127	0.024^
	$T_{b0.05}$	-	-0.159	0.021^
	$T_{b0.20}$	-0.011^	0.105	0.128
	$T_{b0.40}$	0.049	-0.047	0.185
2003	T_w	-0.153	-0.231	-0.069
	$T_{b0.05}$	-0.142	-0.228	-0.037
	$T_{b0.20}$	-0.161	-0.244	-0.014^
	$T_{b0.40}$	-0.147	-0.315	0.015^

Sub-seasonal patterns

Period 1 was characterised by clear diurnal temperature fluctuations in the water column and streambed at all depths (Figure 4.7). At Sites D and E, temperatures were cooler with depth during the morning to early afternoon, with the reverse situation occurring at night. However, at Site F, temperatures were cooler with depth in the daytime, but nocturnal temperatures were warmest in the order $T_{b0.40} > T_w > T_{b0.05} > T_{b0.20}$ (Figure 4.7). At Site D mean temperatures increased and range decreased with depth into the bed. Site F showed greater water column and 0.20 m depth temperature ranges and standard deviations than Site D (Table 4.10) but relatively stable thermal conditions at 0.40 m depth (Table 4.10). Site E had the warmest and least variable temperature regimes at all depths, with a pattern of decreasing temperature with depth, similar to Site F.

For Period 2, meltwater-driven discharge cycles were not generated on most days, and variations in water column and streambed thermal profiles were similarly absent (Figure 4.8). At Site D, average water column and streambed temperatures were identical but temperature range was less at 0.40 m depth (Table 4.10). At Site F, the thermal profile was similar to seasonal patterns (i.e. cooler with increasing depth); however, temperatures at 0.20 and 0.40 m depth were on average very similar (Table 4.10). Notably at Site E, a change from the 2002 seasonal thermal profile occurred, with warmer temperatures at depth into the streambed and the water column slightly warmer than the upper streambed.

During Period 3, warm average and relatively variable bed temperatures were recorded (Table 4.10; Figure 4.9). All sites displayed similar thermal patterns throughout the diurnal cycle, with morning-early afternoon temperatures decreasing with depth, and reversed thermal profiles at night. At Site D, average temperatures were identical from the water column to 0.40 m depth, but more variable than any other period (Table 4.10). At Site E, the average temperatures decrease from the water column to 0.4 m depth was the greatest of all periods (0.7°C). At Site F, maximum temperatures (all depths) and mean temperature (all depths except 0.40 m depth) were the highest of all periods.

In Period 4, similar vertical thermal patterns to those for 2002 seasonally averaged data occurred at all three sites. For all depths at Site E and 0.40 m depth at Site F, temperatures were the warmest for all selected periods in 2002 (Table 4.10). However, short-term changes in thermal patterns in the water column and bed temperatures are evident on days 228 and 230 coinciding with major precipitation events (Figure 4.10). On day 228, temperatures decreased by 3-5°C at all sites at 0.05 m depth, and 1-2°C at 0.20 m depth. Temperatures decreases were also evident on day 230 but lower than for the previous precipitation event. No temperature decreases corresponding to these precipitation events were recorded at 0.40 m depth.

During Period 5 towards the end of the melt season, diurnal thermal profiles at Site D and Site F (Figure 4.11) displayed similar characteristics as for Period 1. Average temperatures at Site D were identical at all depths. Bed temperatures at Site D were considerably cooler compared with Period 4, whilst bed temperatures at Sites E and F remained relatively warm (Table 4.10). Sites E and F had similar thermal profiles during the day (i.e. cooler at depth), but nocturnal temperatures at Site E were warmest in the order $T_{b0.40} > T_w > T_{b0.05} > T_{b0.20}$ (Figure 4.11b).

Period 6 was characterised by clear diurnal fluctuations in water column and bed temperatures punctuated by a very considerable temperature decrease (greater than in Period 4) coinciding with an intense hail/rainstorm (Figure 4.12). Average temperatures for the entire period were warmer with depth at all sites except Site D where temperatures at 0.20 m were warmest (Table 4.10). Temperature variability (range and standard deviation) was greatest for surface waters and lowest at 0.40 m at all sites. The storm resulted in 'extreme' increases in discharge at all sites accompanied by a rapid drop in water column and upper streambed (0.05 m) temperatures at all sites. Minimum temperatures were the lowest recorded for the entire 2003 melt season at all sites, in addition to being the coldest of any sub-seasonal period. Thermal response at depth varied between sites. Temperatures for the Taillon stream sites (D and F; Figure 4.12a and c) decreased considerably by up to 12°C in the water column, 6-7°C at 0.2 m, and ~5°C at 0.4 m. At Site E (Figure 4.12b), the discharge peak coincided with a decrease in temperatures of ~10°C in the water column, and ~3°C at 0.20 m, but temperatures at 0.4 m depth remained unaffected.

In Period 7, strong diurnal variations in water column and streambed temperatures were evident (Figure 4.13), with average temperatures higher than the seasonal means for both years. Average temperatures were also the warmest of any sub-seasonal period (Table 4.10). Average temperatures were cooler with depth at Sites E and F; but, in contrast, Site D was coolest at the surface with warmest temperatures at depth (Table 4.10). Temperature variability was dampened with depth into the streambed at all sites, most evidently at Site D where temperature range was ~5°C less at 0.40 m compared with the water column (Table 4.10). At Site E, water column and upper streambed temperatures (0.05 m) showed a 'stepped' increase in temperature on days 214 and 215 (Figure 4.13b), which occurred due to early morning shading of the Tourettes stream by surrounding mountains during these otherwise clear-sky days.

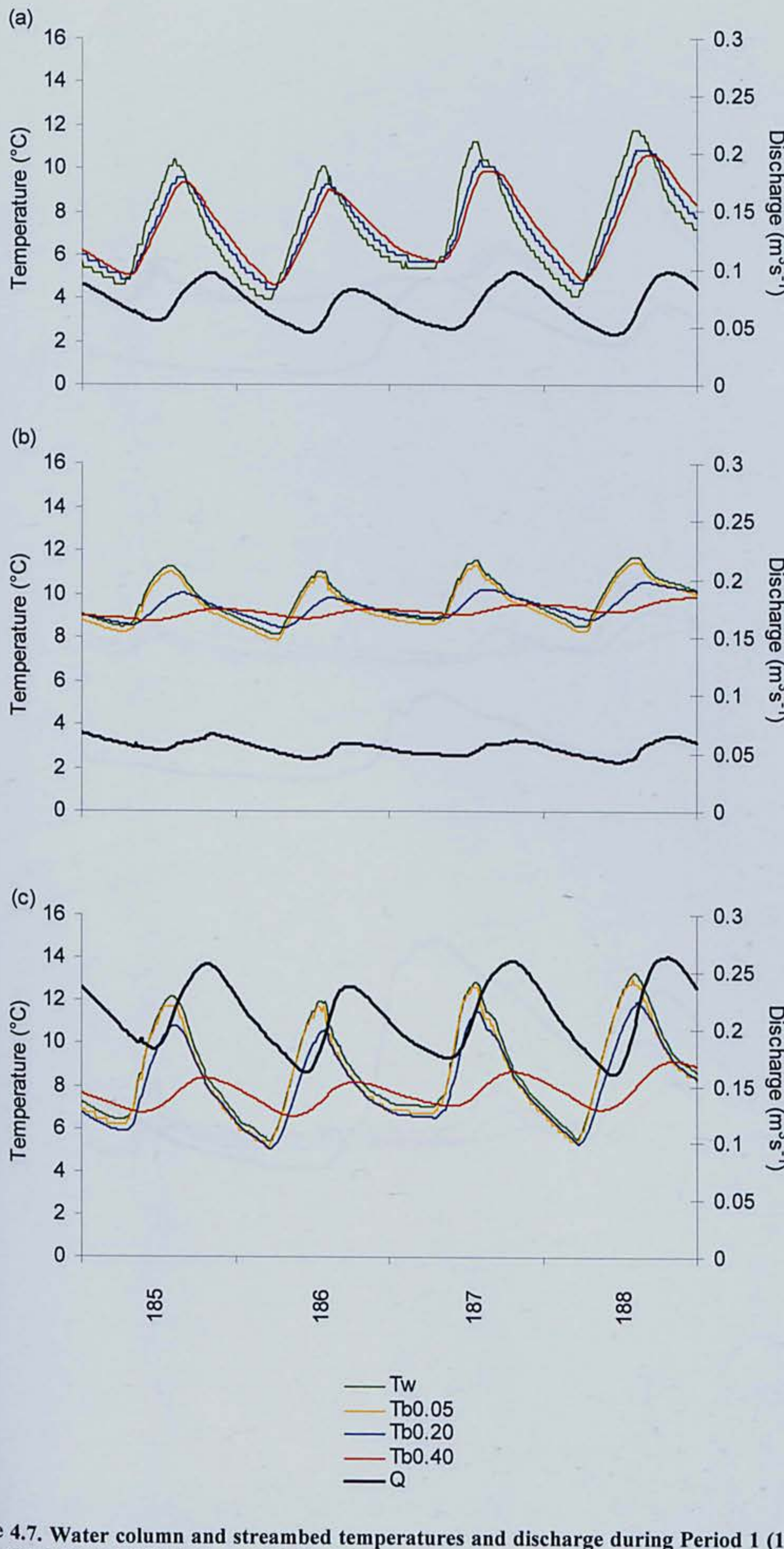


Figure 4.7. Water column and streambed temperatures and discharge during Period 1 (185-188, 2002), at (a) Site D, (b) Site E, and (c) Site F.

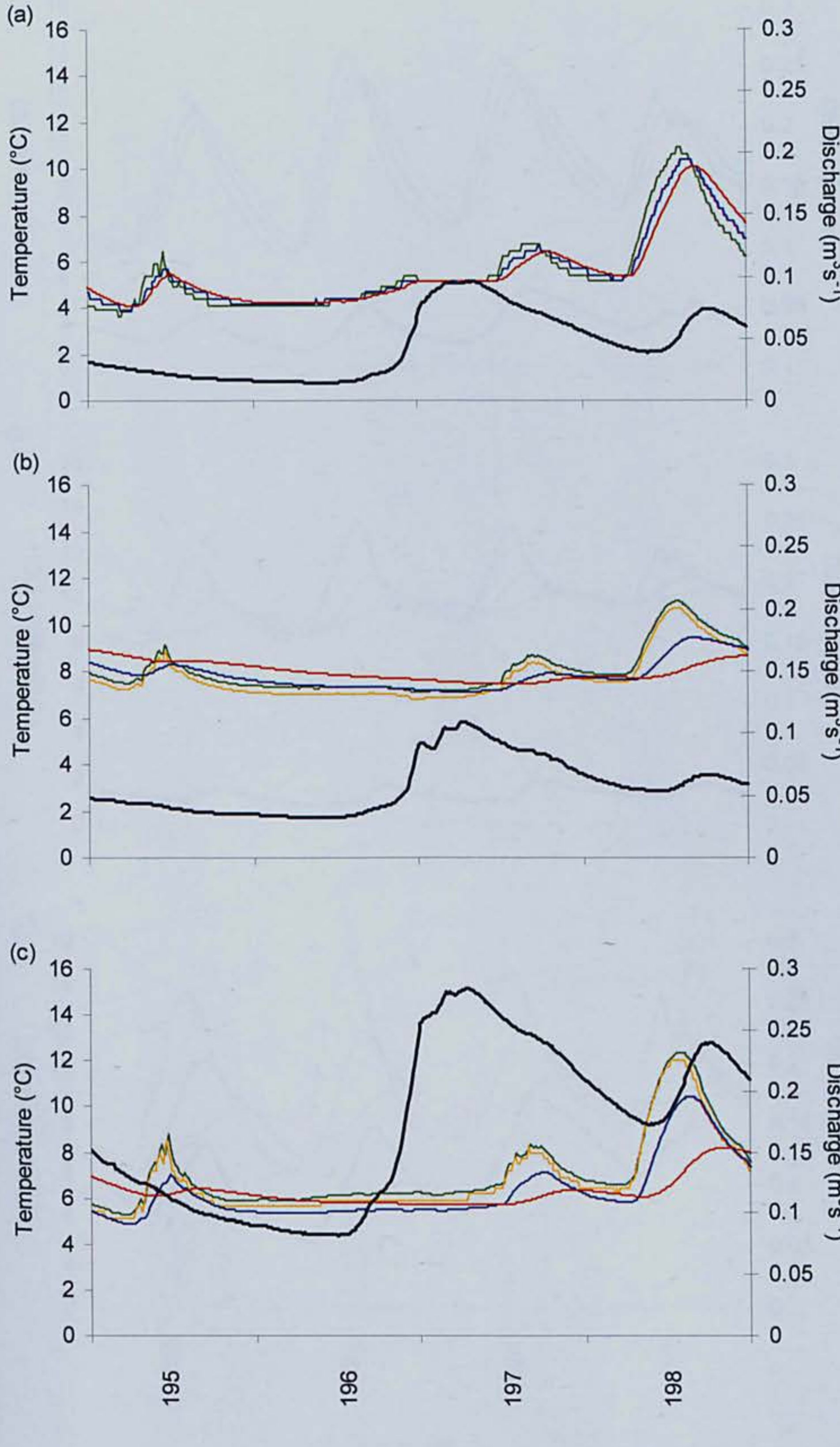


Figure 4.8. Water column and streambed temperatures and discharge during Period 2 (195-198, 2002), at (a) Site D, (b) Site E, and (c) Site F.

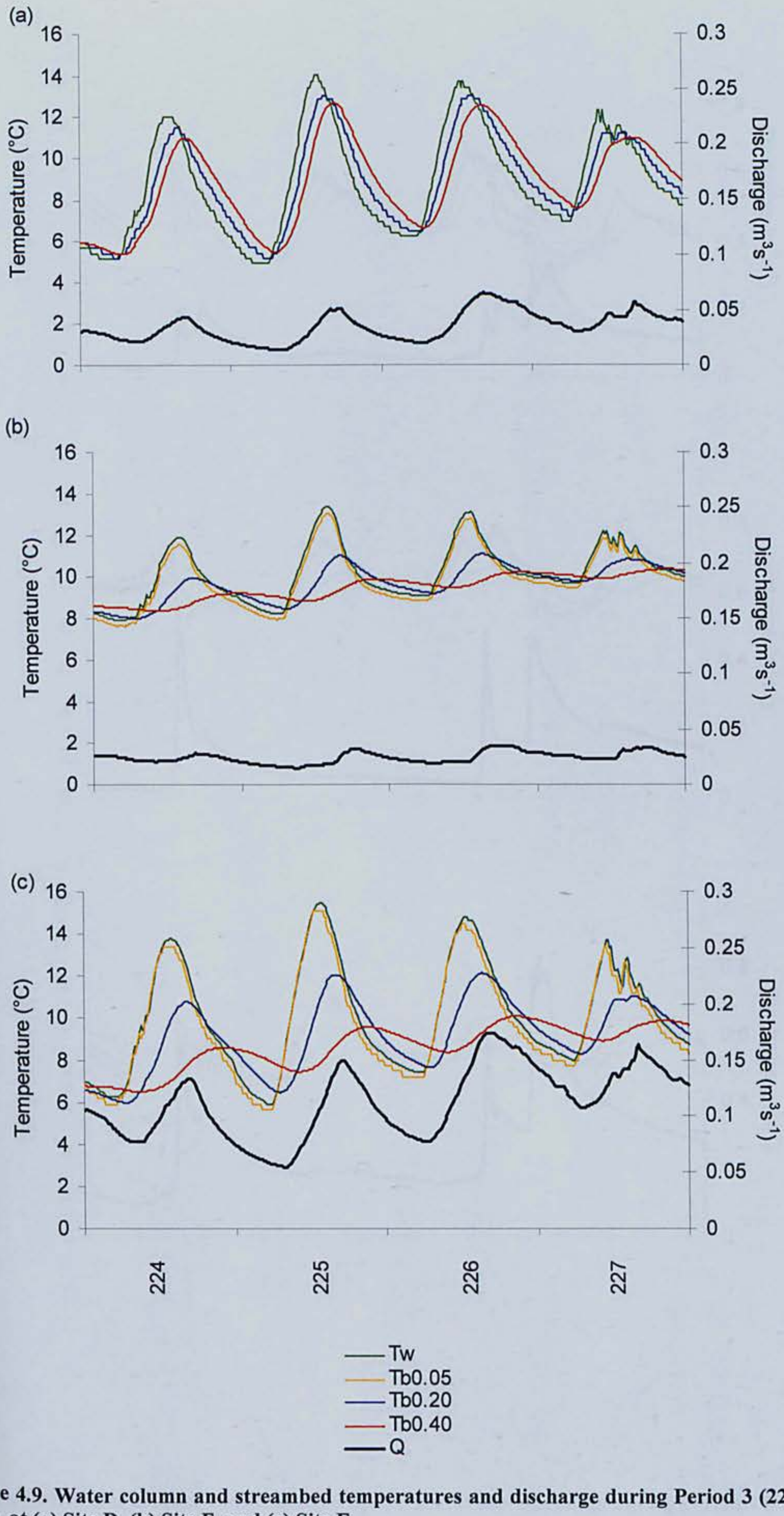


Figure 4.9. Water column and streambed temperatures and discharge during Period 3 (224-227, 2002), at (a) Site D, (b) Site E, and (c) Site F.

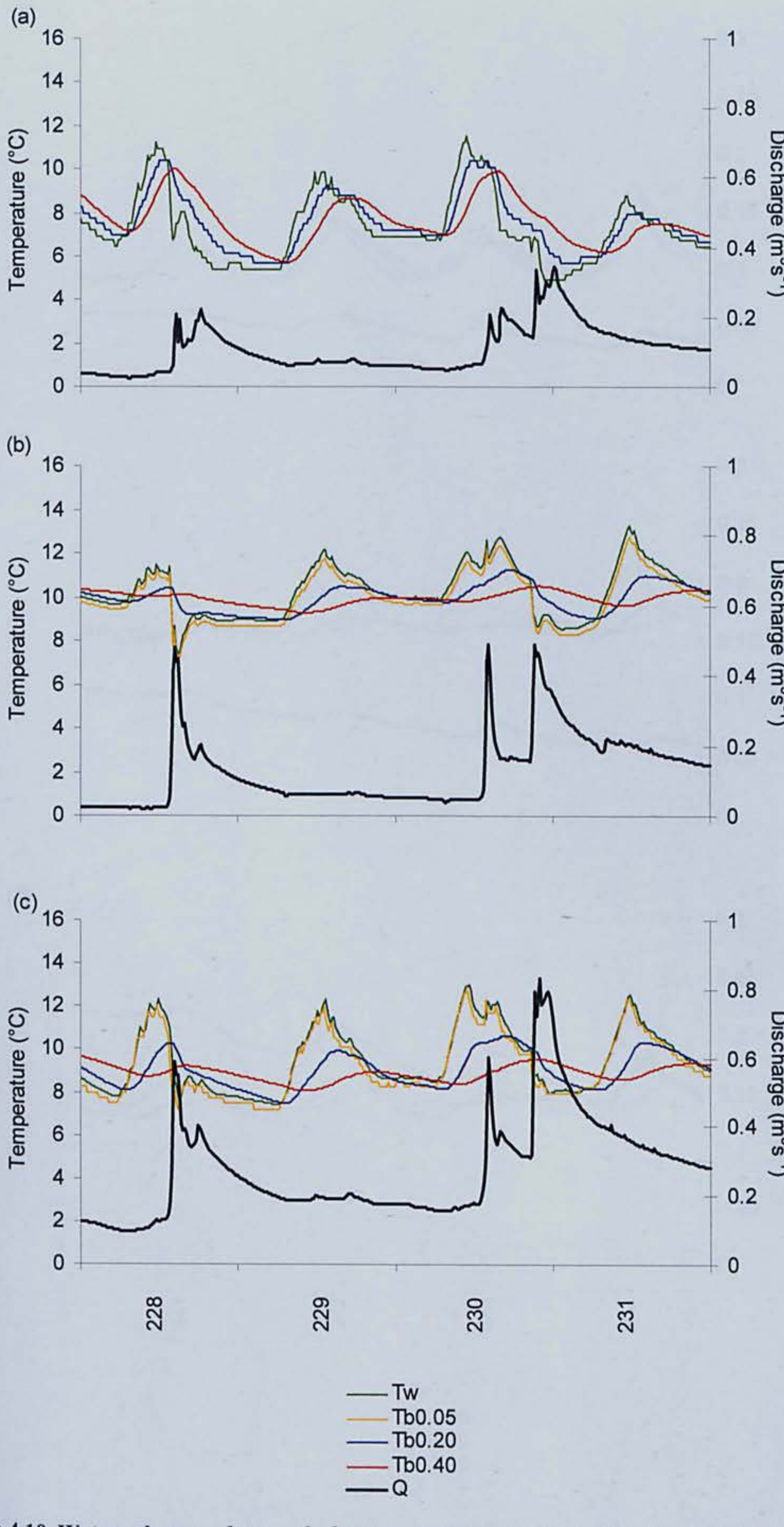


Figure 4.10. Water column and streambed temperatures and discharge during Period 4 (228-231, 2002), at (a) Site D, (b) Site E, and (c) Site F.

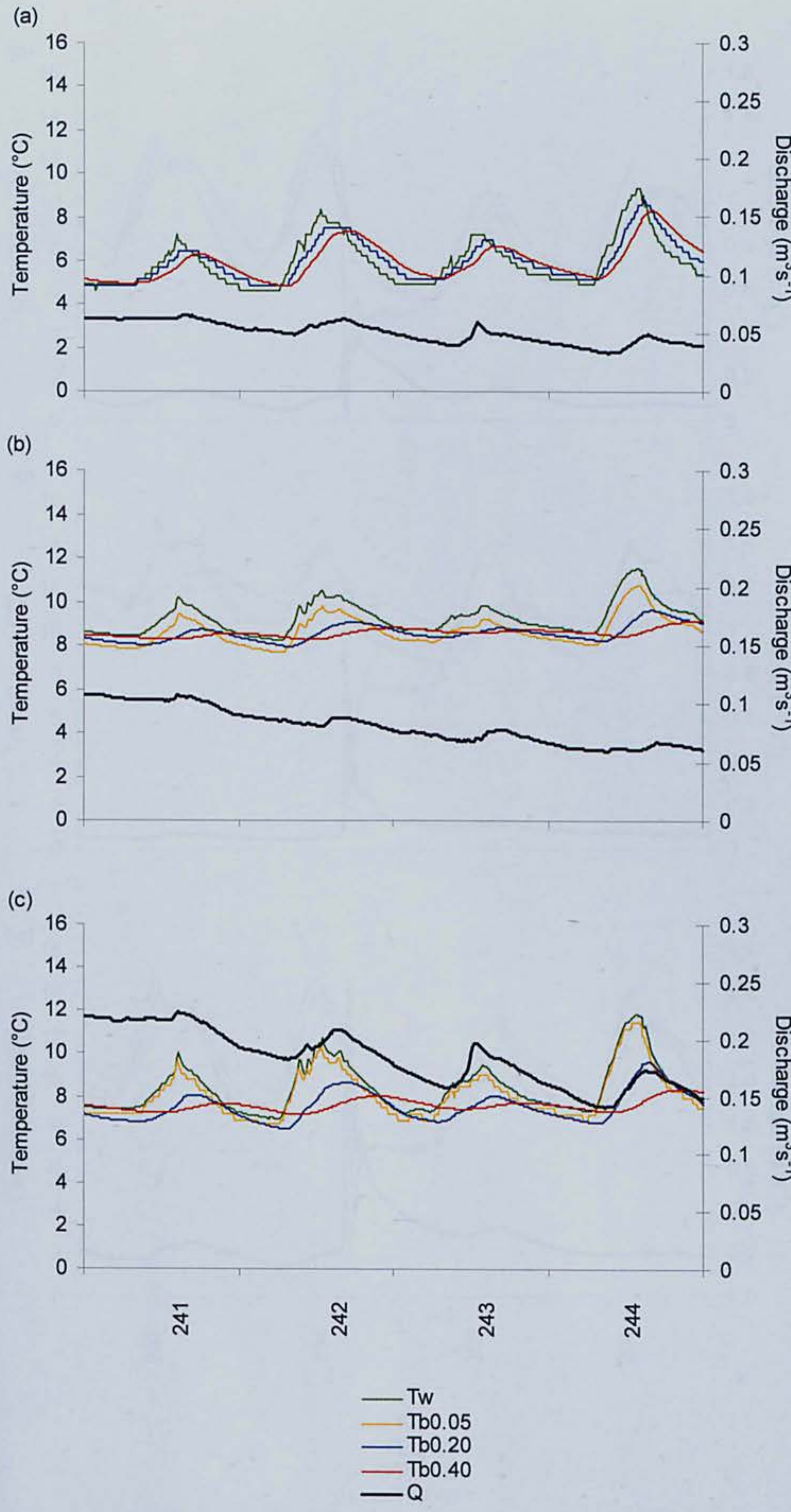


Figure 4.11. Water column and streambed temperatures and discharge during Period 5 (241-244, 2002), at (a) Site D, (b) Site E, and (c) Site F.

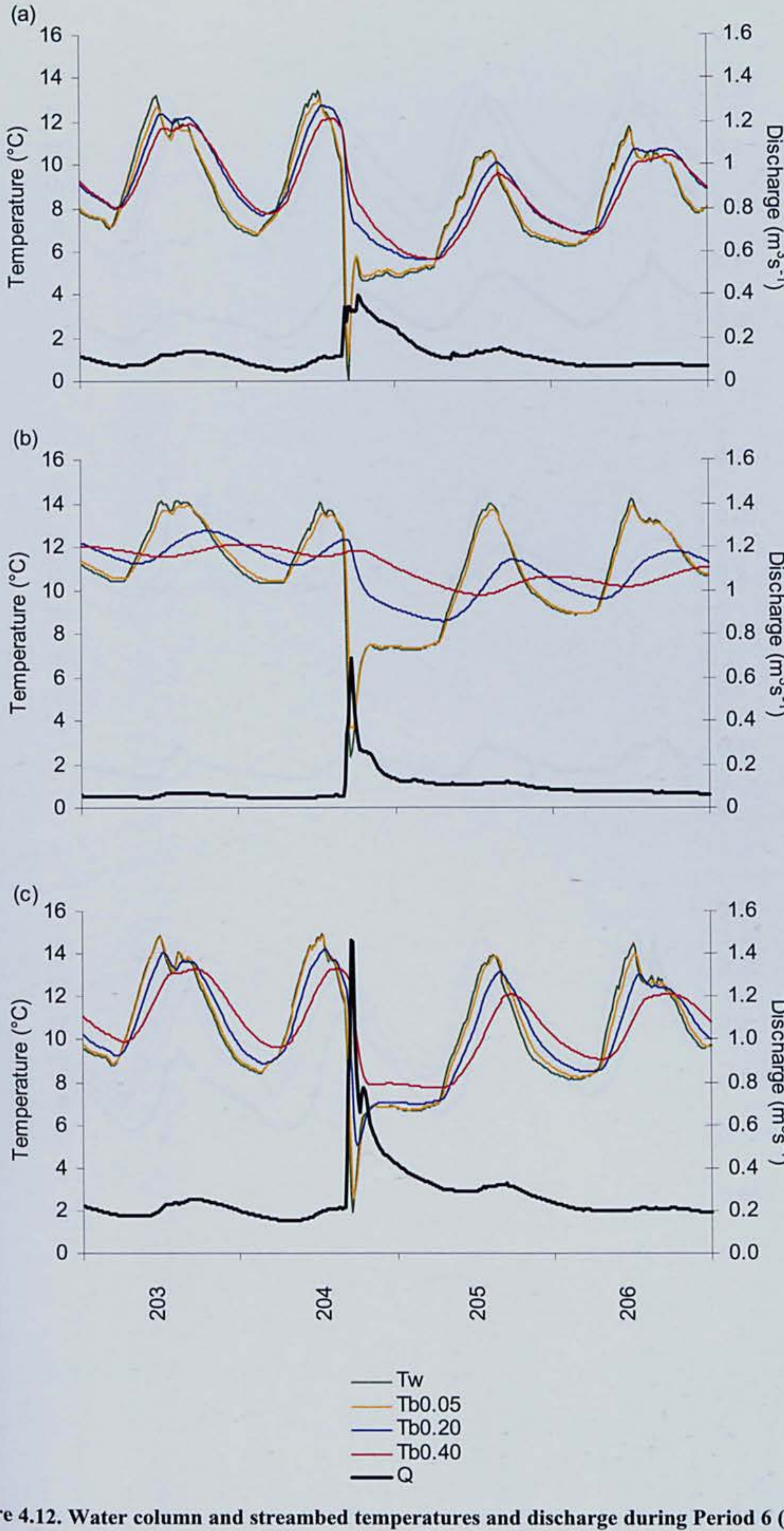


Figure 4.12. Water column and streambed temperatures and discharge during Period 6 (203-206, 2003), at (a) Site D, (b) Site E, and (c) Site F.

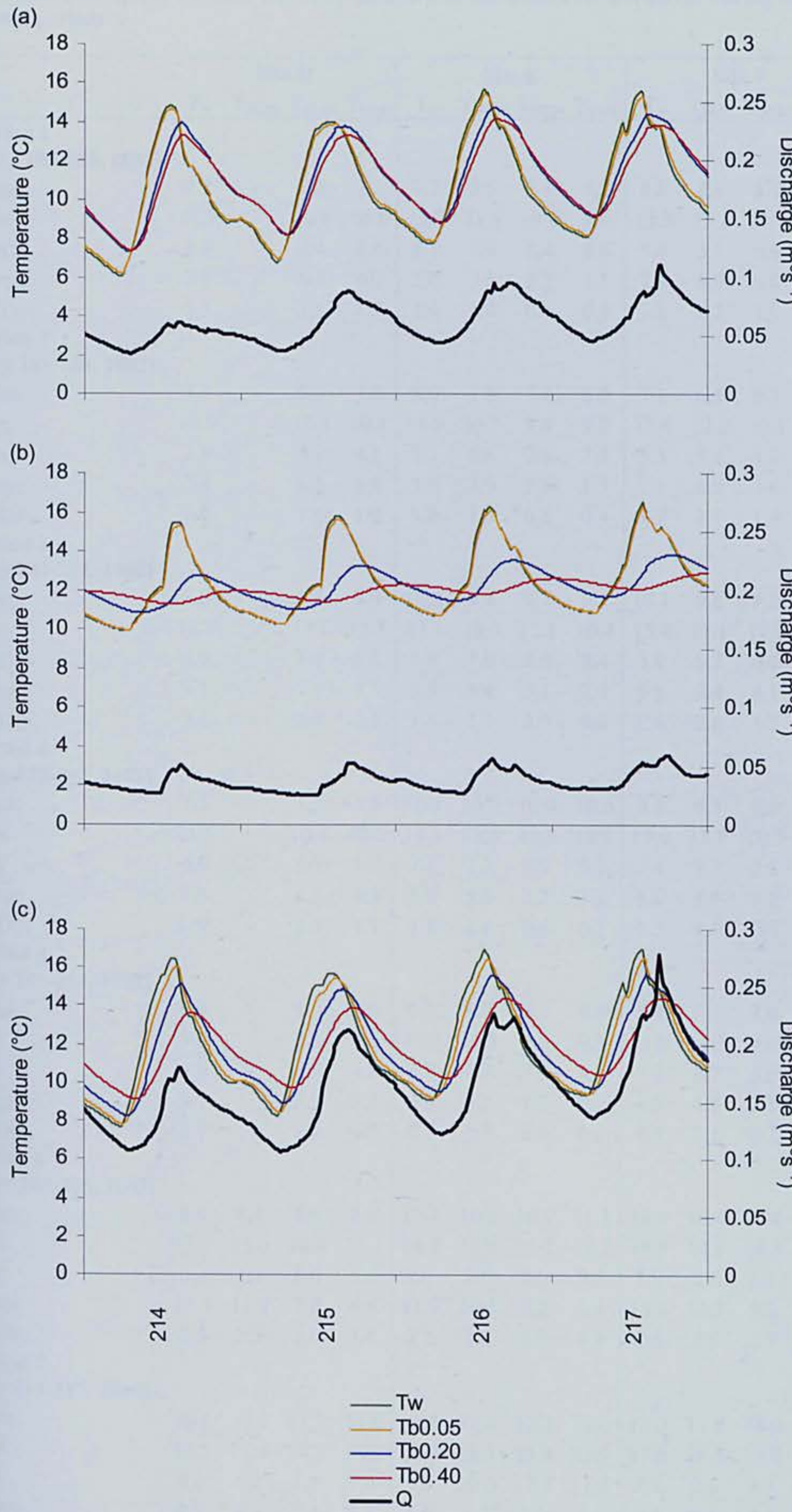


Figure 4.13. Water column and streambed temperatures and discharge during Period 7 (214-217, 2003), at (a) Site D, (b) Site E, and (c) Site F.

Table 4.10. Descriptive statistics for water column and streambed temperatures during the sub-seasonal periods

	Site D				Site E				Site F			
	T_w	$T_{b0.05}$	$T_{b0.20}$	$T_{b0.40}$	T_w	$T_{b0.05}$	$T_{b0.20}$	$T_{b0.40}$	T_w	$T_{b0.05}$	$T_{b0.20}$	$T_{b0.40}$
Period 1 (day 185-188, 2002)												
Mean	7.2	-	7.2	7.3	9.7	9.5	9.4	9.2	8.8	8.5	8.1	7.7
Max	11.7	-	10.9	10.6	11.7	11.5	10.6	9.9	13.3	13.1	11.9	9.2
Min	3.9	-	4.4	4.6	8.1	7.9	8.4	8.8	5.4	5.1	5.1	6.6
Range	7.8	-	6.5	6.0	3.6	3.6	2.2	1.1	7.9	8.0	6.8	2.6
St. Dev.	2.1	-	1.8	1.7	1.0	1.0	0.6	0.3	2.2	2.2	1.9	0.7
Period 2 (day 185-188, 2002)												
Mean	5.6	-	5.6	5.6	8.0	7.8	7.8	8.0	7.1	6.8	6.3	6.3
Max	10.9	-	10.4	10.1	11.0	10.7	9.4	9.0	12.4	12.0	10.5	8.2
Min	3.6	-	3.9	4.1	7.1	6.8	7.1	7.4	5.3	5.1	4.9	5.7
Range	7.3	-	6.5	6.0	3.9	3.9	2.3	1.5	7.1	6.9	5.6	2.5
St. Dev.	1.7	-	1.6	1.6	1.0	1.0	0.6	0.4	1.7	1.7	1.4	0.6
Period 3 (day 224-227, 2002)												
Mean	8.8	-	8.8	8.9	10.2	9.9	9.7	9.5	10.1	9.8	9.2	8.6
Max	14.0	-	13.1	12.7	13.4	13.0	11.1	10.4	15.4	15.1	12.1	10.1
Min	4.9	-	5.2	5.4	7.9	7.6	8.0	8.4	5.9	5.7	6.0	6.5
Range	9.1	-	7.9	7.3	5.5	5.4	3.1	2.0	9.5	9.4	6.1	3.6
St. Dev.	2.5	-	2.3	2.1	1.4	1.3	0.9	0.6	2.6	2.6	1.7	1.1
Period 4 (day 228-231, 2002)												
Mean	7.3	-	7.5	7.6	10.3	10.0	10.0	10.0	9.5	9.3	9.0	8.9
Max	11.5	-	10.4	10.0	13.3	12.8	11.3	10.5	13.0	12.8	10.7	9.7
Min	4.9	-	5.7	5.7	7.4	7.2	9.0	9.3	7.4	7.2	7.5	8.1
Range	6.6	-	4.7	4.3	5.9	5.6	2.3	1.2	5.6	5.6	3.2	1.6
St. Dev.	1.56	-	1.3	1.1	1.2	1.2	0.6	0.3	1.5	1.5	0.9	0.4
Period 5 (day 241-244, 2002)												
Mean	5.9	-	6.0	6.0	9.3	8.7	8.6	8.6	8.4	8.1	7.6	7.6
Max	9.3	-	8.8	8.3	11.5	10.8	9.6	9.1	11.9	11.5	9.6	8.4
Min	4.6	-	4.9	4.8	8.2	7.7	7.9	8.3	7.0	6.7	6.5	7.2
Range	4.7	-	3.9	3.5	3.3	3.1	1.7	0.9	4.9	4.8	3.1	1.2
St. Dev.	1.1	-	1.0	0.9	0.7	0.7	0.4	0.2	1.1	1.1	0.7	0.3
Period 6 (day 203-206, 2003)												
Mean	8.4	8.4	8.9	8.8	10.9	10.9	10.9	11.1	10.4	10.4	10.4	10.6
Max	13.5	13.0	12.8	12.1	14.2	13.9	12.7	12.1	14.9	14.9	14.3	13.3
Min	0.0	1.1	5.6	5.6	2.3	3.6	8.6	9.8	1.9	2.6	5.1	7.7
Range	13.4	11.9	7.2	6.6	11.9	10.3	4.2	2.4	13.0	12.3	9.2	5.6
St. Dev.	2.5	2.3	2.0	1.8	2.3	2.2	1.2	0.8	2.6	2.5	2.2	1.7
Period 7 (day 214-217, 2003)												
Mean	10.6	10.6	11.2	11.0	12.5	12.4	12.2	12.0	12.0	11.9	11.9	11.9
Max	15.7	15.5	14.8	14.2	16.5	16.3	13.9	12.9	17.0	16.5	15.7	14.4
Min	6.0	6.2	7.3	7.4	9.9	10.0	10.8	11.3	7.7	7.8	8.3	9.1
Range	9.7	9.3	7.4	6.8	6.6	6.4	3.0	1.6	9.3	8.8	7.4	5.3
St. Dev	2.6	2.5	2.0	1.9	1.8	1.8	0.9	0.4	2.6	2.4	2.1	1.5

4.5. DISCUSSION

Detailed observations of water column and streambed temperatures enabled characterisation of temporal and spatial variability in alpine stream thermal habitat across a range of melt-season hydroclimatological conditions. Water column temperatures increased longitudinally from the Taillon Glacier snout (Site A) to Site F but this downstream pattern was influenced by inputs from the Crampettes (Tourettes) groundwater-fed tributary, which decreased (increased) temperatures downstream of its confluence with the glacial stream. Similar longitudinal temperature patterns influenced by tributaries have been reported by Gíslason *et al.* (2000) and Knispel & Castella (2003). Groundwater temperatures were considerably different throughout the catchment. Karstic groundwater streams were on average cooler and less variable than the glacial stream with the exception of the site located at the Taillon Glacier snout. The karstic system in the catchment is fed predominantly by melting snowpacks located above sinkholes on Les Gabiétous Massif (Figure 4.1), with transit times to the Crampettes spring (Site C) estimated to be 34-46 hrs (Parc-National-des-Pyrénées, 1991). Once in these networks (some of which are >200 m deep; Parc-National-des-Pyrénées, 1991), waters are unlikely to increase greatly in temperature resulting in cold emerging waters. In contrast, the hillslope groundwater tributary was the most thermally variable and on average warmest; these characteristics are likely enhanced by the snow-free, southerly aspect of this stream's subcatchment.

In the Tourettes stream (Site E), thermal patterns were warmest and variability lowest due to a greater proportion of groundwater contributions to buffer fluctuations. Thermal characteristics downstream of the confluence of the Taillon and Tourettes streams were consistently intermediate of those at Sites D and E reflecting the mix of waters. Typically, each site was characterised by increasingly lagged and attenuated temperature response at depth, which were greatest at Site E. The magnitude of temperature fluctuations in the streambed is probably related to the magnitude of fluctuations in the water column (e.g. Acornley, 1999).

Hence, the smaller fluctuations in the Tourettes stream generate less marked variations than in the Taillon stream through bed conductive and advective processes. Thermal response (i.e. lag times between water column and streambed temperatures) may also be affected by differences in bed sediments (e.g. Malcolm *et al.*, 2004) as coarser sediments with larger interstitial voids may allow water to infiltrate quicker (at Site A, and to a slightly lesser extent, Site C). Contrasting bed temperature behaviour between the sites may, in part, be due to groundwater-surface water interactions (Silliman and Booth, 1993) but independent evidence (e.g. hydraulic head measurements) would be required to determine the extent of such influences.

The role of discharge variations was difficult to clearly elucidate, as relationships with water column and streambed temperatures were inconsistent and weak. This may be a result of a range of factors limiting inference of processes, particularly high flows being sourced from thermally different origins (e.g. meltwater, groundwater and/or rainfall). Furthermore, the small volumes of water conveyed by streams in this study may be insufficient to drive surface water into the streambed to influence thermal profiles. Bed sediment calibre may also affect the extent of advection into the riverbed with fine glacial-sediment possibly clogging interstitial spaces. Nevertheless, during peak flow events caused by precipitation events, thermal patterns were altered to 0.40 m depth; therefore event-based correlations may produce different relationships compared to seasonal data.

Fluctuations at the inter-annual, seasonal and event time-scale, in water source contributions (particularly from snow/ice-melt and groundwaters), atmospheric influences (characterised, in part, by site-specific air temperature and incoming short-wave radiation) and episodic cold precipitation inputs appear key factors determining stream thermal dynamics. The seven four-day periods selected for detailed investigation contrast: (1) early melt season conditions when the upper stream network (covered by snowpacks) was more thermally stable than openly exposed warmer downstream reaches that were more responsive to atmospheric conditions; (2) cold weather conditions when stream thermal conditions at sites were closely related to that of source waters (i.e. snow/ice, or karstic/hillslope groundwaters); (3) a mid-summer glacier-melt dominated period when marked stream temperature fluctuations were strongly related to atmospheric heating; (4) major precipitation events during which typical water column and streambed temperatures to 0.20 m were suppressed by cold rainwater inputs; (5) late melt season conditions when cooler atmospheric conditions were associated with decreased stream temperature variability compared to mid-summer; (6) an extreme precipitation event during which stream thermal profiles to 0.4 m depth into the streambed were strongly disrupted by cold/frozen (rain/hail) water inputs, and (7) an extremely warm mid-summer period stream characterised by large water column and streambed temperature fluctuations and strong longitudinal temperature increases (~10°C) over a distance of only 1km downstream of the Taillon Glacier

Thus, inter-annual and sub-seasonal water column and streambed temperature dynamics appear to relate to differential hydroclimatological forcing. For example, during the cold period (2), when atmospheric energy input was reduced, glacial stream temperatures were influenced by cold meltwater inputs from snow and ice covered areas in the upper catchment as well as a cold (~4°C) karstic groundwater spring inflow, draining the upper catchment. A greater proportion of warmer hillslope groundwaters from the Tourettes stream (Site E) maintained slightly warmer temperatures at Site C. In Periods 3 and 7, atmospheric heating of streams was probably enhanced by complete exposure of channels in the upper catchment following snowline retreat (c.f. Period 1). Strong diurnal water column and streambed temperature fluctuations at these times may be attributed, at least in part, to water flowing in multiple steep, shallow braided channels across Les Gabiétous Massif (Figure 4.1). These channels have a high width:depth (surface area:volume) ratio and so they are potentially highly responsive to atmospheric energy gain/loss (Poole and Berman, 2001). In Periods 4 and 6, diurnal water column and streambed temperature fluctuations driven by atmospheric energy inputs were interrupted by a major cold precipitation events that reduced streambed temperatures even down to 0.40 m depth. Although precipitation temperature was not measured, it may be inferred that the marked drop in temperatures were due to hail\rain advecting cold inputs (not reduced radiative gains under cloud cover, c.f. Period 1, and nocturnally). Interestingly, previous work in temperate river basins suggests precipitation temperature plays a negligible role in the stream energy balance (e.g. Evans *et al.*, 1998).

4.6. IMPLICATIONS FOR ALPINE STREAM HABITAT CLASSIFICATION AND POTENTIAL INFLUENCES UPON ECOLOGICAL COMMUNITIES

In conclusion, the high thermal heterogeneity of the water column and streambed over a range of time-scales (seasonal to diurnal) was closely related to: (1) dynamic water source contributions (e.g. snowmelt, ice-melt and groundwaters), (2) proximity to source, and (3) hydroclimatological conditions, including 'extreme' events. Temperature plays an important role by determining rates of growth, development, emergence and reproduction of aquatic organisms (Ward and Stanford, 1982), and longitudinal faunal gradients in alpine glacial streams (Milner and Petts, 1994; Milner *et al.*, 2001). Considerable changes in macroinvertebrate community composition in the Taillon glacial stream occur over a distance of only 1 km, which may correspond to differences in thermal habitat (Snook and Milner, 2001b, 2002). For the Taillon stream, the presence of additional taxa not predicted by the conceptual model of Milner *et al.* (2001) was attributed to groundwater inputs from tributaries (i.e. the Tourettes and Crampettes streams) acting as modifiers to longitudinal thermal patterns (Milner and Petts, 1994). However, the role of warmer, more stable thermal habitat conditions in the streambed at some sites reported in this paper may be important in explaining their presence. In addition, the high thermal heterogeneity of streams in the catchment may also sustain a number of endemic Pyrénéan macroinvertebrate taxa (Snook and Milner, 2001b).

The wide variability of alpine water column and streambed temperatures in this, and other studies (Ward *et al.*, 1999; Malard *et al.*, 2001) demonstrates the range of thermal habitat available for colonisation by benthic communities over relatively small areas. However, other physical variables (e.g. channel stability and suspended sediment concentration) and biotic processes (e.g. competition and predation) influence macroinvertebrate communities in alpine streams (Brown *et al.*, 2003), and these should be considered in addition to temperature variations when interpreting patterns of richness and abundance.

Importantly, this study shows that Pyrénéan alpine stream thermal regimes are often influenced by more than one water source. This reinforces the problems with traditional ecological alpine stream habitat classifications that assign streams to three broad categories based predominantly upon their perceived source and thermal characteristics (Brown *et al.*, 2003). In this study, water column temperatures variations were absent at the Taillon Glacier snout at the beginning of the study periods due to snowpacks supplying streams and preventing exposure to the atmosphere. Traditional methods classify snowmelt fed streams based on a temperature range of 5-10°C; based on data presented herein this is clearly wrong. The temperature characteristics of the Taillon stream (Site A) were more similar to those of the traditional glacial (kryal) classification (i.e. temperatures between 0-4°C). Temperature variations at Site B in mid-late summer, when snow input to streams was minimal and glacial input predominant were typically from 5-15°C, similar to snowmelt (rithral) temperature ranges of traditional approaches. Traditional classification approaches regard glacier-fed streams (kryal) as having a temperature range of between 0-4°C. These approaches clearly do not consider water temperature increases due to atmospheric heating as water flows downstream from a glacier. Furthermore, variable thermal conditions in groundwater streams (e.g. Sites E and G) in the Taillon-Gabiétous catchment, suggests that some groundwater streams may vary by much more than 1-2°C over an annual cycle. Only the karstic streams (Sites C and H) in this study showed temperature variability similar to that expected for krenal streams. These findings support the need for an alternative approach to alpine stream classification based upon actual contributions from water sources.

Thermal regimes of alpine streams are likely to be altered under scenarios of climate change; thus, stream communities may also be affected (McGregor *et al.*, 1995a). Patterns of glacial retreat, such as those occurring presently in the Taillon-Gabiétous catchment (Gellatly *et al.*, 1995; Association-Moraine-Pyrénéenne-de-Glaciologie, 2003), may further alter stream thermal conditions due to changes in the timing and magnitude of peak ice-melt, and duration/amount of snow cover. However, understanding the potential response of glacial and alpine streams to future climate change is currently limited by a paucity of quality data quantifying air-water-streambed temperature relationships in alpine catchments, and links between thermal habitat and stream communities.

4.7. SUMMARY

This chapter has demonstrated that alpine streams in the Taillon-Gabiétous catchment exhibit high thermal heterogeneity; this thermal variability may have important ecological implications. Importantly, this chapter has further demonstrated that alpine stream temperature may be influenced by factors other than water source. Therefore, classifying streams on the basis of water temperature alone is problematic and an alternative approach is required to accurately describe water source contributions and the physico-chemical habitat characteristics these may generate. Therefore, subsequent chapters describe the application of the alternative approach presented in Chapter 2. Dynamic water source contributions are examined in Chapter 5, and in Chapter 6 relationships between water source contributions and stream physico-chemical habitat are assessed.

CHAPTER 5
CATCHMENT HYDROCHEMICAL FUNCTIONING AND WATER SOURCE DYNAMICS

5.1. CHAPTER OVERVIEW

This chapter adopts a hydrochemical approach to characterise water source dynamics within the study catchment. Initially the hydrochemistry of water sources and bulk meltwaters is analysed (Section 5.4.2) to determine spatial variations in solute concentrations. Snowline retreat and snowpack solute composition is examined in Section 5.4.3 to determine the hydrological and hydrochemical influence of this water source, before rock weathering reactions, that influence the hydrochemical signatures of subglacial and groundwater sources, are assessed (Section 5.4.4). An investigation of hydrochemical evolution along different catchment flow paths is conducted in Section 5.4.5, before a statistical approach to water source identification and hydrograph separation is utilised (End Member Mixing Analysis) to determine water source contributions to bulk meltwaters (Section 5.4.6). The chapter therefore addresses the need to determine actual water source contributions rather than relying on traditional temperature based approaches as reviewed in Chapter 2. An understanding of water source dynamics underpins the hydroecological approaches in subsequent chapters (6-9).

5.2. INTRODUCTION

Meltwater quality variations have been used widely to investigate water source dynamics within glacierized catchments because they often provide information on a range of hydrochemical processes from which hydrological functioning can be inferred (for review see; Brown, 2002). A large proportion of this research has used stream water (bulk meltwater) hydrochemical variation as a means of elucidating glacier drainage pathways (e.g. Collins, 1979; Tranter and Raiswell, 1991; Lamb *et al.*, 1995), based on the assumption that distinct chemical signatures are diagnostic of either the water source, or the pathway along which water has travelled (Tranter *et al.*, 1996). Bulk glacial meltwater chemistry is largely controlled by the chemical composition of snowmelt, icemelt, and chemical weathering processes operating in subglacial and proglacial areas. However, few studies have examined their relative importance at a range of sites within a broader catchment context to investigate dynamic water source contributions (Anderson *et al.*, 2000; Cooper *et al.*, 2002; Hodson *et al.*, 2002).

Bulk glacial runoff principally acquires solute from two sources: (1) the atmosphere (precipitation and dry deposition), which provides sea salt, acidic nitrate and sulphate aerosols, in addition to CO_2 and O_2 to drive chemical weathering reactions, and (2) the chemical weathering of rocks and related materials in subglacial and ice-marginal environments (Tranter *et al.*, 1993; 1996). Following initially high solute levels in early melt season snowmelt (due to preferential elution of ions from snowpacks), snow- and ice-melt is relatively pure (Johannessen and Henriksen, 1978; Tranter *et al.*, 1987). Therefore, much of the solute found in bulk meltwaters is acquired from chemical weathering during rock-water interactions (Brown, 2002).

Most chemical weathering in glacierized catchments is driven by acid hydrolysis reactions, which require a source of aqueous protons to be exchanged for base cations from the mineral surfaces (Raiswell, 1984; Tranter *et al.*, 1993). The dissolution of atmospheric CO_2 provides H^+:

$$CO_2\,(aq) + H_2O\,(aq) \leftrightarrow H^+\,(aq) + HCO_3^-\,(aq) \qquad \textbf{(Equation 5.1)}$$

which can be consumed by carbonate weathering:

$$(Ca,Mg)CO_3\,(s) + H^+\,(aq) \leftrightarrow (Ca,Mg)^{2+} + HCO_3^-\,(aq) \qquad \textbf{(Equation 5.2)}$$

Alternatively, the oxidation of sulphides (e.g. pyrites; FeS_2), which are commonly found in alpine catchments in trace amounts (Brown *et al.*, 1996a) may produce protons:

$$4FeS_2\,(s) + 15O_2\,(aq) + 14H_2O\,(aq) \leftrightarrow 16H^+\,(aq) + 4Fe(OH_3)\,(s) + 8SO_4^{2-}\,(aq)$$

(Equation 5.3)

Sulphide oxidation and carbonate dissolution are often coupled (SO-CD), as demonstrated by studies in a range of glaciated environments (e.g. Raiswell and Thomas, 1984; Tranter *et al.*, 1993; Brown *et al.*, 1996a; Wadham *et al.*, 1998):

$$4FeS_2\ (s) + 16(Ca,Mg)CO_3 + 15O_2\ (aq) + 14H_2O\ (aq) \leftrightarrow$$
$$16(Ca,Mg)^{2+} + 16HCO_3^-\ (aq) + 8SO_4^{2-}\ (aq) + 4Fe(OH_3)\ (s) \qquad \textbf{(Equation 5.4)}$$

The ratio of Ca+Mg to HCO_3^- can therefore be used to identify the relative importance of different weathering processes. A ratio of 1:1 (using equivalents) is consistent with simple carbonate dissolution, whereas a ratio of 2:1 indicates coupled SO-CD (Fairchild *et al.*, 1994). Similarly, the ratio of SO_4^{2-}: $HCO3^-$ (using equivalents) tends toward 1 where SO-CD is dominant but a ratio of <1 typically suggests additional sources of HCO_3^- (e.g. Hodson *et al.*, 2002). These additional sources may be:

(1) Neutralisation of snowpack acid aerosol by carbonates:

$$H^+\ (aq) + NO_3^- + (CaMg)CO_3\ (s) \leftrightarrow (CaMg)^{2+}\ (aq) + HCO_3^-\ (aq) + NO_3^-\ (aq)$$

(Equation 5.5)

(2) Carbonation of carbonates:

$$(CaMg)CO_3\ (s) + CO_2\ (aq) + H_2O\ (aq) \leftrightarrow (CaMg)^{2+}\ (aq) + HCO_3^-\ (aq)$$

(Equation 5.6)

(3) Carbonation of silicates:

$$CaAl_2Si_2O_8\ (s) + 2\ CO_2\ (aq) + H_2O\ (aq) \leftrightarrow Ca^{2+} + H_2Al_2Si_2O_8 + 2HCO_3^-\ (aq)$$

(Equation 5.7)

(4) Oxidation of organic carbon (Sharp *et al.*, 1999):

$$C_{org}\ (s) + O_2\ (aq) + H_2O\ (aq) \leftrightarrow CO_2\ (aq) + H_2O\ (aq) \leftrightarrow H^+\ (aq) + HCO_3^-\ (aq)$$

(Equation 5.8)

Meltwater solute acquisition in subglacial, and recently deglacierised environments, is high due to freshly comminuted rock flour and an abundance of reactive minerals resulting in waters enriched in carbonates and sulphates (Tranter *et al.*, 1993). For older moraines, silicate dissolution may become more dominant as reactive carbonates and sulphides are exhausted (Cooper *et al.*, 2002) and residence times of water increase due to groundwater storage, thus, rock-water interactions increase. However, few studies of catchment-wide hydrochemistry have been undertaken for alpine river systems despite these chemical weathering processes potentially offering a valuable means of fingerprinting spatial patterns of water sources.

The Pyrénées are located at the southern limit of contemporary European glaciation; Therefore, this research provide an insight into catchment hydrochemical characteristics following extensive glacial retreat, which is novel compared with most previous glacierized catchment studies that have focused upon systems with much larger temperate or arctic glacial cover. This study builds upon the few recent studies into the role of the downstream proglacial region (e.g. Malard *et al.*, 1999; Anderson *et al.*, 2000; Hodson *et al.*, 2002) by setting the role of glacial runoff influence in a larger catchment hydrochemistry context using data for three nested sub-catchments, and aims: (1) to determine the principal controls on bulk meltwater hydrochemistry in three nested sub-catchments with varying glacial cover; (2) to characterise water sources within the catchment through hydrochemical signatures; and (3) to quantify variability in the relative contributions of different water sources to streamflow over the course of consecutive melt seasons.

5.3. METHODS

5.3.1. Principal Components Analysis

Principal Components Analysis (PCA) was undertaken for major ion and silica data to reduce the dimensionality and identify the underlying structure of the hydrochemical data sets. PCs were orthogonally rotated using VARIMAX rotation to maximise loading on variables (Norusis, 2003). These PCs were then used to identify the major controls upon stream chemistry (after Hodson *et al.*, 2002). Factors with Eigenvalues <1 were rejected. Analysis focuses on both data sets analysed together because this approach resulted in similar factors to data separated for 2001 and 2002.

5.3.2. Crustal, marine and snowpack derived ions and $p(CO_2)$

Bulk meltwater ion concentrations were separated into crustal, marine and snowpack derived components following Sharp *et al.* (1995b). NO_3^- and Cl^- was assumed to be entirely of atmospheric derivation. Marine contributions of Ca^{2+}, Mg^{2+}, Na^+, K^+ and SO_4^{2-} were removed by calculating standard seawater ratios to Cl^- (Holland, 1978). Atmospherically derived SO_4^{2-} associated with acid aerosols was calculated from the average $^{snow}Cl^-$: SO_4^{2-} ratio measured in the 2002 (0.27) and 2003 (0.82) snowpacks (following Brown *et al.*, 1996a). Hereafter, the prefix '*' is used to denote crustal ions concentrations (i.e. excluding atmospheric sources). Higher partial pressures of CO_2 ($p(CO_2)$), in addition to extended rock-water contact times, can also enhance chemical weathering in glacial environments (Raiswell, 1984). To estimate the rate at which CO_2 diffused into or out of solution relative to chemical weathering and microbial process rates, log $p(CO_2)$ estimates were derived using the MIX 4 programme (Fairchild *et al.*, 1994) where:

$$p(CO_2) = (HCO_3^-)(H^+)/K_1K_H \qquad \textbf{(Equation 5.9)}$$

where K_1 is a coefficient of $10^{-6.58}$ and K_H is a coefficient of $10^{-1.12}$ at 0°C (Langmuir, 1997).

5.3.3. Temporal variation in water source contributions

Following independent hydrological modelling of the Taillon Glacier's drainage structure (Hannah and Gurnell, 2001), bulk meltwaters collected at the Upper Site were assumed to be predominantly a mixture of quickflow (rapidly routed snow- and ice-melt) and subglacial distributed (slower routed, chemically enriched snow- and ice-melt) flow components (Sharp *et al.*, 1995a). Direct measurement of subglacial waters was impossible, therefore concentrations of SO_4^{2-} and Si for the distributed system were estimated following the method of Tranter and Raiswell (1991), as summarised below.

Conservative mixing requires that:

$$Q_tC_t = Q_qC_q + Q_dC_d \qquad \textbf{(Equation 5.10)}$$

where Q refers to discharge, C to a specific solute concentration, and the subscripts refer to total runoff (t), quickflow (q) and delayed flow (d).

Conservation of mass requires that:

$$Q_t = Q_q + Q_d \qquad \textbf{(Equation 5.11)}$$

Equations 5.10 and 5.11 can be combined to solve for the proportion of total discharge routed through the delayed flow component:

$$Q_d = [(C_t-C_q)/(C_d-C_q)]Q_t \qquad \textbf{(Equation 5.12)}$$

Although Q_t and C_t were measured, separation requires distinct chemical signatures for the quickflow and delayed flow reservoirs. Since SO_4^{2-} and Si concentrations were minimal in quickflow waters (supraglacial and eluted snowmelt samples), their presence in bulk meltwaters must derive almost exclusively from the distributed system.

If quickflow concentrations of SO_4^{2-} and Si are taken as 0, Equation 5.12 can be rearranged to give:

$$Q_q/Q_t = (C_d - C_t)/C_d \qquad \textbf{(Equation 5.13)}$$

A linear relationship between SO_4^{2-} or Si concentrations and bulk meltwater discharge gives:

$$C_t = mQ_t + c \qquad \textbf{(Equation 5.14)}$$

Where m (gradient) and c (intercept) are regression constants. Combining Equations 5.13 and 5.14 gives:

$$Q_q/Q_t = 1 - (c/C_d) - (m/ C_d)Q_t \qquad \textbf{(Equation 5.15)}$$

The distributed system component is defined when the mass-fraction of the quickflow component is 0 (i.e. when the left hand side of the equation is 0). Therefore, concentrations of SO_4^{2-} or Si in the distributed component are the regression intercept of c (Tranter and Raiswell, 1991). This method was used to estimate 'Distributed' system solute concentrations for each sampling date. Where estimated concentrations were similar for successive sampling dates, grouped data were reanalysed to produce an end member concentration for an extended time period. This reduced the number of 'Distributed' end member estimates.

To quantify temporal variation in water source contributions to streamflow over the melt season, three-component End Member Mixing Analysis (EMMA; Christopherson *et al.*, 1990; Hooper *et al.*, 1990) was performed on the hydrochemical data collected in the two separate melt seasons. Multiple EMMAs were conducted for separate years' data, to account for measured variability in water source solute concentrations at different time-periods within the melt seasons (Section 5.4.6). This approach resulted in minimal uncertainties, which would otherwise have been introduced by using only one EMMA per year with constant end member water source hydrochemistry (Hoeg *et al.*, 2000; Soulsby *et al.*, 2003). Proportions of water sources for individual bulk meltwater samples were calculated using trigonometric functions (Christopherson *et al.*, 1990).

5.4. RESULTS

Stream discharge data are initially presented to give an overview of the hydrological conditions throughout the melt season (Section 5.4.1). Descriptive statistics and PCA of water source and bulk meltwater samples are examined in Section 5.4.2 to provide an overview of catchment hydrochemistry. Following these data, snowline retreat and snowpack chemical composition data are examined to determine the temporal dynamics of this water source (Section 5.4.3). Crustal mineral weathering processes are assessed in Section 5.4.4 to identify hydrochemical signatures of water source areas throughout the catchment, before Section 5.4.5 examines hydrochemistry evolution along flow pathways, with particular focus on the role of pCO_2. This is important to: (1) give an indication of the processes responsible for furnishing solute in different areas of the catchment, and (2) provide an indication of conservative solutes for use in the EMMA. Altogether, these data (Sections 5.4.2-5.4.5) underpin the EMMA presented in Section 5.4.6, which is used to identify proportions of water source contributions to bulk meltwaters collected at the four main sampling sites. Therefore some interpretation of the results is necessary in Section 5.4 prior to the Discussion (Section 5.5)

5.4.1. Stream discharge

Although discharge magnitude varied between sites (Figure 5.1), the streams displayed broadly similar flow patterns. In 2002, discharge was relatively high at the beginning of the melt season, but with clear diurnal variations until a major precipitation event around day 190 (Figure 5.1a). An extended recession flow followed this event as a result of a period of cold, overcast weather, after which diurnal flow variations resumed. The late 2002 melt season was dominated by a series of rainfall events (days 228 onwards), which led to recession flows from day 236 until the end of monitoring. Mean average discharges were 0.07 (Site A), 0.07 (Site B) and 0.20 m^3s^{-1} (Site C). The 2003 monitoring period also began with recessing flows interrupted by two precipitation events, until a major precipitation event occurred on day 188 (Figure 5.1b). After this time diurnal flow variations were maintained throughout the summer, only interrupted by two storms on days 205 and 208, although smaller rainfall events were recorded toward the end of monitoring. EC showed an inverse relationship with discharge at all sites but tended to gradually increase as the melt season progressed (Figure 5.1). EC was typically greatest at Site B and lowest at Site A.

5.4.2. Water source and bulk meltwater hydrochemistry

Ca^{2+} was the dominant cation in terms of concentration, especially in samples collected from groundwater-fed streams (i.e. karstic, hillslope and Site B; Table 5.1). Mg^{2+} was the second dominant cation, with the exception of snow samples in which Na^+ concentrations were relatively high. Snow samples were enriched in Na^+ and K^+ compared with stream water samples. HCO_3^- was the dominant anion in all samples. Cl^- and NO_3^- concentrations were highest in snow samples, but SO_4^{2-} concentrations were generally very low in snow, as well as supraglacial samples. SO_4^{2-} concentrations were similar at all four main sites with little

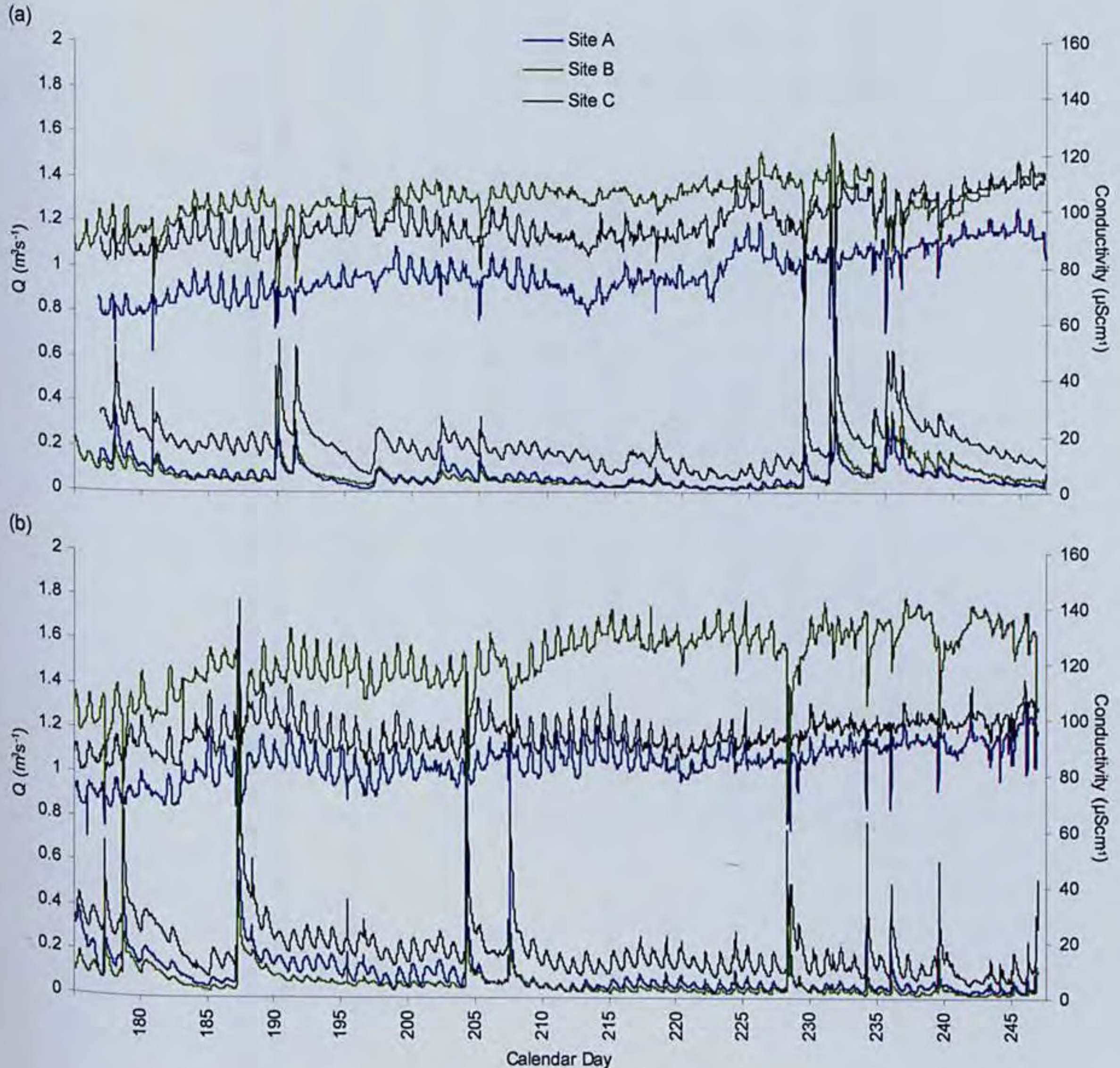


Figure 5.1. Stream discharge and electrical conductivity in (a) 2002 and (b) 2003 at the three gauging sites (The upper 3 lines on each figure are electrical conductivity; the lower 3 lines are discharge)

Table 5.1. Descriptive statistics of major ion, pH and silica data for 2002 and 2003. Mean values are followed by the standard deviation (in parentheses), and the number of samples in italics. Snow (eluted) samples were collected in 2002, 1 week after initial snow collections to examine solute concentrations following elution

Site	Ca^{2+} (μeqL^{-1})	Mg^{2+} (μeqL^{-1})	Na^{+} (μeqL^{-1})	K^{+} (μeqL^{-1})	Cl^{-} (μeqL^{-1})	NO_3^{-} (μeqL^{-1})	SO_4^{2-} (μeqL^{-1})	HCO_3^{-} (μeqL^{-1})	Si (mg L^{-1})	pH
Taillon	580 (103)	380 (127)	24.5 (25.6)	6.5 (6.1)	36.1 (53.8)	17.0 (8.8)	185.0 (70.9)	757 (178)	0.24 (0.07)	8.3 (0.3)
	41	*41*	*41*	*41*	*41*	*41*	*41*	*41*	*41*	*39*
A	925 (123)	430 (87)	15.1 (7.48)	5.5 (4.2)	17.2 (10.1)	15.2 (5.6)	187.4 (39.3)	1157 (167)	0.35 (0.16)	7.9 (0.3)
	37	*37*	*37*	*37*	*37*	*37*	*37*	*37*	*37*	*35*
B	1120 (262)	370 (75)	25.6 (6.7)	6.0 (4.2)	22.6 (49.1)	16.5 (5.7)	186.4 (33.9)	1298 (296)	0.92 (0.17)	7.7 (0.7)
	49	*49*	*49*	*49*	*49*	*49*	*49*	*49*	*49*	*46*
C	922 (196)	390 (85)	18.2 (7.3)	4.8 (3.7)	19.7 (19.4)	17.0 (6.4)	182.7 (35.6)	1122 (249)	0.52 (0.11)	7.9 (0.3)
	51	*51*	*51*	*51*	*51*	*51*	*51*	*51*	*51*	*49*
Snow	184 (185)	23.6 (27.1)	132.2 (115.8)	26.5 (20.7)	77.1 (52.6)	30.4 (20.2)	20.2 (17.0)	627 (485)	0.0 (0.0)	-
	27	*27*	*27*	*27*	*27*	*27*	*27*	*27*	1.0 *27*	
Snow (Eluted)	33.7 (25)	2.6 (0.76)	33.7 (10.1)	4.0 (2.2)	150.1 (70.7)	2.71 (1.6)	1.54 (1.2)	0 (91)	0.0 (0.0)	-
	20	*20*	*20*	*20*	*20*	*20*	*20*	*20*	1.0 20	
Supraglacial	159 (132)	42.2 (21.0)	8.2 (7.2)	2.6 (3.2)	13.5 (13.0)	2.0 (2.4)	7.0 (7.0)	190 (150)	0.1 (0.0)	7.5 (0.4)
	11	*11*	*11*	*11*	*11*	*11*	*11*	*11*	0.2 *11*	*8*
Karstic	1016 (316)	547 (195)	15.0 (7.4)	5.2 (3.3)	18.7 (10.6)	20.9 (6.1)	159.8 (45.8)	1396 (347)	0.65 (0.16)	7.8 (0.5)
	26	*26*	*26*	*26*	*26*	*6*	*26*	*26*	*26*	*19*
Hillslope	1068 (366)	343 (112)	46.3 (12.6)	7.7 (6.4)	48.1 (130.5)	7.1 (7.3)	175.5 (50.1)	1237 (424)	1.49 (0.4)	7.8 (0.5)
	34	*34*	*34*	*34*	*34*	*34*	*34*	*34*	*34*	*32*

downstream change, but were slightly lower in hillslope and karstic stream waters. Si concentrations were negligible in snow and supraglacial samples, and were lowest in stream samples collected at the Taillon Glacier snout. Highest Si concentrations were for streams fed by hillslope groundwaters, as well as Site B. Average pH was greatest at the Taillon Glacier (>8.0), although pH at all other stream was quite similar (7.7-7.9).

PCA produced three components for the Upper Site, and four components for the other main sampling sites (Table 5.2). PC 1 was strongly loaded upon HCO_3^-, Mg^{2+}, Ca^{2+} and SO_4^{2-} at the Upper Site, and Sites B and C, accounting for the majority of variance in the original data. At Site A, these chemical species were split between PCs 1 and 2, with NO_3^- additionally strongly loaded onto PC 1A. PCs 2U, 3A, 2B and 4C include strong loadings from Na^+, K^+, Cl^- and NO_3^-. PCs 3U, 4A, 3B and 2C were all characterised by strong Si loadings, which were associated with other ions (Table 5.2). At the Upper Site, Si loads onto PC 3U with NO_3^-. At the three other sites, Si was associated with Na^+ and K^+.

Overall, the composition of these bulk meltwater PCs suggests that the hydrochemistry of streams in the Taillon-Gabiétous catchment is strongly related to: (1) snowpack chemical composition as indicated by loadings of Na^+, K^+ and Cl^- onto PC 2U at the upper site (2), rapid crustal mineral weathering (especially carbonates, and to a lesser extent, sulphides) as indicated by strong loadings of HCO_3^-, Mg^{2+}, Ca^{2+} and SO_4^{2-} on PCs 1 and 2 at all sites; and (3) slower silicate dissolution, as shown by relatively high Si concentrations in hillslope, karstic, and Site B groundwaters, in addition to groupings of Na^+ and K^+ with Si at Sites A-C.

Table 5.2. Principal Components Analysis for the four bulk meltwater hydrochemical sampling locations. The greatest PC loadings for each chemical species and percentage variance explained by each PC are given in bold. Principal Components are coded by PC and Site letter (i.e. 2B denotes PC2 from Site B)

PC	**Upper Site**			**Site A**				**Site B**				**Site C**			
	1U	**2U**	**3U**	**1A**	**2A**	**3A**	**4A**	**1B**	**2B**	**3B**	**4B**	**1C**	**2C**	**3C**	**4C**
HCO_3^-	**0.96**	-0.02	-0.08	**0.93**	0.29	0.03	-0.08	**0.80**	-0.42	0.02	0.36	**0.96**	0.00	0.19	0.00
Mg^{2+}	**0.95**	-0.07	0.17	0.48	**0.84**	-0.01	0.00	**0.90**	0.02	0.12	-0.14	**0.67**	0.02	0.62	0.11
Ca^{2+}	**0.87**	0.11	0.18	**0.95**	0.10	0.04	-0.05	**0.72**	-0.32	-0.04	0.48	**0.93**	0.01	0.09	0.02
SO_4^{2-}	**0.84**	-0.05	0.23	0.12	**0.96**	0.03	0.06	**0.89**	0.18	-0.01	0.04	0.27	0.14	**0.84**	-0.05
Na^+	0.10	**0.88**	-0.26	0.19	-0.05	**0.91**	0.08	0.09	0.29	**0.84**	0.12	0.08	**0.80**	0.01	0.09
K^+	0.13	**0.81**	-0.48	0.25	0.03	0.38	**-0.75**	0.09	0.09	0.06	**0.88**	0.35	**0.61**	-0.37	-0.23
Cl^-	-0.33	**0.76**	0.42	-0.26	0.07	**0.83**	-0.11	-0.22	**0.66**	-0.01	0.28	-0.08	0.39	-0.47	**0.58**
NO_3^-	0.16	-0.05	**0.83**	**0.69**	0.19	-0.09	0.20	0.12	**0.87**	-0.02	-0.14	0.08	-0.06	0.07	**0.89**
Si	0.28	-0.32	**0.82**	0.25	0.09	0.25	**0.84**	-0.01	-0.36	**0.78**	-0.06	-0.22	**0.65**	0.29	0.02
%Variance	**42**	**27**	**15**	**37**	**20**	**14**	**12**	**35**	**18**	**15**	**12**	**33**	**18**	**15**	**13**

5.4.3. Transient snowline retreat and snowpack chemical composition

In both field seasons, snow cover <2400 m was limited to isolated patches that melted by approximately day 190. The transient snowline on north-facing slopes retreated rapidly so that by day 197 (2002) and day 200 (2003), ice was exposed on the Taillon Glacier at ~2600m (Figure 5.2). In 2002, the snowline retreated to a maximum altitude of ~2710 m by day 220. In 2003, the snowline receded more quickly than the previous year after day 200, reaching ~2750 m by the end of the field season (Figure 5.2). South-facing slopes were devoid of snow cover throughout both monitoring periods. PCA of snow samples produced two components (Table 5.3): (1) SO_4^{2-}, HCO_3^-, Ca^{2+}, NO_3^- and Mg^{2+} (52% of variance), and (2) Cl^-, K^+ and Na^+ (16% variance). Snow samples collected one week after initial snowpit surveys confirmed that rapid elution of ions had occurred (Table 5.1), and these samples were extremely dilute and more typical of supraglacial stream samples collected towards the end of the melt season.

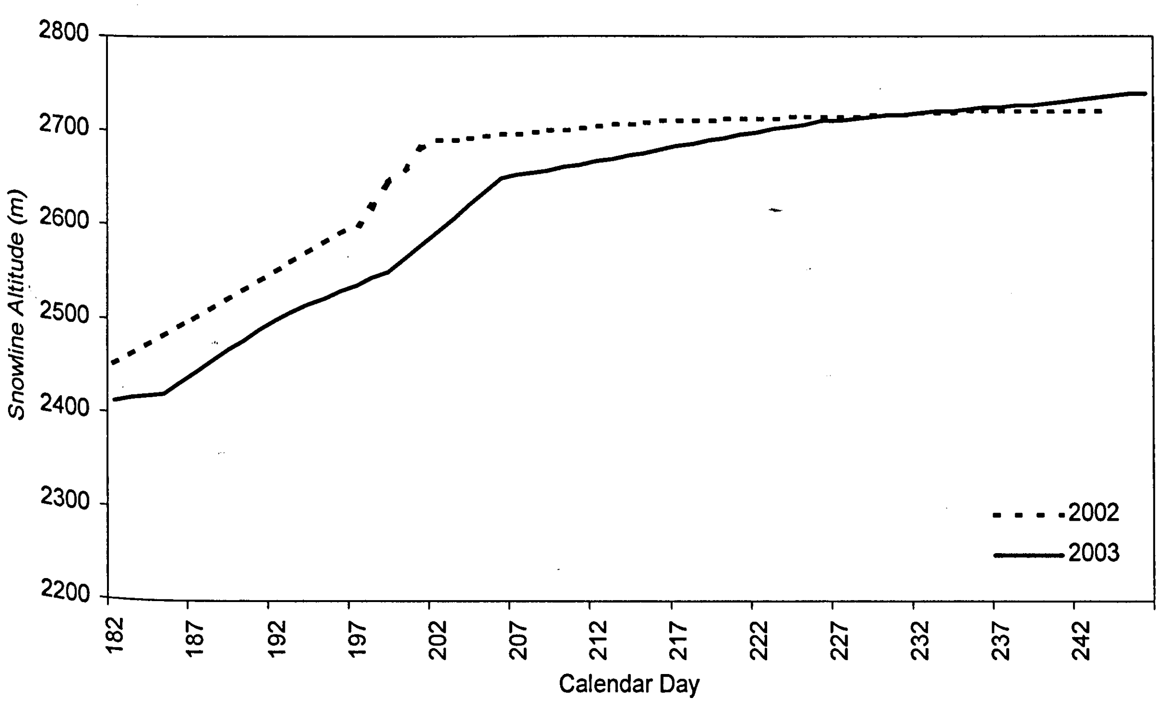


Figure 5.2. Transient snowline altitude during the 2002 and 2003 melt seasons

Table 5.3. Principal Components Analysis of snow samples for 2002 and 2003. The greatest PC loadings for each chemical species, and percentage variance explained by each PC, are given in bold.

PC	1	2
SO_4^{2-}	**0.84**	0.07
HCO_3^-	**0.84**	0.44
Ca^{2+}	**0.81**	0.22
NO_3^-	**0.78**	0.46
Mg^{2+}	**0.65**	0.09
Cl^-	0.24	**0.89**
K^+	0.25	**0.88**
Na^+	0.06	**0.72**
Si	-0.19	**-0.49**
% Variance	**52**	**16**

5.4.4. Crustal mineral weathering

Carbonates and pyrites

The majority of stream water samples illustrate a predominantly Ca^{2+}, Mg^{2+} and HCO_3^- chemistry (Table 5.1) reflecting carbonate weathering. Ca^{2+} was the dominant cation. The sum of Ca^{2+} and Mg^{2+} can be taken as the cationic indicator of carbonate weathering, thus the slope of HCO_3^- against $Ca^{2+} + Mg^{2+}$ suggests that simple hydrolysis or acid hydrolysis is the dominant weathering reaction in the catchment as all values are close to 1 (Table 5.4). The higher slope for the Upper Site is probably due to carbonation of reactive carbonate and silicate dusts and neutralisation of acid aerosol (e.g. SO_4^{2-} and NO_3^-) in snowpacks. Carbonation of Ca-silicates in the Taillon Glacier sub-catchment could also produce similar ratios (Hodson *et al.*, 2002), but their low solubility and the abundance of calcite within the catchment makes this interpretation unlikely. Intercept values increase consistently with distance from the Taillon Glacier with the greatest intercept for Site B samples, indicating a greater excess of HCO_3^- from other sources of weathering in addition to carbonate weathering

Table 5.4. Regression parameters for relationships between [HCO_3^-] and [$Ca^{2+} + Mg^{2+}$]

Site	Slope (*m*)	Intercept (*c*)
Upper	1.13	103.5
A	1.07	112.4
B	1.00	191.6
C	1.01	177.4

The predominance of sulphate as a second anion is a feature of meltwaters collected in the catchment (Table 5.1), despite the dominance of carbonate weathering. Ratios of $HCO_3^-/(HCO_3^- + SO_4^{2-})$ (hereafter the C-ratio, after Brown *et al.*, 1996a) are very high (Table 5.5; >0.80) indicating that coupled SO-CD reactions (ratio ~0.5) are not responsible for controlling bulk meltwater composition. Although ratios are similar for each site, there was a slight downstream decrease. The large increase in mean SO_4^{2-} concentration between snowpacks and the Upper Site suggests sulphide weathering predominantly occurs beneath the Taillon Glacier. A negative relationship between $^*SO_4^{2-}$ and discharge at the Upper Site (Figure 5.3) demonstrates that sulphate acquisition is greatest when discharge is lowest, as is commonly found when a distributed drainage system is present beneath glaciers (e.g. Tranter and Raiswell, 1991; Tranter *et al.*, 1996).

Table 5.5. Average C-ratios ($HCO_3^-/(HCO_3^- + SO_4^{2-})$) calculated for all samples (After Brown *et al.*, 1996a)

Site	C-ratio
Upper	0.81
A	0.86
B	0.85
C	0.87

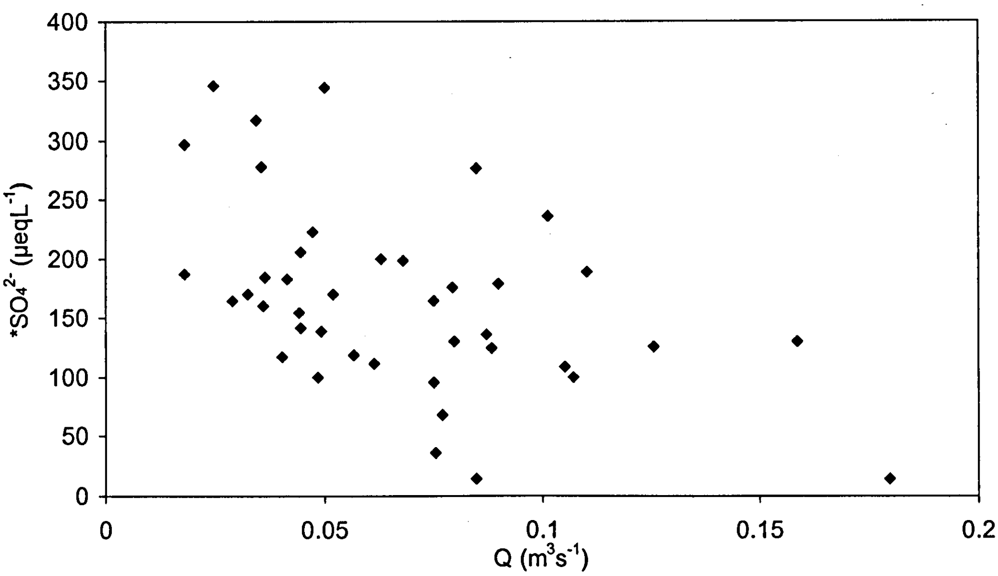


Figure 5.3. Relationship between $*SO_4^{2-}$ and discharge at the Upper Site

Silicate dissolution

Ratios of $*Na^++*K^+/*Ca^{2+}+*Mg^{2+}$ at all sites were on average 0.01-0.02, demonstrating that carbonate weathering is the dominant process, which occurs at a much higher rate than silicate dissolution (Wollast and Chou, 1998). However, Si concentrations between the four sites are very different, with maximum concentrations measured at Site B, and increasing concentrations with distance downstream from the Taillon Glacier (Table 5.1). Furthermore, mean molar $*K^+/Si$ ratios are very high with a wide range and standard deviation at the Upper Site. Mean $*K^+/Si$ ratios decrease at sites downstream from the Taillon Glacier, with reduced variability, particularly at Site B (Figure 5.4). Mean ratios approach 1.0 at the Upper Site as found in other glacial hydrochemistry studies (Anderson *et al.*, 1997; Hodson *et al.*, 2000; Hodson *et al.*, 2002) indicating that minimal silicate weathering occurs in Taillon Glacier meltwaters.

Downstream decreases in $*K^+/Si$ ratios indicate mixing with longer residence time soil and groundwaters, where silicate weathering is likely to have progressed further than in glacial meltwaters. Conversely, lower $*K^+/Si$ ratios downstream may simply be due to $*K^+$

sequestration by plants and clays (Hodson *et al.*, 2002). Despite these sinks, the lower $^{*}K^{+}/Si$ ratios and highest concentrations of Si in hillslope groundwaters demonstrate that weathering of silicates is greater for stable hillslopes. Clearly, Si concentrations offer the potential for tracking soil and groundwater contributions to proglacial bulk meltwaters in the catchment.

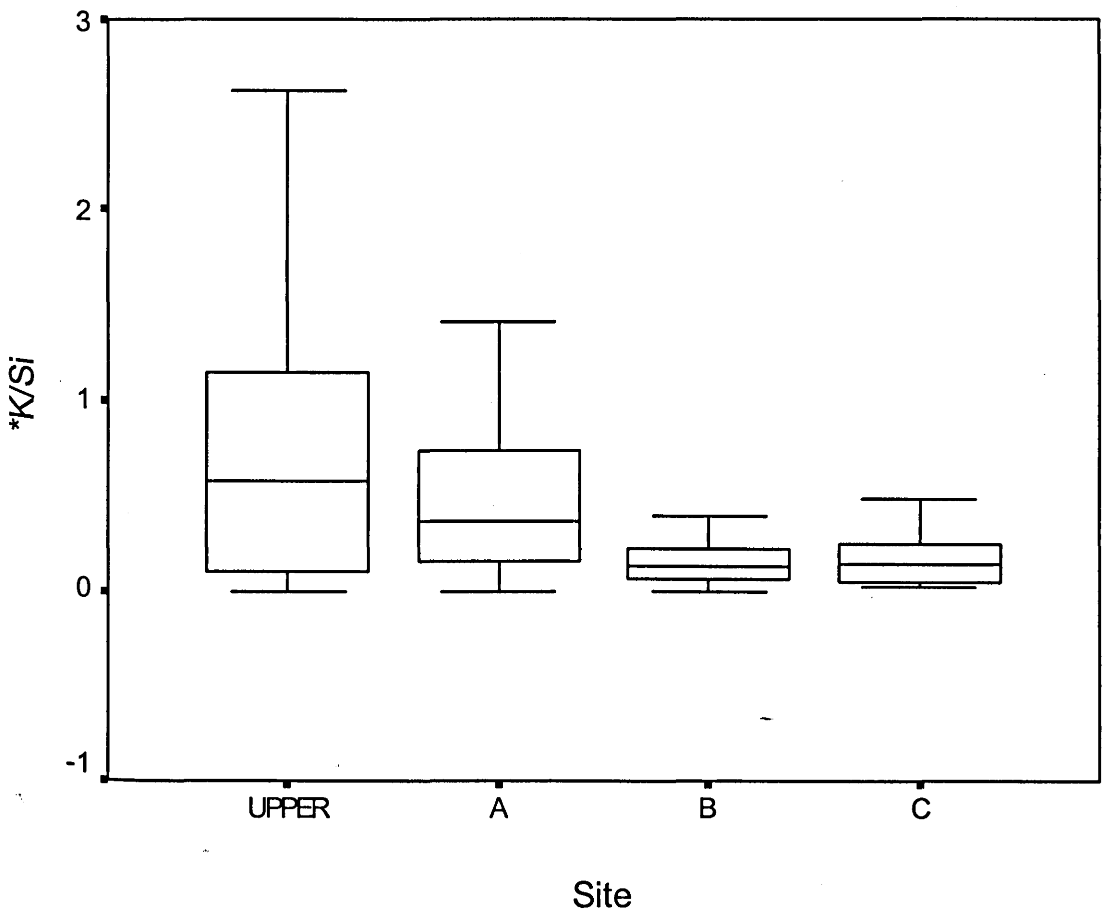


Figure 5.4. Box plots of *K/Si concentrations (molar concentrations) by site. *n* = 37 for each site

5.4.5. Hydrochemistry evolution along flow pathways

Runoff at the Upper Site was more dilute than at the lower sites, whereas Site B had higher solute concentrations than the other three main sites. Snowmelt and supraglacial runoff had low concentrations of all ions, resulting in dilute meltwaters compared with other sampling locations. Low concentrations of SO_4^{2-} are common in snowmelt following preferential elution during the early melt season (Johannessen and Henriksen, 1978), and snowpack chemistry is dominated by marine ions and dust weathering artefacts. Therefore, carbonate weathering dominates the hydrochemistry of the Upper Site. SO_4^{2-} concentrations are considerably greater in bulk meltwaters compared with snowpack and supraglacial melt samples, indicating the likely presence of slower distributed drainage pathways beneath the Taillon Glacier where sulphide oxidation occurs. Concentrations of Ca^{2+}, Mg^{2+} and HCO_3^- increase downstream possibly due to chemical weathering of soils and proglacial moraines, or continued weathering of suspended sediments in bulk meltwaters (e.g. Brown *et al.*, 1996b). Silica concentrations increase markedly between the Upper and three lower sites, possibly accounting for the additional HCO_3^- not attributed to Ca^{2+} and Mg^{2+} concentrations. Concentrations of SO_4^{2-} are on average very similar at all four main sites. Overall, these data highlight the differences in chemical composition of water source areas in the Taillon-Gabiétous catchment.

Low $p(CO_2)$ concentrations relative to atmospheric values (-3.5 to –3.6) were characteristic of Upper Site samples (Figure 5.5) indicating CO_2 consumption proceeds quicker than it can be replenished. Closed system weathering occurs at the Taillon Glacier, as dilute samples of supraglacial melt and Upper Site samples show a marked depletion in CO_2 concentration as they dissolve carbonate and samples become saturated (carbonate saturation index (SIcc) = 0 ± 0.1; Fairchild *et al.*, 1994). This closed system weathering is probably due to high CO_2 consumption by mineral weathering, in addition to low exchange of CO_2 between the atmosphere and subglacial environments (Raiswell, 1984). Downstream from the Taillon

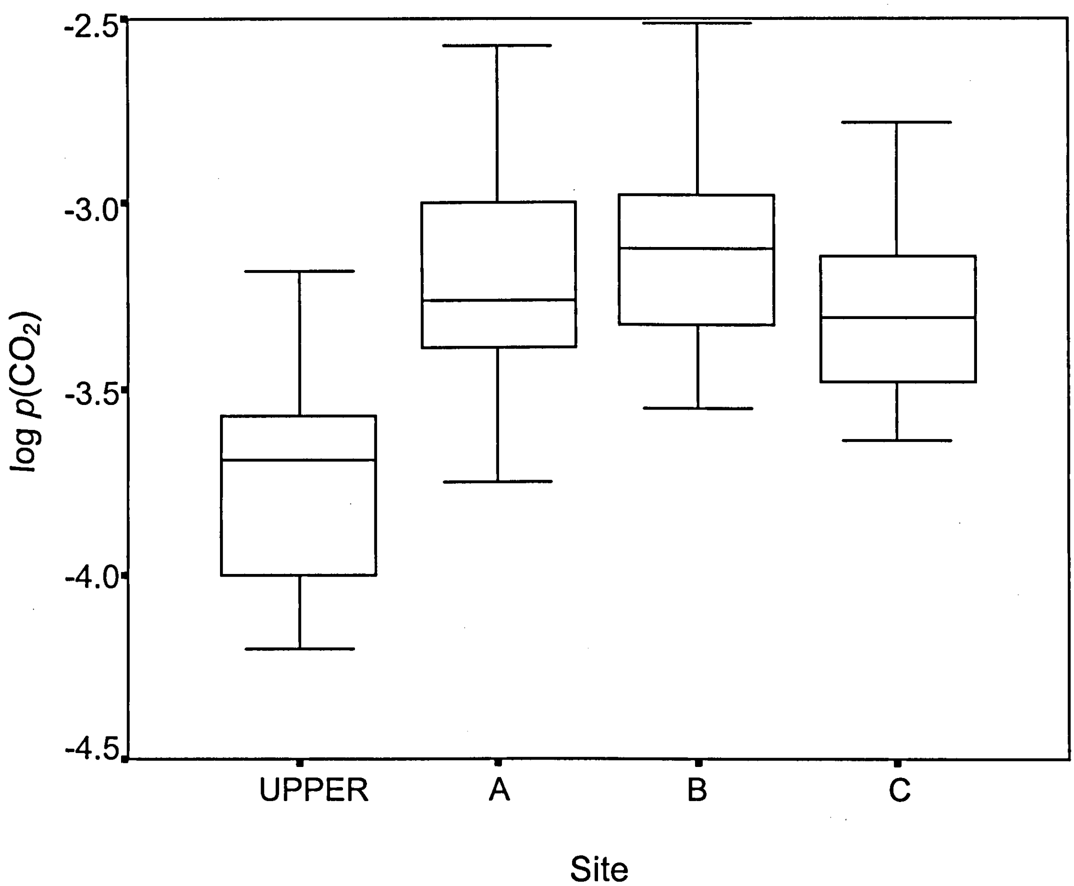


Figure 5.5. Box plots of log $p(CO_2)$ concentrations by site. $n = 34$ for each site

Glacier, CO_2 input exceeds consumption by weathering (Figure 5.5); thus, open system weathering occurs (CO_2 replenished>consumption) and samples are less saturated with respect to calcite (Figure 5.6).

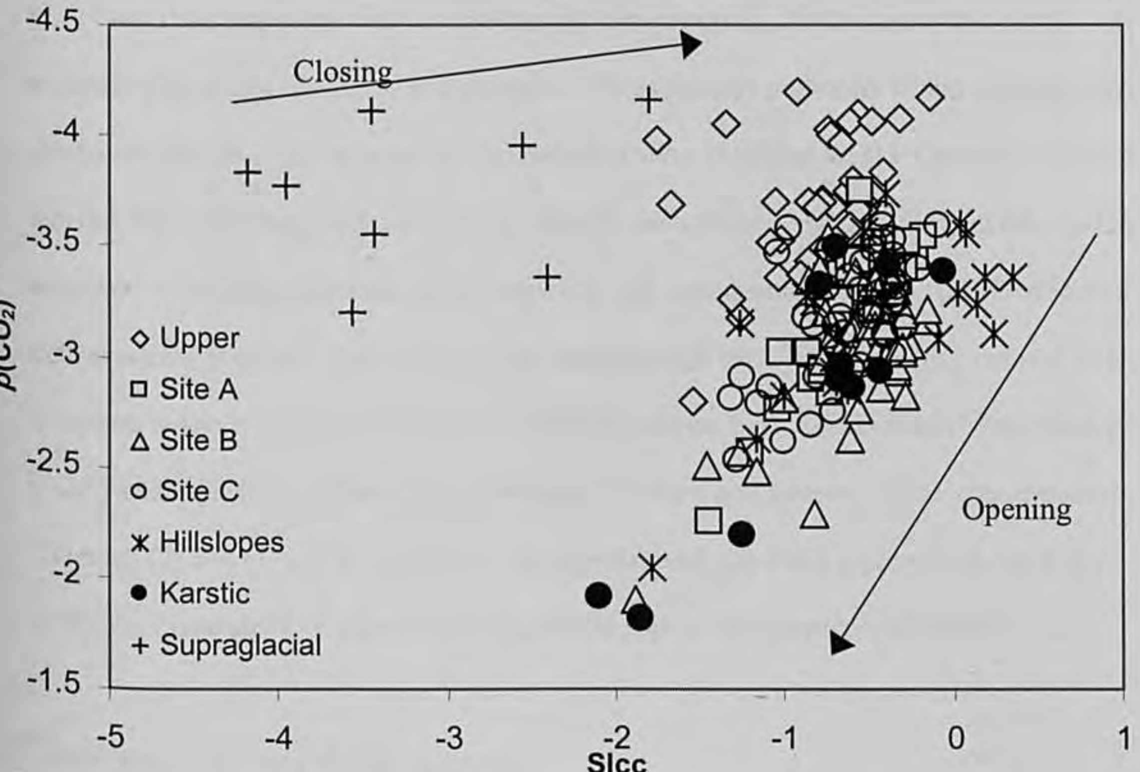


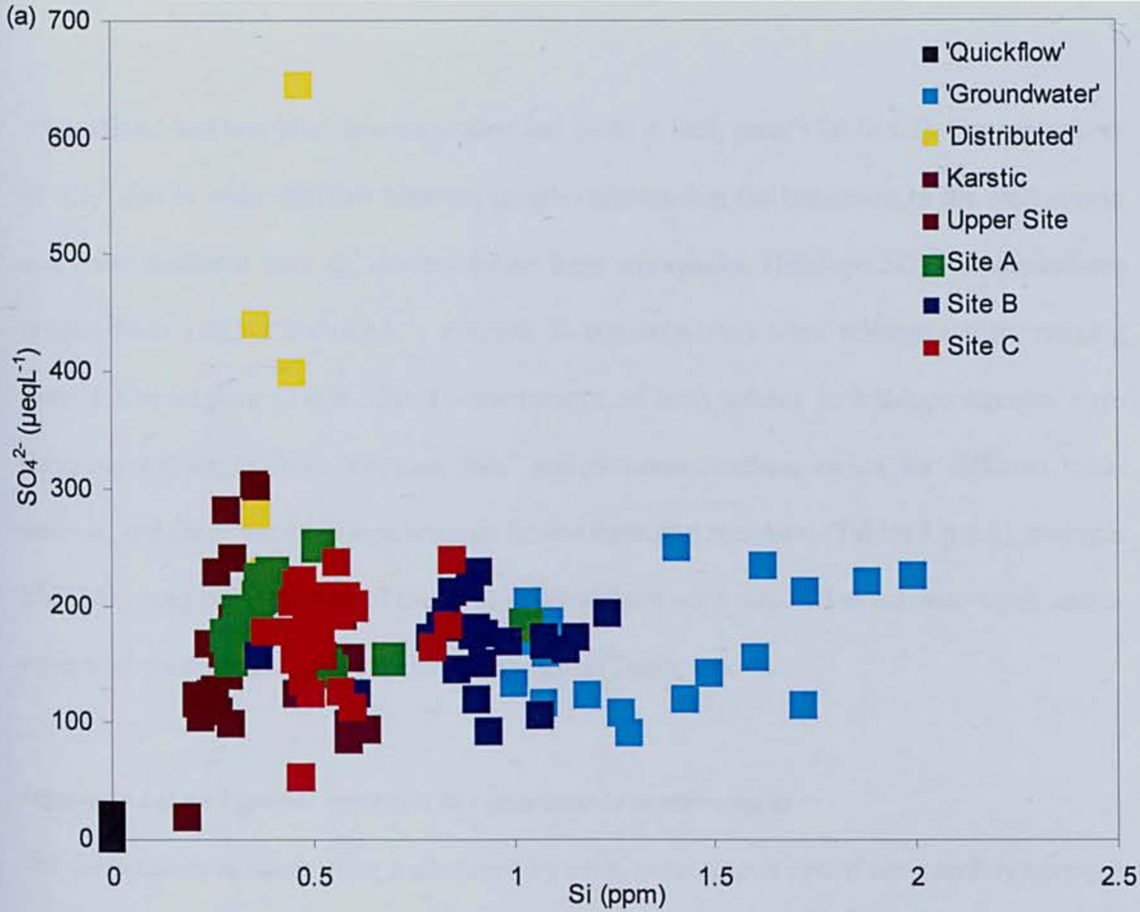
Figure 5.6. Plot of $p(CO_2)$ versus calcite saturation index (SIcc) for 2002 and 2003 data

5.4.6. End Member Mixing Analysis

EMMA was undertaken using SO_4^{2-} and Si concentrations since these solutes produced triplots for both years' data in which three end members bounded all the bulk meltwater samples (Figure 5.7). Experimental studies simulating the mixing of dilute and concentrated meltwaters have shown SO_4^{2-} acquisition from suspended sediment to be minimal (Brown *et al.*, 1994); thus, this solute was assumed to mix conservatively. Silica uptake by diatoms was assumed to be negligible due to low densities of these primary producers within streams in the catchment (Brown *et al.*, in press-b). End members were identified as: (1) 'Quickflow' waters derived from snowmelt and supraglacial icemelt (low [SO_4^{2-}] and low [Si]) defined using measured solute concentrations from snowmelt and supraglacial samples, (2) 'Distributed' system waters from subglacial delayed flow sources (high [SO_4^{2-}] and low [Si]) defined using estimated solute concentrations, and (3) longer residence time 'Groundwater' (intermediate [SO_4^{2-}] and high [Si]) defined using measured hillslope groundwater solute concentrations. Although (2) and (3) can be considered as pathways and not water sources (e.g. Beck *et al.*, 1990), their distinctive chemical signatures enable their inclusion within an EMMA.

Water source SO_4^{2-} and Si concentrations

Regression of SO_4^{2-} and Si concentrations against discharge showed significant negative linear relationships (Table 5.6) for five different time periods in 2002 and four time-periods in 2003. Estimated SO_4^{2-} concentrations within distributed system waters ranged from 228.9-648.6 μeq L^{-1} in 2002 and from 238.5-623.2 μeq L^{-1} in 2003 (Table 5.6). Maximum and minimum estimated SO_4^{2-} concentrations were similar in both years. Estimated Si concentrations ranged from 0.36-0.45 ppm in 2002 and from 0.22-0.47 ppm in 2003. Concentrations of both solutes fluctuated between periods in 2002, whereas 2003 was characterised by a trend of decreasing concentrations throughout the summer until end of melt season increases.



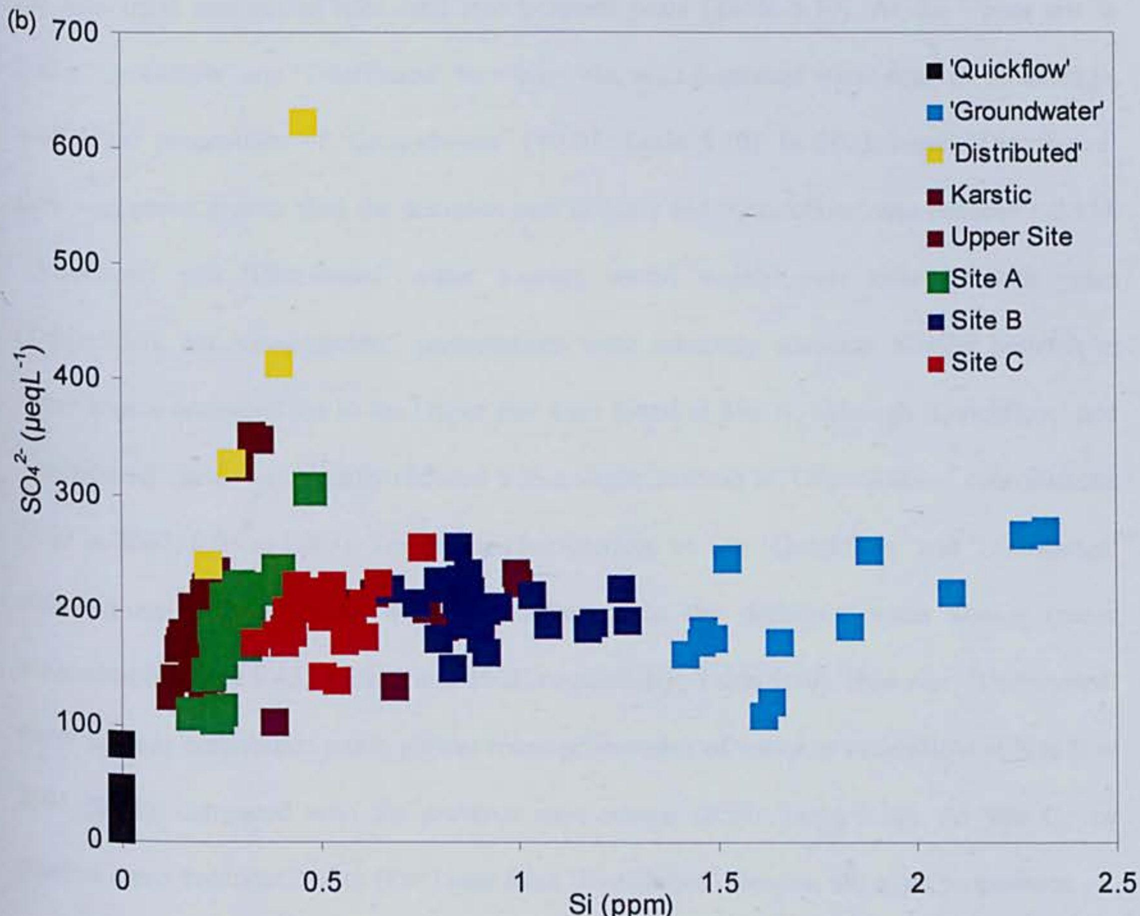


Figure 5.7. EMMA plots for (a) 2002 and (b) 2003. Error bars are standard deviations for end member concentrations

'Quickflow' had low SO_4^{2-} concentrations and no Si in both years (Table 5.7). Concentrations of SO_4^{2-} and Si were different between samples collected at the beginning of the melt season and those collected later on, due to elution from snowpacks. Hillslope SO_4^{2-} concentrations ranged from 156.5-209.0 μeq L^{-1}, whereas Si concentrations were relatively high, ranging from 1.32-1.91 ppm (Table 5.8). Concentrations of both solutes in hillslope streams were generally higher in 2003. Because SO_4^{2-} and Si concentrations varied for different time-periods, and these were not synchronous for the three end members (Tables 5.6-5.8), multiple EMMAs using combinations of the three end members were required to estimate water source contributions for weekly bulk meltwater samples (Table 5.9).

Inter-annual and spatial variation in water source contributions

The proportions of streamflow contributed by each water source varied considerably between the four main monitoring sites, and also between years (Table 5.10). At the Upper site in 2002, 'Quickflow' and 'Distributed' flow were the most dominant water sources on average, with lower proportions of 'Groundwater' (<0.07; Table 5.10). In 2003, mean 'Distributed' flow was much greater than the previous year (+0.20) and 'Quickflow' was reduced (-0.15). 'Quickflow' and 'Distributed' water sources varied widely over time in both years (Table 5.10), but 'Groundwater' contributions were relatively constant. Similar patterns in water source contributions to the Upper site were found at Site A, although 'Quickflow' and 'Distributed' flow were slightly reduced with a slight increase in 'Groundwater' contributions (0.09 in 2002; 0.05 in 2003). Site B was characterised by low 'Quickflow' and 'Distributed' contributions in both years, with 'Groundwater' as the dominant water source (mean proportion 0.58 and 0.45, in 2002 and 2003, respectively; Table 5.10). However, 'Distributed' water sources contributed much greater mean proportions of water to streamflow at Site B in 2003 (0.41), compared with the previous melt season (0.24; Table 5.10). At Site C, the greatest mean contributions to flow came from 'Distributed' sources, although proportions

Table 5.6. Linear regression equations for SO_4^{2-} (μeq L^{-1}) and Si (ppm) against discharge (m^3 s^{-1}) for five sub-seasonal periods in 2002 and four sub-seasonal periods in 2003. Estimated concentrations and standard deviations of SO_4^{2-} and Si in 'Distributed' waters are given by the regression intercepts for each time period.

Time Period	Calendar Days	SO_4^{2-}	Si
2002			
1	178-187	-2466.8Q + 228.9±63.4	-2.221Q + 0.38±0.06
2	197-202	-2723.6Q + 398.6±40.8	-3.622Q + 0.45±0.05
3	209-228	-2868.5Q + 277.5±63.9	-2.535Q + 0.36±0.05
4	237	-4008.1Q + 644.6±82.6	-1.481Q + 0.47±0.03
5	244	-4416.6Q + 438.7±36.8	-2.072Q + 0.36±0.02
2003			
1	177-185	-5826.0Q + 623.2±101.0	-2.912Q + 0.46±0.06
2	192	-1067.1Q + 327.4±36.4	-0.633Q + 0.28±0.02
3	199-241	-1039.6Q + 238.5±30.4	-0.907Q + 0.22±0.03
4	246	-2634.4Q + 413.6±18.1	-4.922Q + 0.40±0.03

Table 5.7. Mean concentrations and standard deviations of SO_4^{2-} (μeq L^{-1}) and Si (ppm) concentrations in 'Quickflow'.

Time Period	Calendar Days	SO_4^{2-}	Si
2002			
1	178-187	5.0±3.9	0.0±0.0
2	197-244	5.1±5.7	0.0±0.0
2003			
1	177-185	21.2±11.4	0.0±0.0
2	192-246	11.7±3.8	0.0±0.0

Table 5.8. Mean concentrations and standard deviations of SO_4^{2-} (μeq L^{-1}) and Si (ppm) concentrations in 'Groundwater' sources

Time Period	Calendar Days	SO_4^{2-} (μeq L^{-1})	Si (ppm)
2002			
1	pre 183	171.2±38.0	1.38±0.41
2	183-212	167.7±52.5	1.41±0.44
3	212-244	156.5±53.5	1.32±0.42
2003			
1	pre 187	187.1±53.9	1.51±0.23
2	187-217	209.0±52.2	1.87±0.43
3	217-246	192.7±61.9	1.91±0.32

were 0.15 greater in 2003. Mean proportions from each source at Site C were typically intermediate of those at Sites A and B, reflecting the mix of Taillon and Tourettes stream water.

Intra-annual variation in water source contributions

Clear seasonal patterns in water source contributions were evident from the EMMA output for the Upper Site (Figure 5.8). In 2002, 'Quickflow' was the dominant water source during the early melt season (before day 209; Figure 5.8a). After this time, a greater proportion of streamflow was sourced from the 'Distributed' system, although towards the end of the melt season, proportions from both these sources were similar. 'Groundwater' contributed approximately 10% of streamflow throughout, with minimal variations. In 2003, 'Quickflow' dominated for a much shorter period of time at the beginning of the melt season (Figure 5.8b). After day 199, the 'Distributed' system contributed the majority of streamflow at all times, with the exception of Days 219 and 226 at high flow when 'Quickflow' contributions were similar to those from 'Distributed' sources. 'Groundwater' contributions were greatest at the beginning of the melt season, but decreased to virtually nil after day 199.

Table 5.9. Combinations of end member time periods used in multiple EMMAs, to determine proportional water source contributions to bulk meltwaters collected on different calendar days. See Tables 5.6-5.8 for time period codes.

Bulk meltwater sampling days	Time periods for End Members		
	'Distributed'	'Quickflow'	'Groundwater'
2002			
178-187	1	1	1
187-197	1	2	2
197-202	2	2	2
209-212	3	2	2
212-228	3	2	3
237	4	2	3
244	5	2	3
2003			
177-185	1	1	1
192	2	2	2
199-213	3	2	2
219-246	4	2	3

Table 5.10. Descriptive statistics of proportional contributions of water sources to streamflow at the four main monitoring sites, in 2002 and 2003

	2002				2003			
	Upper	**A**	**B**	**C**	**Upper**	**A**	**B**	**C**
'Quickflow'								
Mean	0.49	0.46	0.18	0.32	0.34	0.35	0.14	0.26
Max	0.90	0.91	0.42	0.69	0.75	0.77	0.39	0.58
Min	0.04	0.17	0.01	0.05	0.08	0.00	0.00	0.04
Range	0.86	0.75	0.41	0.64	0.67	0.77	0.00	0.55
'Groundwater'								
Mean	0.07	0.18	0.58	0.30	0.02	0.07	0.45	0.21
Max	0.13	0.48	0.91	0.59	0.10	0.16	0.77	0.36
Min	0.01	0.07	0.15	0.17	0.00	0.03	0.28	0.11
Range	0.12	0.41	0.76	0.42	0.10	0.12	0.49	0.25
'Distributed'								
Mean	0.44	0.37	0.24	0.38	0.64	0.58	0.41	0.53
Max	0.95	0.76	0.47	0.72	0.91	0.90	0.70	0.82
Min	0.07	0.02	0.03	0.07	0.16	0.11	0.06	0.10
Range	0.88	0.74	0.44	0.66	0.75	0.79	0.70	0.71
No. of samples	19	21	23	23	22	22	22	22

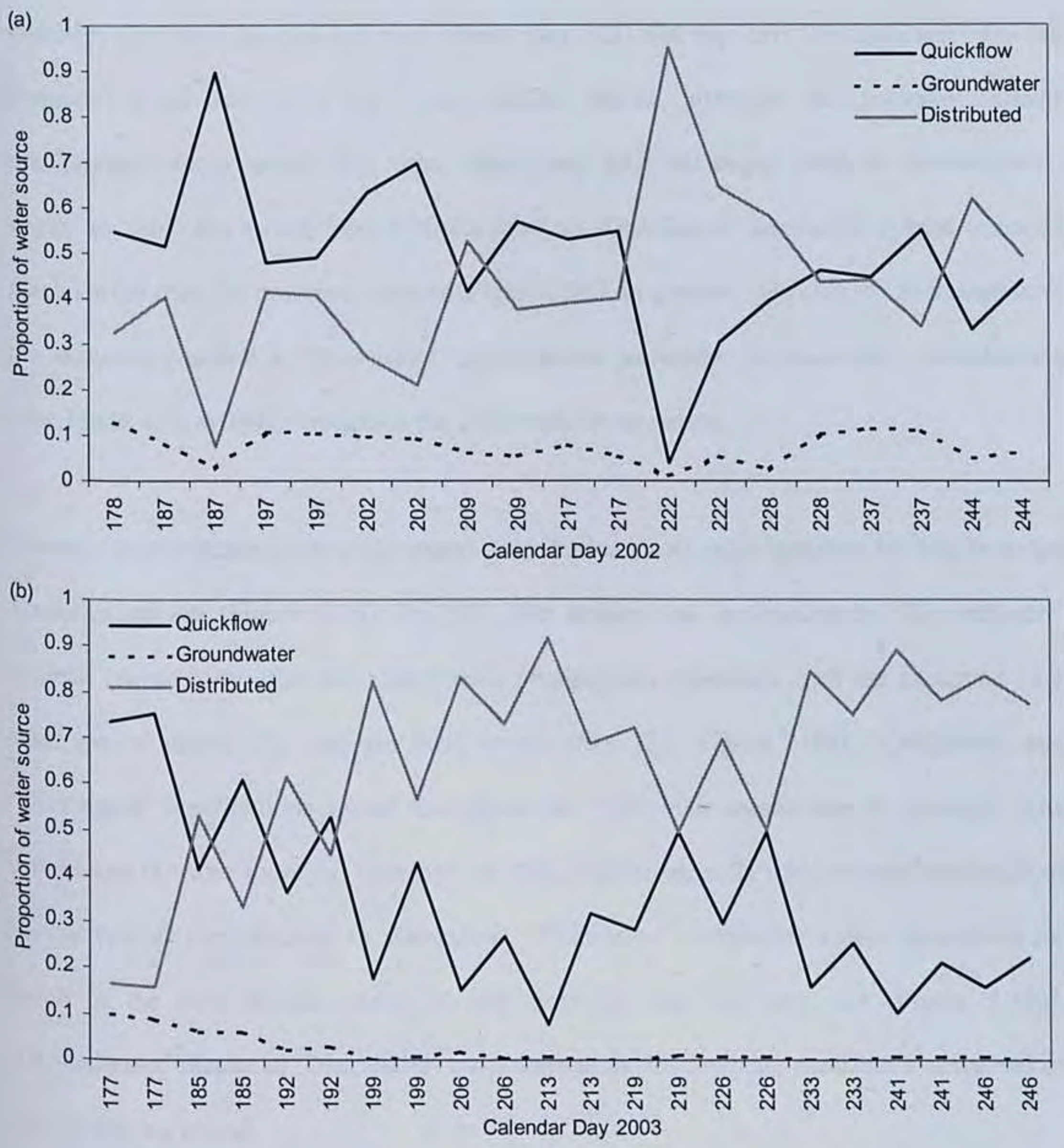


Figure 5.8. Temporal variation in water source contributions at the Upper Site in (a) 2002 and (b) 2003

In 2002 at Site A, 'Quickflow' was the dominant water source until mid melt season (day 217; Figure 5.9a). After this time, 'Quickflow' showed a general pattern of decline, while 'Distributed' system contributions increased. 'Groundwater' contributions were relatively low until the mid-late melt season (day 222). On day 237, 'Groundwater' was the dominant water source to the lower Taillon stream, although this probably reflects precipitation events around this time, which may have recharged shallow 'Groundwater' stores. In 2003, the switch from a 'Quickflow' to 'Distributed' dominated system occurred much earlier than the previous summer (Figure 5.9b). In general, 'Quickflow' decreased over the monitoring period as 'Distributed' contributions increased. 'Groundwater' contributions were lower than in 2002 throughout the 2003 monitoring period.

Between year differences in water source contributions were most apparent for Site B on the Tourettes stream (Figure 5.10). In 2002, the stream was predominantly 'Groundwater' sourced (particularly after late melt season precipitation episodes), with the exception of a short period during the mid-late melt season (day 222; Figure 5.10a). 'Quickflow' and 'Distributed' contributions varied throughout the 2002 melt season due to low/high flow differences in water sourcing. However, in 2003, despite an early melt season dominance of 'Groundwater' contributions to streamflow, 'Distributed' subglacial waters dominated for much of the melt season, except at low flow on days 213 and 223 (Figure 5.10b). 'Groundwater' displaced 'Distributed' water sources as the dominant contributor at the end of the monitoring period.

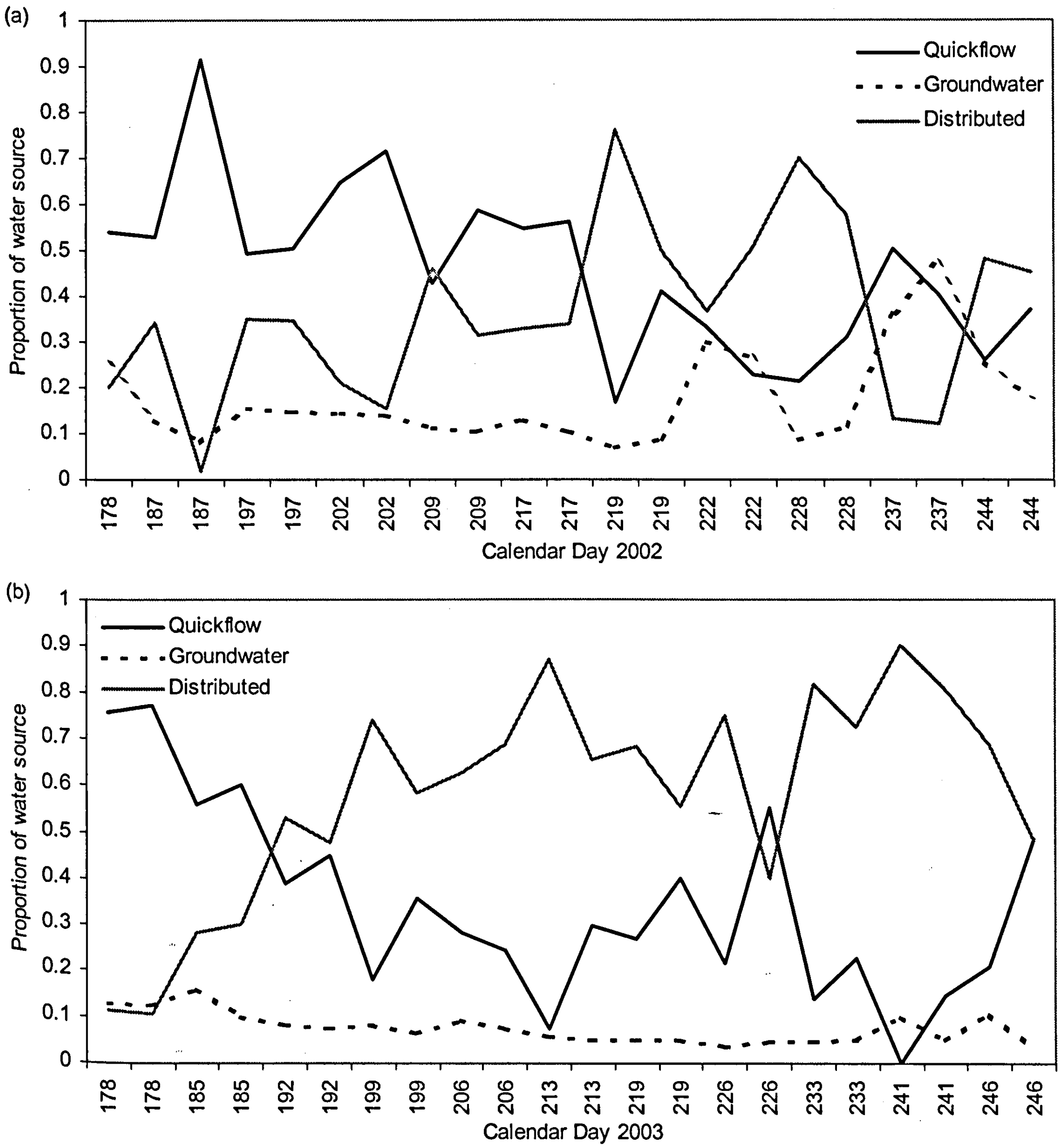


Figure 5.9. Temporal variation in water source contributions at Site A in (a) 2002 and (b) 2003

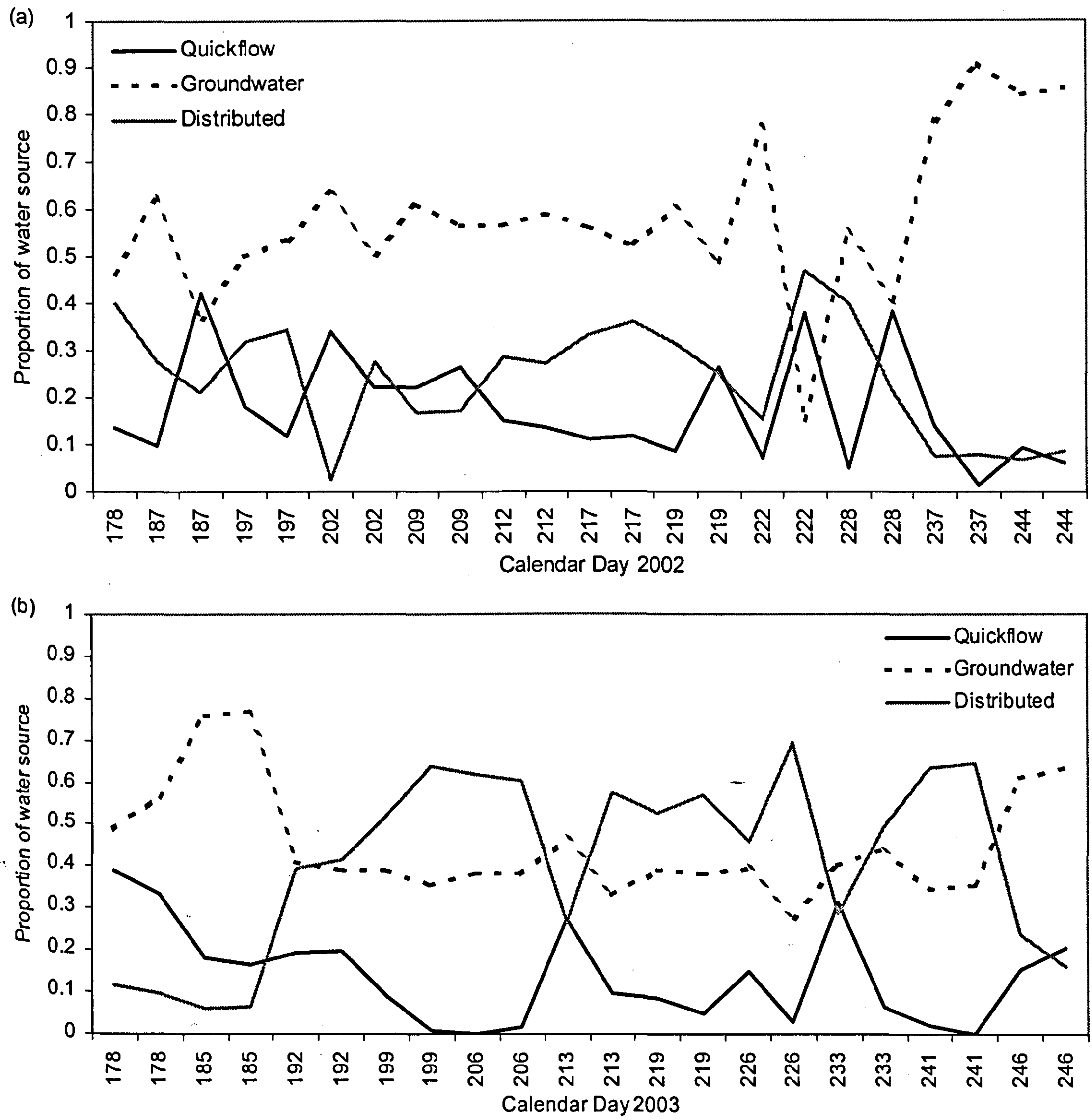


Figure 5.10. Temporal variation in water source contributions at Site B in (a) 2002 and (b) 2003

At Site C, similar general patterns to Site A were found in both years, but with a greater proportion of 'Groundwater' to streamflow (Figure 5.11). In 2002, 'Quickflow' ('Distributed') contributions generally decreased (increased) over the summer melt season. 'Distributed' contributions were greatest between days 209-228. Thereafter, 'Groundwater' contributed the greatest proportion of flow (Figure 5.11a). In 2003, 'Quickflow' dominance was usurped by 'Distributed' contributions much earlier than in 2002 (Figure 5.11b). For the remainder of the monitoring period, 'Quickflow' and 'Groundwater' source contributions remained relatively low.

5.5. DISCUSSION

Stream hydrochemical sampling provided further insights into the hydrological functioning of the Taillon-Gabiétous catchment, and complements earlier detailed hydrological studies of the Taillon Glacier sub-catchment (Hannah, 1997; Smith, 1999; Hannah *et al.*, 2000b; Hannah and Gurnell, 2001; Smith *et al.*, 2001). In addition, the study also provided further information on the role of glacial runoff influence in a larger catchment hydrochemistry context (e.g. Anderson *et al.*, 2000; Cooper *et al.*, 2002). The results suggest that the major controls on stream hydrochemistry are:

1. snowpack solute release (which generally decrease over the melt season; Section 5.4.2 and 5.4.3). This is indicated by groupings of marine and atmospheric aerosols (Na^+, K^+, Cl^- and NO_3^-) for bulk meltwaters in the PCA (see Hodgkins and Tranter, 1998; Hodson *et al.*, 2002);
2. rapid weathering of carbonates and pyrites (uncoupled reactions; Sections 5.4.2 and 5.4.4) as indicated by the groupings of HCO_3^-, Mg^{2+}, Ca^{2+} and SO_4^{2-} in the PCA. High C-ratios indicated coupled sulphide oxidation and carbonate dissolution reactions were not responsible for furnishing solute to bulk meltwaters, and;

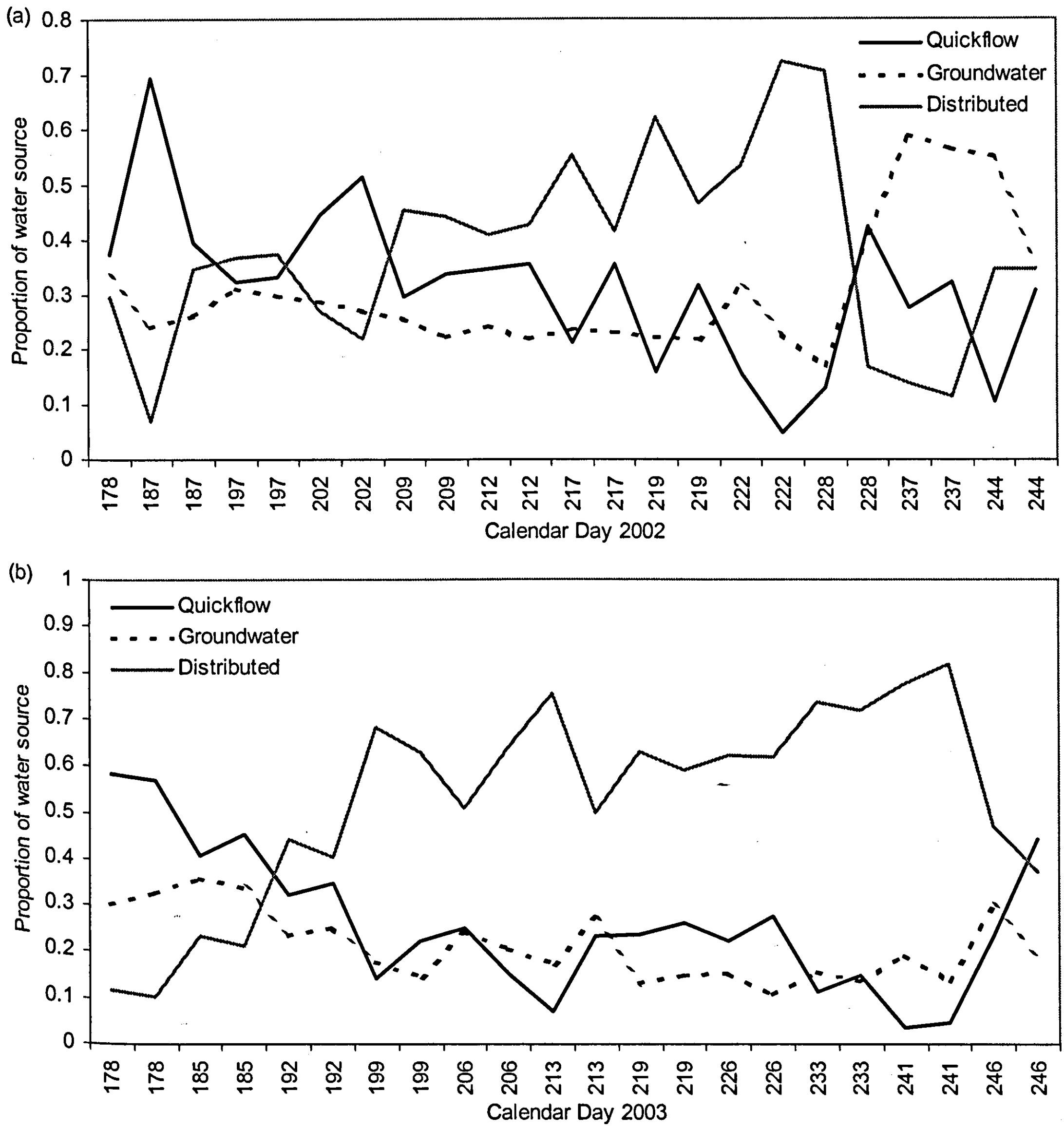


Figure 5.11. Temporal variation in water source contributions at Site C in (a) 2002 and (b) 2003

3. slow dissolution of silicate minerals (Sections 5.4.2 and 5.4.4), as demonstrated by PC groupings of Si with Na^+ and K^+ in bulk meltwaters collected in the lower catchment, and lower $*K^+/Si$ ratios in bulk meltwaters draining areas of the catchment with reduced glacierized area.

5.5.1. Spatial variation in mineral weathering and solute provenance

The three major controls on bulk meltwater hydrochemistry appear to operate at different rates in distinct areas of the catchment, as water passes along different pathways. For example, snowmelt and rapid mineral weathering (carbonate dissolution/sulphide oxidation) dominate in the Taillon sub-catchment, whereas silicate dissolution increases in importance in the lower catchment where glacierized area is reduced. Weathering processes operating in different areas of the catchment play a clear role in influencing stream hydrochemical signatures. Therefore, temporal dynamics of bulk meltwater runoff hydrochemistry reflect variability in discharge from these 'source areas'.

In the upper parts of the catchment (Les Gabiétous Massif and the Taillon Glacier sub-catchment; Upper Site), snowmelt plays an important role influencing proglacial stream hydrochemistry. In both years of the study, snowpack solute concentrations were relatively low, possibly because snowmelt onset had occurred earlier than the initiation of the study, as suggested by the relatively high snowline altitude at the beginning of the monitoring period. Snowmelt and supraglacial waters were the most dilute of any samples collected within the catchment, with relatively low SO_4^{2-} concentrations in snow collected at the beginning of the melt season reflecting its preferential elution from snowpacks (Johannessen and Henriksen, 1978; Brimblecombe *et al.*, 1986). Dilute (low solute concentration) 'Quickflow' contributions to bulk meltwaters resulted in relatively strong diurnal fluctuations in electrical conductivity of the Taillon Glacier stream even up to 1.5 km from the Taillon Glacier (Site A), as is typical in glacier-fed rivers (Fenn, 1987). However, these fluctuations were even maintained following the confluence with the predominantly groundwater-fed Tourettes stream (Site C) emphasising the influence of 'Quickflow' for streams in areas of the catchment with low % snow and ice cover.

Following early season snowpack solute elution and subsequent snowpack and snowline retreat, proglacial stream hydrochemistry was dominated by solute acquisition from crustal weathering sources. Stream hydrochemistry was dominated by carbonates produced by simple hydrolysis or acid hydrolysis. Ca^{2+} was the dominant cation, indicating a control by Calcite dissolution, similar to the findings of most glacial hydrochemistry studies (e.g. Fairchild *et al.*, 1994). Sulphide oxidation was also important in furnishing solute to the proglacial stream although high C-ratios ($HCO_3^-/(HCO_3^- + SO_4^{2-})$) suggested that coupled sulphide oxidation-carbonate dissolution reactions were not particularly prevalent within the catchment. Furthermore, sulphide oxidation decreased (higher C-ratios) in importance with distance from the Taillon Glacier where glacierized area was reduced. Weathering may be dominated by carbonate dissolution and sulphide oxidation where glacierized area is relatively large due to an abundance of recently exposed and comminuted glacial sediments. With reduced glacierized area (i.e. Sites A-C), sources of pyrite in older moraines are likely to have been strongly depleted over time by chemical weathering reactions (Anderson *et al.*, 2000).

Although carbonate dissolution dominates throughout the entire catchment (reflecting the calcareous geology), silicate weathering is increasingly important with distance from the Taillon Glacier as glacierized area decreases. However, high $*K^+/Si$ ratios for the Taillon Glacier sub-catchment are similar to those found in most glacial catchments, demonstrating low silicate mineral weathering compared with global means (e.g. Holland, 1978; Anderson *et al.*, 1997). This is probably a result of limited contact times of freshly comminuted minerals with bulk meltwaters (despite the small size of the Taillon Glacier and its relatively low discharge) and low temperatures at altitudes >2500 m (Chapter 4). Ratios of $*K^+/Si$ were lower for Site B reflecting the longer residence times of hillslope water sources (where chemical weathering may progress further to silicate mineral dissolution) discharging into the

Tourettes stream. Alpine grasses and shrubs growing on south-facing catchment slopes at lower altitudes in this part of the catchment may also promote silicate dissolution by stabilizing slopes, and enhancing weathering through the release of organic and carbonic acids during decomposition (e.g. Anderson *et al.*, 2000).

Changes between closed and open systems in the catchment suggest that weathering is staged (Fairchild *et al.*, 1994). Low $p(CO_2)$ concentrations relative to atmospheric values were characteristic of Upper Site samples; here Carbonate dissolves in a closing system because mineral weathering consumes CO_2 quicker than it can be replenished due to the low exchange of CO_2 between the atmosphere and subglacial environments (Raiswell, 1984). These reactions are generally unaccompanied by pyrite oxidation producing waters saturated with respect to calcite. Downstream, the introduction of CO_2 partly balanced by carbonate dissolution results in further cation acquisition (CO_2 input exceeds consumption by weathering). At Sites A to C, pCO_2 is relatively high compared with atmospheric values and samples are less saturated with respect to calcite, indicating that runoff equilibration with the atmosphere is not possible during transit times through the catchment stream network (Hodson *et al.*, 2002). This is most likely due to mixing of active layer soil and hillslope waters (with elevated p(CO2) due to microbial respiration, e.g. Pecher, 1994; Hodson *et al.*, 2002) with glacial runoff. Similar to the findings of Hodson *et al.* (2002), this indicates that chemical weathering is important in non-glacierized areas of the catchment and that downstream changes in bulk meltwater hydrochemistry are strongly influenced by the mixing of groundwaters with snow- and ice-melt runoff.

5.5.2. Temporal variation in water source contributions to streamflow

Hydrochemical mixing models were a successful means of demonstrating spatial and temporal variability in water source contributions to streamflow. Seasonal changes in water chemistry were linked to the dynamics of different hydrological reservoirs in a similar manner to other alpine glacierized catchment studies (e.g. Malard *et al.*, 1999). However, an important finding was that water source dynamics varied considerably between melt seasons. In 2003, the period when 'Quickflow' dominated during early parts of the monitoring period was much shorter due to earlier peak snowmelt. Therefore, the switch to 'Distributed' subglacial water source contributions dominating streamflow occurred earlier than in 2002.

This variability of water source contributions supports previous studies showing that the classical 'glacial discharge regime' can be highly variable over time (Smith *et al.*, 2001). Furthermore, the variability of water source contributions in the Taillon Glacier stream appears to be different to seasonal progressions (i.e. early season snowmelt, mid melt season glacier melt, late melt season groundwater dominated periods) described in previous studies (Malard *et al.*, 1999, 2000; Smith *et al.*, 2001). Results from this study show that groundwater contributions were generally highest at the beginning of the melt season following snowmelt recharge of aquifers (e.g. Flerchinger *et al.*, 1992). Groundwater only contributed a large proportion of flow at the end of the melt season in 2002 following a prolonged period of rainfall (Brown *et al.*, 2004, in press-a). In addition, the Tourettes stream, which was predominantly groundwater-fed in 2002, was strongly influenced by 'Distributed' meltwaters in 2003 as greater quantities of meltwater (as a consequence of the warmer summer) could be conveyed to this stream due to its upstream connection with glacial stream channels.

Karstic stream water samples typically plotted towards the 'Quickflow' end member of the EMMA scatter triangle, indicating that these streams were most likely sourced from slow routed meltwaters. This supports previous independent dye tracing studies (Parc-National-des-Pyrénées, 1991) that suggested meltwaters enter sinkholes located on Les Gabiétous Massif, and then flow through subterranean caverns (transit times of between 34-46 hrs) before re-emerging in the lower Vallée des Pouey Aspé. Elevated silica concentrations in comparison to 'Quickflow' and 'Distributed' meltwater sources suggest that either limited silica dissolution occurs within the karst networks, or meltwaters mix with soil waters whilst flowing across Les Gabiétous Massif prior to entering sinkholes.

The findings from the Upper Site EMMA using the Distributed' (high [SO_4^{2-}] and low [Si]) and 'Quickflow' (low [SO_4^{2-}] and low [Si]) end members supports earlier independent hydrological modelling results (Hannah and Gurnell, 2001), further increasing confidence in the findings of both studies. The earlier hydrological modelling approach demonstrated that the Taillon Glacier is characterised by a slow drainage pathway probably representing the snowpack and firn aquifer draining into a delayed flow subglacial system beneath the glacier ('Distributed'), and a fast reservoir ('Quickflow') draining over the ice surface and through a semi-distributed system beneath the lower glacier (Hannah and Gurnell, 2001). Interestingly, these fast drainage pathways appear to evolve little over the ablation season unlike in other studies where their increasing efficiency can result in variation in the processes and rates of runoff, and, thus, bulk meltwater solute acquisition (e.g. Tranter *et al.*, 1993; Brown *et al.*, 1994). The hydrochemistry results support the hypothesis that snowline retreat and decreasing snowpack size are the most important control on the Taillon glacier sub-catchment's water source dynamics (Hannah and Gurnell, 2001), and not the evolution of a more efficient subglacial distributed system as the melt season progresses (cf. larger European temperate glaciers; Fountain and Walder, 1998).

Estimates of subglacial derived SO_4^{2-} and Si from Taillon Glacier proglacial meltwater concentrations provided consistent concentrations for both years of the study. Although direct measurements of subglacial waters (e.g. Lamb *et al.*, 1995) would have been more desirable for determining Distributed system SO_4^{2-} and Si concentrations, these methods were impractical due to constraints imposed by the glacier's location within a national park. Furthermore, given the Taillon Glacier's small size (0.15 km^2), repeated drilling of replicate boreholes direct from the ice surface to the bed may have inadvertently affected the glacier's hydrological functioning.

5.5.3. Conclusions

Using EMMA for four sites over two melt seasons has demonstrated the temporal dynamics of water sources throughout an alpine catchment in greater detail than previous studies. This has demonstrated that simple models of water source variations across the melt season (i.e. early snowmelt, mid glacier melt, late groundwater dominated) should not be considered as a common framework, particularly for catchments such as the Taillon-Gabiétous with minimal glacierized area. Patterns of glacial retreat, such as those occurring presently in the Taillon-Gabiétous catchment (Chapter 3) may result in changes in the duration/amount of snow cover and the timing and magnitude of peak meltwater production. This would lead to further variability in 'Distributed', 'Quickflow' and 'Groundwater' contributions to bulk meltwaters. Further knowledge of catchment water source dynamics such as those demonstrated in this paper is particularly desirable to inform studies of physico-chemical habitat variability and ecological functioning of alpine river systems, plus their potential response to any future changes.

5.6. SUMMARY

This chapter has demonstrated the spatial and temporal variability in water source contributions to streams within the Taillon-Gabiétous catchment. The hydrochemical separation provides a means of determining water source contributions, and these can be applied to the conceptual models developed in Chapter 2. These 'Quickflow', 'Distributed' and 'Groundwater' proportions are used in subsequent chapters to determine relationships between water source contributions and stream physico-chemical habitat conditions (Chapter 6), and to produce an integrated hydroecological (water source-physico-chemical habitat-benthic community) assessment in Chapter 9.

CHAPTER 6
STREAM PHYSICAL AND CHEMICAL HABITAT CHARACTERISTICS, AND THEIR RELATIONSHIPS WITH WATER SOURCE DYNAMICS

6.1. CHAPTER OVERVIEW

This chapter relates dynamic water source contributions, determined previously in Chapter 5, to stream habitat conditions. The chapter examines stream physico-chemical habitat data (e.g. electrical conductivity, solute concentrations, stream discharge, water temperatures and habitat stability) as a function of the proportions of different water sources contributing to streamflow at different times of the melt season (Chapter 5). Seasonal variations in these key habitat variables are characterised (Section 6.4.1), before relating habitat measurements to water source contributions for weekly low and peak flow (Section 6.4.2). Water source contributions are used to examine changes in the stream habitat classifications proposed in Chapter 2 (Section 6.4.3). The habitat characteristics proposed in this earlier Chapter for the nine classification categories are tested against field observations (Section 6.4.4). These analyses underpin the hydroecological relationships examined in Chapters 7-9.

6.2. INTRODUCTION

Stream environments are often spatially and temporally heterogeneous in terms of hydrological and other physico-chemical conditions. Glacier-fed streams are characterised by distinctive seasonal and diurnal patterns of discharge (Röthlisberger and Lang, 1985; Hannah *et al.*, 1999a; Hannah *et al.*, 2000b) and relatively-high fine suspended sediment concentrations (SSC; Gurnell, 1982, 1983; Collins, 1989; Gurnell *et al.*, 1996). Stream hydrochemical characteristics are strongly influenced by seasonal snowmelt, and the development of glacier drainage systems (Sanchez and Lemmens, 1987; Brown and Tranter, 1990; Tranter and Raiswell, 1991; Collins, 1995; Hodson *et al.*, 2002; Chapter 5). Snowmelt-fed streams also display characteristic diurnal hydrographs (Hannah *et al.*, 1999a), although suspended sediment concentrations are typically much lower than glacier-fed streams (Ward, 1994). A distinctive early melt season peak in solute concentration also occurs due to preferential elution of sulphate and nitrate from snowpacks (Johannessen and Henriksen, 1978). Alpine groundwater streams typically have relatively constant habitat conditions, with low suspended sediment concentrations (Ward *et al.*, 1999) and relatively high electrical conductivity (EC) and ionic enrichment (Ward, 1994; Ward *et al.*, 1999; Malard *et al.*, 2001).

Temporal changes in the hydrological influence of icemelt, snowmelt (Quickflow and Distributed system flows) and groundwater contributions (e.g. Hannah and Gurnell, 2001; Smith *et al.*, 2001; Brown *et al.*, 2003) results in dynamic habitat conditions within alpine streams. Streams are typically characterised by a range of channel forms and dynamics (e.g. Gurnell *et al.*, 1999; Malard *et al.*, 2000), variable SSC (e.g. Gurnell and Fenn, 1984) hydrochemical variability (e.g. Hodson *et al.*, 2002; Tranter *et al.*, 2002) and thermal heterogeneity (Chapter 4). However, integrated studies considering the spatial and temporal dynamics of multiple stream physical and chemical habitat characteristics are few (Füreder, 1998; Smith *et al.*, 2001; Hieber *et al.*, 2002).

Most studies of alpine stream physico-chemical habitat dynamics have focused upon individual stream environmental characteristics (e.g. SSC, hydrochemistry; reviewed by Gurnell and Clark, 1987). However, some recent studies have taken a multivariate approach to studying alpine stream habitat dynamics. For example, Tockner *et al.* (1997) were able to distinguish different channel types (e.g. main channel, intermittently connected channels, tributaries) by making detailed observations of physico-chemical variables, and Malard *et al.* (2000) found marked seasonal changes in turbidity, EC and solute concentrations associated with shifts from groundwater dominated winter streamflow to summer periods of high snow- and ice-melt over 1.5 yrs. Furthermore, high temporal resolution measurements (15 min) throughout consecutive melt seasons illustrated clear differences in stream habitat (e.g.

discharge, SSC, EC, water temperature) with distance from the Taillon Glacier (Smith *et al.*, 2001). A small number of studies considering a range of habitat variables, based on spot measurements of habitat conditions only, have been conducted as baseline data for ecological sampling (Vinçon, 1987; Gíslason *et al.*, 2000; Lods-Crozet *et al.*, 2001; Hieber *et al.*, 2002). No detailed (high spatial and temporal resolution) multivariate studies have been undertaken to examine habitat dynamics of alpine streams in relation to dynamic water source contributions.

It is evident that streamflow is generated by the mixing of different alpine water sources stream habitat conditions may be highly dynamic (reviewed by; Brown *et al.*, 2003). For example, where relatively warm groundwater mixes with a glacier-fed stream, it may be hypothesised that water temperatures would become less variable, SSC would typically decrease (dilution), and discharge variations may be somewhat ameliorated (due to the relatively constant flow contribution). Based upon the potential mixes of alpine water source contributions (glacial icemelt, snowmelt, groundwater), alpine stream classifications and associated physical and chemical habitat variables were proposed for further testing and field validation by Brown *et al.* (2003) and in Chapter 2. This chapter summarises the field validation of these alpine stream classifications in the French Pyrénées. Because water source contributions identified in Chapter 5 were classified as 'Quickflow' (rapid routed snow- and ice-melt), 'Distributed' (slow routed snow and ice-melt), and 'Groundwater', a revised reference table for each stream classification category is provided (Table 6.1).

Detailed, high-resolution (15 min) integrated studies of suspended sediment concentrations, electrical conductivity, stream discharge, and water column and streambed temperatures were undertaken over the 2002 and 2003 summer melt seasons. These measurements were considered alongside spot measurements of other important habitat attributes including channel stability and solute concentrations, to examine relationships with water source

Table 6.1. Summary of alternative alpine stream classifications based on proportions of water sources

Reference	Classification	Water source contributions
A	Krenal	High proportion of Groundwater (>70%). Combined Distributed and Quickflow total <30%
B	Kreno-nival	Groundwater dominant (35 - 70%). Quickflow contribution > Distributed
C	Kreno-kryal	Groundwater dominant (35 – 70%). Distributed contribution > Quickflow
D	Nivo-krenal	Quickflow dominant (35 – 70%). Groundwater contribution > Distributed
E	Kryo-krenal	Distributed dominant (35 – 70%). Groundwater contribution > Quickflow
F	Nival	High proportion of Quickflow (>70%). Combined Distributed and Groundwater total <30%
G	Nivo-kryal	Quickflow dominant (35 – 70%). Distributed contribution > Groundwater
H	Kryo-nival	Distributed dominant (35 – 70%). Quickflow contribution > Groundwater
I	Kryal	High proportion of Distributed (>70%). Combined Quickflow and Groundwater total <30%

contributions (quantified in Chapter 5). This chapter adopts a multivariate approach to understand alpine stream habitat dynamics and aims: (1) to examine the relationships between stream physico-chemical habitat conditions and alpine stream water-source contributions, and; (2) to test the conceptual model presented in Chapter 2, by comparing observed stream physico-chemical habitat conditions for different water source contributions with those proposed for the classification categories.

6.3. DATA ANALYSIS

Water source contributions determined in Chapter 5 were used to classify streams into the nine categories (Table 6.1). To graphically depict the variability of water source contributions and alpine stream classifications throughout the two monitoring periods, data were plotted using a modified version of *Triplot*. *Triplot* is a spreadsheet designed to produce ternary (triangular) diagrams for the representation of soil particle shape and size (Graham and Midgley, 2000). Physico-chemical habitat data were subsequently analysed for the nine separate stream classification categories to facilitate comparison with earlier hypothesised physical and chemical variables (Brown *et al.*, 2003; Chapter 2). Box-plots were constructed using SPSS 11.0 (Norusis, 2003) to enable accurate dissemination of the habitat data collected for each stream classification.

6.4. RESULTS

This section is structured as follows: firstly the physico-chemical variables measured at the three gauging sites draining different catchment water sources are examined to provide an overview of the spatial and temporal variability in stream habitat over the two field seasons (Section 6.4.1). These data are considered alongside other spot measurements (habitat stability and solute concentrations) collected in the field to examine the relationships between stream physico-chemical habitat conditions and water-source contributions (Section 6.4.2). Based upon these data, spot measurements of the habitat variables were extracted corresponding to the times when hydrochemical samples were collected to quantify water source contributions (Chapter 5). Spatial and temporal water source contributions are used to identify stream classifications in Section 6.4.3, before stream habitat data are considered in relation to each of the nine classification categories (Section 6.4.3) to test the predictions proposed in Chapter 2.

6.4.1. Gauging station data

Although discharge magnitude varied between sites (Table 6.2), the stream sites displayed broadly similar flow patterns within each year (Figures 6.1 and 6.2). Mean discharge at Site A was slightly higher in 2003 than 2002; discharge at Site B was marginally higher in 2002, and similar in both years at Site C (Table 6.2). However, maximum discharges were much higher in 2003 (approximately double those in 2002). The sum of discharges for Sites A and B minus the discharge at Site C, was due to a karstic tributary input into the Taillon stream (Resurgence des Crampettes), and a glacial/snowmelt-fed tributary discharging into the Tourettes stream downstream of Site B (Chapters 3 and 4). Discharge at Site B showed less diurnal variation than Sites A and C, as the Tourettes stream is largely fed by groundwaters with limited connectivity meltwater streams.

EC tended to increase gradually as the melt season progressed (Figures 6.1 and 6.2; Chapter 5). Mean EC was highest at Site B and lowest at Site A over the two melt seasons (Table 6.2) with the greatest range at Site B. Diurnal variations in EC at all sites was inversely related to discharge (Figures 6.1 and 6.2). In 2003, diurnal variations were more pronounced than 2002. More intense storms in 2003 also resulted in lower minimum EC at all sites than in 2002 (Figure 6.2; Chapter 5).

Table 6.2. Descriptive statistics for stream physico-chemical habitat variables measured in 2002 and 2003. (Q = stream discharge, EC = electrical conductivity, SSC = suspended sediment concentration, Tw = water column temperatures and Tbdepth = streambed temperatures)

	2002			2003		
	Site A	Site B	Site C	Site A	Site B	Site C
Q						
Mean	0.07	0.07	0.20	0.09	0.06	0.20
Max	0.34	0.49	0.83	0.67	0.69	1.79
Min	0.01	0.01	0.05	0.02	0.01	0.06
Range	0.33	0.48	0.78	0.65	0.68	1.73
St.Dev	0.04	0.06	0.10	0.06	0.05	0.12
EC						
Mean	77.5	103.1	95.2	84.5	121.8	94.7
Max	101.2	127.9	118.1	107.0	143.9	115.0
Min	44.8	48.4	53.7	32.8	42.2	42.7
Range	56.4	79.5	64.4	74.2	101.7	72.3
St.Dev	8.4	7.3	7.8	7.2	12.0	6.2
SSC						
Mean	85.5	9.8	60.6	78.5	20.6	73.2
Max	5165.1	895.3	1129.1	1641.4	872.7	1976.0
Min	51.0	2.2	44.2	2.0	0.0	17.8
Range	5114.1	893.1	1084.9	1639.4	872.7	1958.3
St.Dev	203.1	14.9	57.2	187.7	71.4	205.9
Tw						
Mean	7.3	9.6	8.7	8.7	10.9	10.1
Max	15.0	13.4	15.4	16.1	16.5	17.0
Min	3.8	7.1	5.2	0.0	2.3	2.0
Range	11.1	6.3	10.3	16.0	14.2	15.1
St.Dev	2.2	1.2	1.9	2.4	1.9	2.3
Tb0.05m						
Mean	-	9.3	8.5	8.6	10.9	10.3
Max	-	13.0	15.1	15.7	16.3	16.8
Min	-	6.8	4.9	1.8	3.6	2.8
Range	-	6.2	10.2	13.9	12.7	14.0
St.Dev	-	1.2	1.9	2.3	1.8	2.2
Tb0.20m						
Mean	7.1	9.3	8.1	8.5	10.7	10.2
Max	13.1	11.7	12.4	15.1	13.9	15.8
Min	3.9	7.1	4.9	2.9	6.9	5.2
Range	9.2	4.6	7.6	12.2	6.9	10.6
St.Dev	1.9	1.0	1.5	2.3	1.3	2.0
Tb0.40m						
Mean	7.1	9.4	8.0	8.6	10.7	10.3
Max	12.7	11.0	10.4	14.8	13.0	14.5
Min	4.1	7.4	5.7	3.7	7.7	6.2
Range	8.6	3.6	4.7	11.2	5.2	8.3
St.Dev	1.8	0.8	1.0	2.1	1.2	1.6

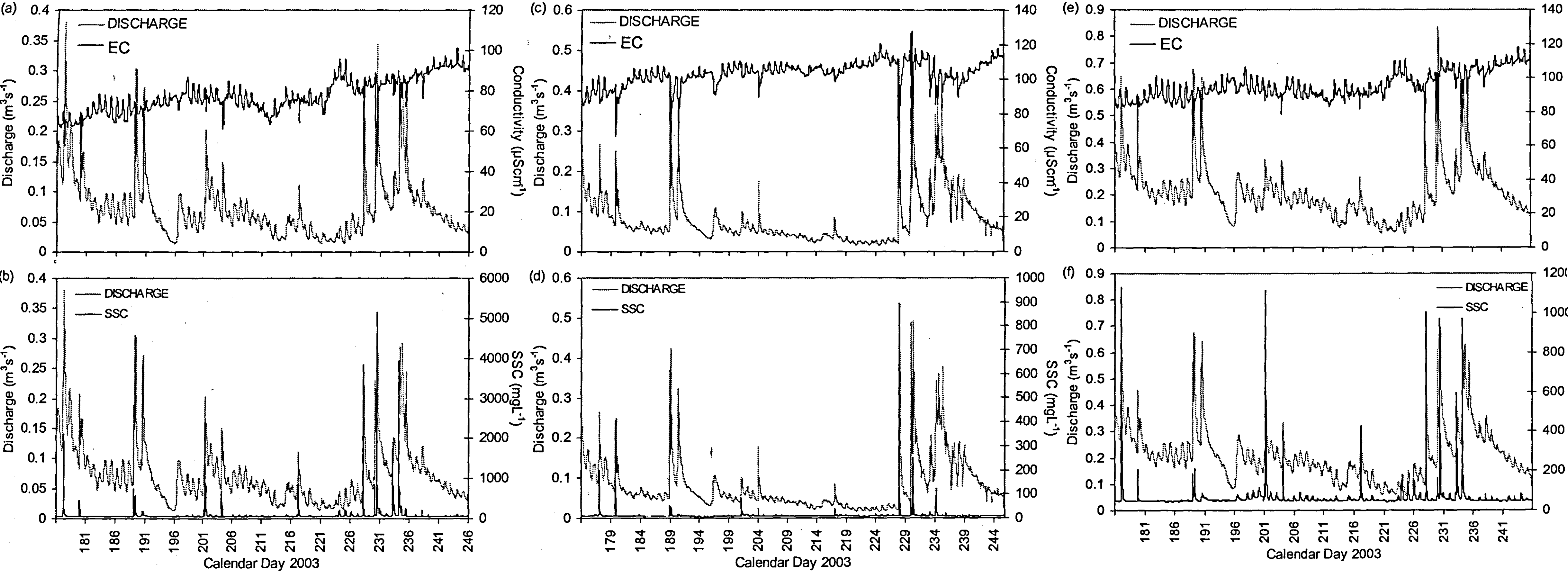


Figure 6.1. Discharge, electrical conductivity and suspended sediment concentration (SSC) time series for the 2002 melt season at (a) and (b) Site A; (c) and (d) Site B; and (e) and (f) Site C.

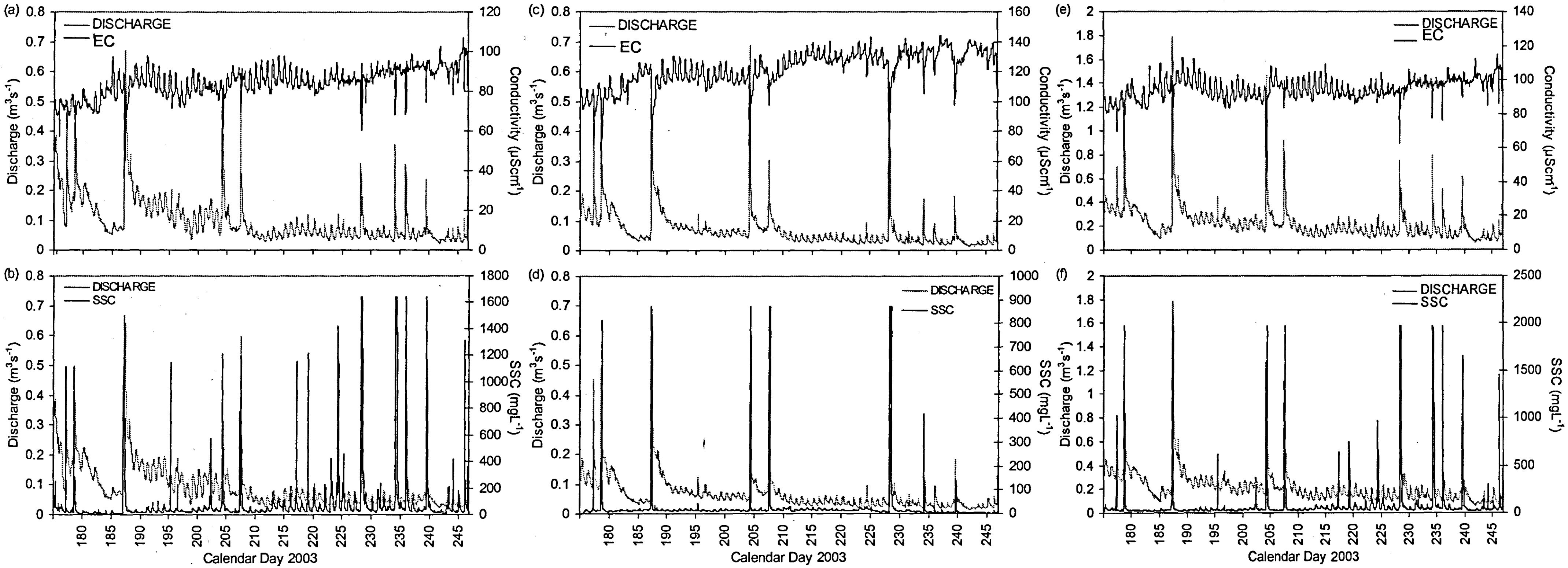


Figure 6.2. Discharge, electrical conductivity and suspended sediment concentration (SSC) time series for the 2003 melt season at (a) and (b) Site A; (c) and (d) Site B; and (e) and (f) Site C.

SSC was highest at Site A, and lowest at Site B during both melt seasons (Table 6.2). Site C had marginally lower SSC than Site A due to dilution of Taillon Glacier meltwaters by discharge from the Tourettes stream. Sites A and C displayed clear diurnal variations in SSC, particularly in 2003. However, these glacier melt induced SSC fluctuations were low when compared with peak SSC pulses associated with peak stream discharge following intense precipitation events (Figures 6.1 and 6.2). Maximum SSC in 2002 was recorded at Site A, but in 2003, Site C had the highest maximum (Table 6.2; Figures 6.1 and 6.2). Diurnal SSC variations and peak flow SSC pulses were generally dampened at Site B (Figure 6.1d and 6.2d)

Water column and streambed temperatures are described in detail in Chapter 4. Briefly, water column temperatures were on average coldest, and most variable, at Site A (Table 6.2). Mean water column temperatures were warmest and least variable at Site B. Water column temperatures at Site C were intermediate between Sites A and B (Table 6.2). At Site A in both years temperatures at all depths were similar to the water column and variability decreased with depth into the streambed. Site B streambed temperatures were similar on average to those in the water column and less variable with depth. At Site C, mean streambed temperatures were warmer, but less variable with depth.

6.4.2. Water source-stream physico-chemical habitat relationships

Discharge was significantly correlated with the proportion of 'Quickflow' (positive) and 'Distributed' (negative; Figure 6.3a; Table 6.3). EC was lower when 'Quickflow' proportions were greatest and increased significantly as the proportion of 'Groundwater' increased (Table 6.3; Figure 6.3b). Water column temperature was significantly correlated (negative) with increased 'Quickflow' and 'Distributed' contributions to streamflow, but increased 'Groundwater' contributions were associated with warmer temperatures (Table 6.3). No significant correlations between streambed temperatures and water source contributions were found (Table 6.3; Figures 6.3c-f). SSC was significantly related to increased 'Quickflow', but negatively correlated with 'Groundwater' contributions (Table 6.3; Figure 6.3g). As higher values for Pfankuch stability scores (PFAN) indicate less stable conditions, stability was generally lower with increased 'Quickflow' and 'Distributed' contributions to streamflow and highest when 'Groundwater' contributions increased (Table 6.3; Figure 6.3h).

'Groundwater' was negatively correlated with pH, whereas 'Quickflow' was associated with higher pH (Table 6.3; Figure 6.3i). Si and Ca^{2+} concentrations were strongly correlated with the proportion of 'Groundwater', but negatively correlated with 'Quickflow' and 'Distributed' source contributions (Table 6.3; Figure 6.3j). Mg^{2+} and SO_4^{2-} increased significantly as the proportion of 'Distributed' flow increased, but these solutes negatively correlated with 'Quickflow' and 'Groundwater' contributions (Table 6.3; Figure 6.3l). Na^+ was only weakly correlated (negative) with the proportion of 'Quickflow' (Table 6.3; Figure 6.3m). K^+, Cl^- and NO_3^- had no significant relationships with any water source contribution (Table 6.3; Figures 6.3n-p). HCO_3^- was significantly lower when 'Quickflow' contributions to streamflow were high, but increased when 'Groundwater' contributions were high (Figure 6.3r).

Physico-chemical habitat relationships with water source contributions are summarised in Table 6.4. Most habitat variables were negatively correlated with 'Quickflow', especially the hydrochemical variables (with the exception of pH). 'Groundwater' contributions were positively correlated with most variables, whereas 'Distributed' contributions had an equal number of positive and negative relationships with physico-chemical variables.

Table 6.3. Pearson's correlation coefficients (*r*) for spot measurements of physico-chemical habitat variables against proportion of water sources contributing to streamflow at all sites. (Q = discharge (m^3s^{-1}); EC = electrical conductivity (μScm^{-1}); Tw = water column temperature (°C) and Tb (depth in m) = streambed temperature (°C); SSC = suspended sediment concentration (mgL^{-1}); Si measured in mgL^{-1}; all other major ions measured in μeqL^{-1}. Asterisks denote significant correlations: * = $p < 0.05$, ** = $p < 0.01$)

	Q	EC	Tw	Tb0.05	Tb0.20	Tb0.40	SSC	PFAN	pH
'Quickflow'	0.238**	-0.578**	-0.271**	-0.039	-0.046	-0.146	0.355**	-0.321	0.288**
'Groundwater'	0.079	0.584**	0.420**	-0.009	-0.019	-0.007	-0.373**	0.622**	-0.327**
'Distributed'	-0.277**	-0.072	-0.159**	0.038	0.052	0.113	0.054	-0.360*	0.073

	Si	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-
'Quickflow'	-0.484**	-0.507**	-0.489**	-0.196**	-0.048	0.069	-0.062	-0.536**	-0.538**
'Groundwater'	0.948**	0.430**	-0.181**	0.142	-0.108	-0.022	0.084	-0.074	0.331**
'Distributed'	-0.511**	-0.002	0.565**	0.024	0.14	-0.034	-0.03	0.502**	0.116

Table 6.4. Summary of significant relationships between physico-chemical habitat variables and water sources contributions at all sites. (Q = discharge (m^3s^{-1}); EC = electrical conductivity (μScm^{-1}); Tw = water column temperature (°C); SSC = suspended sediment concentration (mgL^{-1}); Si measured in mgL^{-1}; all other major ions measured in μeqL^{-1}. All correlations are significant at $p<0.05$)

	Q	EC	Tw	SSC	PFAN	pH	Si	Ca^{2+}	Mg^{2+}	Na^+	SO_4^{2-}	HCO_3^-
'Quickflow'	+	-	-	+		+	-	-	-	-	-	-
'Groundwater'		+	+	-	+	-	+	+	-			+
'Distributed'	+		-		-		-		+		+	

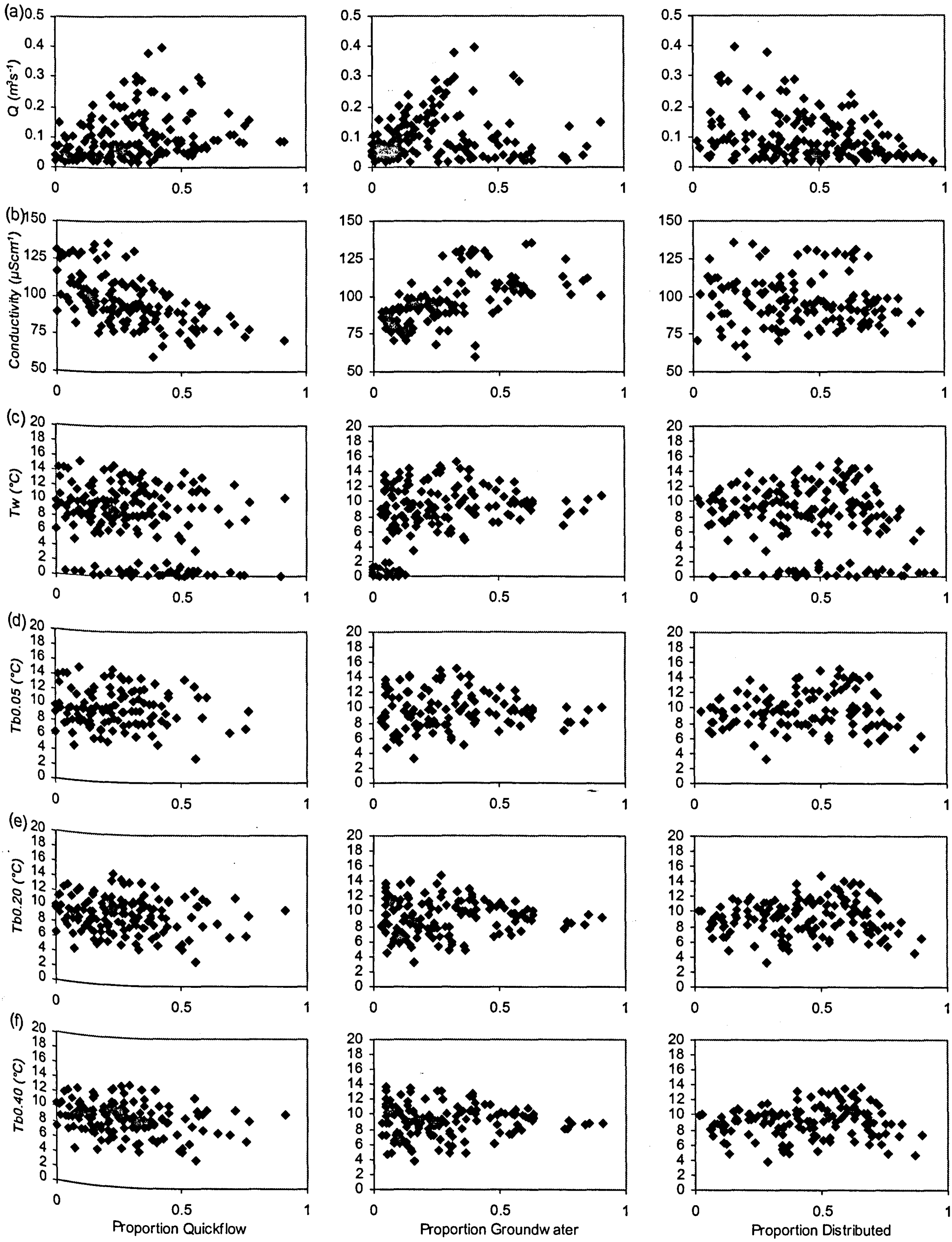


Figure 6.3. Scatter plots of stream physical and chemical habitat characteristics against proportions of 'Quickflow', 'Distributed' and 'Groundwater': (a) discharge; (b) electrical conductivity; (c) water column temperature; (d) streambed temperature (0.05m depth); (e) streambed temperature (0.20m depth); (f) streambed temperature (0.40m) depth:

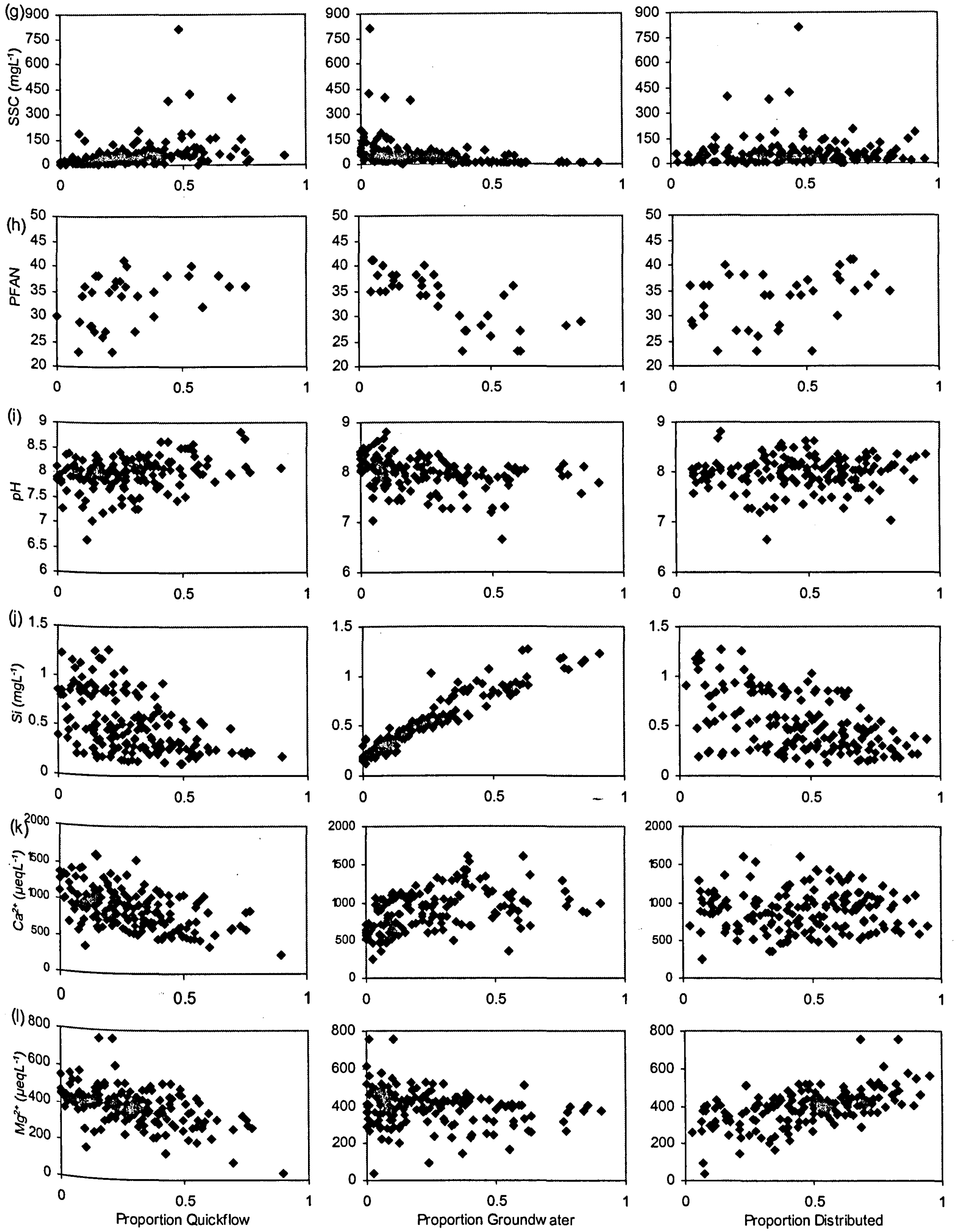


Figure 6.3.cont. (g) suspended sediment concentration; (h) Pfankuch stability index; (i) pH; (j) silica concentration; (k) calcium concentration; (l) magnesium concentration

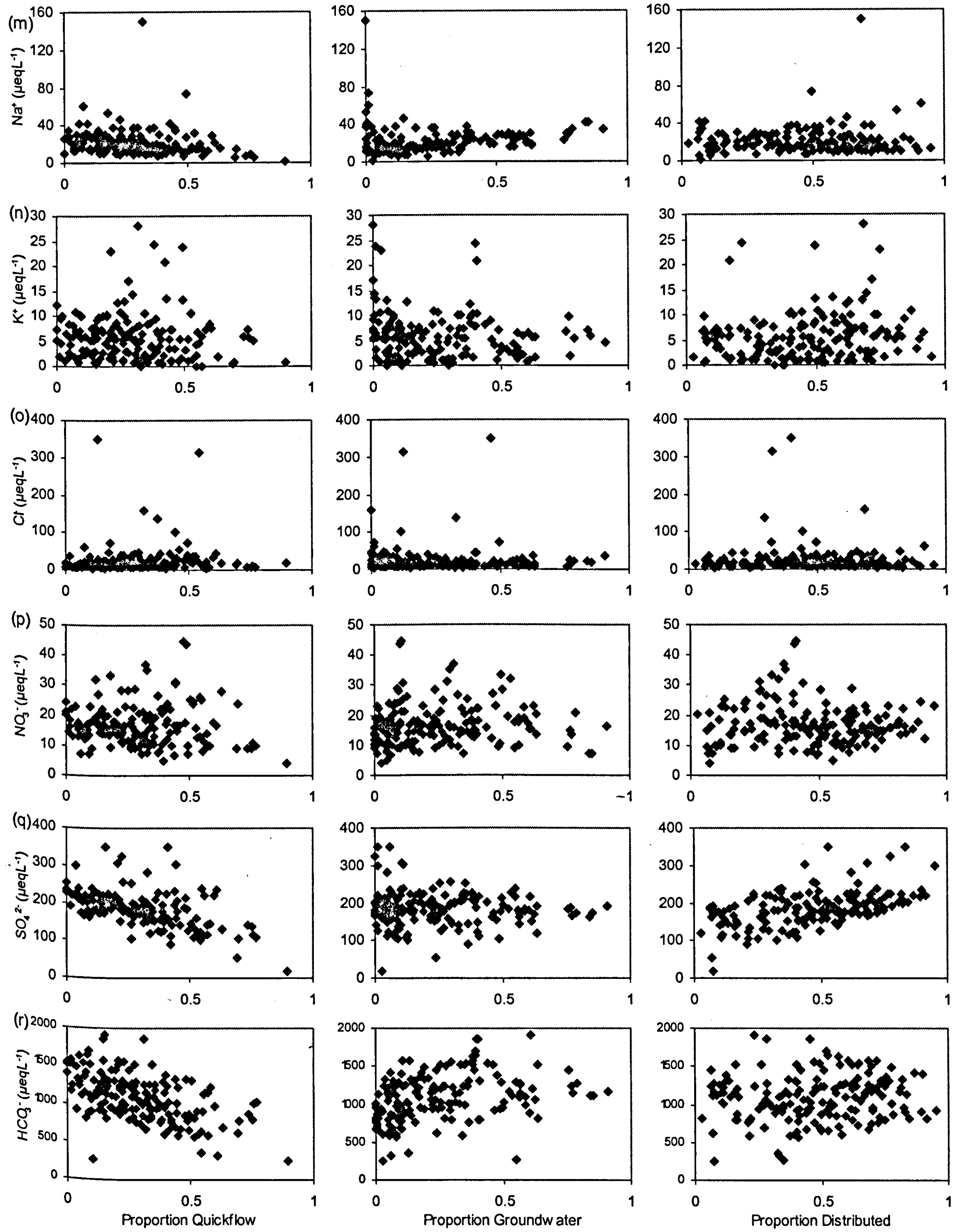


Figure 6.3.cont. (m) sodium concentration; (n) potassium concentration; (o) chloride concentration; (p) nitrate concentration; (q) sulphate concentration; (r) bicarbonate concentration

6.4.3. Water source contributions and stream habitat classifications

Stream classifications varied by site and year based on seasonally averaged contributions (Figure 6.4). The Upper Site close to the Taillon Glacier snout was classified as Nivo-kryal in 2002, and Kryo-nival in 2003 (Figure 6.4), reflecting the overall dominance by 'Quickflow' and 'Distributed' contributions. At Site A, the overall classifications were the same as the Upper Site in both years due to minimal tributary inputs between these two sites, although the proportion of 'Quickflow' and 'Groundwater' was marginally higher for downstream Site A. Site B was classified as Kreno-kryal in both 2002 and 2003, although in 2002 a greater proportion of 'Distributed' flow resulted in classification closer to Kryo-krenal (Figure 6.4). Site C was intermediate (Kryo-nival) between Sites A and B in both years, as a result of the mixing of waters at the Taillon-Tourettes confluence. In 2003, all four sites were located more towards the lower right hand corner of the ternary diagram compared with 2002 indicating greater 'Distributed' contributions.

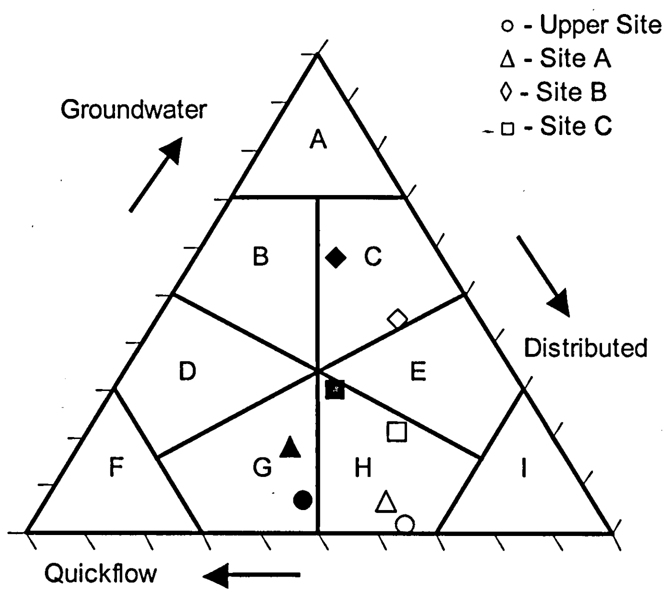


Figure 6.4. Melt season averaged water source contributions during 2002 and 2003. (Filled symbols represent 2002 data)

Weekly variations in water source contributions to the Upper Site resulted in the same four stream classifications in both years (Figure 6.5). However, water source contributions were more variable during 2002, with numerous shifts, particularly between Nivo-kryal and Kryo-nival. Low and high flow contributions were similar to each other, with the exception of one high flow sample when 'Quickflow' dominated (Nival classification; F) and one low flow when 'Distributed' flows prevailed (Kryal classification; I; Figure 6.5a). Temporal variations in water source contributions showed a clearer trend in 2003, exhibiting a shift from Nival at the beginning of the melt season, through Nivo-kryal and Kryo-nival, to Kryal by the end of the monitoring period (Figure 6.5b). Low and high flow had similar classifications and followed similar trends, although after the first week of the monitoring period (weeks 2-3) low flows had a greater proportion of 'Distributed' water and were classified as Kryo-nival (cf. Nivo-kryal early melt season high flow samples reflecting increased snowmelt during mid-late afternoon).

Over the 2002 melt season at Site A, water source contributions varied between seven of the nine possible alpine stream categories (Figure 6.6a). For most weeks (at both low and high discharge), the stream was typically either Nivo-kryal or Kryo-nival. At the start of the melt season, low flow Nivo-kryal and high flow Nivo-krenal were clearly separated. However, by the end of the melt season low and high flows converged to become Kryo-nival (Figure 6.6a). In 2003, water source variability was much reduced, with only four of the nine stream-categories experienced. Most notably in 2003, 'Groundwater' contributions were generally lower (Figure 6.6b). The overall pattern of water source dynamics in 2003 resembled that for the Upper Site (Taillon Glacier snout) with early melt season Nival classifications at both low and high flows. A broad shift occurred in the late melt season so that 'Distributed' dominated classifications (e.g. Kryal) occurred at low discharge, and Kryo-nival classifications at high flow (Figure 6.6b).

Water source contributions at Site B were highly variable during both summer melt seasons (Figure 6.7). In 2002, most stream classifications were either Krenal, Kreno-nival or Kreno-kryal due to high 'Groundwater' contributions (Figure 6.7a). High flow samples in 2002 typically had greater 'Distributed' and 'Quickflow' contributions (Nivo-krenal/ Kryo-nival), whereas low flows had greater proportions of 'Groundwater' (Krenal/Kreno-nival/Kreno-kryal). However, low and high flow classifications were the same at the beginning (Kreno-kryal) and end (Krenal) of the melt season (Figure 6.7a). In 2003, more 'Distributed' water source contributions resulted in the stream classifications often being either Kryo-krenal or Kreno-kryal (Figure 6.7b), and with less distinction between low and high flows than the previous year. Low and high flows were both Kreno-nival at the beginning of the melt season, but on the last sampling date, low flows were Kreno-kryal and high flows Kreno-nival (Figure 6.7b).

Site C water source contributions were typically intermediate of Sites A and B. (Figure 6.8). In 2002, stream classifications changed frequently, with low and high flows often dissimilar from each other. However, at the start of the melt season, low and high flows were both Nivo-krenal (Figure 6.8a). Most samples typically plotted towards the middle of the ternary diagram, reflecting similar proportions from each of the three sources. However, low flows towards the end of the 2002 melt-season indicated reduced 'Quickflow' and 'Distributed' contributions (i.e. Kreno-kryal/Kryo-krenal) compared with earlier in the melt season. In 2003, the pattern of water source contributions more strongly resembled that of Site A but with increased 'Groundwater' contributions (Figure 6.8b). Low and high flows early in the melt season were Nivo-krenal, shifting to Kryo-krenal and Kryo-nival during the mid-late melt season. Site C was also classified as Kryal on five occasions, at both low and high flows, despite inputs from the Tourettes tributary. At the end of the monitoring period, low flows were classified as Kryo-krenal, whereas high flows were Nivo-kryal, illustrating clear low-high flow differentiation in water source contributions at this time.

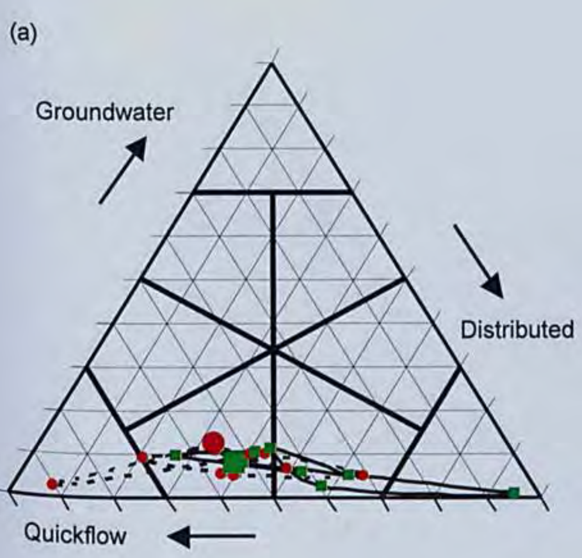


Figure 6.5. Weekly water source contributions at the Upper Site during (a) 2002, and (b) 2003. (red circles joined by broken lines represent high flow samples; green squares joined by solid lines represent low flow samples)

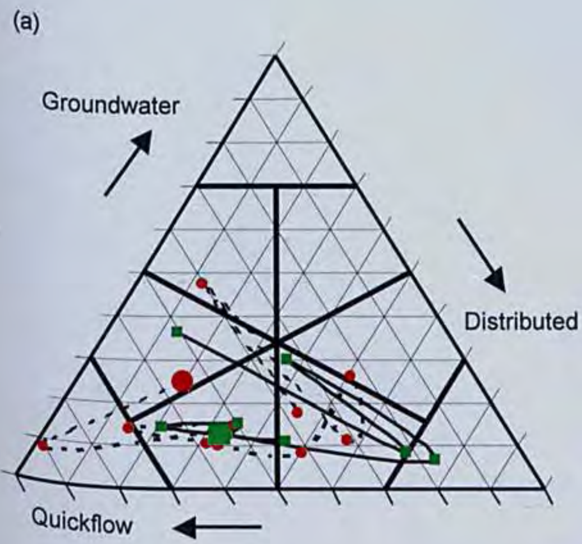


Figure 6.6. Weekly water source contributions at Site A during (a) 2002, and (b) 2003. (red circles joined by broken lines represent high flow samples; green squares joined by solid lines represent low flow samples)

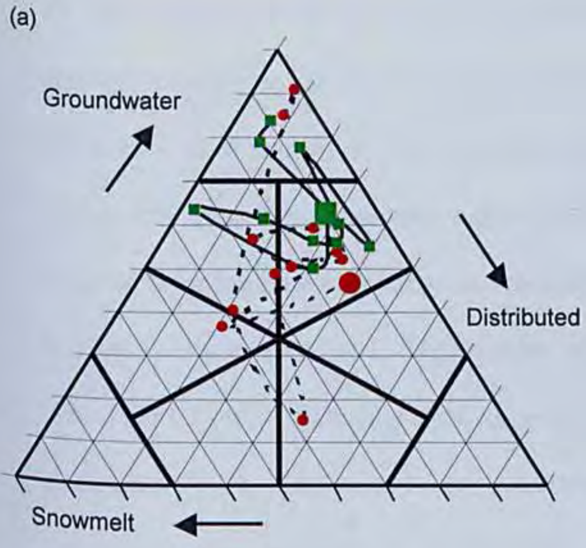


Figure 6.7. Weekly water source contributions at Site B during (a) 2002, and (b) 2003. (red circles joined by broken lines represent high flow samples; green squares joined by solid lines represent low flow samples)

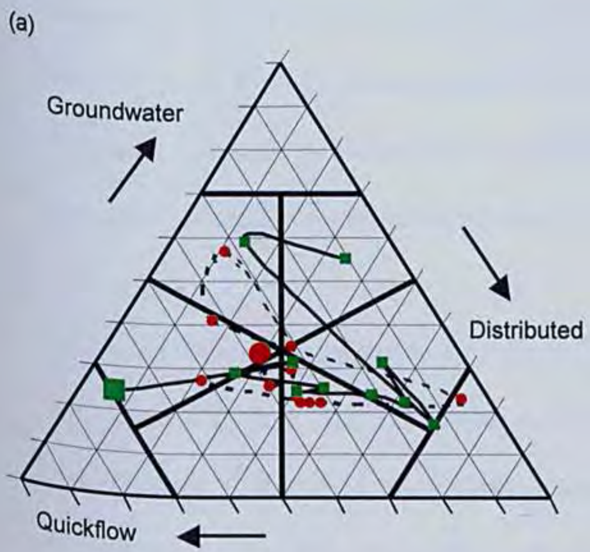


Figure 6.8. Weekly water source contributions at Site C during (a) 2002, and (b) 2003. (red circles joined by broken lines represent high flow samples; green squares joined by solid lines represent low flow samples)

6.4.4. Physico-chemical habitat characteristics for stream classification categories

By integrating physical and chemical habitat data collected over two melt seasons from four sites and classifying the 167 individual samples based upon water source contributions, clear differences were evident in physico-chemical habitat between the nine alpine stream classes (Table 6.5). Thus, it was possible to quantify the physical and chemical variables predicted in Chapter 2 for the nine classification categories; these associations are illustrated using box-whisker plots (Figure 6.9). The number of observations of habitat variables for each classification varied from seven (Nival and Krenal) to 35 (Kryo-nival). This was due to the difficulties of assessing water source contributions to stream discharge within the field, such that comparable numbers of samples for each classification could not be methodically collected.

Mean discharge was highest for Nivo-krenal samples and this classification yielded the widest discharge range (Table 6.5; Figure 6.9a). Discharge was, on average, also relatively high and variable for the Kryo-nival stream class. The Kryal stream classification had the lowest mean discharge, although discharge was variable as a result of diurnal cycling in meltwater production. Mean Krenal stream discharge was relatively low (Figure 6.9a).

SSC was lowest and least variable for Krenal stream classifications (Table 6.5). Kreno-kryal SSC were also low, but the mean and range of SSC were greater than for Krenal classifications (Table 6.5). Nivo-kryal classifications had the most variable and greatest average SSC (Table 6.5). Nival SSC were on average greater than Kryal, although the latter was more variable. Kryo-nival SSC was more similar to, but ranged intermediate of Kryal than Nival. Kryo-krenal and Kreno-nival had very similar average and range of SSC.

Channel stability (i.e. low PFAN) was associated with Krenal, Kreno-kryal and Kreno-nival (Table 6.5) classes but PFAN was much more variable for Kreno-kryal and Kreno-nival streams (Figure 6.9c). The least stable channels were related to classifes dominated by

'Quickflow' and 'Distributed' system contributions (i.e. Nivo-krenal, Nival, Nivo-kryal, Kryo-nival and Kryal). The most variable channel stability was for the Kryo-krenal classification (Figure 6.9c).

High EC was typical of Krenal streams, which also showed relatively high concentrations of Si, HCO_3^- and Ca^{2+} (Table 6.5; Figures 6.9d-n). Nival classes had relatively high pH, low concentrations of Cl^- and acid anions (NO_3^- and SO_4^{2-}; Table 6.5) and low conductivities, with low variability of these hydrochemical variables (Figures 6.9d-n). Electrical conductivity, and Si, Ca^{2+}, Na^+ Cl^- and HCO_3^- concentrations of Kryal classes were intermediate of Krenal and Nival; however, all other ion concentrations were greater on average for Kryal classes (Table 6.5). However, most hydrochemical variables had wider ranges for Kryal stream classifications than for Krenal and Nival (Figures 6.9d-n).

Stream classifications composed of mixtures of water source contributions inevitably showed a range of hydrochemical characteristics (Table 6.5; Figures 6.9d-n). For example, the highest Ca^{2+} and HCO_3^- concentrations were associated with kryo-krenal classifications whereas the lowest average pH and Na^+ concentrations, and widely ranging Ca^{2+} concentrations were found for Kreno-kryal classes (Table 6.5). Relatively low conductivities and Ca^{2+}, Mg^{2+} and HCO_3^- concentrations were typical of the Nivo-krenal classes.

Although water column and streambed temperatures were not included in the habitat variables predicted by Brown *et al.* (2003), they were analysed to further demonstrate the problems of linking temperatures to water source contributions (see also Chapter 2). Krenal water column temperatures averaged 9.1°C and they were cooler with depth into the bed; thermal variability was the lowest of any classification (Table 6.5; Figures 6.9o-r). The coldest water temperatures were for Nivo-kryal water source contributions, although mean Kryal water temperatures (5.2°C) were similar to, but greater than, the 4°C limit discussed in earlier alpine stream studies (e.g. Ward, 1994). Mean and range of water column temperatures for Nival

(5.0 and 12.0°C, respectively) were very similar to Kryal (Table 6.5). The warmest water column temperatures were for the Kryo-krenal classification, with temperature average and range decreasing with depth into the streambed (Table 6.5; Figures6.9o-r).

Table 6.5. Measured physico-chemical habitat variables for alpine stream categories based on relative proportions of water source contributions. N = number of observations; Sites = Sites at which each classification was observed, in order of number of occurrences per site; Q = discharge (m^3s^{-1}); SSC = suspended sediment concentration (mgL^{-1}); PFAN = Pfankuch stability index; EC = electrical conductivity (μScm^{-1}); Si measured in mgL^{-1}; all other ions measured in μeqL^{-1}; Tw = water column temperature (°C) and Tb (depth) = streambed temperature (°C).

			Q	SSC	Stability	Hydrochemistry											Temperatures (°C)			
Classification	N	Sites			PFAN	EC	pH	Si	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	Tw	Tb0.05m	Tb0.20m	Tb0.40m
Krenal	7	B																		
Average			0.07	9.4	29	110.0	7.9	1.15	1026.6	358.4	33.4	5.9	20.5	12.8	176.5	1215.8	9.1	8.7	8.6	8.6
Max			0.15	14.4	29	124.5	8.15	1.23	1300.2	407.0	41.9	9.7	34.7	20.9	192.0	1444.2	10.8	10.2	9.6	9.1
Range			0.13	8.2	1	23.7	0.6	0.16	437.4	137.7	19.4	7.9	27.0	13.6	29.9	327.3	4.0	3.2	1.9	1.0
Kreno-nival	13	B,C,A																		
Average			0.11	25.3	29	107.3	7.8	0.88	1048.0	333.2	22.0	6.1	15.7	16.0	153.6	1225.3	9.8	9.9	9.7	9.8
Max			0.30	82.6	36	135.9	8.0	1.3	1542.8	443.6	30.8	24.2	44.8	23.0	190.7	1850.0	12.5	12.3	11.3	11.5
Range			0.28	76.3	13	75.9	0.8	0.66	855.5	210.0	15.4	23.1	38.9	13.6	85.6	1047.6	5.3	4.8	3.9	3.6
Kreno-kryal	15	B,C																		
Average			0.07	15.4	28	106.5	7.7	0.88	942.8	370.9	26.6	4.0	43.7	20.2	197.6	1083.3	9.7	9.5	9.3	9.3
Max			0.17	74.6	34	134.5	8.1	1.3	1606.6	511.9	31.0	10.2	349.9	33.2	238.4	1909.4	12.9	12.6	11.2	10.6
Range			0.15	74.4	11	43.3	1.5	0.68	1250.7	347.9	15.5	9.4	343.2	26.0	69.6	1640.9	5.7	5.7	4.4	3.3
Nivo-krenal	12	C,A,B																		
Average			0.22	49.2	37	88.8	7.9	0.58	832.7	288.5	15.4	5.3	26.8	18.6	139.4	959.6	9.2	9.4	9.2	8.7
Max			0.39	100.3	40	103.6	0.9	2.0	1095.4	411.6	25.8	20.7	138.3	31.3	223.6	1310.1	13.9	13.7	11.9	10.1
Range			0.34	91.5	8	36.2	0.6	0.47	605.8	316.4	19.5	20.2	134.2	22.4	170.9	723.1	9.0	8.6	6.5	3.8

Table 6.5. Cont.

Classification	N	Sites	Q	SSC	Stability PFAN	Cond	pH	Si	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	NO_3^{-}	SO_4^{2-}	HCO_3^{-}	Tw	Tb0.05m	Tb0.20m	Tb0.40m
						Hydrochemistry											Temperatures (°C)			
Kryo-krenal	23	B,C,A																		
Average			0.08	28.4	32	112.9	7.9	0.73	1191.3	434.8	22.7	6.1	13.7	16.0	209.7	1417.0	11.0	11.1	10.4	10.4
Max			0.21	81.4	38	131.1	8.3	1.0	1611.5	521.2	36.9	12.3	28.5	22.0	254.2	1864.2	15.3	15.2	14.7	13.2
Range			0.19	78.3	15	54.2	1.1	0.57	887.1	159.1	26.7	11.6	22.9	11.3	76.4	940.9	9.5	9.5	8.8	6.1
Nival	7	B,U																		
Average			0.11	71.0	36	75.9	8.3	0.22	641.3	257.1	6.4	5.0	10.1	8.5	104.0	788.6	5.8	8.4	8.1	7.7
Max			0.16	151.6	36	81.3	8.8	0.2	850.6	348.9	8.6	7.4	19.0	10.6	141.1	1019.9	12.3	9.6	9.4	8.9
Range			0.08	137.0	0	10.3	0.8	0.06	597.3	315.1	7.1	6.6	12.6	6.5	121.9	772.0	12.2	2.5	2.7	2.6
Nivo-kryal	27	U,A,C																		
Average			0.09	159.0	38	82.5	8.2	0.29	677.9	345.0	16.8	4.1	40.9	21.4	166.4	817.3	4.9	9.3	9.1	8.5
Max			0.25	811.6	38	99.1	8.6	0.5	1081.2	519.5	37.7	10.6	313.5	44.7	303.4	1332.5	13.1	12.8	12.7	12.1
Range			0.21	808.7	0	28.4	1.1	0.33	724.0	316.8	30.9	10.6	308.0	36.8	204.2	1008.3	13.1	9.5	9.5	8.4
Kryo-nival	35	C,B,A																		
Average			0.14	53.7	37	91.0	7.9	0.41	910.6	415.8	18.1	5.2	20.5	16.3	184.3	1130.1	9.9	10.1	9.9	9.7
Max			0.29	205.6	41	108.2	8.6	0.6	1218.5	759.4	152.6	28.0	158.7	37.2	350.9	1576.3	14.3	14.3	14.1	13.7
Range			0.27	142.7	7	32.4	1.0	0.39	608.3	442.0	38.0	12.0	40.7	32.4	160.2	809.7	8.3	8.8	8.6	7.9
Kryal	28	U,A,C																		
Average			0.06	57.3	36	90.0	8.0	0.32	849.5	477.9	19.1	6.5	16.9	16.4	218.7	1112.8	5.2	8.1	8.1	8.4
Max			0.17	188.2	38	98.7	8.4	0.6	1221.3	754.3	59.9	22.9	61.4	24.2	348.3	1566.4	12.1	12.1	12.1	11.7
Range			0.15	172.8	3	22.5	1.4	0.41	663.4	387.0	51.4	22.0	57.0	15.3	173.9	805.6	12.0	7.5	7.7	7.0

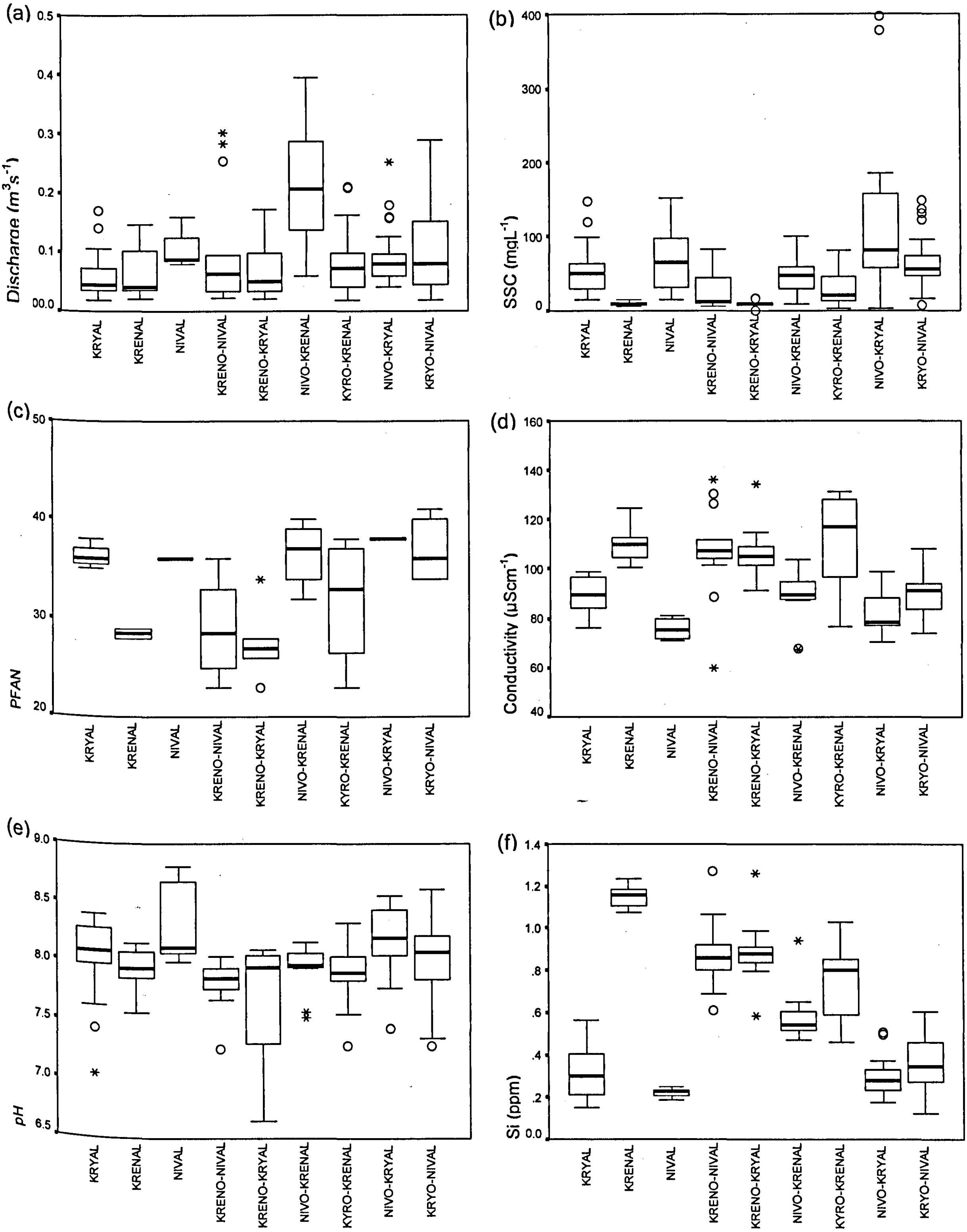


Figure 6.9. Box plots of stream physical and chemical habitat characteristics for nine stream classification categories. Open circles represent outliers and asterisks represent extreme values. (a) discharge; (b) suspended sediment concentration; (c) Pfankuch stability index; (d) conductivity; (e) pH; (f) Silica concentration

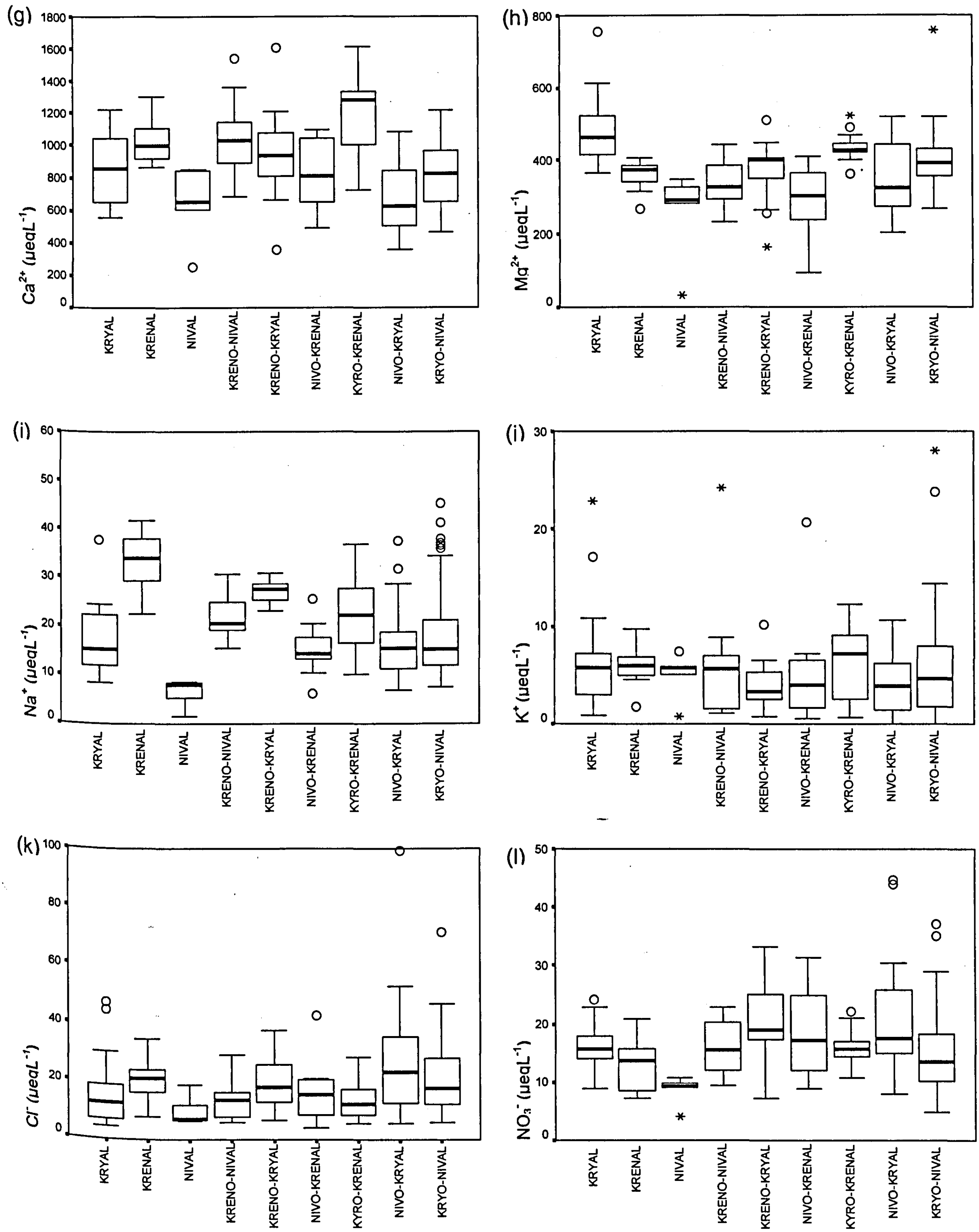


Figure 6.9.cont. (g) calcium concentration; (h) magnesium concentration; (i) sodium concentration; (j) potassium concentration; (k) chloride concentration; (l) nitrate concentration

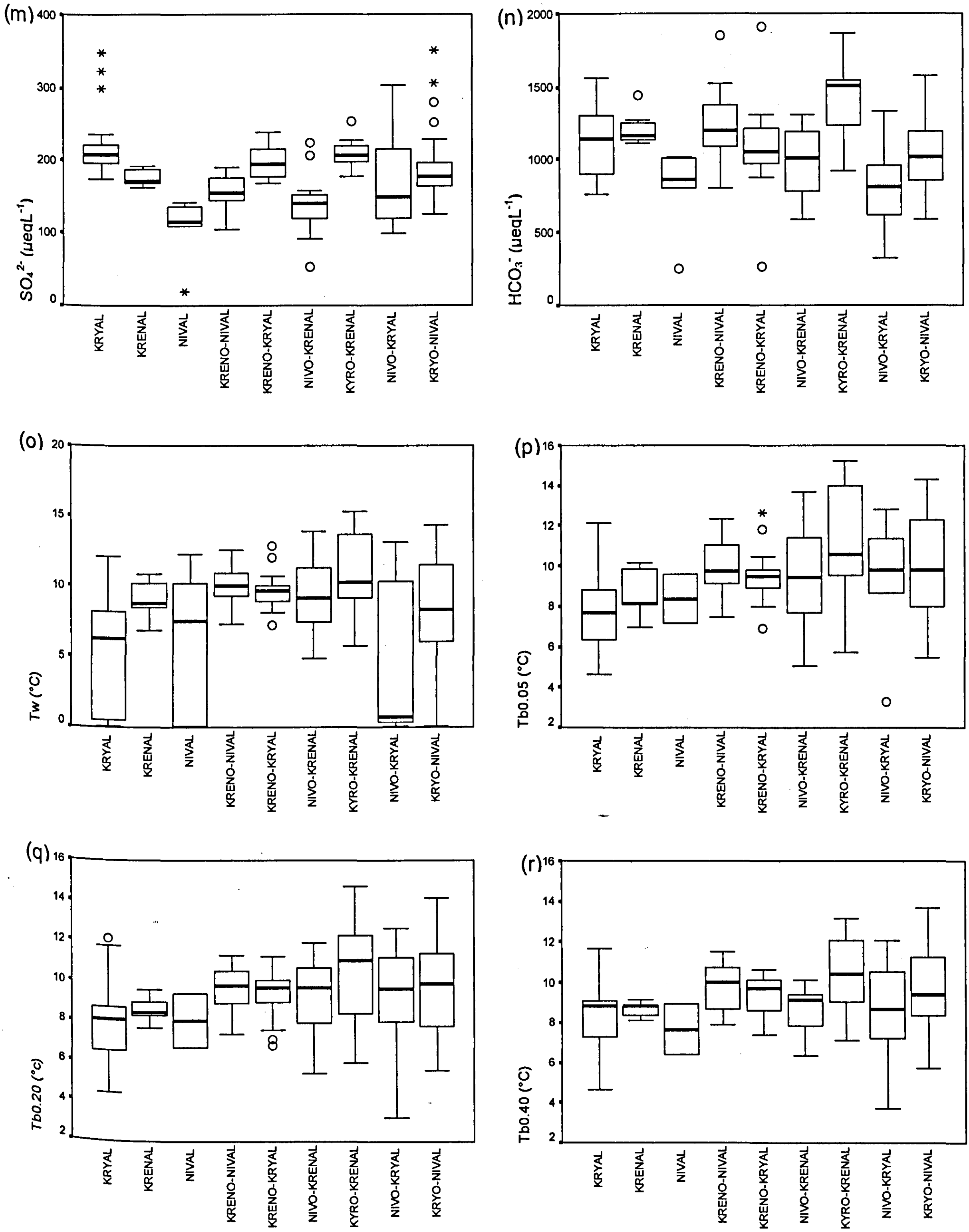


Figure 6.9.cont. (m) sulphate concentration; (n) bicarbonate concentration; (o) water column temperature; (p) streambed temperature (0.05m depth); (q) streambed temperature (0.20m depth); (r) streambed temperature (0.40m depth)

6.5. DISCUSSION

Clear spatio-temporal variability of stream physical and chemical habitat characteristics was demonstrated within this small alpine catchment. Stream habitat characteristics were related to the relative proportions of: (1) snow- and ice-melt ('Quickflow'); (2) meltwaters routed through a subglacial drainage system ('Distributed'), and; (3) 'Groundwater' contributions to streamflow. Because these water source contributions were previously identified in Chapter 5, revised water source contribution criteria were developed for the determination of the nine classification categories (Chapter 2). For stream reaches where water sources mixed, stream habitat characteristics were inherently highly variable, enabling alpine stream classes proposed by Brown *et al.* (2003) and in Chapter 2 to be quantified. All stream reaches switched between several classes over the course of the melt season due to temporal variations in water source contributions. Notably, sites further downstream from the Taillon Glacier tended to be more variable in terms of the number of stream classifications that were applicable due to dynamic contributions of meltwaters mixing with relatively constant 'Groundwater' contributions from tributaries in the Vallée des Pouey Aspé.

6.5.1. Water source-stream physico-chemical habitat relationships

Water source contributions played an important role influencing stream habitat conditions. For example, the negative correlation of electrical conductivity with 'Quickflow' reflects dilute meltwater inputs from snow- and ice-melt (Collins, 1995; Tockner *et al.*, 1997). High SSC when 'Quickflow' was dominant is in part related to the positive correlation of 'Quickflow' and stream discharge. During mid-late afternoon when snow- and ice-melt ('Quickflow') is rapidly routed to proglacial stream reaches (Hannah and Gurnell, 2001), increased stream discharge mobilises available exposed sediments at the glacier snout, in addition to sediment deposits at stream margins (e.g. Gurnell *et al.*, 1996; Richards and Moore, 2003). Si concentrations were negatively correlated with the proportion of 'Quickflow' and 'Distributed' contributions to streamflow, whereas concentrations increased with the proportion of 'Groundwater'. Although this would be expected due to the highest (lowest) measured concentrations being found in groundwater streams (snowmelt), the strength of the relationship may be an artefact of the inclusion of Si within the EMMA (Chapter 5).

'Quickflow' and 'Distributed' system contributions are both initially sourced by dilute snow- and ice-melt. Whereas 'Quickflow' retains much of the snow- and ice-melt source physico-chemical characteristics (e.g. Nival classifications), 'Distributed' flow is modified in the subglacial environment (Tranter *et al.*, 1996) such that this 'pathway' may be considered separately as a 'source' (Kryal classes). This distinction is critical as the physico-chemical habitat conditions they generate are quite markedly different. In previous studies, the term kryal has been widely used to describe proglacial streams with high SSC and low water temperatures during peak summer flow (Ward, 1994; Lods-Crozet *et al.*, 2001; Robinson *et al.*, 2001). This is because these earlier studies made no distinction between the physico-chemical habitat characteristics generated by different water source contributions (i.e. 'Quickflow' and 'Distributed'); instead kryal was simply used to refer to both these water source contributions together. This study has demonstrated that close to the glacier snout, proglacial stream habitat variables vary predominantly due to dynamic contributions from 'Quickflow' and 'Distributed' sources. When taken in this context, Kryal classifications in this study are different to those previously defined in the literature because they are usually associated with low flow conditions (i.e. subglacial drainage contributions are more dominant as opposed to rapidly routed snow- and ice-melt). High suspended sediment concentration, low solute levels and generally the harshest habitat conditions in proglacial streams were associated more with Nivo-kryal classifications in this study, as are generally more common during mid-late afternoon when meltwater generation is high and 'Quickflow' and 'Distributed' contributions mix at the glacier snout (e.g. Hubbard and Nienow, 1997).

6.5.2. Spatial and temporal variation in water source contributions and stream habitat

The Upper Site and Site A were characterised by similar water source contributions particularly in 2003, reflecting limited tributary inputs between the sites. However, although classifications were often similar, suspended sediment concentration was often lower at Site A, perhaps due to sediment deposition as meltwaters travelled downstream through the stream network (Richards and Moore, 2003). Overall, when 'Groundwater' contributions were greatest (e.g. Krenal, Kreno- prefix categories; typically at Site B), physico-chemical habitat variability was generally low, similar to the findings of previous studies (Tockner *et al.*, 1997; Ward *et al.*, 1999). Site C was most variable in terms of the range of classifications covered because of its location below the confluence of the Taillon and Tourettes streams, and the switching of water sources contributing to streamflow between low (Tourettes stream dominant) and high flow (Taillon stream more important).

Water temperatures increased by up to 7°C on average between the Upper Site and Site A (Chapter 4) even though water source contributions were quite similar. This reinforces earlier assertions that the conflation of water source and water temperature in alpine streams can be misleading (Brown *et al.*, 2003). Although streams classified as Krenal had the most stable thermal regimes supporting the findings of Ward (Ward, 1994; Ward *et al.*, 1999), some south-facing alpine hillslope groundwater streams (Site G; Chapter 4) have been shown to vary by >14°C (Chapter 4). These wide differences in alpine groundwater stream thermal regimes probably reflect a range of factors including: length and aspect (Füreder, 1999) and source (e.g. alluvial, karstic, hillslope).

Inter-annual variability in water source contributions and, in turn, the seasonal habitat classification progressions further supports the assertion that that the classical 'glacial discharge regime' can be highly variable seasonally and year-to-year (Smith *et al.*, 2001; Chapter 5). In 2002, climatological conditions (Chapter 4) resulted in less meltwater production (particularly during very cold periods) and therefore, a greater proportion of groundwater to streamflow. As a consequence, stream classifications varied more in 2002 than 2003. Furthermore, towards the end of the 2002 melt-season the switch in classifications for Sites B and C towards Krenal, Kreno-nival and Kreno-kryal classes probably reflected increased groundwater contributions following prolonged precipitation events at these times, which may have recharged hillslopes and other aquifers.

In 2003, the reduced sub-seasonal variability of water source contributions and, in turn, habitat classification can be attributed to more constant meltwater contributions throughout the monitoring period than in 2002, as a result of warmer climatological conditions (no extended cold periods) and fewer prolonged rain storms resulting in more constant 'Groundwater' contributions. The progression in water source contributions at the Upper Site in 2003 from a 'Quickflow' dominated classification (Nival) to 'Distributed' dominated (Kryal) habitat class at the end of the melt season suggests that as the snowline retreats and snowpacks become smaller, 'Quickflow' contributions are reduced. Therefore, 'Distributed' contributions become proportionally more important during the mid-late melt season. This supports earlier findings that snowline retreat is the major control on the relative proportions of 'Quickflow' and 'Distributed' contributions for the Taillon Glacier, as opposed to the evolution of a more efficient subglacial drainage system (Hannah and Gurnell, 2001). The clear relationship between climate variability and meltwater contributions, demonstrated in earlier studies for the Taillon-Gabiétous catchment (McGregor *et al.*, 1995a; Hannah *et al.*, 1999b, 2000a), results in streamflow variability across the wider catchment where glacierized area may be as low as 2% (i.e. Site B). Thus, given scenarios of future climate change and associated glacial retreat/reduced snow cover, marked changes may be expected in the relative contributions of snowmelt, glacial icemelt and groundwater to streamflow, and, in turn, shifts in stream classifications and their associated physico-chemical habitat variables may be observed.

6.5.3. Physico-chemical habitat characteristics for stream classifications

The physical and chemical variables examined in this chapter provide an initial quantification of those proposed as part of the stream classification conceptual model in Chapter 2. Hydrochemistry variables were generally well predicted for the nine classes when applied to the Taillon-Gabiétous catchment with the exception of Cl^- and NO_3^-, which showed few clear patterns in relation to water source contributions. The observed concentrations of Cl^- for stream classes was different to those predicted in Chapter 2 probably due to its relatively rapid elution from snowpacks (Johannessen and Henriksen, 1978), whereas NO_3^- concentrations may have been influenced by livestock within the catchment. The Pfankuch index was useful for quantifying channel stability because water source contributions may influence the categories: substrate brightness (related to algal growth/staining) and bryophytes/vegetation presence/absence.

Suspended sediment concentration for Krenal and Kreno- prefix categories were well predicted in Chapter 2. However, the proposed classifications dominated by snow- and ice-melt insufficiently described suspended sediment concentration due to the role of 'Quickflow' in generating peak diurnal flows, and thus, mobilising subglacial sediment supplies at the glacier snout. Discharge variability was typically similar to the characteristics proposed in Chapter 2. However, it was difficult to accurately determine diurnal discharge ranges for the nine classification categories (Chapter 2; Table 2.3) because variations in flow throughout the day reflect changes in water source contributions, and, thus, result in a different classification.

Although there were very clear variations in physico-chemical habitat conditions between the nine classifications, it is recognised that these categories are based upon an *a priori* division of the ternary diagram with respect to mixtures of water source contributions. Clearly there are alternative approaches to identify classification boundaries as opposed to the simple weighting of the three water sources. One approach would be to subdivide classification categories based upon similarity of stream environmental variables; another method would involve the use of known habitat preference of macroinvertebrate communities. However, such approaches are outside the scope of this research project given time constraints and the thesis word limit; these are avenues for future research (Chapter 9) Nevertheless, the approach undertaken herein provides a robust framework for examination of the role of water source contributions upon stream habitat, which can be used to identify the influence of dynamic water source contributions upon stream communities (Chapters 7 and 8).

6.5.4. Conclusion

Temporal changes in stream classifications were useful for summarising changes in a range of stream physical and chemical characteristics, and demonstrated the wide range of habitat conditions to which stream benthic communities are adapted. To determine how specific the data presented in this chapter may be to the study catchment, comparative studies are required in other catchments with varying degrees of snow, glacier and groundwater influence and across a range of catchments with different geologies to influence stream hydrochemistry. This would provide a comprehensive assessment of water source-stream physico-chemical habitat relationships, which could better inform studies of ecological communities in these streams.

6.6. SUMMARY

This chapter has utilised estimates of water source contributions to streamflow (Chapter 5) and examined their relationships with stream physico-chemical habitat variables. The data therefore provide a quantification of the nine alternative alpine stream habitat classification categories previously proposed in Chapter 2. Subsequent chapters in this thesis will consider the role of these stream physico-chemical habitat dynamics upon stream benthic macroinvertebrate communities (Chapters 7 and 8), before an integrated assessment examining stream community composition in relation to the nine classification categories (and their associated physico-chemical habitat characteristics) is undertaken in Chapter 9 to test and refine conceptual models.

CHAPTER 7

TEMPORAL PATTERNS OF STREAM COMMUNITIES AND SPECIES TRAITS IN RELATION TO STREAM ENVIRONMENTAL VARIABLES

7.1. CHAPTER OVERVIEW

This chapter examines temporal variation in alpine stream benthic communities in relation to the stream physico-chemical variables identified for the nine stream classes in Chapter 6. Macroinvertebrate data are summarised using community level analyses (Section 7.5.1), before dynamics of the most abundant taxa are examined in more detail in Section 7.5.2 to give an indication of how populations respond to habitat variability. Adaptive traits of macroinvertebrate taxa for survival within dynamic alpine stream habitats are considered in Section 7.5.3. Taxa and trait dynamics are related to physico-chemical habitat variables throughout these sections.

7.2. INTRODUCTION

Stream ecosystems are frequently heterogeneous, and abiotic variables within may play an important role in determining macroinvertebrate community composition over time (e.g. Poff and Ward, 1989; Lancaster *et al.*, 1996; Giller and Malmqvist, 1998). Alpine stream environmental conditions (e.g. water temperature, discharge, suspended sediment concentration, electrical conductivity, habitat stability) can fluctuate considerably over multiple temporal scales from diurnal to inter-annual due to dynamic water source inputs from snowmelt, glacial ice-melt and groundwater (Smith *et al.*, 2001; Brown *et al.*, 2003). Although these habitat variables may lead to predictable spatial patterns in macroinvertebrate communities in glacial and other alpine streams (Milner and Petts, 1994; Ward, 1994; Milner *et al.*, 2001), the role of stream physico-chemical variations upon benthic community temporal dynamics is less clear (Burgherr *et al.*, 2002; Brown *et al.*, submitted).

Changes in alpine stream benthic macroinvertebrate communities may occur over seasonal time-scales in relation to physico-chemical habitat variations (Burgherr and Ward, 2001; Robinson *et al.*, 2001; Schutz *et al.*, 2001). In main glacial stream channels, macroinvertebrate communities within may be strongly influenced by changes in water sources and flow paths, with reduced densities during summer periods of peak glacial melt (Burgherr *et al.*, 2002). Conversely, more stable patterns in benthic macroinvertebrate assemblages are typically found in streams when groundwater contributions are high (Füreder *et al.*, 2001; Snook and Milner, 2001b; Burgherr *et al.*, 2002). However, despite recent research upon alpine stream benthic communities (e.g. Milner *et al.*, 2001), our understanding of their temporal dynamics, particularly over short-term time-scales, is limited. Because alpine stream habitat characteristics may vary temporally over diurnal to sub-monthly scales (Smith *et al.*, 2001; Brown *et al.*, 2003), an understanding of the influences of these variations upon stream community structure is required to accurately predict responses to water source contribution changes under potential climate change scenarios (McGregor *et al.*, 1995a).

Life history strategies of organisms may be shaped by the physico-chemical habitat characteristics (habitat templet) to which they are exposed (Southwood, 1977, 1988; Robinson *et al.*, 2002), thus taxa may adopt adaptive strategies as a means of existing within a particular habitat. Southwood (1988) divided these strategies into five categories: (1) physiological adaptations, (2) defensive adaptation (against biotic interactions), (3) food collection and growth, (4) reproductive strategies, and (5) migration ability. Investment incurs costs to organisms, often resulting in trade-offs (Southwood, 1988). Traits maybe directly relevant to a habitat templet, or combinations of traits may provide adaptive solutions (Townsend and Hildrew, 1994). Either way, species traits dynamics may afford insights into the structure and functioning of communities under variable habitat conditions (e.g. Resh *et al.*, 1994; Usseglio-Polatera *et al.*, 2000)

Traits compositions often vary between different habitats, particularly for lotic ecosystems (e.g. Tachet *et al.*, 1994; Usseglio-Polatera and Tachet, 1994b; Charvet *et al.*, 2000). A previous study of the spatial distribution of macroinvertebrate traits in the Taillon Glacier stream demonstrated clear separation of taxa at sites with distance from the glacier snout (Snook and Milner, 2002). Stable channels with warmer water temperatures were inhabited exclusively by taxa possessing semi-voltine life histories, crawler/swimmer movement, and streamlined body shapes. At disturbed sites, macroinvertebrate communities were found to contain significantly higher numbers of individuals typically possessing: small body size, high adult mobility, clinger, and streamlined/flattened body shape traits similar to the findings of studies in other streams (Statzner *et al.*, 1997; Townsend *et al.*, 1997a; Townsend *et al.*, 1997b). Trait composition of stream communities was suggested to vary in response to transient snowline retreat at sites lower in the catchment (Snook and Milner, 2002). However, the role of stream environmental conditions in determining species trait dynamics over short temporal scales remains unclear.

This study examines macroinvertebrate communities collected during the 2002 and 2003 summer melt seasons, from three French Pyrénéan alpine streams. Consecutive bi-weekly samples were collected along with high temporal resolution (15min) stream physico-chemical habitat data. The study aims were to: (1) examine the temporal variability of benthic macroinvertebrate communities over two melt seasons (late June to early September 2002-2003) (2) examine the temporal dynamics of the most abundant taxa, and their trait composition, and (3) relate abundant taxa and trait dynamics to physico-chemical habitat variability.

7.3. METHODS

Based upon physical habitat data (methods detailed in Chapter 2), a measure of habitat stability was estimated using an approach similar to Death and Winterbourn (1994) and

Burgherr *et al.* (2002). A multivariate ordination of five variables (substrate size, substrate diversity, discharge (Q) range, maximum velocity, and PFAN) was used to characterise habitat stability over the 14 days prior to each sampling date. The measurements were combined into a single measurement of habitat stability (STAB) using Principal Components Analysis (PCA) with Varimax rotation. The first component of such an analysis is always unipolar (Noy-Meir, 1973); thus lower values can be used to indicate greater habitat stability. Scores on Axis 1 of the PCA accounted for 62% of the variation in the five measurements, similar to that of other studies (e.g. Death and Winterbourn, 1995), thus, the approach provided an appropriate measure of habitat stability.

7.4. DATA ANALYSIS

7.4.1. Community analysis

Prior to the calculation of community analysis metrics, the five replicate samples collected for each site/date were pooled to minimise variation due to small (patch) scale spatial effects, thus enabling clearer elucidation of temporal trends (e.g. Woodward *et al.*, 2002). Macroinvertebrate community structure was summarised using six measures:

(1) Macroinvertebrate abundance expressed as the total number of individuals from five $0.1m^2$ Surber samples. Data were $\log_{10}(x+1)$ transformed to ensure normality and homogeneity of variance for statistical tests,

(2) Number of taxa (i.e. taxa richness),

(3) Number of EPT taxa,

(4) 1/Simpson's diversity index:

$$1/(SI = \frac{\sum n_i(n_i - 1)}{N(N-1)}) \quad \textbf{Equation 7.1}$$

where N is the total number of individuals in a sample, and n_i is the number of individuals of taxon I,

(5) Taxonomic dominance or evenness (D) estimated using the Berger-Parker index:

$$D = N_{max}/N \qquad \textbf{Equation 7.2}$$

where N_{max} is the number of individuals in the most abundant species and N is the total number of individuals collected, and

(6) Percent Ephemeroptera, Plecoptera, Trichoptera, Chironomidae, Diptera (exc. Chironomidae) and Other taxa.

Repeated measures ANOVA was used to test for significant differences in total abundance, number of taxa, Berger-Parker dominance and 1/Simpson's diversity between sampling dates, followed by Tukey's multiple comparison tests. Samples were considered significantly different where $p < 0.05$.

7.4.2. Macroinvertebrate community trait compositions

Macroinvertebrate community trait compositions were determined using the method of Snook and Milner (2002). Although the abundance of taxa and biological traits can be adequately described by generic and family level identification (Dolédec *et al.*, 2000), identification for the purposes of this study was to the lowest possible taxonomic level. Where immature taxa were identified only to family, taxa were identified as morphospecies; if insufficient trait information was available, taxa were omitted from analyses. Seven life history traits were characterised for 36 taxa (Table 7.1) using published papers, unpublished theses and personal communications (detailed in Snook, 2000; plus see Appendix B). Four taxa (i.e. *Rhyacophila eatoni*, *Ecdyonurus*, *Seratella ignita*, *Siphonoperla torrentium*) in this study were different from those presented in Snook and Milner (2002), following recent taxonomic revisions and sample collection from only three of the five sites in the previous study. Life history information for *Diamesa* species (*D. aberrata* (Lundbeck), *D. bertrami* (Edwards), *D. latitarsis* (Goetghebuer) and *D. zernyi* (Edwards)/*bohemani* (Goetghebuer) recorded in the Taillon-Gabiétous catchment was also included in the analysis (Snook, 2000).

Table 7.1. Trait characteristics of 37 taxa from the Taillon-Gabiétous catchment (1 indicates possession of the trait category). Modified after Snook and Milner (2002)

Species Trait	Life History			Body Size		Functional Feeding Group					Attachment to Substrate				Body Form	Diet				Case
Category	Semivoltine	Univoltine	Multivoltine	Large	Small	Shredder	Scraper	Collector-gatherer	Collector-filterer	Predator	Swimmer	Crawler	Burrower	Clinger	Streamlined	Detritus	Algae	Diatoms	Invertebrates	Case constructor
Category Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Diamesa			1		1		1	1						1		1	1	1		
Pseudodiamesa branickii			1	1			1	1						1		1		1		
Pseudokiefferiella parva			1		1		1	1						1		1		1		
Corynoneura		1	1		1			1				1		1		1		1		1
Eukiefferiella/ Orthocladius			1		1		1	1		1		1	1			1		1		1
Eukiefferiella/Tvetenia			1		1		1	1		1		1				1		1		1
Metriocnemus			1		1			1		1			1	1		1		1		
Orthocladius			1		1		1	1		1			1	1		1		1		
Parametriocnemus stylatus			1		1			1						1		1		1		
Rheocrictopus effusus			1		1	1		1		1				1		1		1		
Micropsectra/ Stempellinella		1	1		1			1				1				1		1		1
Tanypodinae			1		1					1	1								1	
Capnioneura brachyptera	1				1	1		1				1				1				
Protonemoura		1		1	1	1						1				1	1			
Leuctra		1		1	1	1						1				1				
Perla grandis	1			1						1		1		1	1				1	
Perlodes intricatus	1			1						1		1		1	1				1	
Siphonoperla torrentium	1			1	1	1				1	1	1							1	
Chloroperla breviata	1			1	1	1				1	1	1							1	
Rithrogena loyolaea	1	1		1			1							1	1	1	1	1		
Rithrogena semicolorata	1	1					1							1	1	1	1	1		
Habroleptoides berthelemyi	1	1			1	1						1				1		1		
Baetis		1	1		1		1	1			1			1	1		1			
Seratella ignita		1			1		1					1	1			1	1	1		
Ecdyonurus		1		1			1	1			1			1	1	1	1	1		
Rhyacophila intermedia	1			1						1		1							1	
Rhyacophila angelieri	1			1						1		1							1	
Rhyacophila eatoni	1			1						1		1							1	
Hydropsyche pellucidula	1	1		1					1			1				1	1		1	
Agapetus fuscipes		1			1		1					1				1	1	1		1
Thremma gallicum	1				1		1					1			1		1	1		1
Chaetopterygini	1	1		1		1						1					1			1
Drusus	1	1			1		1					1				1	1	1		1
Sericostoma personatum	1			1		1						1				1				1
Simuliidae		1	1	1	1				1			1		1		1	1	1		
Empididae		1			1					1				1					1	
Limoniinae		1		1	1					1			1	1			1		1	

For each trait, up to five sub-categories were identified and taxa coded in relation to trait presence (moderate or strong link with trait) or absence (weak or no link; Snook and Milner, 2002). Where taxa abundance was determined for genus level only, trait information relating to the different species in samples was averaged. For species where trait affinity changes throughout the life cycle, the presence/absence of a trait was determined in relation to the relative length of individual developmental stages (Usseglio-Polatera and Tachet, 1994a). Abundance data assembled for the 36 taxa used for trait analysis were combined with the identified trait compositions to produce data tables relating to the percentage of individuals in each sample possessing a given trait (Snook and Milner, 2002).

7.4.3. Taxa and trait composition relationships with stream environmental variables

From the measured physico-chemical habitat variables, mean values and mean daily range statistics (to characterise variability) were calculated for the two weeks prior to each sampling date. A preliminary Detrended Correspondence Analysis was conducted on the macroinvertebrate data, which showed that gradients were below 2.5SD. Because all gradients were short, subsequent analyses used constrained ordination methods to test for linear trends in compositional change at individual sites. Direct gradient analysis (Redundancy Analysis; RDA) in CANOCO 4.0 (Lepš and Šmilauer, 2003) was used to determine: (1) if the abundances of 20 of the most abundant Ephemeroptera, Plecoptera, Trichoptera, Chironomidae, Diptera (Non-Chironomidae) and Coleoptera taxa varied temporally (Table 7.2), and how temporal changes in these taxa were related to habitat conditions, and (2) if community trait composition varied temporally, and how changes in over time were related to habitat conditions.

Data were initially centred by species and trait by subtracting the mean:

$$z_{ij} = x_{ij} - m_j \qquad \textbf{Equation 7.3}$$

where

$$m_j = \Sigma_i p_i x_{ij} \text{ (mean)} \qquad \textbf{Equation 7.4}$$

x_{ij} represents the value of the *i*th sample and *j*th trait, *pi* represents the *i*th row (sample) weight (1/row number). This provided an average sample-average trait composition reference point, against which all other samples were compared. Samples were therefore ordinated by the quantity of taxa and trait categories. Calendar day was included initially as a 'dummy' explanatory variable in each analysis to test for linear relationships of community and trait composition with Time. Forward selection was used to determine which variables explained a significant ($p < 0.05$) proportion of the variance within the data set. The significance of the constrained model was tested against 199 Monte-Carlo permutations. Separate ordinations were conducted for each site:year to avoid spatial patterns obscuring temporal variation.

For site:date pairings where time explained a significant proportion of the variation in the taxa or trait data, analyses were repeated using a partial Redundancy Analysis (*p*RDA) similar to the method used by Borcard *et al.* (1992). This method subtracts the variability in the macroinvertebrate community data explained by Time, then a constrained ordination is conducted on the residual variability explained by the habitat variables (Ter Braak and Šmilauer, 2002). The effect of Time (co-variable) is therefore partialled out (eliminated), thus the influence of the environmental variables on stream communities can be determined more easily.

7.5. RESULTS

Community structure is examined initially to provide an indication of the taxonomic composition, diversity, richness and dominance of communities at each of the three main sampling sites (Section 7.5.1). From this analysis of community structure, twenty taxa were selected from six groups of macroinvertebrates so variability in relation to physico-chemical habitat dynamics could be assessed (Section 7.5.2.). These were typically the most abundant taxa from six groups present for most of the sampling periods. Temporal dynamics of trait compositions at the three sites are then examined in Section 7.5.3 in relation to stream physico-chemical variables to increase understanding of adaptations to habitat variability.

7.5.1. Community structure

Taxon abundance varied between sites and sampling date (Figures 7.1a and b), but was consistently highest at Site B, with the exception of July 1 (date 1) in 2002 when large numbers of *Diamesa* (>6000 per $0.5m^2$) were present at Site A. Total abundance peaked mid season at Site B, whilst Site C was always intermediate of Sites A and B. In 2003, total abundance was generally lower than in 2002 (Figure 7.1b). Abundances were significantly different between sampling dates for all sites in both years ($p<0.05$). Full taxa lists are given in Appendices C and D.

Taxa richness was generally highest at Site B except for July 2002 when more taxa were found at Site C (Figure 7.1c). Site B had more taxa during the early melt season whilst Site C showed a mid melt season peak (Figure 7.1c). In 2003 taxa richness at Site A increased steadily over time, but Site B and C numbers were greatest in late June (Figure 7.1d). Taxa richness was only significantly different between sampling dates at Site C (2002: $F = 2.892$, $p = 0.035$; 2003: $F = 3.016$, $p = 0.03$). EPT taxa richness showed similar patterns to total number of taxa; lowest numbers were found at Site A and highest at Site B (Figure 7.1e-f). In 2003, EPT taxa numbers at each site were comparable to 2002 but temporal patterns differed (Figure 7.1f). Significant differences in numbers of EPT taxa richness were found only for Site C in 2002 ($F = 4.470$; $p = 0.005$) and Site B in 2003 ($F = 2.653$; $p = 0.048$).

Table 7.2. Abbreviations of twenty abundant taxa selected for detailed analysis of temporal variations in abundance, and relationships with stream physico-chemical habitat variables

Taxa	Abbreviation
Baetis spp.	Baet
Rithrogena spp.	Rith
Habroleptoides berthelemyi	Habro
Chloroperla breviata	Chlo
Capnioneura brachyptera	Capn
Protonemoura spp.	Proto
Leuctra spp.	Leuc
Perlodes	Perl
Perla grandis	Perla
Rhyacophila spp.	Rhya
Hydropsyche pellucidula	Hydro
Thremma gallicum	Threm
Coleoptera spp.	Coleo
Tipulidae	Tipu
Simuliidae	Simu
Diamesa spp.	Diam
Corynoneura	Cory
Eukiefferiella spp.	Euk
Orthocladius spp.	Orth
Tanypodinae	Tany

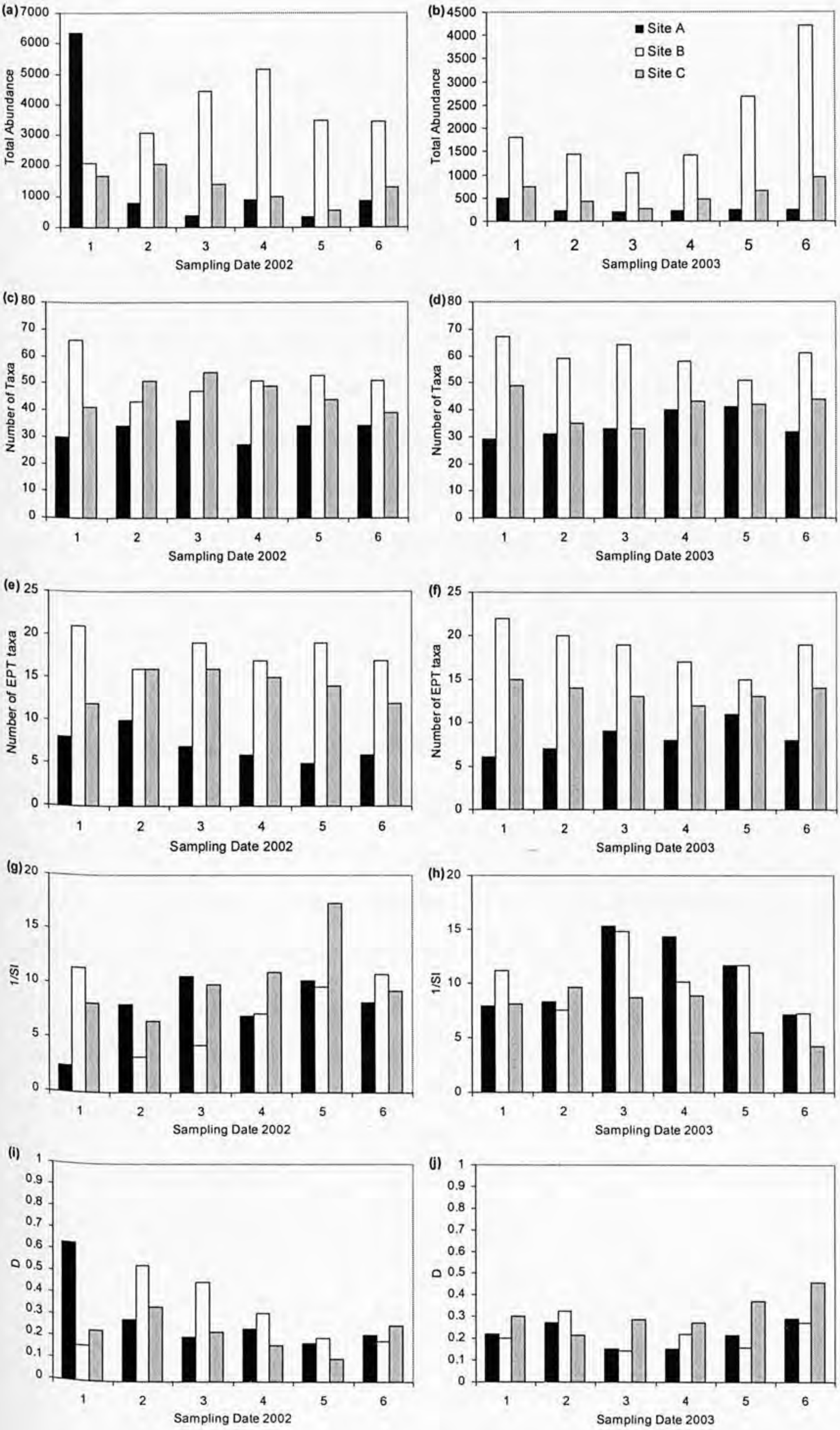


Figure 7.1. Bar charts showing community metrics for 2002 (left column) and 2003 (right column). (a and b) Total abundance, (c and d) Number of Taxa, (e and f) Number of EPT taxa, (g and h) 1/Simpson's diversity index, and (i and j) Berger-Parker dominance (D)

In 2002, the lowest diversity was found at Site A on July 1 (date 1; Figure 7.1g). The lowest diversity of any site in 2002 was found at Site B on July 11 (date 2). Site C had the most diverse community of any site in 2002 on Aug. 21 (date 5). In 2003, Site A remained ≥diverse than the other sites after July 24 (date 3; Figure 7.1h). Site B was also diverse mid melt-season, followed by a general trend of decreasing values. Diversity at Site C decreased after early August (date 4). Diversity was significantly different between sampling dates for all sites in both years. Berger-Parker scores showed no clear trends, and generally scores were similar between years (~0.2). For Site A on date 1, 2002, dominance was the highest of any site/date (Figure 7.1i). In contrast at Site B, dominance was lowest at the beginning of the melt season. Dominance was highest at Site C at the end of the 2003 melt-season. Scores were only significantly different between sampling dates for Sites A and B when dominated by *Diamesa* ($p<0.05$).

Chironomidae constituted a large proportion of the community at Site A during 2002, particularly at the onset of the melt season (Figure 7.2a). Trichoptera were found after early July (~10-15%), and Ephemeroptera increased over time. Chironomidae also contributed a large part of the community at Site B in 2002 (Figure 7.2b). Ephemeroptera made up a greater proportion of the Site B community than at Site A, but there was no clear temporal pattern. Other taxa (inc. Coleoptera and Planariidae) comprised a relatively large proportion of the community at times. At Site C in 2002, Chironomidae were dominant, with the exception of mid melt-season when

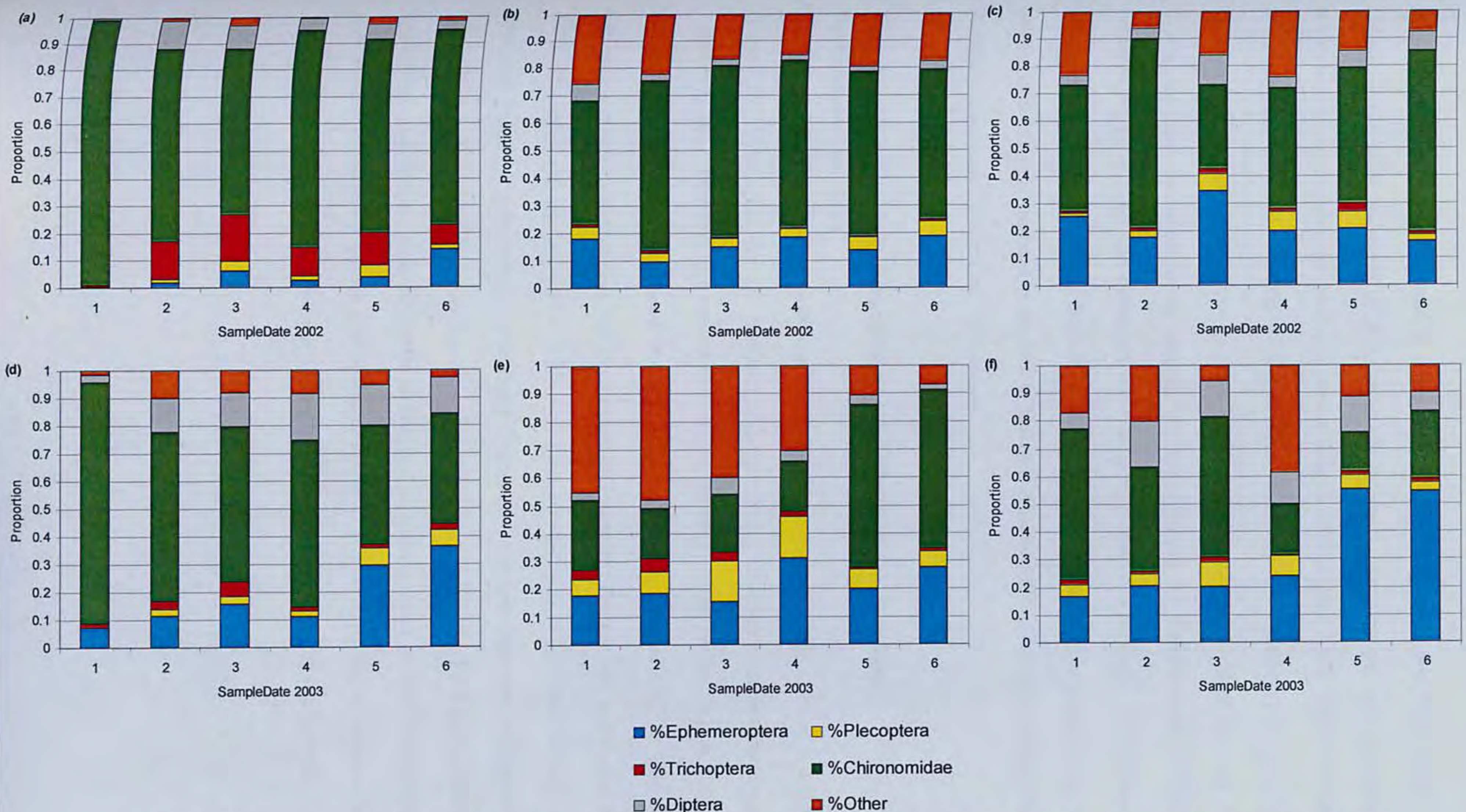


Figure 7.2. Proportions of individuals belonging to six Orders on the six sampling dates for each site/year. (a) Site A, 2002; (b) Site B, 2002; (c) Site C, 2002; (d) Site A, 2003; (e) Site B, 2003; and (f) Site C, 2003.

Ephemeroptera and Plecoptera made up a large part of the community (Figure 7.2c). In 2003, Chironomidae were dominant at Site, although for early sampling periods, a greater proportion of non-chironomid taxa were present than in 2002 (Figure 7.2d). Ephemeroptera and Plecoptera increased over time. At Site B, Other taxa made up the greatest proportion of individuals in stream communities for most of the melt season, (due to large numbers of *Esolus* spp. and *Esolus/Oulimnius* larvae), but were usurped by Chironomidae towards September (Figure 7.2e). Ephemeroptera and Plecoptera proportions peaked in mid summer. Chironomidae made up a large proportion of the Site C community, but Ephemeroptera increased over time dominated at the end of the melt season (>50%). Plecoptera and Other taxa proportions were greatest mid melt season.

7.5.2. Temporal dynamics of abundant taxa and relationships with stream environmental variables

Baetis spp. (*B. alpinus, B. gadeai)* were typically abundant, particularly at Sites A and B (Figure 7.3). *Rithrogena* spp. (*R. loyolaea, R. semicolorata)* abundance was also typically high throughout. *Diamesa* spp. were found during the melt season in the Taillon glacial stream, although abundances were greatest early melt-season, (Figure 7.3). At Site B, *Diamesa* spp. were always scarce, and even absent on 2 sampling dates in July and August in 2002. *Eukiefferiella* spp. and *Orthocladius* spp. were present most of the time. Simuliidae spp. were found for almost every site:date pair (Figure 7.3). Tipulidae spp. were also present on most sampling dates but abundances were always very low. The Pyrénéan endemic Leptophlebiidae species, *Habroleptoides berthelemyi* was omnipresent at Site B and found only intermittently in the Taillon glacial stream at Site C (Figure 7.3). Similar occurrences were found for the Trichoptera species' *Thremma gallicum*, and *Hydropsyche pellucidula*,

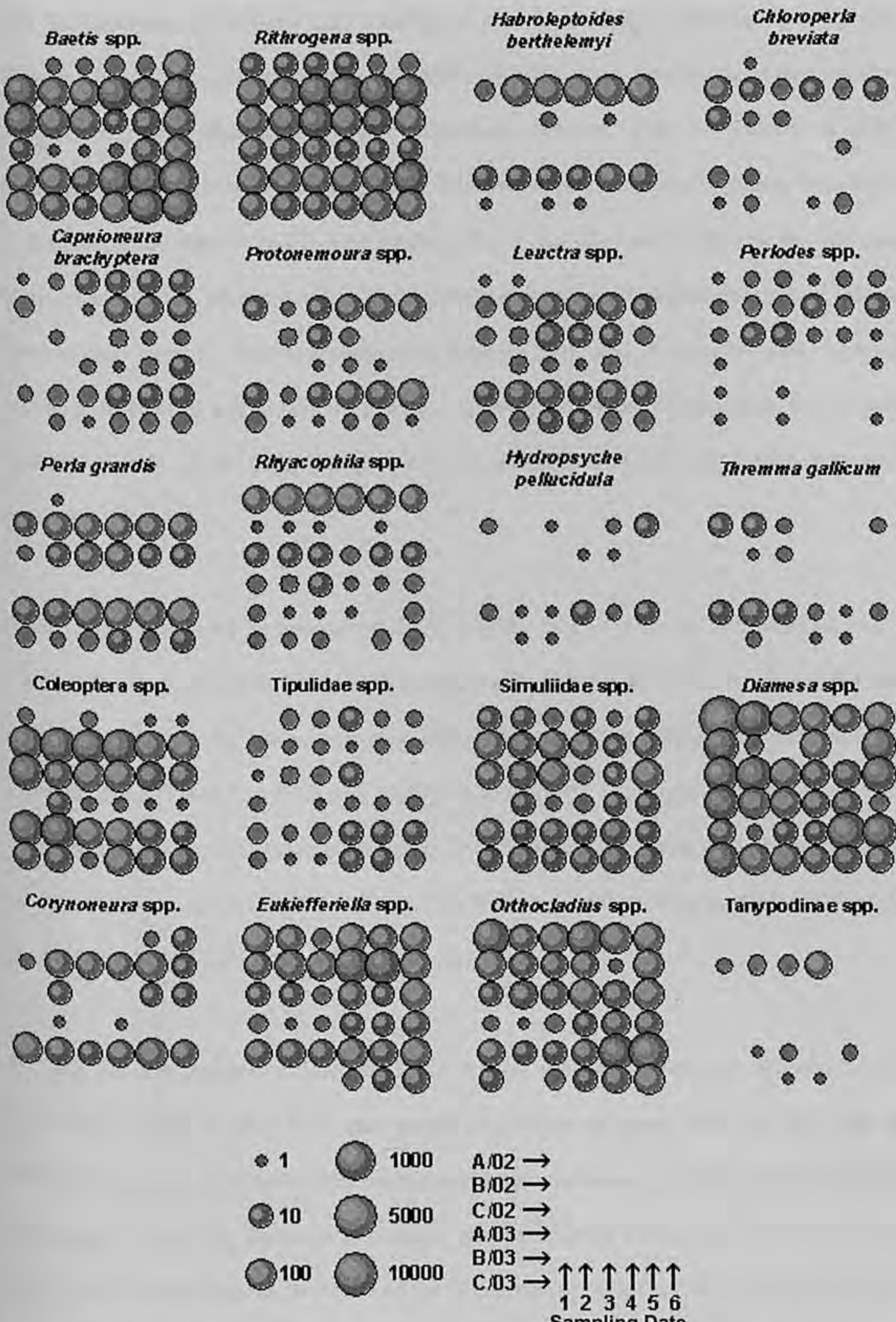


Figure 7.3. Bubble plots showing total abundance of selected taxa for sites/years (rows) and sampling dates (columns)

and Tanypodinae spp. (Figure 7.3). Coleoptera spp. were mostly found at Sites B and C (Figure 7.3). *Corynoneura* were most abundant at Site B, but no clear temporal patterns were evident. Rhyacophilidae showed clear differences between sites, particularly in 2002, although changes over time were negligible. Different species of Rhyacophilidae were found at the three sites; Sites A and B were inhabited by *R. angelieri* and *R. intermedia*, but these were fewer in 2003, whereas at Site B, the only species was a Pyrénéan endemic, *R. eatoni*. *Chloroperla breviata,* Protonemoura spp., *Leuctra* spp. and *P. grandis* were typically restricted to Sites B and C (Figure 7.3). *Capnioneura brachyptera* abundance was greatest towards the end of the melt season at all sites, whereas *Perlodes* spp. abundances were greatest in 2002.

Axes 1 and 2 accounted for approximately 48% of the taxa variance in both years for Site A (Table 7.3). Mean discharge, suspended sediment concentration (SSC) and water temperature (TEMP) were important habitat variables, although a significant relationship with Time was found for 2002 (Table 7.3). Both axes explained almost 90% of the taxa-habitat variance each year and these were significantly correlated (r >0.950, p<0.05; Table 7.3). Time explained 29.1% of the variance in the *p*RDA (Table 7.4). Both axes of the *p*RDA explained 30% of the taxa variance, and 83.2% of the taxa-habitat variance.

In 2002, the first samples collected from Site A were grouped by *Diamesa* (Figures 7.4a-b), and weakly related to mean Q. A clear switch in community composition occurred after the first sampling date, as communities were less strongly dominated by one taxon and grouped by a range of species. Subsequent samples were associated with lower STAB and mean TEMP, and located towards the centre of the ordination plot (Figure 7.4a-b), until towards the end of the melt season *Baetis* spp. and *Corynoneura* were important members of the community. In 2003, *Diamesa* were also distinct at the beginning of the melt season. Although Coleoptera and *Rithrogena* were again present throughout, *Corynoneura* was not strongly associated with late melt-season samples (Figure 7.4c-d). *Baetis* spp. strongly grouped later melt-season samples as in the first year of monitoring.

Clear groupings of samples from Site B were found for different sampling dates in both years (Figure 7.5). Axes 1 and 2 accounted for 31.6% of the taxa variance at Site B in 2002, and 38.5% in 2003 (Table 7.3). Mean Q, mean SSC and mean TEMP were important habitat variables in both years. No relationships with time were found for either year (Table 7.3). The percentage of the taxa-habitat variance explained by both axes was 80% in 2002 and 84% in 2003; both were significantly correlated (r >0.850, p<0.05; Table 7.3).

Samples collected early in 2002 at Site B were grouped by Chloroperlidae and *T. gallicum*, and related to low diurnal electrical conductivity (EC) variability and mean SSC (Figure 7.5a-b). Coleoptera and Rhyacophilidae grouped communities in July. Late melt season samples were associated with a large number of taxa, including *Rithrogena*, *Perlodes*, *Corynoneura* and *Eukiefferiella* when EC diurnal range was greatest (Figure 7.5a). Samples collected in early September were widely spaced reflecting varying faunal compositions but were associated with warmer mean TEMP and high mean Q. In 2003, early melt season samples showed little separation and were associated with low STAB and high SSC (Figure 7.5c). Early samples were strongly grouped by *C. breviata*, and *T. gallicum* (c.f. 2002) whilst later samples after Aug. 6 (date 4) were more variable (Figure 7.5c-d). Samples collected at the end of the 2003 monitoring period were widely spaced, but generally grouped by *Baetis* spp. *Protonemoura* and *Hydropsyche* (c.f. 2002), as well as *P. grandis* (mid melt season 2002), and Orthocladiinae and Tipulidae (early melt season samples, 2002).

Table 7.3. Summary statistics for Redundancy Analysis of taxa abundances and percentage of individuals possessing strong links with trait categories. Asterisks denote significant forward selected habitat variables, and significance of correlations of taxa/trait Axis 1 with physico-chemical habitat data (p<0.05) tested with Monte-Carlo permutations. (Q = discharge (m^3s^{-1}), EC = electrical conductivity (μeqL^{-1}), SSC = suspended sediment concentration (mgL^{-1}), STAB = habitat stability, TEMP = water temperature (°C); DR = diurnal range of associated habitat variable)

	Taxa				Traits			
Site/Year	Forward Selected Habitat Variables	% Taxa Variance Ax1 (Ax1+2)	% Taxa-Habitat Variance Ax1 (Ax1+2)	TaxaAx1-HabAx1 Correlation	Forward Selected Habitat Variables	% Trait Variance Ax1 (Ax1+2)	% Trait-Habitat Variance Ax1 (Ax1+2)	TraitAx1-HabAx1 Correlation
A/02	QMEAN*; TIME*; SSCMEAN; STAB; TEMPMEAN	35.3 (47.5)	65.1 (87.5)	0.962*	QMEAN*; TIME*; ECMEAN*; TEMPDR; TEMPMEAN	57.3 (68.7)	76.3 (91.6)	0.954*
B/02	QMEAN*; TEMPMEAN*; SSCMEAN*; ECDR*; ECMEAN	22.9 (31.6)	57.1 (78.9)	0.872*	TIME*; TEMPDR*; STAB*; ECDR; TEMPMEAN	40.4 (58.7)	66.0 (95.8)	0.856*
C/02	QMEAN*; STAB*; ECDR*; QDR*; TEMPMEAN	22.0 (34.3)	47.9 (74.7)	0.844*	STAB*; TEMPMEAN*; ECDR*; SSCDR; QMEAN	34.1 (49.5)	62.8 (91.2)	0.841*
A/03	SSCMEAN*; ECMEAN*; TEMPMEAN; SSCDR; QMEAN	41.6 (48.4)	76.6 (89.1)	0.974*	TIME*; SSCDR*; QMEAN*; SSCMEAN; TEMPMEAN	43.0 (51.6)	73.2 (87.8)	0.950*
B/03	STAB*; ECDR*; TEMPMEAN*; SSCMEAN; QMEAN	31.6 (38.5)	69.1 (84.0)	0.935*	STAB*; ECDR*; SSCMEAN*; TEMPDR*; TEMPMEAN	48.6 (56.7)	76.1 (88.8)	0.922*
C/03	SSCDR*; TIME*; STAB*; ECMEAN*; TEMPMEAN	33.3 (41.0)	65.9 (81.2)	0.940*	SSCMEAN*; TEMPDR*; TIME*; QMEAN*; TEMPMEAN	49.7 (64.7)	72.9 (94.9)	0.941*

Table 7.4. Summary statistics for Redundancy Analysis of taxa abundances and percentage of individuals possessing strong links with trait categories after partialling out Time.

	Key Taxa				Traits			
Site/Year	% Variance Explained by Time	% Variance Explained by Habitat Variables	% Species Variance Ax1 (Ax1+2)	% Species-Habitat Variance Ax1 (Ax1+2)	% Variance Explained by Time	% Variance Explained by Habitat Variables	% Species Variance Ax1 (Ax1+2)	% Species-Habitat Variance Ax1 (Ax1+2)
A/02	29.1	26.1	25.5 (30.2)	70 (83.2)	41.3	34.8	42.2 (55.8)	72.5 (95.9)
B/02	-	-	-	-	27.1	35.1	38.5 (44.7)	81.0 (93.9)
C/02	-	-	-	-	-	-	-	-
A/03	-	-	-	-	43.2	16.6	15.6 (25.9)	54.3 (90.2)
B/03	-	-	-	-	-	-	-	-
C/03	25.9	24.6	20.0 (27.9)	60.2 (83.8)	44.1	24.1	29.5 (40.6)	68.5 (94.2)

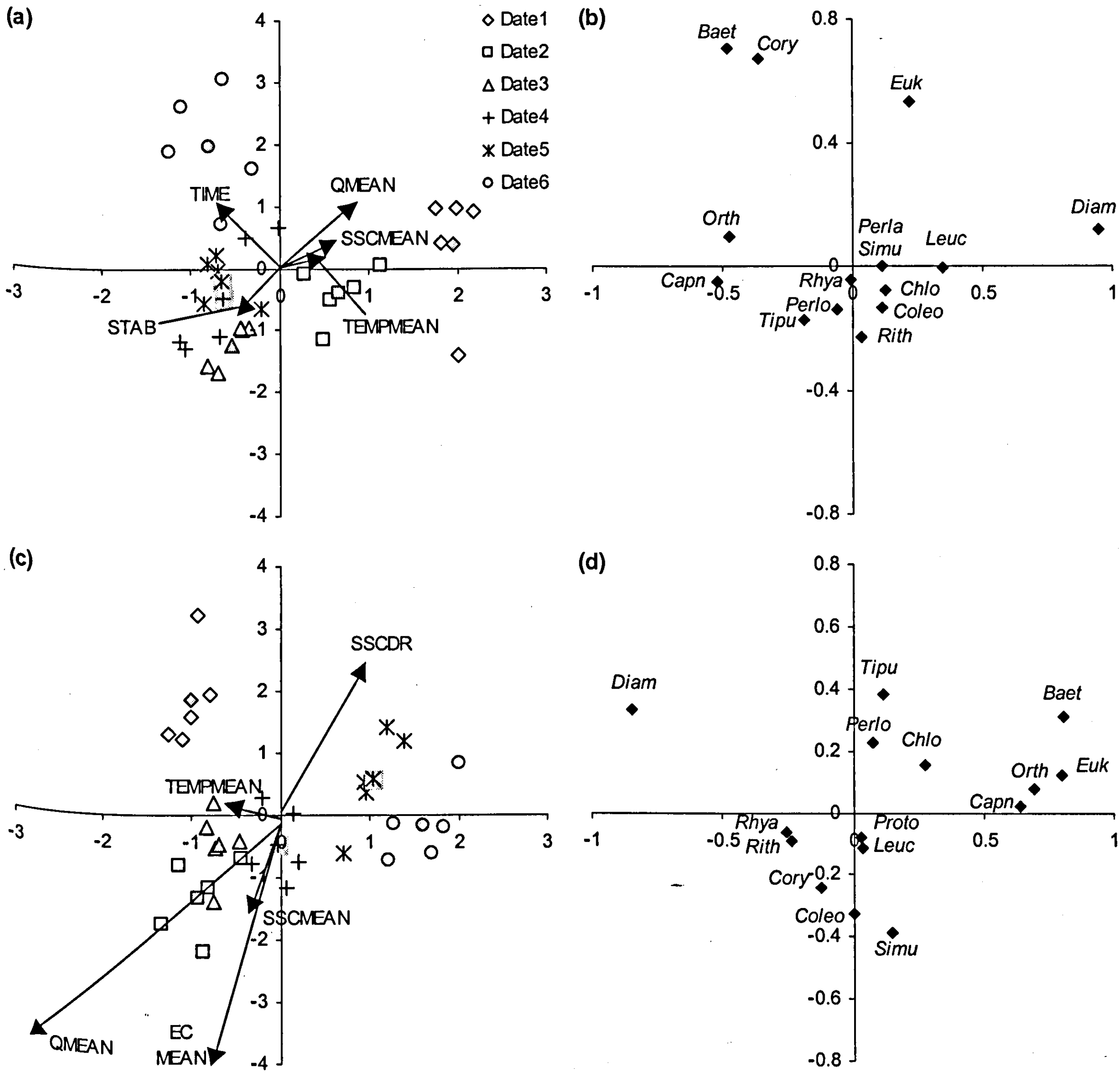


Figure 7.4. Redundancy Analysis showing taxa abundance relationships with forward selected stream environmental variables on consecutive sampling dates at Site A. (a) The distribution of replicate samples and their weighted averages (filled symbols) for 2002 with arrows indicating stream environmental variables, (b) relationships between taxa on F1xF2 factorial plane in 2002 (See Table 7.2 for abbreviations), (c) as per (a) for 2003, (d) as per (b) for 2003

Clear groupings of samples from Site C were found for different sampling dates in both years (Figure 7.6). Axes 1 and 2 accounted for 34.3% of the taxa variance in 2002, and 41.0% in 2003 (Table 7.3). Mean TEMP and STAB were important habitat variables in both years, although a significant Time trend was evident in 2003 (Table 7.3). Both axes explained 74.7% of the taxa-habitat variance in 2002 and 81.2% in 2003. Axes were significantly correlated (r >0.840, p<0.05; Table 7.3) for both years' data. Time explained 25.9% of the variance in the *p*RDA (Table 7.4). Both axes of the *p*RDA explained 27.9% of the taxa variance, and 83.8% of the taxa-habitat variance. Samples collected on Jul. 2 (date 1) in 2002 were grouped by *Baetis* spp. and *C. breviata*, and were associated with high mean Q (Figures 7.6a-b). Mid melt season, *P. grandis*, *Leuctra* spp., and *Hydropsyche* grouped samples, whereas at the end of the 2002 melt season, samples were mainly grouped by Chironomidae taxa, particularly *Corynoneura*, *Eukiefferiella* and Orthocladiinae spp., in addition to *C. brachyptera*. Diurnal range of EC was strongly associated with the late melt season samples (Figure 7.6a). In 2003, *Diamesa* grouped early samples (Figure 7.6c). Low STAB and high diurnal SSC range was found in late July (date 3), and communities were characterised by Tanypodinae, *Leuctra* spp., and *Hydropsyche* (Figure 7.6c-d). Later in the melt season communities were more strongly associated with *C. brachyptera*, *Eukiefferiella* and Orthocladiinae spp. as in 2002. However, other abundant taxa grouping samples at these times included Rhyacophilidae and *Rithrogena* spp. that were present earlier in the 2002 melt season.

7.5.3. Temporal dynamics of community trait composition and relationships with stream environmental variables

Multivoltine life history trait was found in a large percentage of individuals in both years (Figure 7.7a-b). The percentage of individuals possessing the trait was more variable in 2003 (Figure 7.7a-b). The percentage of individuals with univoltine life histories increased over time at Site B in 2002 and decreased over the 2003 melt season (Figure 7.7a-b). Semivoltine life histories were relatively scarce among individuals. Small body size was more common than large body size (Figure 7.7c-d), although in 2002, a mid melt season small body size low

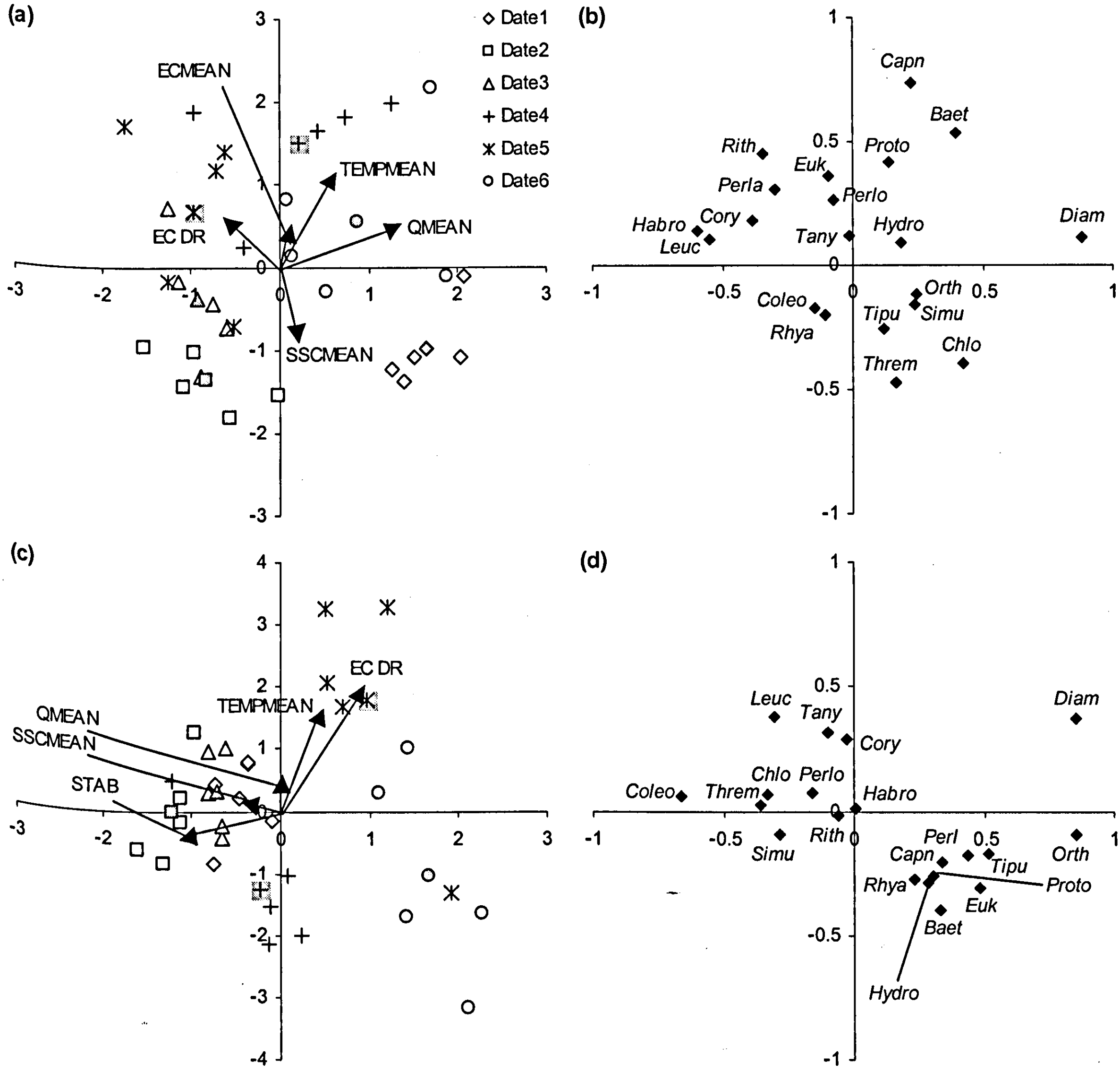


Figure 7.5. Redundancy Analysis showing taxa abundance relationships with forward selected stream environmental variables on consecutive sampling dates at Site B. (a) The distribution of replicate samples and their weighted averages (filled symbols) for 2002 with arrows indicating stream environmental variables, (b) relationships between taxa on F1xF2 factorial plane in 2002 (See Table 7.2 for abbreviations), (c) as per (a) for 2003, (d) as per (b) for 2003

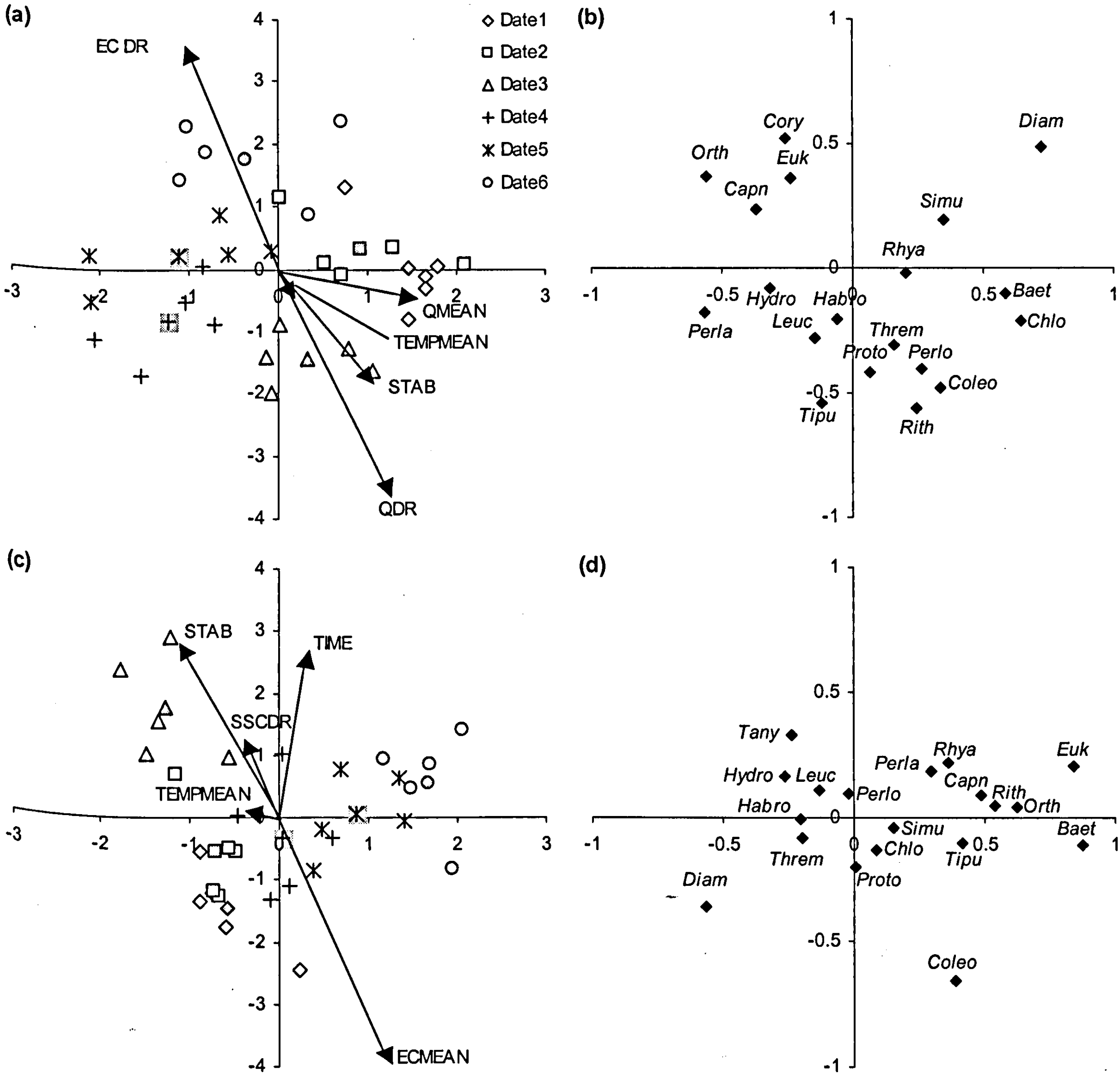


Figure 7.6. Redundancy Analysis showing taxa abundance relationships with forward selected stream environmental variables on consecutive sampling dates at Site C. (a) The distribution of replicate samples and their weighted averages (filled symbols) for 2002 with arrows indicating stream environmental variables, (b) relationships between taxa on F1xF2 factorial plane in 2002 (See Table 7.2 for abbreviations), (c) as per (a) for 2003, (d) as per (b) for 2003

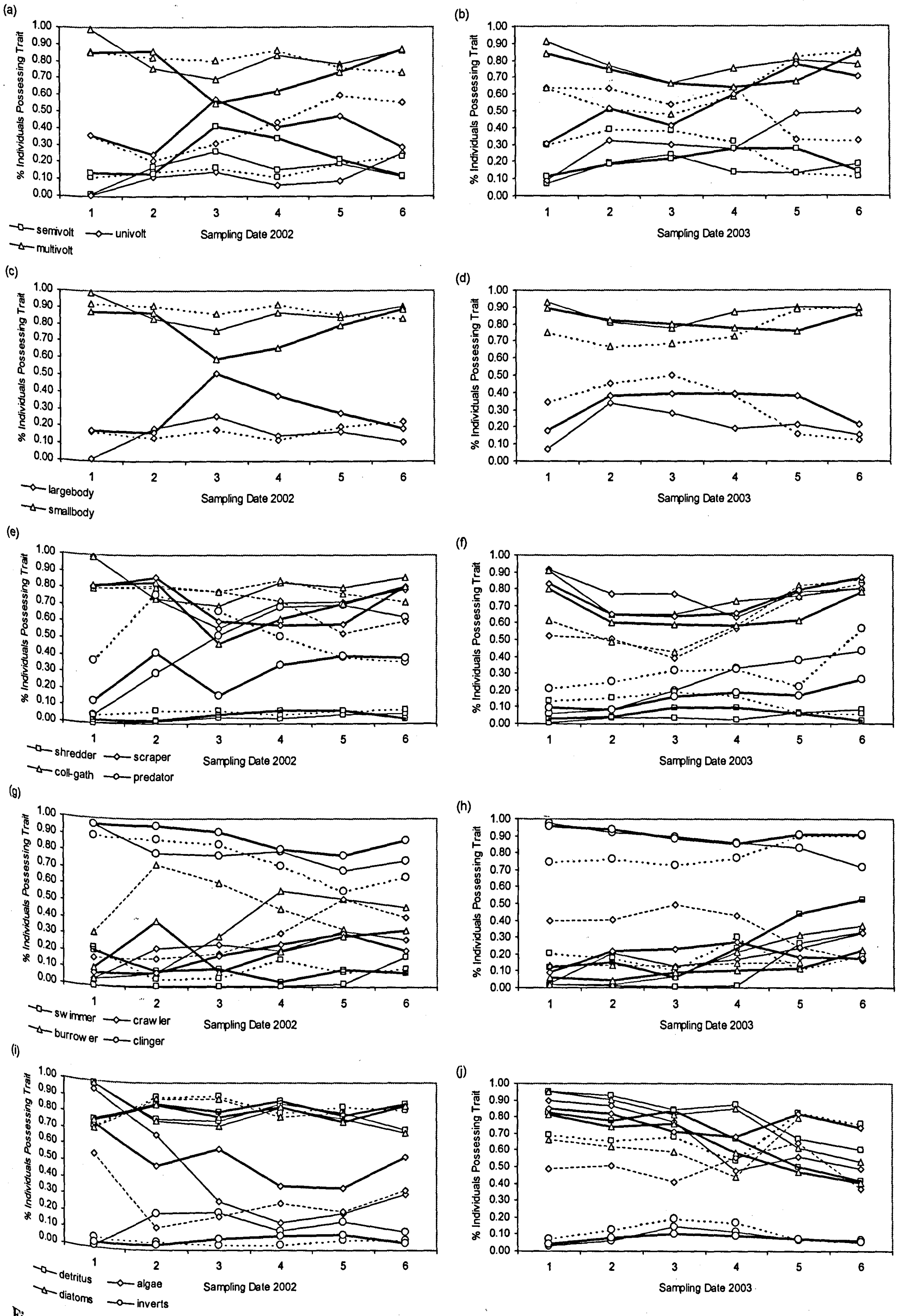


Figure 7.7. Percentage of individuals possessing a trait category over time during 2002 (left column) and 2003 (right column). (a and b) life history traits; (c and d) body size traits; (e and f) functional feeding groups; (g and h) substrate attachment traits, and (i and j) diet. Solid thin lines represent Site A, dashed lines represent Site B, and Solid heavy lines represent Site C

contrasted with a peak in large body size at Site C (Figure 7.7c). Shredders were scarce throughout both melt seasons (Figure 7.7e-f). Collector-filterers were often absent so no trend lines are shown. Predators increased over both melt seasons at Sites A and C (Figure 7.7e-f). Collector-gatherers and scrapers generally accounted for the greatest percentage of individuals and were typically least abundant mid melt season.

Clinger was the most dominant method of attachment trait (Figure 7.7g-h). In 2002, a large percentage of burrowers were present early in the melt season at Site B, but numbers steadily decreased over time (Figure 7.7g). In contrast, burrowers increased over the melt-season particularly at Site A. (Figure 7.7g-h). Few swimmers were present in 2002, but in 2003, percentages were relatively high towards the end of the melt season (Figure 7.7h). Detritus and diatom consumers dominated stream communities. In 2003 these traits decreased consistently over the course of the melt season (Figure 7.7j). The percentage of individuals feeding on invertebrates was low in both years, although in 2002 at Site A, and in 2003 at all sites, a slight mid melt season peak was evident (Figure 7.7i-j). A large percentage of algae consumers were present at the beginning of both melt seasons at all sites, but numbers generally decreased steadily over time (Figure 7.7i). In 2003, Site B showed a steady increase in algae consumers over time until a large decrease occurred in September (Figure 7.7j).

Axes 1 and 2 of the RDA accounted for 68.7% of the trait variance in 2002 and 51.6% in 2003 at Site A (Table 7.3). Mean Q and TEMP were important in both years, although significant relationships with time were evident (Table 7.3). Both axes accounted for ~90% of the trait-habitat variance in both years and these were significantly correlated ($r > 0.950$, $p < 0.05$; Table 7.3). Time explained 41.3% of the variance in the *p*RDA for 2002, (Table 7.4), and 43.2% for 2003. Both axes of the *p*RDA explained 55.8% of the trait variance in 2002, and 25.9% in 2003. Of the trait-habitat variance, both axes explained >90% of the variance in both years (Table 7.4).

In 2002, Site A was dominated early in the melt season by an abundance of individuals possessing strong links with clinger traits, and detritus/algae/diatom diet during a time of high mean Q (Figure 7.8a-b). Communities collected in July (dates 2-3) were grouped according to invertebrate diet, large body size and semivoltine life history, and were strongly related to mean EC. Samples collected on the last 3 sampling dates in 2002 showed little differentiation in trait composition and were grouped by predators and shredders, and burrowers and swimmers (Figure 7.8b). In 2003, early samples were also associated with algae and diatom diet, and clinger attachment (Figure 7.8c-d). Samples collected from July-August (Dates 2-4) showed little separation. Later samples were grouped by very similar traits as 2002, particularly burrowers and predators (Figure 7.8d).

Axes 1 and 2 accounted for 58.7% of the trait variance in 2002 and 57.7% in 2003 (Table 7.3) at Site B. STAB, diurnal EC range and mean TEMP were important habitat variables, and time was significant in 2002 (Table 7.3). The percentage of the trait-habitat variance explained by both axes was >95% in 2002 and 88.8% in 2003; both were significantly correlated (r >0.850, p<0.05; Table 7.3). Time explained 27.1% of the trait variance in the *p*RDA for 2002 (Table 7.4). Both axes of the *p*RDA explained 44.7% of the trait composition variance. Of the trait-habitat variance, both axes explained over 90% of the variance (Table 7.4).

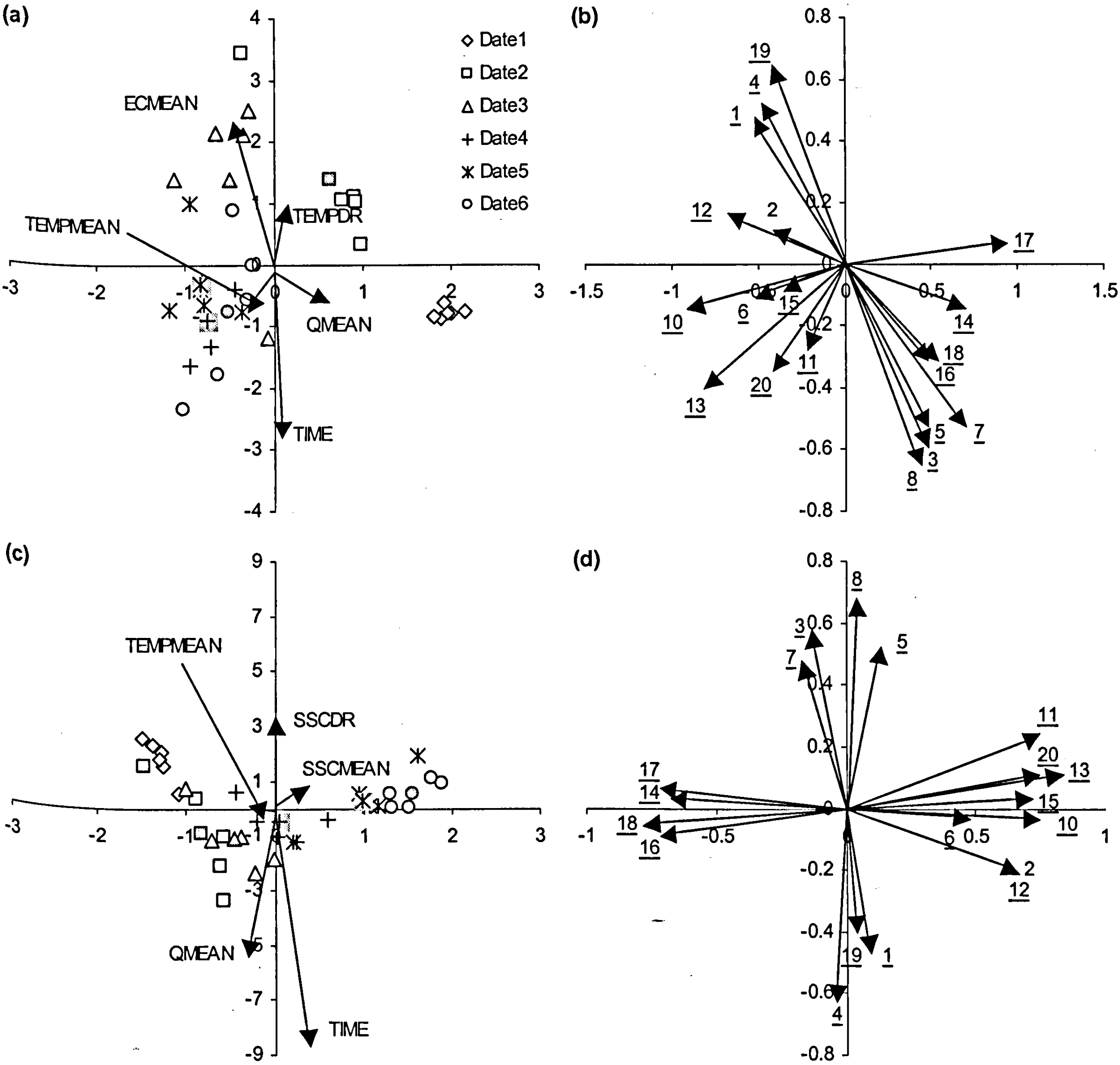


Figure 7.8. Redundancy Analysis showing percentage of individuals possessing a trait category and relationships with forward selected stream environmental variables on consecutive sampling dates at Site A. (a) The distribution of replicate samples and their weighted averages (filled symbols) for 2002 with arrows indicating stream environmental variables, (b) relationships between traits on F1xF2 factorial plane in 2002 (See Table 7.1 for category numbers), (c) as per (a) for 2003, (d) as per (b) for 2003

Swimmer and algal diet grouped the samples collected in late June 2002 at Site B, and were moderately related to low STAB (Figure 7.9a-b). In July, samples were strongly grouped by burrowers and predators. Towards the end of the 2002 melt season when diurnal TEMP range was wide, communities grouped by individuals possessing univoltine life histories, case constructors and crawlers (Figure 7.9b). Large body size and semivoltine life history was also associated with late melt season communities. In 2003, clear differences in the percentage of individuals possessing traits were found for same times of the melt season to 2002 (Figures 7.9c-d). In comparison with 2002, early melt season samples were strongly grouped by case constructors. Crawler, univoltine life history, large body, scraper and invertebrate diet were traits associated with communities collected in July-early August in 2003. The first three of these traits were also associated with late melt season samples in 2002. Samples collected on Aug. 20 (date 5) were strongly separated by detritus and diatom diets, but predators and burrowers grouped those collected in September. Both of these trait combinations were found together in 2002 (suggesting a trade off by individuals possessing them) but much earlier in the melt season.

Axes 1 and 2 accounted for 49.5% of the trait variance in 2002, and 64.7% in 2003 at Site C (Table 7.3). Mean Q, TEMP, SSC, and diurnal TEMP range were important habitat variables, with a significant temporal trend in 2003 (Table 7.3). Both axes explained >90% of the trait-habitat variance in both years. Axes were significantly correlated (r >0.840, p<0.05; Table 7.3) for both years' data. Time explained 44.1% of the variance in the 2003 trait composition pRDA (Table 7.4). Both axes of the pRDA explained 40.6% of the trait variance, and 94.2% of the trait-habitat variance.

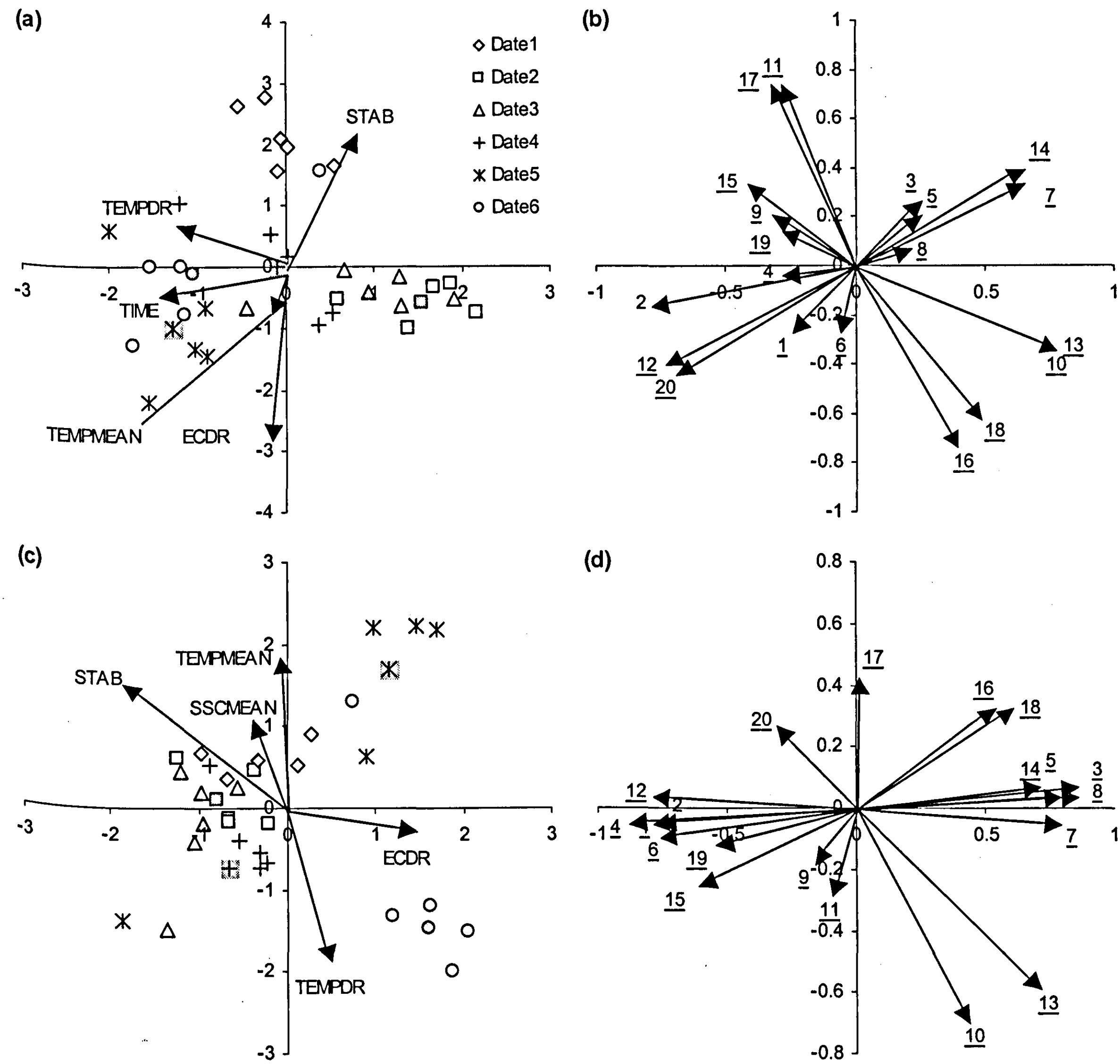


Figure 7.9. Redundancy Analysis showing percentage of individuals possessing a trait category and relationships with forward selected stream environmental variables on consecutive sampling dates at Site B. (a) The distribution of replicate samples and their weighted averages (filled symbols) for 2002 with arrows indicating stream environmental variables, (b) relationships between traits on F1xF2 factorial plane in 2002 (See Table 7.1 for category numbers), (c) as per (a) for 2003, (d) as per (b) for 2003

Samples collected in early July 2002 at Site C were grouped by clinger, algae diet and swimmer traits, and were strongly related to mean Q (Figures 7.10a-b). Melt season communities progressed through stages where large percentages of individuals possessed streamlined body form, large body size and univoltine/semivoltine life histories (July; date 3), to August samples where Crawlers, Shredders, and invertebrate diet traits were influential in grouping samples (dates 4 and 5). At the end of the melt season, swimmer, burrower and scraper were important traits, and related to EC diurnal range (Figure 7.10b). Algal diet and clinger traits were strongly associated with samples collected at the beginning of the 2003 melt season (c.f. 2002), in addition to small body size. Shredders, filterers and detritus diet grouped July-August melt season communities (dates 2-4). Later melt season trait compositions were strongly influenced by mean Q and Univoltine life histories and streamlined body form traits were associated with communities at this time (Figure 7.10d). At the end of the 2003 melt season, samples were grouped by scrapers, burrowers, swimmers and case constructors and associated with warmer TEMP. With the exception of case constructors, all these traits also grouped Site C late melt season communities in 2002.

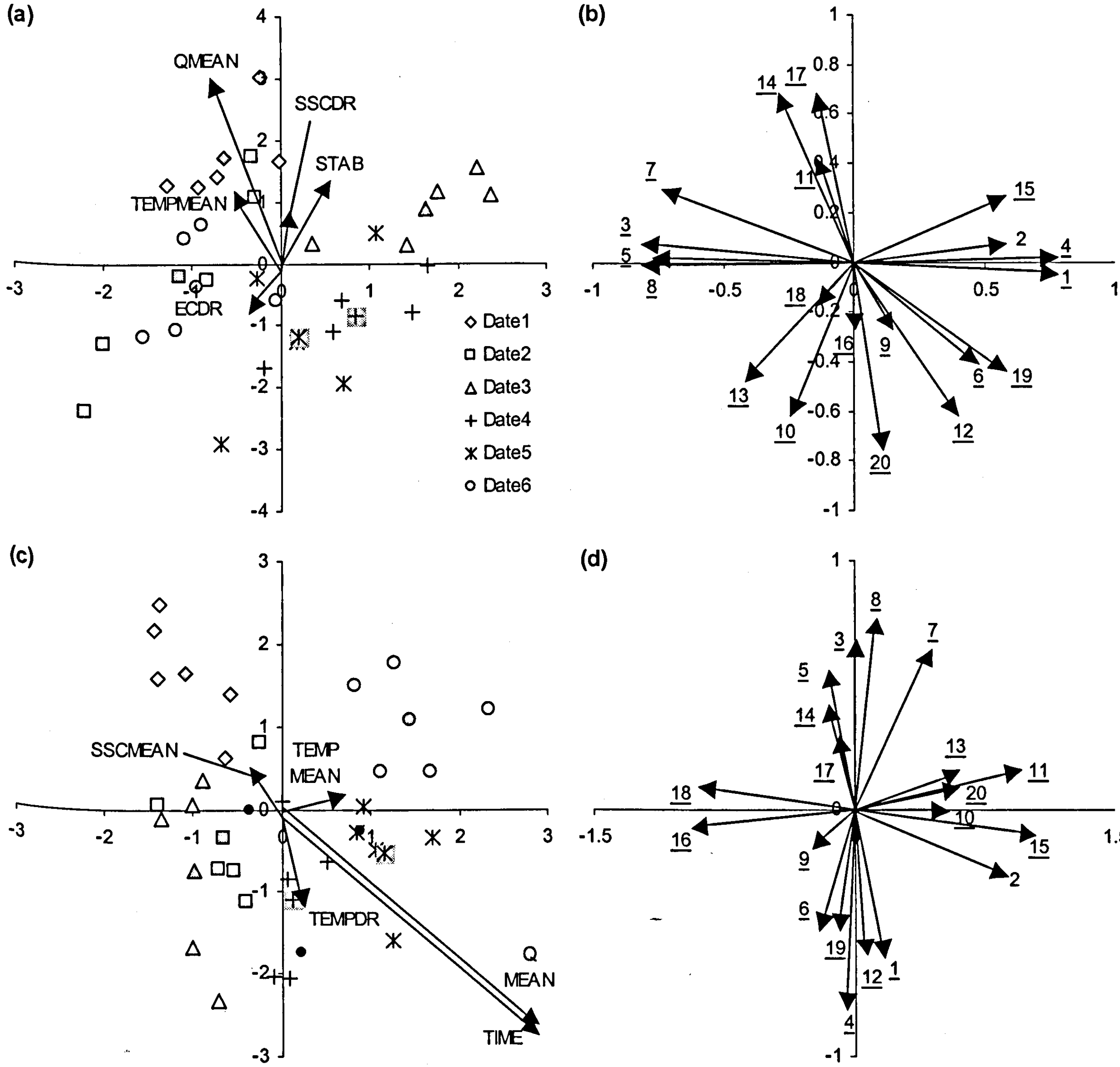


Figure 7.10. Redundancy Analysis showing percentage of individuals possessing a trait category and relationships with forward selected stream environmental variables on consecutive sampling dates at Site C. (a) The distribution of replicate samples and their weighted averages (filled symbols) for 2002 with arrows indicating stream environmental variables, (b) relationships between traits on F1xF2 factorial plane in 2002 (See Table 7.1 for category numbers), (c) as per (a) for 2003, (d) as per (b) for 2003

7.6. DISCUSSION

7.6.1. Community dynamics

Community dynamics of alpine streams have not previously been documented at sub-monthly time scales, thus, current knowledge is biased towards annual (between consecutive years) or seasonal (>monthly) variation (but see; Brown *et al.*, submitted and Chapter 8). This study has shown that alpine stream communities can be highly dynamic both in terms of community structure and trait compositions. Much of this variation is driven by stream environment dynamics over the summer melt season, in particular water temperature and suspended sediment concentrations, and to a lesser extent variability in stream discharge and channel stability. However, community dynamics were different between years suggesting that inter-annual variations in stream physico-chemical conditions (Chapter 6) may be important in structuring alpine stream communities.

Abundance was significantly different between sampling dates at all three sites. In particular, large numbers of *Diamesa* spp. at the beginning of the melt seasons resulted in large temporal changes in total abundance at Site A as found by Snook and Milner (2001b), suggesting taxa dominating early melt season communities maybe similar to those found in 1996-97. This is despite changes in the persistence of late melt season communities between 1996-2003 at the three sites, and particularly at Site A (see Chapter 8). Total abundance was always highest in the predominantly groundwater fed Site B, which was similar to the findings of Burgherr et al. (2002) and Füreder et al. (2001; 2003a) who found higher densities in groundwater channels compared to glacially influenced streams. Abundance increased in the Taillon stream at Site C, as a result of more stable stream environmental conditions due to discharge from the Tourettes stream, similar to benthic community changes commonly found at stream confluences (Rice et al., 2001).

Lower densities in 2003 than 2002 for streams in the Taillon-Gabiétous catchment may be related to between year habitat conditions (Chapter 6). Maiolini & Lencioni (2001) ascribed inter-annual differences in abundance/density to precipitation events, differences in winter/spring temperatures and winter snow cover duration between melt seasons (see also; Lods-Crozet *et al.*, 2001). Although the number of taxa varied little over the melt season, other studies have shown significant seasonal increases in winter (Robinson *et al.*, 2001; e.g. Schutz *et al.*, 2001). No ecological studies have been undertaken in the Taillon-Gabiétous catchment outside the summer melt season, thus community (and stream environment) dynamics at other times of the year are unknown. The lower diversity at Sites A and C in 2002, and mid melt-season peak diversity at Sites A and B in 2003 suggest that the timing of peak diversity within the melt season varies between years, possibly also as a result of different habitat conditions. Burgherr *et al.* (2002) found significant differences between seasons, with generally higher diversities in autumn/early winter. Longer-term monitoring (i.e. across seasons) is required in the Taillon-Gabiétous catchment to place these melt season findings into an annual context.

Noticeable differences in taxa abundances were found between sampling dates, although a large part of the community at Site A was typically dominated by Chironomidae (particularly *Diamesa* spp. and Orthocladiinae). The decrease in Chironomidae as the melt season progressed in 2003 may be due to early melt season communities being dominated by taxa better adapted to winter/spring conditions (e.g. higher mean discharge, colder water temperature), which are then slowly replaced by other taxa (e.g. Ephemeroptera/Plecoptera) as habitat conditions (e.g. water temperature) improve.

7.6.2. Temporal dynamics of abundant taxa

Clear differences between sampling dates in the composition of selected taxa highlighted the dynamic nature of alpine stream benthic communities. *Orthocladius* spp. grouped late melt season samples in 2002-03, but in previous studies they were associated more with samples collected in July (Snook and Milner, 2001b). Early melt season communities at Site B were grouped by Simuliidae, *C. breviata*, Coleoptera spp. and *T. gallicum* in both years. Snook

(2000) also found early melt season communities at this site dominated by Coleoptera spp. (notably *Esolus*) and *T. gallicum* along with *Baetis* and *Corynoneura*. In 2002-03, *Baetis* was more strongly associated with late melt season communities, whereas *Corynoneura* was found mostly in mid melt season samples in 2002 and earlier in 2003. Spatial and temporal variations in selected taxa abundances (resulting in inconsistent relationships with Time in the *p*RDAs) may be due to stream physico-chemical habitat dynamics resulting in modifications to life history patterns (affecting hatching and/or emergence; Céréghino and Lavandier, 1998), or food resource availability (Zah *et al.*, 2001; Füreder *et al.*, 2003a). Alternatively, variations in taxa abundance may simply be related to habitat selection choices as a result of their preferences for different physico-chemical conditions (e.g. Vinçon and Thomas, 1987).

Although some taxa were common to communities at similar times in 2002 and 2003 at Site C, others were more variable between years. Specifically, early melt season communities in 2002 included *Baetis* and *Rithrogena,* whereas in 2003, they were more strongly associated with late melt season communities. Peak *Baetis* abundances were also found to switch from the end (1996) to the beginning (1997) of the melt season in previous studies (Snook, 2000). Many adult *Baetis* have been recorded to lay eggs in a range of different stream types in the French Pyrénées, but larvae disappear when habitat conditions are unfavourable (Lavandier, 1979; Lavandier and Décamps, 1984). This situation may enable *Baetis* to survive during the early melt season in years when stream environmental conditions are favourable. However, in years when habitat conditions are more 'harsh' early in the melt season (e.g. colder water temperatures and/or higher discharge as a result of increased snowmelt), these taxa may only be found later in the summer when conditions have improved. Little is known of potential knock-on effects of stream environmental conditions during previous melt seasons and/or over winter upon alpine stream populations (Brown *et al.*, submitted).

7.6.3. Temporal dynamics of community trait compositions

Trait composition of communities at Site A were similar to those described by Snook and Milner (2002). At the beginning of both melt seasons, algal diet and clinger habit were strongly associated with stream communities dominated by *Diamesa*. During these periods, discharge was typically high due to early melt season snowmelt, thus taxa such as *Diamesa* are highly resistant/resilient to periods of increased discharge and turbulent conditions as a result off morphological clinger type (e.g. long posterior pro-legs) adaptations (Townsend *et al.*, 1997a). In addition, *Diamesa* are tolerant of cold water temperatures (Milner *et al.*, 2001) associated with increased snowmelt at these times (Brown *et al.*, 2004, in press-a).

Shredders and collector-filterers were scarce throughout the study probably reflecting limited allocthonous inputs to streams above the treeline (Zah and Uehlinger, 2001). As a consequence, FPOM concentrations in alpine streams are low (Snook, 2000; Füreder *et al.*, 2003a). However, detrital processing must occur in these streams because detritus diet and collector-gatherer feeding groups were important traits, similar to other studies which have demonstrated the dominance of detritus in alpine stream invertebrate diets (Zah *et al.*, 2001; Füreder *et al.*, 2003a, b). The large percentage of individuals with a scraper feeding group or diatom diet suggests a strong reliance on attached algae and diatoms as food sources as found in other studies (Füreder *et al.*, 2003a). However, there is growing evidence that alpine stream insects display extremely flexible feeding behaviour in response to periods of low food quantity and quality (Zah *et al.*, 2001; Füreder *et al.*, 2003a, b), but understanding the extent to which temporal variations in community structure reflects availability of food resources is hindered due to only a limited number of studies on primary producers and food webs.

The abundance of individuals with algal diets in early melt season samples corresponded with periods of high benthic primary productivity (possibly due to elevated nutrient concentrations and low SSC from snowmelt) when large quantities of filamentous algae (*Hydrurus foetidus*) were present (ash free dry mass of CBOM 2-3x greater than later sampling dates; *L.E. Brown; unpublished data*). These findings would appear to support recent studies that have demonstrated that primary production in glacial stream may be more important than previously considered (Robinson *et al.*, 2001; Füreder *et al.*, 2003a, b). However, peak discharge induced streambed movements and high sediment loads following precipitation events resulted in reduced algal cover. Thus, a complex situation may arise, whereby the direct effects of stream habitat conditions upon macroinvertebrate community taxa/trait compositions maybe supplemented with indirect effects via stream environmental conditions influencing food resources (primary producers). These potentially important interactions between bottom-up biotic interactions where communities are influenced by food availability, and top-down forces where stream environmental conditions shape stream communities, have not been studied in alpine streams.

7.6.4. The influence of stream environmental variables on selected abundant taxa and community trait dynamics

Although taxa and species trait composition dynamics at Site A followed similar patterns in both study years (and to previous studies in 1996-1997; Snook, 2000; Snook and Milner, 2001b, 2002), Site B was much more variable between the two melt seasons. At Site A, following early melt season conditions, the stream community shifted to one dominated by predacious taxa (e.g. *Rhyacophila*) and *Baetis* towards the mid-late melt season. Despite some variability in habitat conditions between years, the Taillon glacial stream probably supports similar communities since summers in which melt is relatively high (e.g. due to warmer summers or greater winter snow cover increasing melt) should not result in different habitat conditions to when melt is relatively low. Under both scenarios, the stream will be predominantly sourced by snow and ice melt (Chapter 5), with associated cold water temperatures, elevated sediment loads and relatively low electrical conductivity (Chapter 6). Higher discharge may result in lower streambed stability, but most taxa found in this reach are considered to be resistant/resilient to disturbance (Snook and Milner, 2002)

In contrast, summers with increased melt may significantly change the nature of the predominantly groundwater-fed Tourettes stream (Site B) due to upstream connections with glacial channels. In 2002 the Tourettes stream was mostly sourced from groundwater flow since meltwater inputs were comparatively low. In contrast, the summer of 2003 was exceptionally warm and melt increased accordingly (Brown *et al.*, 2004) resulting in more meltwater input to the Tourettes stream (Chapter 5). Therefore, the relatively homogenous habitat conditions typical of groundwater-fed streams in alpine catchments (Ward, 1994; Brown *et al.*, 2003) were not so evident in 2003, resulting in greater diurnal SSC, water temperature and electrical conductivity variability (Chapters 4 and 6). These variable habitat conditions may have been unsuitable for some taxa, resulting in changes in stream community and trait composition across this melt season.

Variations in the occurrence and abundance of taxa found in this study may in part reflect resistance/resilience to the timing and magnitude of habitat dynamics. If stream environmental conditions are unsuitable at the time of oviposition/egg hatching (e.g. due to cold water temperatures and/or high sediment load, etc.) then recruitment could be affected due to poor survival (Lavandier and Décamps, 1984). In other years, stream environmental conditions may be more suitable, thus more individuals may persist. Taxa that were found at the same time in successive melt seasons, despite differences in habitat conditions, are presumably better adapted for survival in these stream environments, being able to tolerate a range of environments. In these scenarios, stream environment dynamics may maintain high diversity by providing different habitat templets (c.f. Southwood, 1977, 1988) over a range of temporal scales. The spatial 'mosaic' of channel types (with different habitat conditions) previously found to support biodiversity within glacial floodplains (Burgherr *et al.*, 2002) may therefore be applicable temporally when applied to individual stream reaches.

7.6.5. Conclusions

In conclusion, alpine stream communities and their trait compositions are highly dynamic, responding to stream physico-chemical variability within and between melt seasons.

Community composition response to physico-chemical variables results in variability in adaptive traits found at different times. Furthermore, alpine stream habitat may indirectly influence community and trait composition by influencing macroinvertebrate food sources. This demonstrates the need for a fuller understanding of alpine stream environment dynamics and their linkages with benthic communities in order to fully understand future climate change influences on community structure.

7.7. SUMMARY

This chapter has examined the variability of the most abundant macroinvertebrate taxa in relation to stream physico-chemical habitat, and the adaptive traits of these taxa for living in these stream environments. The next chapter further considers variability in benthic macroinvertebrate community composition in relation to stream physico-chemical habitat variability by taking a community level approach to examine stability (similarity over time with respect to relative abundance) and persistence (similarity over time with respect to presence/absence). Changes in community composition since 1996 are also considered to increase understanding of community response to understand longer-term variability.

CHAPTER 8

STABILITY AND PERSISTENCE OF ALPINE STREAM COMMUNITIES AND THE ROLE OF PHYSICO-CHEMICAL HABITAT DYNAMICS

8.1. CHAPTER OVERVIEW

This chapter follows on from the previous analysis of benthic macroinvertebrate community composition and dynamics (Chapter 7) by examining the stability and persistence of alpine stream communities in relation to stream habitat dynamics. The chapter briefly summarises stream physico-chemical variables (Section 8.5.1) and community structure (Section 8.5.2) to provide a context for the ecological analyses. Archived data are examined to consider long-term inter-annual changes in community composition between 1996/97 and 2002/03 (Section 8.5.3). Intra-annual community stability and persistence is examined for 2002 and 2003 (Section 8.5.4) to consider relationships with stream physico-chemical habitat variables (Section 8.5.5).

8.2. INTRODUCTION

Many stream environments are temporally heterogeneous in terms of hydrological and physico-chemical habitat conditions, and these play an important role in determining the composition of macroinvertebrate communities over time (Giller and Malmqvist, 1998). Community persistence defined as the relative constancy of taxa presence/absence over time (Connell and Sousa, 1983), involves elements of resistance (ability to resist disturbance) and resilience (ability to recover from disturbance). Community stability refers to similarity over time with respect to relative abundances (Scarsbrook, 2002). The persistence and stability of stream communities is typically greatest where environmental conditions are relatively constant (Robinson *et al.*, 2000), or where conditions change slowly over long periods of time (Woodward *et al.*, 2002). Where environmental conditions fluctuate or are interrupted by disturbances, persistence and stability are often low (Lake, 2000), except where stream communities are adapted to prevailing variations in environmental conditions (Miller and Golladay, 1996).

Several studies have concentrated on community change between two sampling occasions to determine the persistence of macroinvertebrate communities over long temporal scales (Ward, 1975; Townsend *et al.*, 1987; Johnson *et al.*, 1994). Recently there has been considerable interest in examining variation over inter-annual time-scales (McElravy *et al.*, 1989; Bradt *et al.*, 1999; Robinson *et al.*, 2000; Bradley and Ormerod, 2001; Scarsbrook, 2002; Woodward *et al.*, 2002). Persistence is generally assessed for samples collected at the same time during study years, although Boulton *et al.* (1992) identified consistent seasonal cycles of benthic community composition over short temporal scales (i.e. sub-annual), reflecting changes in presence/absence rather than relative abundances of taxa. In addition, Death and Winterbourn (1994) found high persistence of dominant invertebrate taxa throughout the Southern Alps of New Zealand over three-monthly sampling intervals.

Alpine stream physico-chemical habitat conditions (e.g. water temperature, discharge, suspended sediment concentration, electrical conductivity, habitat stability) can fluctuate considerably over multiple temporal scales from diurnal to inter-annual due to dynamic water source inputs from snowmelt, ice-melt and groundwater (Smith *et al.*, 2001; Brown *et al.*, 2003). Alpine stream ecology has received considerable recent attention (for review see; Milner *et al.*, 2001) but no studies have looked at community dynamics over time-scales greater than two consecutive years. However, Gíslason *et al.* (1994) monitored populations of Simuliidae and Chironomidae over long-time scales in Icelandic rivers showing changes due to variability in FPOM supply. Longer term monitoring may provide a more accurate analysis of ecosystem structure (e.g. Bradt *et al.*, 1999). Alpine stream macroinvertebrate densities and diversity have been found to vary considerably between seasons (Burgherr and Ward, 2001; Füreder *et al.*, 2001; Schutz *et al.*, 2001). Alpine stream benthic macroinvertebrate community dynamics have been studied year-round at monthly intervals in snowmelt fed streams (Lavandier and Décamps, 1984), but there is a paucity of data relating short-term community dynamics to stream physico-chemical habitat variability in glacierized catchments.

This study examines the stability and persistence of macroinvertebrate communities between 1996-2003 (data collected in four summer melt seasons) for the three study sites in the lower Vallée des Pouey Aspé. Community variability was also determined for consecutive bi-weekly samples in 2002 and 2003 in relation to stream physico-chemical habitat dynamics. Although studies of persistence can only examine annual changes where at least one complete population turnover has occurred (Connell and Sousa, 1983), standard methods for assessing community dynamics were utilised for shorter temporal scales to determine if short-term fluctuations in alpine stream habitat conditions exert a strong influence on community composition. Comparison of shorter time scale variability over two melt seasons also reduces the confounding effect of life history variation obscuring community variability as a result of stream habitat dynamics.

Stream community stability and persistence were examined for the three sites with the aim of: (1) investigating the stability and persistence of benthic macroinvertebrate communities inter-annually (late melt season; 1996 to 2003) and intra-annual variability (bi-weekly; late June-early September, 2002 and 2003) in streams with different water sources; (2) evaluating the persistence/variability of the most abundant taxa within these streams; and (3) identifying links between intra-annual community variability/change and environmental conditions over the summer melt season.

8.3. DATA ANALYSIS

8.3.1. Community analysis

The five replicate Surber samples collected for each site/date were pooled to minimise variation due to small scale spatial effects, thus enabling clearer elucidation of temporal dynamics (e.g. Woodward *et al.*, 2002). Taxonomic resolution of inter-annual samples (1996-2003) was combined to a similar level to minimise the effect of changes in French Pyrénéan taxonomic knowledge since 1997, and different sample processors (i.e. Metzeling *et al.*, 2002). Macroinvertebrate community structure was summarised using number of taxa (i.e. richness; number of taxa), macroinvertebrate abundance and Simpson's diversity index (1/Simpson's).

Temporal variations in relative abundances of benthic macroinvertebrates (i.e. stability) were examined using Non-metric Multi Dimensional Scaling (NMDS). All data were $\log_{10}(x+1)$ transformed prior to ordination. NMDS calculates a set of metric coordinates for samples, most closely approximating their non-metric distances (Legendre and Legendre, 1998). Dissimilarity between samples is calculated initially, then random coordinates assigned in n-dimensional space. The Euclidean distance between samples is then calculated using these random coordinates, which are then compared with the original dissimilarity between samples. Stress functions ranging from 0 to 1 provided a measure of goodness of fit (0 = good fit). Similarity (stability) of macroinvertebrate community composition (relative abundances) between successive samples was summarised by calculating Bray-Curtis (BC) distances (Bray and Curtis, 1957). BC is a measure of percentage dissimilarity; values range from 0-1 with values of zero for identical samples. Pearson's Product Moment Correlation co-efficients were computed to assess relationships between NMDS axis scores and community composition. Correlations were considered significant where $p<0.05$.

BC was also calculated for the 15 taxa (BC15) that were most abundant at each site in the first sample appropriate to the comparison: (i.e. for comparison of 1996-2003 sample pairs, 15 most abundant taxa in 1996 data; for comparison of bi-weekly sample pairs in 2002, 15 most abundant taxa in first set of samples in 2002). The 15 most abundant taxa comprised >80% of the assemblages, as is common for lotic systems (e.g. Robinson *et al.*, 2000). This measure enabled analyses excluding rare taxa, which may significantly alter estimates of community stability and persistence (e.g. Cao *et al.*, 1998). NMDS comparison of all sites/years together was not undertaken for the 15 most abundant taxa since they varied between sites and successive years.

Following methods detailed in previous studies (Townsend *et al.*, 1987; Hawkins and Norris, 2000), persistence (constancy of community composition expressed as presence/absence) between sampling dates was measured by Jaccard's co-efficient of similarity calculated for all identified taxa (J). Values range from 0 (no similarity; low persistence/constancy) to 1 (identical; high persistence/constancy). J was also calculated for the 15 most abundant taxa (J15) at each site in the first sample appropriate to the comparison.

8.3.2. Intra-annual stream community-habitat relationships

From the measured physico-chemical habitat variables (TEMP, Q, SSC, EC), minimum (MIN), maximum (MAX), standard deviation (STDEV), average (MEAN) and mean daily range (XDR) statistics were calculated for the two weeks prior to each sampling date. For individual sites, values for physico-chemical habitat variables and STAB were related to measures of stability (BC and BC15) and persistence (J and J15) by calculating Pearson's Product Moment correlation co-efficients. Stream community-habitat relationships were not explored for inter-annual (1996-2003) stability and persistence measures as physico-chemical habitat data outside the summer melt season were not available. Correlations were considered significant where $p < 0.05$.

8.4. RESULTS

Spatial and temporal variability in stream environmental data are initially recapped (Section 8.5.1) to set the scene for subsequent examination of relationships with community stability and persistence. Community structure is briefly recapped to facilitate comparison with data collected in 1996/97 (Section 8.5.2). Inter-annual variability in community stability and persistence are examined in Section 8.5.3, followed by intra-annual community and stability in Section 8.5.4. Relationships between community stability and persistence and habitat variables are then examined in Section 8.5.5.

8.4.1. Stream environmental variables

Mean TEMP was lowest and most variable at Site A, whereas Site B was warmest, with the most stable thermal regime during both years (Figure 8.1a). Stream Q at Site C was greatest in both years but more variable in 2003. Sites A and B had similar mean Q in 2002 but in 2003, Q was higher and more variable at Site A (Figure 8.1b). SSC was highest at Site A, and lowest at Site B. In 2003, SSC variability was greater than the previous year (Figure 8.2c). EC was greatest in the order Site B>C>A in both years, but in 2003, EC was much higher than Sites A and C compared with 2002 (Figure 8.1d). STAB differences between sites were similar in both years of the study and varied little between sampling periods (i.e. low St. Dev). Site B was the most stable, and Site A was slightly less stable than Site C (Figure 8.1e). All habitat variables were significantly different between sites (ANOVA; $p<0.05$).

8.4.2. Community structure

Taxon abundance varied between sites and sampling dates but was consistently greatest at Site B (Table 8.1). The maximum abundance was recorded at Site A in early July 2002 (A/2002/1), when large numbers of Diamesinae were collected. For samples collected in early September (1996, 1997, 2002/6 and 2003/6), abundance fluctuated over time at Site A with no clear trend, increased at Site B and decreased at Site C. Abundance at each site was generally greater for samples collected in 2002 than 2003. Taxon richness at Sites A and C was similar from 1996-2003 but increased for consecutive yearly samples at Site B. The number of taxa was generally highest at Site B and lowest at Site A (Table 8.1). For 2002-2003, richness ranged from 29-41 at Site A, 44-67 at Site B and 33-56 at Site C.

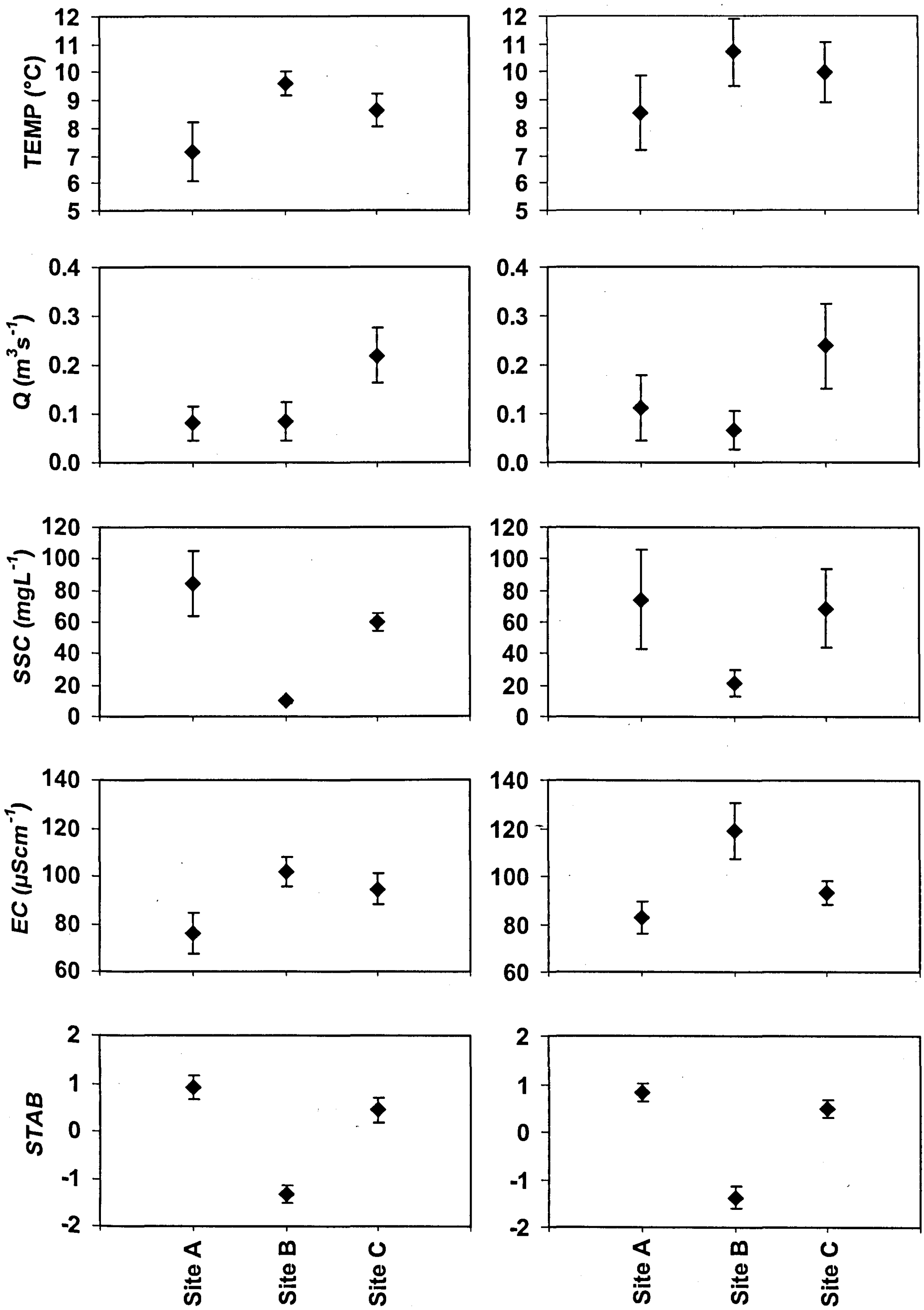


Figure 8.1. Mean values (±1 St.Dev.; error bars) for (a) water column temperatures (TEMP), (b) discharge (Q), (c) suspended sediment concentration (SSC), (d) electrical conductivity (EC), and (e) habitat stability (STAB)

Table 8.1. Descriptive statistics for macroinvertebrate community measurements. ABUN = abundance, TAXA = number of Taxa, SI = 1/Simpson's Index. Parentheses enable comparison of TAXA and SI between inter-annual (1996-2003) samples where taxonomic resolution was reduced.

SAMPLE		SITE A			SITE B			SITE C	
DATE	ABUN	TAXA	SI	ABUN	TAXA	SI	ABUN	TAXA	SI
96	368	(18)	(5.24)	-	-	-	2116	(29)	(1.84)
97	766	(22)	(5.44)	2096	(34)	(12.68)	547	(24)	(5.16)
02/1	6350	32	2.37	2098	66	11.37	1688	44	8.09
02/2	790	35	8.06	3149	44	3.28	2052	54	6.54
02/3	392	38	10.62	4484	48	4.30	1402	56	9.87
02/4	895	29	6.94	5183	52	7.18	1005	50	11.02
02/5	330	35	10.26	3509	54	9.67	563	45	17.45
02/6	841	35 (23)	8.24 (4.94)	3444	51 (38)	10.80 (9.01)	1305	40 (29)	9.32 (6.67)
03/1	504	30	7.91	1810	67	11.14	734	49	8.06
03/2	229	31	8.25	1429	59	7.52	436	36	9.63
03/3	198	34	15.26	1027	64	14.82	260	33	8.65
03/4	224	42	14.34	1411	58	10.14	471	43	8.87
03/5	243	41	1.66	2688	51	11.63	644	43	5.51
03/6	259	32 (22)	7.09 (6.34)	4202	62 (45)	7.22 (4.92)	946	45 (28)	4.26 (3.89)

Intra-annual diversity (SI) varied between years and was typically highest at Site B (Table 8.1). Diversity of bi-weekly samples varied considerably both spatially and temporally. Of the 15 most dominant taxa, Chironomidae (Diamesa) generally dominated the Taillon glacial stream at Site A and Diamesa/Ephemeroptera/Coleoptera at Site C. However, at Site B, a range of taxa (Orthocladiinae, Ephemeroptera (Baetis, *Rithrogena semicolorata*), Plecoptera and Coleoptera) typically comprised the most abundant taxa within the community. Some taxa were common to the three sites (*Baetis alpinus, Rithrogena loyolaea, Esolus angustatus*).

8.4.3. Stability and persistence: inter-annual variations (1996-2003)

NMDS showed three distinct groupings along Axis 1 reflecting faunal differences between the three sites (Figure 8.2). Axis 1 was most strongly correlated ($p<0.05$) with *Polycelis* ($r = 0.873$), *Thremma gallicum* ($r = 0.868$), *Protonemoura* ($r = 0.861$), *Leuctra* ($r = 0.835$) and *R. loyolaea* ($r = 0.815$). Axis 2 was most strongly correlated with *Pediciini* ($r = 0.755$), Oligochaeta ($r = 0.657$), and *Chaetopterygini* ($r = 0.634$). Community stability (BC) was typically highest for Site B, whereas Sites A and C had similar Bray-Curtis distances (Table 8.2). Stability of the 15 most abundant taxa was always greater than the whole community. Composition of the 15 taxa for each site was most similar over time at Site B and least similar at Site A.

Site A showed a minimal change in community composition between 1996 and 2003, but in 2003 had a reversed trajectory of change along Axis 2 with community composition more similar to 1996. Site B showed the greatest trajectory (difference) between 1997-2002 along Axis 2, although in 2003 trajectory reversal similar to that for Site A was evident. Site C was grouped intermediate of Sites A and B. Site C was most similar between 1996-1997, and 2002-2003. In 1996 Site C samples grouped closer to Site A than Site B. In subsequent years the trajectory moved across towards Site B until a shift back along Axis 2 in 2003 indicating community structure was more similar to Site A at this time (Figure 8.2).

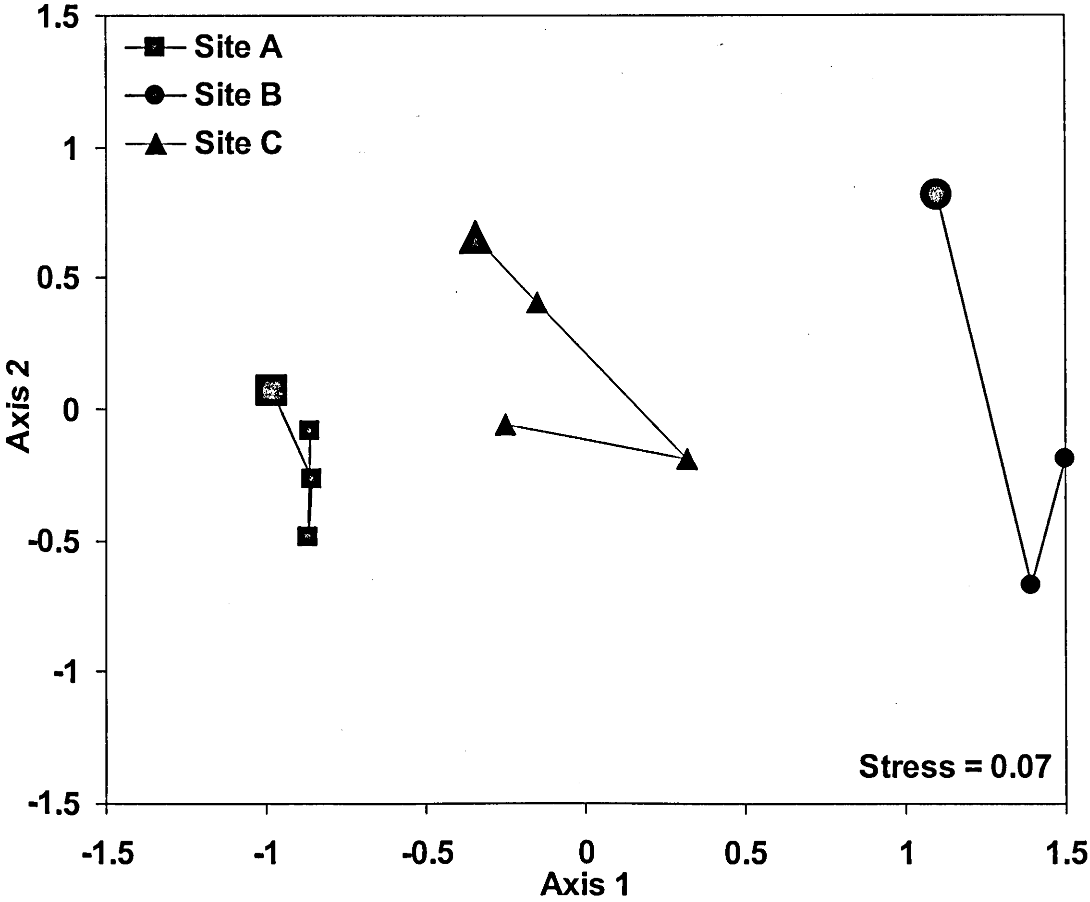


Figure 8.2. Non-metric Multi Dimensional Scaling ordination of stream communities over inter-annual (1996-2003) timescales. Large data point markers correspond to the position of stream communities at the beginning of the study period, thus temporal trends can be seen by following the lines to subsequent data point markers

Inter-annual persistence (J) was greatest for Site B and lowest at Site A (Table 8.2), although comparison of Site B with Sites A and C should be cautioned, as between year comparisons start in 1997 for Site B. Similarly for the 15 most abundant taxa, persistence (J15) was highest at Site B and intermediate at Site C. The 15 most abundant taxa at Site B were found every year (J15 = 1) from 1997 to 2003. With the exception of J15 at Site B, persistence for each site decreased consistently over time.

Table 8.2. Values of stability and persistence for macroinvertebrate communities between inter-annual (1996-2003) samples collected in late August/Early September. (BC and BC15 = Bray-Curtis distance for the stream community, and 15 most abundant taxa, respectively; J and J15 = Jaccard's similarity index for the stream community, and 15 most abundant taxa, respectively).

	Year Comparison	BC	BC15	J	J15
Site A	96-97	0.32	0.20	0.48	0.87
	96-02	0.29	0.15	0.48	0.80
	96-03	0.29	0.24	0.39	0.73
Site B	97-02	0.24	0.12	0.71	1.00
	97-03	0.21	0.10	0.65	1.00
Site C	96-97	0.29	0.16	0.61	0.93
	96-02	0.32	0.19	0.60	0.93
	96-03	0.29	0.15	0.57	0.80

8.4.4. Stability and persistence: intra-annual variations (bi-weekly samples 2002-2003)

Six groupings were evident from the NMDS, although the three sites clearly separated out along Axis 1. Axis 1 was most strongly correlated ($p<0.05$) with *Esolus/Oulimnius* larvae (r = -0.836), *Ephemerella ignita* (r = -0.750), *Ecdyonurus venosus* (r = -0.741), and *Perla grandis* (r = -0.732). Axis 2 was most strongly correlated with *R. semicolorata* (r = -0.697), Tipulidae (r = 0.513) and Planorbiidae (r = 0.480). Sites B and C showed a positive move along Axis 1 from 2002 to 2003, whereas Site A showed a negative change (Figure 8.3). The largest differences in community composition between consecutive intra-annual bi-weekly samples were at Site B, with the lowest differences at Sites A and C in 2003 (Figure 8.3). Site B had a relatively long trajectory along Axis 1 for early-mid melt season samples in 2002, but this shift was not evident in 2003. Clear differences in trajectories were evident between the two years for each site. In 2002, Sites A and C had relatively long trajectories along Axis 2, whereas in 2003 both had similar trajectories with more similar community composition than the previous year (Figure 8.3).

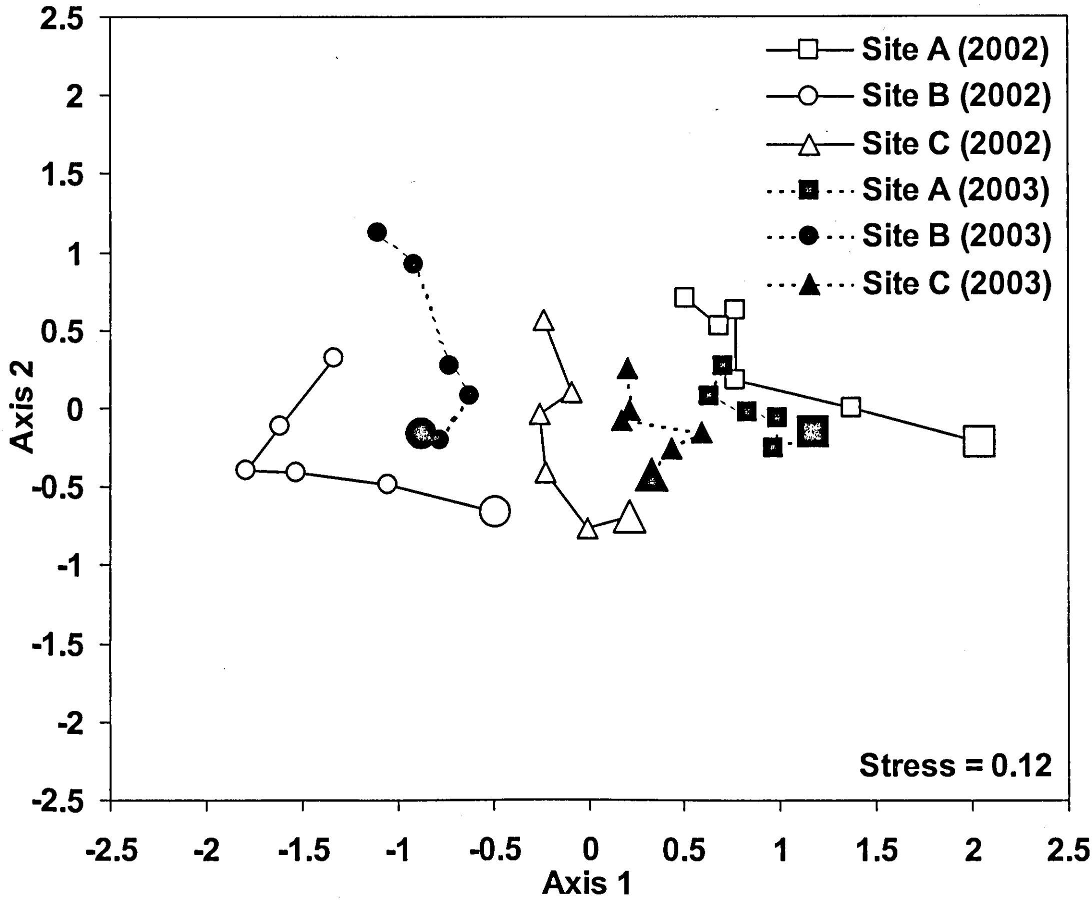


Figure 8.3. Non-metric Multidimensional Scaling ordination of stream communities over intra-annual bi-weekly time-scales during 2002 and 2003. Large data point markers correspond to the position of stream communities at the beginning of each study period, thus, short-term temporal variations can be seen by following the lines to subsequent data point markers

Stability (BC) was highest in 2002 for Site C and lowest for Site A (Table 8.3). In 2003 stability was generally highest at Site A (with the exception of the first pair of samples which were relatively dissimilar; Table 8.3) and highest at Site C. Community stability was generally lower in 2003 than 2002 at Sites B and C. The first pair of samples collected at Site B was also most dissimilar for this site in 2003. With the exception of Site C in 2002, all sites showed overall increases in community stability from the first to last pair of bi-weekly samples. Stability of the 15 most abundant taxa (BC15) was always higher than for the entire community (Table 8.3). In 2002, stability was typically highest for Site C and lowest for Site A. However, in 2003, stability was generally higher for Site A and typically lower at Site C.

Table 8.3. Values of stability and constancy of community composition for macroinvertebrate communities between intra-annual bi-monthly samples. (BC and BC15 = Bray-Curtis distances for the stream community, and 15 most abundant taxa, respectively; J and J15 = Jaccard's similarity index for the stream community, and 15 most abundant taxa, respectively)

	2002	BC	BC15	J	J15	2003	BC	BC15	J	J15
SITE A	02/1-02/2	0.31	0.20	0.60	1.00	03/1-03/2	0.37	0.15	0.53	0.93
	02/2-02/3	0.39	0.32	0.46	0.80	03/2-03/3	0.26	0.11	0.63	1.00
	02/3-02/4	0.31	0.22	0.56	0.58	03/3-03/4	0.21	0.08	0.65	0.93
	02/4-02/5	0.37	0.34	0.52	0.50	03/4-03/5	0.19	0.11	0.63	0.93
	02/5-02/6	0.29	0.19	0.67	0.89	03/5-03/6	0.20	0.16	0.52	0.79
SITE B	02/1-02/2	0.27	0.09	0.47	0.93	03/1-03/2	0.39	0.25	0.75	1.00
	02/2-02/3	0.24	0.12	0.59	0.93	03/2-03/3	0.27	0.14	0.64	0.93
	02/3-02/4	0.25	0.17	0.67	0.93	03/3-03/4	0.29	0.18	0.67	1.00
	02/4-02/5	0.24	0.15	0.71	0.93	03/4-03/5	0.29	0.19	0.70	0.93
	02/5-02/6	0.23	0.19	0.72	0.87	03/5-03/6	0.30	0.19	0.61	0.86
SITE C	02/1-02/2	0.21	0.08	0.61	1.00	03/1-03/2	0.32	0.17	0.52	0.93
	02/2-02/3	0.22	0.12	0.69	1.00	03/2-03/3	0.33	0.23	0.47	0.73
	02/3-02/4	0.22	0.10	0.68	0.80	03/3-03/4	0.40	0.28	0.46	0.79
	02/4-02/5	0.23	0.10	0.64	0.86	03/4-03/5	0.26	0.15	0.59	0.87
	02/5-02/6	0.23	0.13	0.70	0.86	03/5-03/6	0.21	0.08	0.73	1.00

Persistence (constancy of stream community composition; J) for each pair of samples between consecutive bi-weekly samples ranged from 0.46 to 0.75 (Table 8.3). In both 2002 and 2003, persistence was most constant at Site B, lowest for Site A and intermediate for Site C. In 2002, persistence of the last pair of samples for each site was highest. In 2003, the most persistent communities were found in late June – early July (2003/1-2003/2) at Site B, late August – early September at Site C (2003/5-2003/6), and mid melt-season (late July-early August; 2003/3-2003/4) at Site A. Persistence of the 15 most common taxa collected each year (J15) ranged from 0.50-1.00; all J15 values were greater than those for the entire community except during August 2002 (A/2002/4-A/2002/5; Table 8.3). Between consecutive samples, persistence was typically greatest for Site B in both years (J15 >0.86). Persistence ranged widely for Site A (0.50-1.00) but was higher in 2003 (0.79-1.00).

8.4.5. Stability and community variability relationships with environmental variables

Measures of stability and persistence/constancy of community composition were significantly correlated ($p<0.05$) with different habitat variables at each site (Table 8.4). At Site A, community stability (BC) increased with TEMPMEAN but BC15 increased (lower stability) with increasing SSCMIN (Table 8.4). Community stability (BC) at Site B decreased with greater QMIN, ECXDR and SSCXDR. At Site C, community stability significantly decreased with a range of TEMP statistics (Table 8.4), but was greatest when SSCMAX was lowest. Stability of the 15 abundant taxa (BC15) decreased with increasing TEMPMEAN, TEMPDEV and TEMPXDR. At Site A, persistence of the 15 abundant taxa (J15) was only correlated with minimum discharge (QMIN) but at Site B, increased when TEMPDEV and SSCMEAN were high. At Site C, persistence (J) was lowest when water temperatures (MAX, DEV, XDR) and discharge (MAX) were highest.

Table 8.4. Pearson's product moment correlation co-efficients between intra-annual (bi-monthly) measures of community persistence and stability, and physico-chemical habitat variables. Only significant correlations (* = *p*<0.05, ** = *p*<0.01) are shown. Abbreviations are defined in Section 8.3.2.

Stability/ persistence measure	**Site A**	**Site B**	**Site C**
BC	TEMPMEAN (-0.646*)	QMIN (0.638*); CONDXDR (0.780**); SEDXDR (0.751*)	TEMPMAX (0.636*); TEMPMEAN (0.645*); TEMPDEV (0.670*); TEMPXDR (0.789**) SEDMAX (0.640*);
BC15	SEDMIN (0.753*)		TEMPMEAN (0.658*); TEMPDEV (0.652*); TEMPXDR (0.768**)
J			TEMPMAX (-0.639*); TEMPDEV (-0.711*); TEMPXDR (-0.912**); QMAX (-0.705*)
J15	QMIN (0.788**)	TEMPDEV (0.670*); SEDMEAN (0.657*)	

8.5. DISCUSSION

This study has shown that benthic communities of different alpine streams within a small area of the catchment have different levels of stability and persistence. At inter-annual time scales (1996-2003), community stability and persistence decreased from 1996 to 2003. Over shorter time-scales (bi-weekly melt season samples), communities varied in response to stream physico-chemical habitat variations influenced by dynamic water source contributions.

8.5.1. Inter-annual community stability and persistence

In alpine headwater catchment streams, habitat conditions vary markedly from relatively stable groundwater-fed streams to more harsh, physico-chemically variable glacial streams (Ward, 1994; Smith *et al.*, 2001; Brown *et al.*, 2003). Clear groupings of samples from the three sites within the inter-annual ordination clearly highlighted the different faunal compositions (particularly EPT taxa) between streams fed by different water sources and with different physico-chemical habitat conditions as found in other studies (Schutz *et al.*, 2000; Füreder *et al.*, 2003a). Between 1996 and 2002, community structure at Site C became more similar to that at Site B, suggesting more favourable habitat conditions for macroinvertebrate taxa preferring groundwater stream conditions, to colonise downstream of the confluence of the Taillon and Tourettes streams. Conversely, in 2003, Site C was more similar to Site A due to the greater contribution of flow from the Taillon Glacier sub-catchment in this year (Brown *et al.*, 2004) resulting in habitat conditions less suitable (e.g. more variable SSC and water column temperatures) for taxa common to the Tourettes stream to establish. Inter-annual persistence of late melt-season macroinvertebrate communities was typically highest in the predominantly groundwater-fed Tourettes stream (Site B), and lowest in the Taillon stream (Site A), which is analogous to high persistence being found under more constant stream habitat conditions in other environments (e.g. Townsend *et al.*, 1987; Weatherley and Ormerod, 1990; Death and Winterbourn, 1994; Robinson *et al.*, 2000).

The specific reasons for these changes in community structure over longer time-scales are unclear, as stream habitat conditions were not monitored between 1997 and 2002, and winter conditions between years are unknown due to accessibility problems and logistics of reliable data collection in extreme winter weather. However, comparison of habitat data for 2002 and 2003 (Sites A and C) with those presented by Smith *et al.* (2001) for 1996 and 1997 shows water temperature was warmer on average in 2002 and 2003, and mean stream discharge lower. These habitat changes may be tentatively attributed to a combination of negative mass-balance of the Taillon glacier (estimated to be 6.4 myr-1; Association-Moraine-Pyrénéenne-de-Glaciologie, 2003), earlier peak snowmelt (inferred from the higher late June snowline altitude in 2002/2003 reported by Brown *et al.*, 2004; c.f. Hannah *et al.* 1999a), and warmer summers resulting in warmer water temperatures. However, longer data sets (>decadal) are required to identify any trends in stream conditions and also to verify the importance of potential changes in the timing and magnitude of meltwater runoff and associated stream habitat conditions. There is also a clear need for detailed studies linking alpine physico-chemical variability and stream benthic community composition outwith the summer melt-season.

8.5.2. Intra-annual community stability and persistence

Clear groupings within the intra-annual ordination further demonstrate different faunal compositions between the stream sites (see Chapter 7). Differences in trajectories between the two melt seasons for each site indicates life history variability is not entirely responsible for variability in community stability in these streams. However, changes in relative abundance of macroinvertebrates over time as life cycles progress may account for some of the general pattern of decreasing community stability from early to late melt season communities. Although the most stable communities varied between sites and years, persistence was highest intra-annually at Site B. Similar discrepancies in stability and persistence have been reported elsewhere (Meffe and Minckley, 1987; Boulton *et al.*, 1992; Scarsbrook, 2002). These contrasts in community stability and persistence emphasise the role of environmental variability in determining stream communities; changes in physico-chemical habitat conditions typically impact community composition in terms of relative abundance. However, more extreme disturbance events are often necessary to effect changes within presence/absence of taxa (i.e. cause extinctions or provide habitat for colonisation by previously absent taxa; Scarsbrook, 2002).

Although Sites A and C were characterised by greater intra-annual physico-chemical habitat variability than Site B, stream communities were typically most stable in the glacial stream. Thus, sites with more stable physico-chemical habitat (e.g. in groundwater streams) may not necessarily have the most stable community because species abundance patterns may be additionally influenced by changes in resource availability and biotic interactions (Scarsbrook, 2002). In the Taillon-Gabiétous catchment, summers with increased melt result in changes to habitat conditions within the predominantly groundwater-fed Tourettes stream (Site B) due to upstream connections with glacial channels. The summer of 2003 was exceptionally warm and melt increased accordingly (Brown *et al.*, 2004) resulting in more snow- and ice-melt input to the Tourettes stream (Chapter 5). Therefore, the relatively homogenous habitat conditions typical of groundwater-fed streams in alpine catchments (Ward, 1994; Brown *et al.*, 2003) were disrupted (Chapter 6) and may account for the lower community stability during 2003 at this site.

8.5.3. Stability and persistence relationships with stream environmental conditions

Short-term changes in environmental conditions clearly exerted an influence upon intra-annual community composition, but notably, they were largely uncorrelated with persistence at Site A, which may suggest some other habitat variable (e.g. nutrients and other water quality variables) or biotic interactions (e.g. food availability) are important in driving presence/absence of taxa in this glacial stream (Chapter 7). Alternatively, the lack of correlation between stream habitat conditions and community persistence/stability may be due to life history strategies of taxa. Higher community stability at Site A was related to increased water temperature, supporting the concept of warmer water temperature providing more favourable conditions for alpine stream communities (e.g. Milner and Petts, 1994; Ward, 1994; Milner *et al.*, 2001). However at Site C, warmer more variable temperatures resulted in reduced community stability because communities at these groundwater-fed sites may be better adapted to thermally constant conditions. Alternatively, thermal constancy or temperature minima may be more important than mean or maximum temperatures for stream communities (Townsend *et al.*, 1987).

Lower community stability at Sites A and B (and J15 Site B) under conditions of high/variable suspended sediment concentrations emphasises the adverse effect of suspended sediment upon alpine stream communities through abrasion, reduced light penetration and associated primary production, and degradation of substrate (Milner and Petts, 1994; Gíslason *et al.*, 1998). Habitat stability was not significantly related to any measure of community stability or persistence at any site and within each site varied little between sampling periods. Therefore, habitat stability may only be an important habitat variable determining community composition spatially. Overall, this suggests changes in water quality conditions over short-time scales may be important determinants of alpine stream communities. This contrasts with the findings of Death and Winterbourn (1994) and Scarsbrook (2002), that showed changes in community structure were more strongly related to changes in flow conditions. Water quality variations may be more important over the short time-scales discussed in this study due to macroinvertebrate taxa possessing resistance and resilient adaptive traits/strategies to flow variations (e.g. small body size, clinger habit, multivoltine life-cycle; Snook and Milner, 2002; Chapter 7) in these mountain streams. However, these short-term water-quality driven variations are probably superimposed upon the more widely studied seasonal changes driven by the annual melt season flow pulse typical of alpine streams (Robinson *et al.*, 2001; Schutz *et al.*, 2001; Burgherr *et al.*, 2002).

Persistence and stability of the 15 most abundant taxa was consistently higher than for the entire community, suggesting a common pool of taxa are present for the majority of the time in these alpine streams (cf. Townsend *et al.*, 1987; Winterbourn, 1997). However, this is unsurprising as rarer taxa are unlikely to be sampled consistently between dates using only five replicate samples (Townsend *et al.*, 1987). Furthermore, the 15 most abundant taxa provide a more useful measure of any significant changes to community composition as stability and persistence measures for these taxa are unlikely to be influenced by immigration and emigration of transient taxa (Scarsbrook, 2002). The high persistence and stability of these core taxa over inter-annual to bi-weekly time scales may indicate resistance and resilience adaptations to a wide range of physico-chemical habitat conditions. Resistance and resilience of macroinvertebrate communities to discharge fluctuations is directly affected by food availability and refugia (e.g. Boulton *et al.*, 1992), but little is known of the role of these habitat variables in alpine streams (Uehlinger *et al.*, 1998). The relative importance and mechanisms of resistance and resilience elements needs to be addressed for taxa inhabiting high alpine streams.

8.5.4. Conclusions

In conclusion, this study supports the view that streams originating from different alpine water sources are characterised by distinct benthic macroinvertebrate assemblages, and streams with the least variable habitat conditions support high diversity with low variability in assemblage structure. Although inter-annual stability and persistence of these alpine stream communities is relatively high, temporal variation of communities in individual stream reaches can be influenced by variable physico-chemical habitat conditions (Chapter 7). This demonstrates the need for an integrated understanding of alpine stream physico-chemical habitat dynamics and their linkages with benthic communities (e.g. Brown *et al.*, 2003) in order to fully predict their likely response to predicted future changes in the timing and magnitude of peak snow- and ice-melt, and associated stream habitat changes (McGregor *et al.*, 1995a).

8.6. SUMMARY

This chapter has built upon the findings of Chapter 7 by adopting a more statistical approach to examine temporal variation in macroinvertebrate communities. These changes in community composition in terms of relative abundances (stability) and presence-absence (persistence), in addition to the descriptive approach in Chapter 7, enable a better understanding of community dynamics in these systems. The final chapter in the thesis will bring together the results and conclusions from all the chapters, in order to provide an integrated understanding of alpine stream water source-physico-chemical habitat-ecological relationships.

CHAPTER 9
AN INTEGRATED APPROACH TO UNDERSTANDING THE HYDROECOLOGY OF ALPINE STREAMS

9.1. CHAPTER OVERVIEW

This chapter synthesises the key findings of the research in this thesis to identify hydroecological patterns and processes operating within the Taillon-Gabiétous catchment. The chapter advances conceptual models of alpine water source contribution dynamics and associated physico-chemical habitat variability that influences benthic communities at different spatial and temporal scales. Water source contributions and stream physico-chemical variables are summarised in Sections 9.2.1 and 9.2.2, respectively. These water source-habitat relationships are also considered within the context of habitat conditions outlined in Chapter 2. An assessment of hydroecological relationships within the Taillon-Gabiétous catchment is made in Section 9.2.3. The constraints of the study are assessed alongside suggestions for future alpine stream hydroecological research (Section 9.3). The final section reinforces the contributions of the thesis to hydroecological understanding in alpine streams and freshwater lotic ecosystems more generally (Section 9.4).

9.2. GENERAL CONCLUSIONS

Previous chapters have examined collected data sets and presented results showing water column and streambed temperature dynamics (Chapter 4), hydrochemistry and water source contributions (Chapter 5), stream physico-chemical habitat variability (Chapter 6), and stream benthic community relationships with habitat variables (Chapter 7 and 8) to enable field testing and refinement of the alternative approach to alpine stream habitat classification proposed in Chapter 2. These results follow a three-tiered hydroecological cascade linking: (1) water source dynamics, (2) stream physico-chemical habitat variability, and (3) benthic macroinvertebrate community responses, which typically vary both spatially (between sites) and temporally (diurnally, seasonally and inter-annually). The following sections consider the elements and links in this water source-habitat-benthic community cascade.

9.2.1. Water source dynamics

The Taillon–Gabiétous catchment contains three distinct and highly dynamic hydrological sources: (1) the Taillon and Gabiétous Glaciers, (2) seasonal snowpacks below 2700 m, and (3) a hillslope groundwater system. These water sources contribute different proportions of flow to streams within the Vallée des Pouey Aspé, with inputs varying at diurnal, seasonal and inter-annual time-scales.

Hydrochemical signatures for different water sources within the Taillon-Gabiétous catchment were distinct, thus providing a robust basis for separating their relative contributions to streamflow in space and time using end member mixing analysis (Chapter 5). Close to the Taillon Glacier snout, where percentage glacierized area was high, streams were dominated by 'Quickflow' (rapid routed, snow and ice meltwaters; low [SO_4^{2-}] and low [Si]) and 'Distributed' (slow subglacial routed, snow and ice meltwaters; high [SO_4^{2-}] and low [Si]) waters. With increasing distance from the Taillon Glacier (and reduced glacierized area), streamflow was more influenced by 'Groundwater' (longer residence time groundwaters; intermediate [SO_4^{2-}] and high [Si] contributions.

Water source contributions varied markedly over and between the melt seasons, with 'Quickflow' dominant in late June-early July, and 'Distributed' dominant in August-early September. However, 'Groundwater' contributions only followed the expected trend conceptualised at the outset of the study (i.e. to be highest at the end of the melt season; Figure 2.3) in 2002, following several prolonged mid-late melt season rainfall events that recharged aquifers, and, hence, resulted in greater discharge from springs and small groundwater streams. Groundwater stream discharge measurements showed that the highest discharges (outwith precipitation events) occurred during late June, suggesting that hillslope groundwater aquifer recharge may have occurred prior to the beginning of the monitoring period from snowmelt. This suggests that the seasonal water source contribution progression should be reconsidered so that streamflow is dominated by snowmelt ('Quickflow') and 'Groundwater' early in the melt season (Figure 9.1). 'Distributed' is more dominant during the mid-late melt season after snowpacks have receded and subglacial flow paths contribute more to proglacial stream discharge (Figure 9.1). These hydrochemical results support the findings of independent modelling of the Taillon Glacier's drainage structure (Hannah and Gurnell, 2001) indicating that within the Taillon-Gabiétous catchment, snowline retreat and decreasing snowpack size are the most important control on water source dynamics and the diurnal proglacial hydrograph, not the evolution of a more *efficient* subglacial drainage system; (cf. work on larger European temperate glaciers e.g. Fountain and Walder, 1998). Variations in water source contributions are also reflected in diurnal (low and high flow) water source contributions at different times of the melt season as conceptualised in Figure 9.1.

However, climate conditions, particularly major, episodic precipitation events may influence this water source progression. Samples collected during recession flows following precipitation events typically had greater proportions of groundwater to streamflow, presumably following aquifer recharge. However, weekly hydrochemical sampling did not provide sufficient temporal resolution to examine immediate streamflow responses to rainfall events, therefore the contributions of each water source during these precipitation events is uncertain. More intensive sampling during precipitation events may allow for event specific end member compositions, to account for the combination of event characteristics, antecedent conditions and seasonality influencing water source responses to precipitation events (Soulsby *et al.*, 2003).

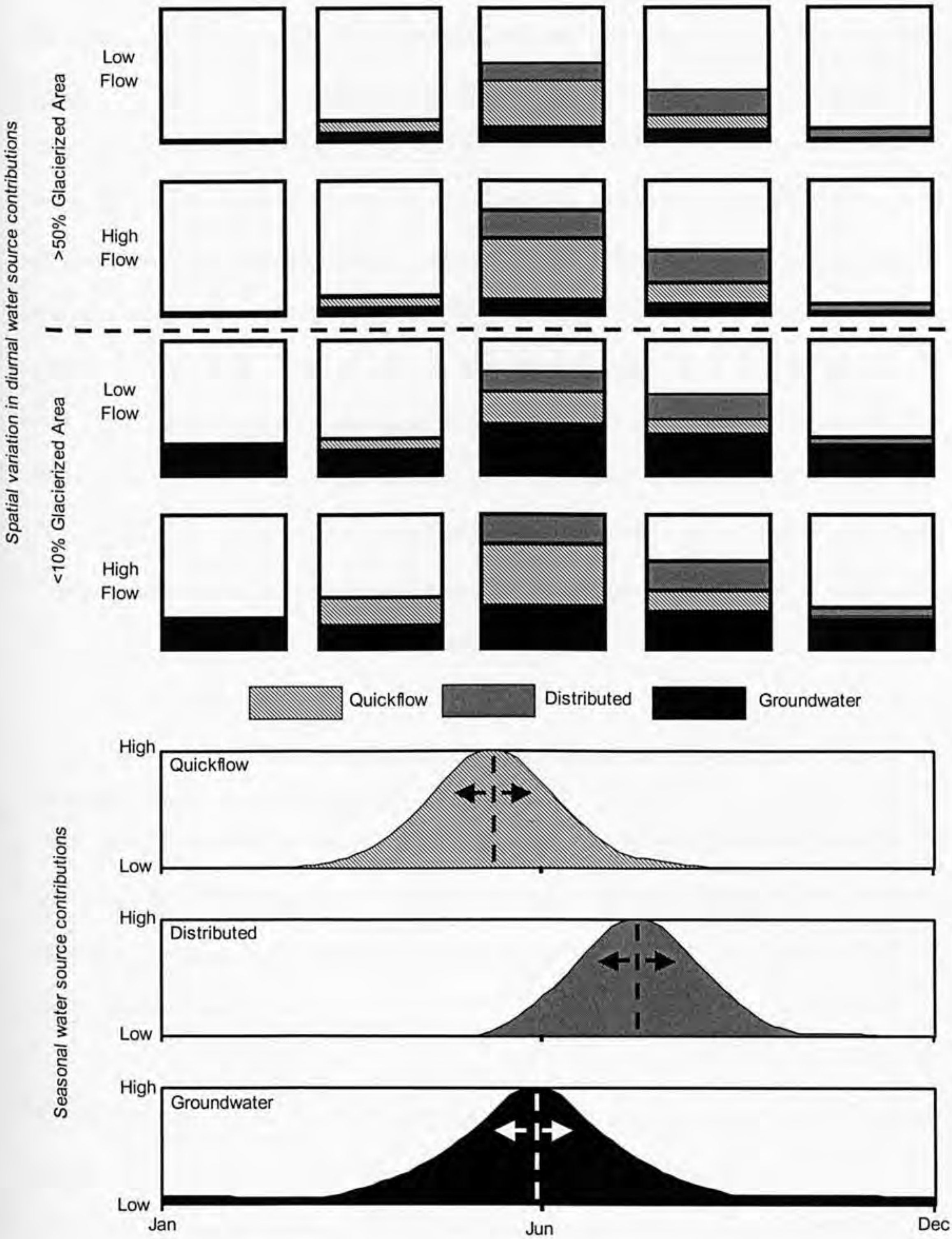


Figure 9.1. A conceptual model of spatial and temporal (diurnal and seasonal) variations in water source contributions in alpine glacierized catchments

Climate conditions (characterised herein by incoming short-wave radiation, air temperature and precipitation) influenced water source contributions, both within years and inter-annually. In 2003, 'Quickflow' contributions to streamflow decreased and were replaced by 'Distributed' inputs earlier than in the 2002 melt season due to warmer conditions resulting in increased early melt season snowmelt. 'Groundwater' contributions were generally lower in 2003 and even the Tourettes stream, which was previously assumed to be predominantly groundwater-fed, was dominated by 'Distributed' flow for the majority of the melt season. This may reflect lower 'Groundwater' proportions due to less recharge from precipitation events, as opposed to greater volumes of water being routed via subglacial 'Distributed' flow paths. The potential year-to-year variability in water source contributions is depicted in Figure 9.1 by dashed lines and arrows. This variability should be an important consideration within subsequent alpine stream studies on order to consider the influence of inter-annual climate conditions on water source contributions.

9.2.2. Water source and stream physico-chemical dynamics: An alternative approach to alpine stream habitat classification

This section summarises the main findings for relationships between water source contributions and stream physico-chemical habitat variables. Changes to the alternative approach to alpine stream habitat classification proposed in Chapter 2 are discussed following field validation in Chapter 6.

Cooler and less variable water column and streambed temperatures were characteristic of karstic groundwater streams when compared to the Taillon glacial stream in the lower catchment due to the effect of downstream temperature increases driven predominantly by atmospheric energy fluxes. Over a distance of ~1km from the Taillon Glacier snout, mean water column temperatures increased by between 7-8°C. Although clear differences in thermal regime were evident between the Taillon stream and tributaries, the use of water temperature to characterise water sources would appear impractical since streams fed from

'Quickflow' and 'Distributed' sources had similar temperature regimes whilst groundwater stream temperatures varied between cool, relatively constant temperatures in karstic springs, to highly variable and relatively warm temperatures in hillslope streams. Stream thermal dynamics were partly influenced by water source dynamics, but with increasing distance from the source, this relationship was confounded by thermal effects of atmospheric energy fluxes (Chapter 4). These findings demonstrate the potential problems of using temperature based classification, and emphasise the need for an alternative approach.

Although the alpine stream habitat classifications proposed in Chapter 2 were based on water source contributions from snowmelt, glacial icemelt and groundwater, the hydrochemical data presented in Chapter 5 demonstrated the difficulty in separating snow and ice contributions due to their similar chemical composition (following snowpack ion elution). However, clear hydrochemical signatures based on measured Si and SO_4^{2-} concentrations enabled the separation of snow- and ice-melt that flowed either through a rapid drainage system ('Quickflow') with limited rock-water contact time, or through a slower, subglacial drainage system at the glacier-bed ('Distributed'), using end member mixing analysis. Thus, changes were necessary to the naming of water source contributions from meltwater sources (i.e. dilute snow- and ice-melt = 'Quickflow'; enriched snow- and ice-melt = 'Distributed'). 'Groundwater' contributions in this study referred to water from streams draining hillslope aquifers. Karstic streams were not considered as a source, as the end member mixing analysis suggested that these streams were fed by slower routed meltwaters as found in independent tracer studies (Parc-National-des-Pyrénées, 1991).

The proposed alternative classifications remain highly applicable despite changed water source terminology. For example, Krenal equates to 'Groundwater' dominated; Nival incorporates snowmelt, but is supplemented by dilute ice-melt contributions from supraglacial areas following snowline retreat. Both snow and ice-melt contributing to the Nival classification have similar physico-chemical characteristics (dilute, cold temperatures, low

SSC). Kryal classifications are still glacier-fed, but this classification should refer to chemically enriched subglacial drainage (snow- and ice-melt) as opposed to glacial icemelt that rapidly reaches the proglacial stream as 'Quickflow'. This distinction between rapid and slow water routing results in clear differences in terms of reference for habitat conditions between traditional kryal classifications (e.g. Ward, 1994) and the alternative classification. In particular, SSC was classed as being high for traditional kryal stream classifications since the former classification makes no separation between snow and ice contributions to glacial stream discharge. However, in this study, SSC increased when 'Quickflow' contributions were highest since these rapid water flow paths (associated with peak discharges) mobilised available fine sediment deposits at the glacial snout and in proglacial reaches (channel margins).

Within the Taillon-Gabiétous catchment, dynamic water source contributions were linked with diurnal and seasonal patterns in a range of stream physico-chemical variables. Stream discharge, suspended sediment concentration, electrical conductivity and solute concentrations were all strongly related to contributions of 'Quickflow', 'Distributed' and 'Groundwater' sources (Chapter 6). Overviews of the principal stream habitat characteristics as related to water source contributions in the Taillon-Gabiétous catchment are given in Table 9.1.

In stream reaches where 'Quickflow', 'Distributed' and 'Groundwater' sources mixed, stream habitat characteristics were highly variable. Since variable water source contributions resulted in all nine proposed classification categories (Chapter 2) being experienced across the 2002 and 2003 melt seasons, it was possible to quantify a range of physico-chemical variables for each habitat classification (Chapter 6). By integrating a range of stream physico-chemical habitat variables with water source contributions, the alternative classification is better hydrologically informed than earlier classification systems, and, thus, provides a better method of understanding alpine stream habitat variability to inform ecological studies.

Table 9.1. Principle stream physico-chemical habitat characteristics for three water sources identified within the Taillon-Gabiétous catchment

Physico-chemical variable	Quickflow	Distributed	Groundwater
Water column and Streambed temperatures	Very cold (<1°C) at source due to snow and ice meltwaters contributing to flow, but potential for large downstream increases (>7°C on average over ~1km) and diurnal fluctuations (up to 11°C) due to atmospheric energy fluxes		Warmer at source (4-5°C), but potential for downstream increases and diurnal fluctuations due to atmospheric energy fluxes, particularly on south-facing hillslopes
Discharge (Q)	Contributes to high Q mid-afternoon when snow- and ice-melt feed rapid flow paths (englacial). High diurnal variability in response to atmospheric energy fluxes	Dominates proglacial reaches when snow- and ice-melt rapid flow paths contribute little. Sub-glacial flow paths and low diurnal variability	Relatively constant Q Higher flows following aquifer recharge by snowmelt and precipitation
Suspended Sediment Concentration (SSC)	Mobilises large amounts of proglacial sediment when glacier most active following snowline retreat. Turbulent mixing mobilises proglacial sediments and stream channel deposits	Relatively high SSC due to sub-glacial flow paths in contact with freshly ground sediments at glacier snout	Low SSC since minimal connection to proglacial sediment deposits and subterranean water sources and pathways.
Channel Stability	Low due to fluctuating Q and mobile sediment deposits	Low due to variable Q and mobile sediment deposits	High since relatively constant Q and generally relatively stable substratum
Hydrochemistry	Low conductivity since little interaction with weathered material before reaching stream Low/No Si Low SO_4^{2-} + Mg^{2+} Low Na^+	Conductivity >Quickflow due to sub-glacial flow paths and chemical weathering but <Groundwater Low Si High SO_4^{2-} + Mg^{2+} High *K/Si: low Si weathering	High electrical conductivity due to long interaction time with soils and weathered material High Si, Na^+ and Mg^{2+} Intermediate/Low SO_4^{2-} Low *K/Si: high Si Weathering

9.2.3. Hydroecological responses of Pyrénéan alpine streams: Relationships between water source contributions and stream benthic macroinvertebrate communities

Benthic macroinvertebrate abundances and diversity in the Taillon-Gabiétous catchment varied temporally during both melt seasons, demonstrating the importance of habitat variability upon stream populations (Chapter 7). Changes in community composition were reflected in variable trait compositions, demonstrating the range of adaptive strategies utilised in response to habitat dynamics. Although stability and persistence of these alpine stream communities were relatively high (Chapter 8), differences in physico-chemical habitat conditions played an important role in determining relative abundances and presence/absence of taxa. Clear differences in community structure, trait composition, community stability and persistence were also evident spatially (between sites around the confluence of the Taillon and Tourettes streams) reflecting water source and habitat variability. Because 'Quickflow', 'Distributed' and 'Groundwater' contributions strongly influence stream habitat conditions (Chapter 6), macroinvertebrate community structure and trait compositions are subsequently examined in relation to water source contributions and alpine stream classification categories.

Benthic macroinvertebrate community descriptives for the nine classification categories show the highest total abundances, taxon richness and number of EPT taxa were associated with streamflow classifications with high proportions of 'Groundwater' (classifications A-E; Table 9.2). Mean diversity (1/Simpson's) was greatest for the Krenal and Kryo-krenal categories. Mean Berger-Parker dominance scores were typically highest for classification categories where community diversity was lowest (Pearson's correlation co-efficient r = -0.882). Benthic macroinvertebrate community descriptives showed strong relationships with proportions for the three water sources (Figure 9.2; see Appendix E for relationships with all community descriptives). The proportion of 'Groundwater' had the strongest relationships with total abundance, number of taxa and EPT taxa richness. These three macroinvertebrate community descriptives were significantly positively correlated with 'Groundwater', but negatively correlated (and lower r-values) with 'Quickflow' and

Table 9.2. Mean values of benthic macroinvertebrate community descriptive statistics for the nine alternative alpine stream habitat classification categories

Habitat Classification	Classification name	Total Mean Abundance (0.5m^2)	No. Taxa	No. EPT Taxa	1/Simpson's Index	Berger-Parker Dominance	Proportions of Taxa					
							Ephemeroptera	Plecoptera	Trichoptera	Chironomidae	Diptera	Other
A	Krenal	3444	51	17	10.80	0.19	0.19	0.05	0.01	0.54	0.03	0.18
B	Kreno-nival	3108	52	19	6.24	0.40	0.14	0.04	0.02	0.50	0.02	0.28
C	Kreno-kryal	3157	54	17	9.40	0.23	0.19	0.05	0.01	0.58	0.04	0.14
D	Nivo-krenal	2536	45	14	7.10	0.35	0.19	0.03	0.01	0.57	0.05	0.14
E	Kryo-krenal	938	52	17	11.72	0.22	0.21	0.10	0.03	0.31	0.06	0.28
F	Nival	647	33	9	7.98	0.25	0.05	0.01	0.08	0.79	0.07	0.01
G	Nivo-kryal	1222	46	14	8.58	0.27	0.12	0.03	0.09	0.65	0.06	0.05
H	Kryo-nival	529	37	10	9.47	0.24	0.20	0.04	0.04	0.51	0.10	0.12
I	Kryal	442	42	12	8.58	0.30	0.43	0.06	0.01	0.28	0.14	0.08

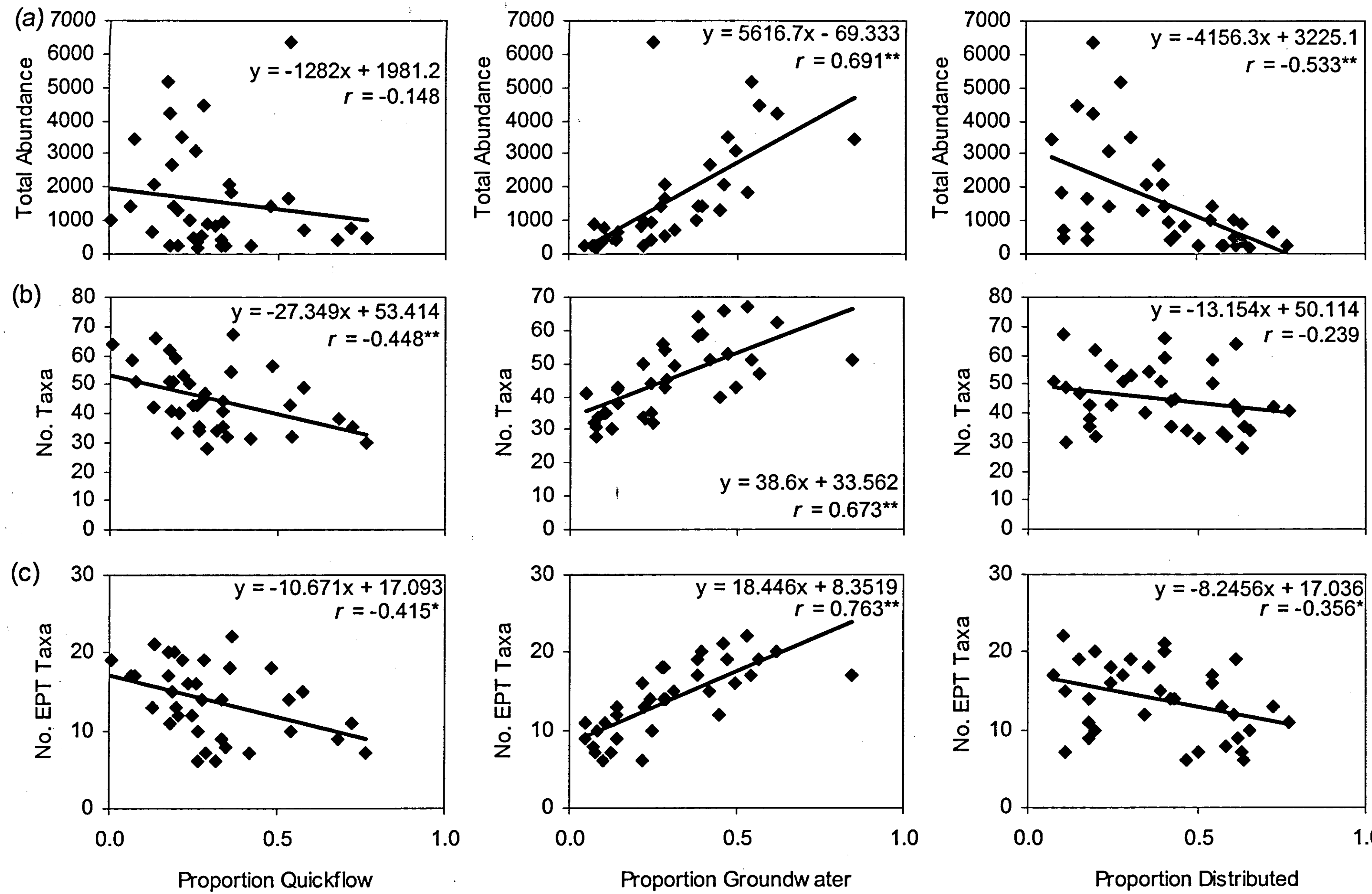


Figure 9.2. Scatter graphs showing relationships between (a) mean total abundance, (b) mean number of taxa, and (c) mean number of EPT taxa, in relation to proportions of 'Quickflow', 'Groundwater' and 'Distributed' water source contributions. Asterisks denote significant relationships (* = p<0.05; ** = p<0.01).

'Distributed' contributions emphasising the findings of other studies in alpine catchments where groundwater provides more favourable habitat for benthic macroinvertebrate communities (e.g. Füreder *et al.*, 2001; Malard *et al.*, 2003).

Mean abundances of the most common taxa showed distinct differences between the nine categories (Figure 9.3). Ephemeroptera were typically most abundant in categories within the upper ternary diagram (A, B and C) indicating a preference for groundwater dominated stream habitats where water temperatures and channel stability are typically higher (Milner *et al.*, 2001). Plecoptera were also more abundant when 'Groundwater' dominated streamflow, but were largely absent from categories D - I (i.e. increased 'Quickflow' and 'Distributed' contributions). In contrast, *Rhyacophila* (Trichoptera) were more abundant in categories D–H with the greatest proportion of 'Quickflow' and 'Distributed' contributions, reflecting their preference for colder water temperatures and low channel stability in the Taillon-Gabiétous catchment. However, the trichopteran genus *Hydropsyche* was only found in Krenal, Kreno-kryal and Kryo-krenal categories (A, C and E), highlighting clear differences in habitat preferences for genera within the same Order in these alpine streams. *Hydropsyche* are net spinning filter-feeding taxa therefore they prefer alpine streams with relatively low suspended sediment concentrations (e.g. predominantly groundwater fed) to prevent sedimentation of their nets. Mean abundances of Chironomidae were typically greatest for Krenal (A) and Kreno-kryal (C) classifications. However, *Diamesa* showed a clear tendency towards categories D and F (Nival and Nivo-krenal), due to its preference for cold, low stability meltwater streams (Steffan, 1971; Milner and Petts, 1994).

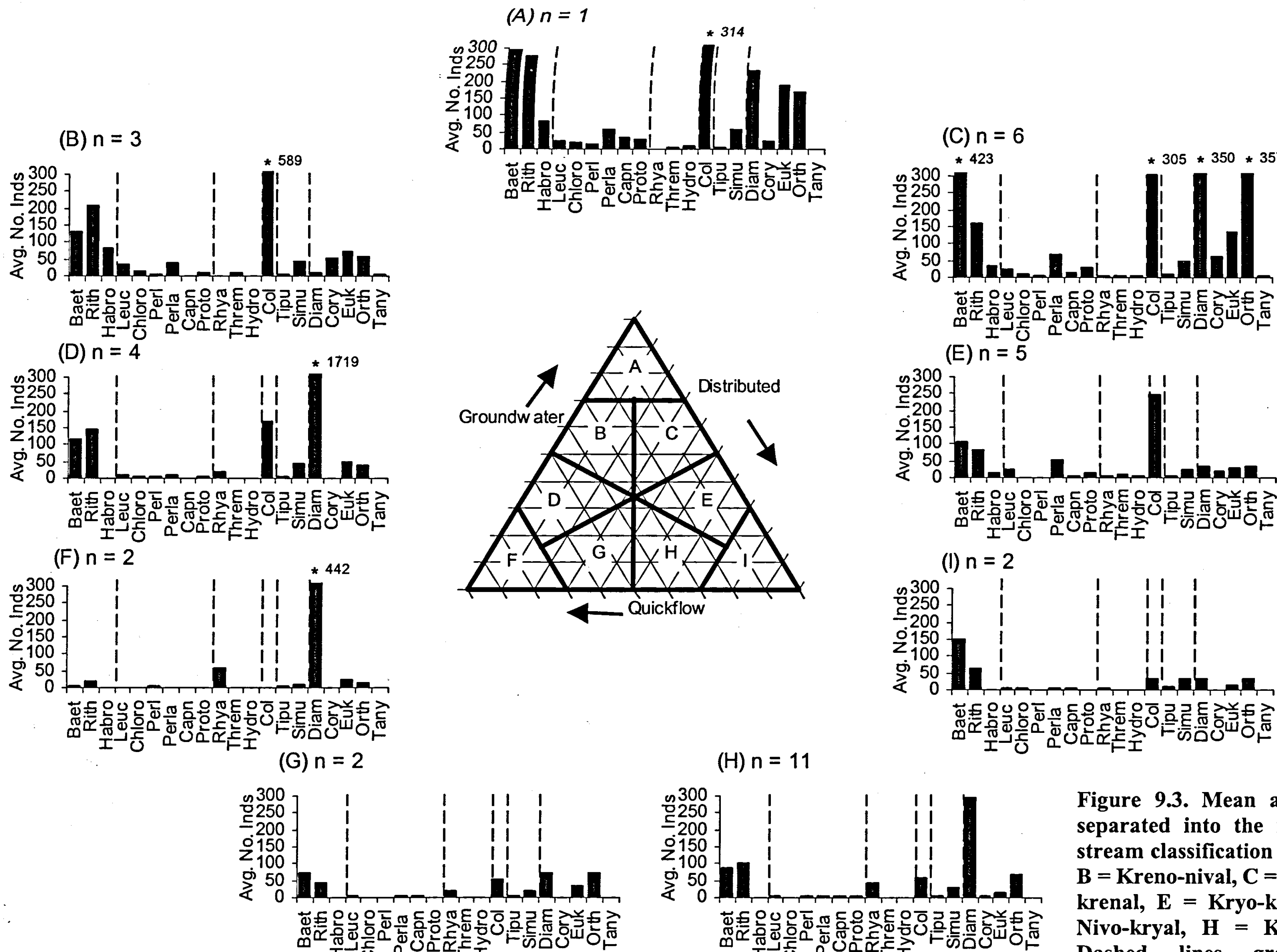


Figure 9.3. Mean abundances of 20 taxa separated into the nine alternative alpine stream classification categories.(A = Krenal, B = Kreno-nival, C = Kreno-kryal, D = Nivo-krenal, E = Kryo-krenal, F = Nival, G = Nivo-kryal, H = Kryo-nival, I = Kryal. Dashed lines group: Ephemeroptera, Plecoptera, Trichoptera, Coleoptera, Non-chironomid Diptera, and Chironomid taxa)

Common taxa showed similar responses to water source contributions, with mean abundances generally increasing with the proportion of 'Groundwater', and decreasing where 'Quickflow' and/or 'Distributed' contributions were proportionally greatest (Figure 9.4; see Appendix F for water source relationships with all selected abundant taxa from Chapter 7). One exception to the common trend was *Rhyacophila* abundance (Figure 9.4e), which decreased with increasing 'Groundwater' contributions, and was largely absent where the 'Groundwater' contributions were >50%. This may be due to physiological stress for these taxa in groundwater streams (e.g. warmer water temperature, hydrochemistry) as these taxa immediately released themselves into drift in preliminary boulder transplant experiments from the Taillon to the Tourettes stream. *Habroleptoides berthelemyi* (Figure 9.4c) and *Hydropsyche* (Figure 9.4f) mean abundances generally increased when the proportion of 'Groundwater' was >50%, reflecting their inability to colonise predominantly meltwater-sourced streams with high suspended sediment concentrations.

Proportions of individuals possessing strong links with a range of adaptive traits (Chapter 7) for each classification category are shown in Figure 9.5. Each classification category typically had a greater proportion of individuals with life history in the order multivoltine>univoltine>semivoltine. However, for Nival and Nivo-krenal classifications, multivoltine life history was found in a much greater proportion of individuals compared to uni- and semi-voltine, than for the other classifications (Figure 9.5). This is probably a resilience trait for adaptation to life in the harsh physico-chemical habitat conditions in these meltwater streams because the production of multiple generations each year favours rapid recolonisation following disturbance (Townsend and Hildrew, 1994). Univoltine life history was most strongly associated with the Krenal category, probably reflecting the more stable year-round physico-chemical habitat conditions in which life cycles can be completed relatively slowly (i.e. one per year). Small body size was more dominant than large body size for all categories reflecting the requirement for resistance to hydraulically rough environments in these relatively steep headwater streams.

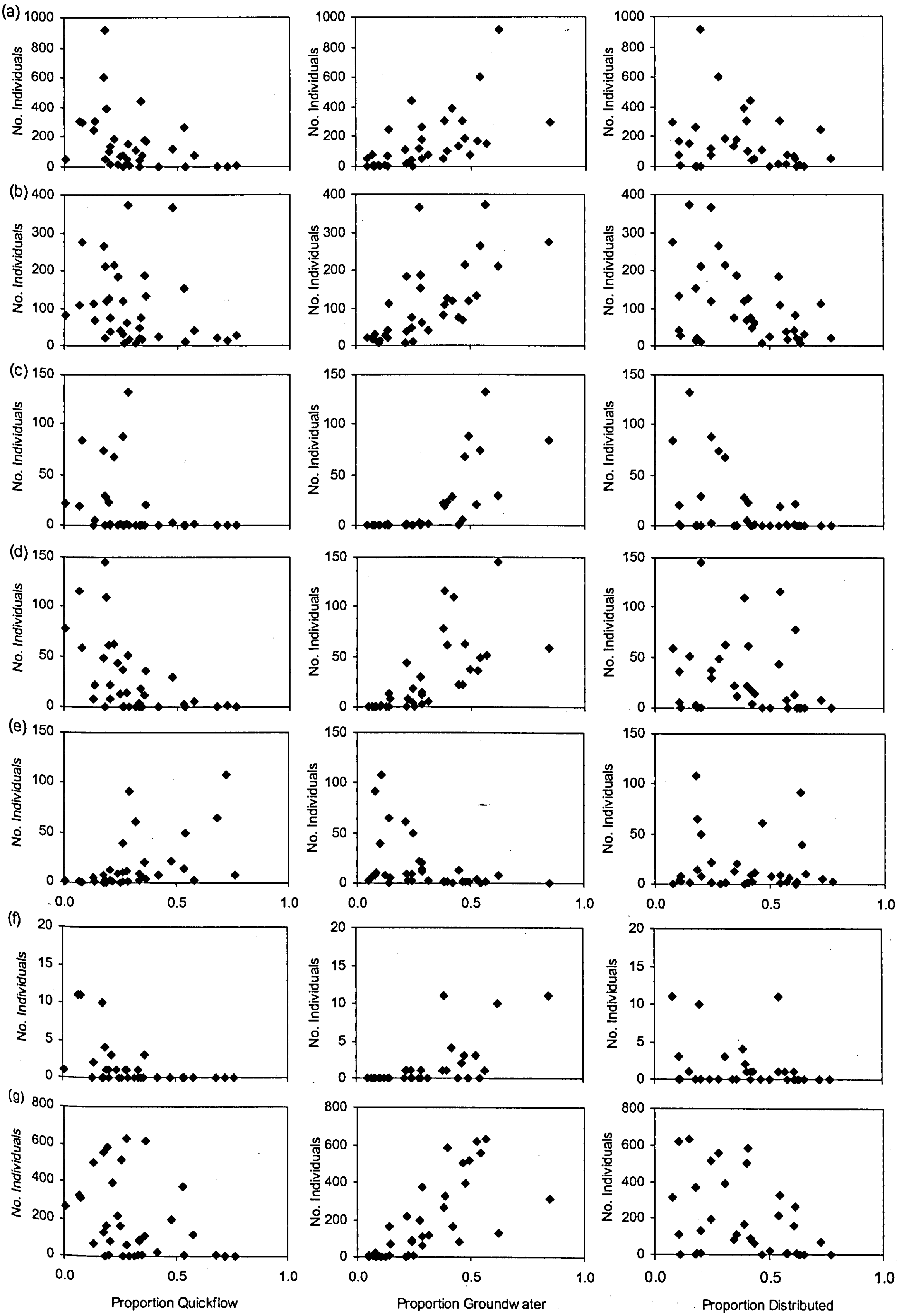


Figure 9.4. Scatter graphs showing relationships between mean abundance of (a) *Baetis*, (b) *Rithrogena*, (c) *Habroleptoides berthelemyi*, (d) *Perla grandis*, (e) *Rhyacophila*, (f) *Hydropsyche pellucidula*, and (g) Coleoptera, and proportions of 'Quickflow', 'Groundwater' and 'Distributed' water source contributions

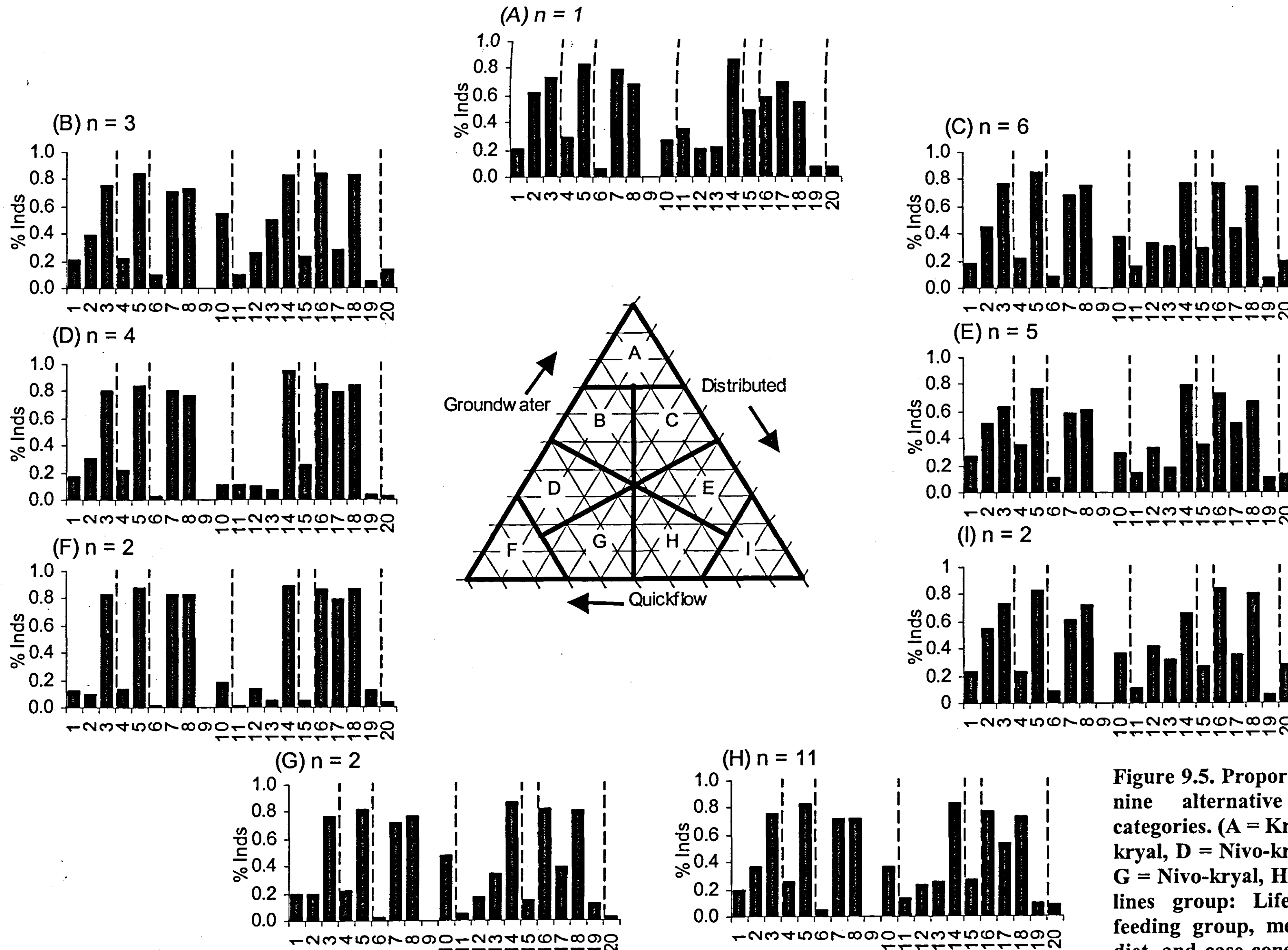


Figure 9.5. Proportions of 20 traits separated for the nine alternative alpine stream classification categories. (A = Krenal, B = Kreno-nival, C = Kreno-kryal, D = Nivo-krenal, E = Kryo-krenal, F = Nival, G = Nivo-kryal, H = Kryo-nival, I = Kryal.) Dashed lines group: Life history, body size, functional feeding group, method of attachment, body form, diet, and case construction traits. Refer to Table 7.2 for definitions of category numbers

Functional feeding groups were similar between classification categories; scraper and collector-gatherers were always dominant and typically found in the similar proportions of individuals, reflecting the prevalence of diatom and detritus food sources and the lack of allocthonous leaf litter inputs to streams in alpine areas above the treeline (Zah and Uehlinger, 2001). The four methods of attachment were found in different proportions for the nine categories. Clinger was dominant for all classes, but was more exclusive in the Nival and Nivo-krenal categories (D and F) where greater hydraulic stresses require attachment methods that promote resilience. Swimmers were mostly associated with the Krenal category possibly because flows were typically slower and less turbulent compared to meltwater streams. Thus, these taxa are less likely to be swept downstream in these habitats when moving around.

In summary, the spatio-temporal variability of water source inputs, the physico-chemical habitat variability these create, and subsequent ecological response, can be considered within a refined conceptual flow diagram (after Chapter 2; Figure 2.1) highlighting the range and scale of hydroecological linkages (Figure 9.6). Key differences between the new model and that proposed at the outset of the study are: (1) the incorporation of differences in water flow time along different pathways, and the interaction of snowmelt, icemelt and karstic/hillslope groundwater to produce 'Quickflow', 'Distributed' and 'Groundwater' end members within the ternary classification, (2) increased understanding of interactions between water source contributions and stream physico-chemical variables, and (3) potential variability of habitat influences upon different trophic levels of stream communities influencing the strength of trophic linkages. The model provides a holistic means of summarising the high spatio-temporal variability in linkages between hydrological stores, hydrological controls, stream properties, and their relationships with stream communities.

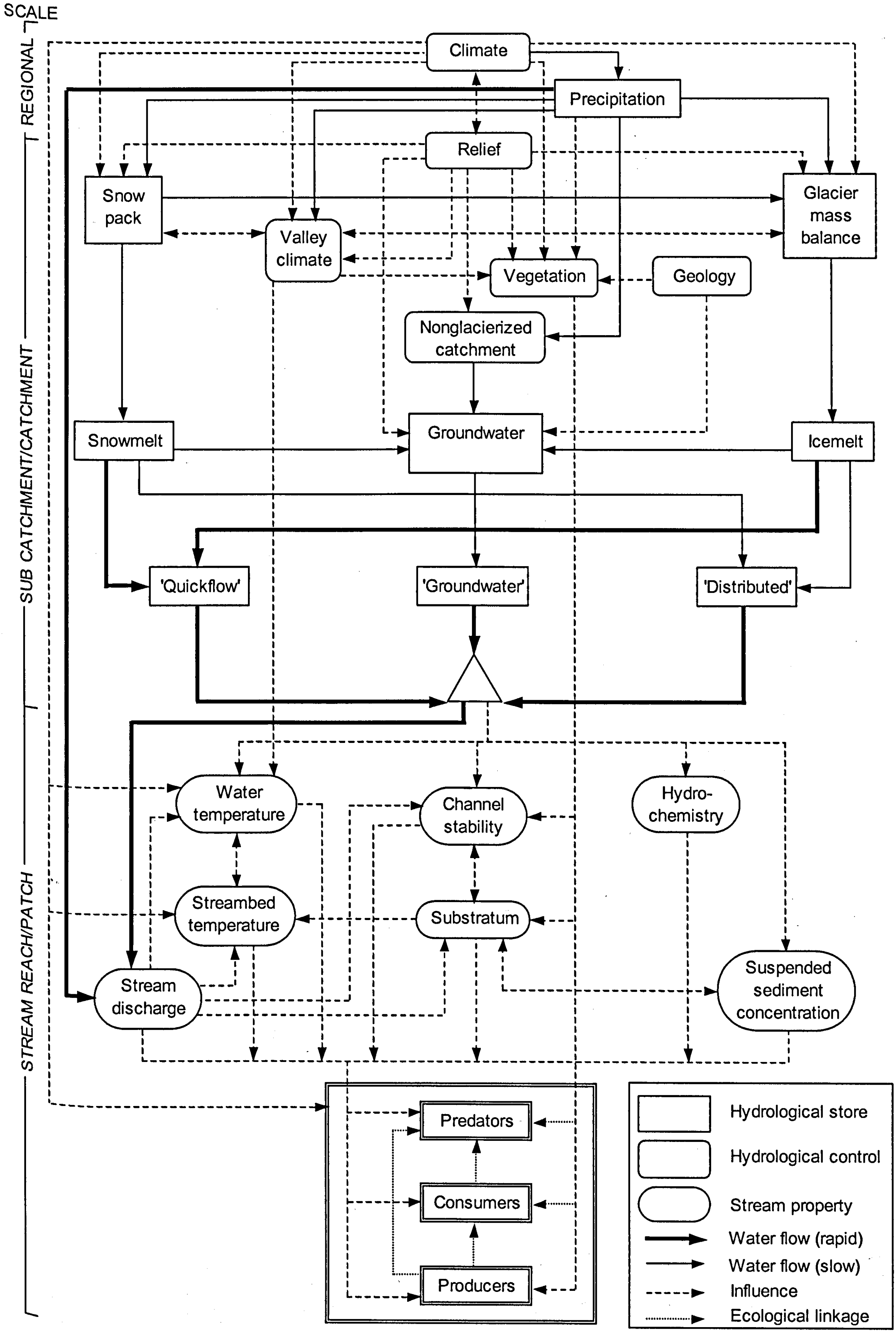


Figure 9.6. A revised conceptual model of the environmental variables influencing benthic communities in alpine streams at different spatial scales.

9.3. SUGGESTED IMPROVEMENTS FOR FUTURE RESEARCH

This section proposes recommendations for further progress in three areas: (1) data collection; (2) data analysis, and (3) potential future research directions. These ideas may enable further refinement of the conceptual models presented previously in Section 9.2, in addition to improving understanding of hydroecological relationships within the Taillon-Gabiétous and/or other alpine glacierized catchments.

9.3.1. Field data collection

1. The weekly hydrochemical sampling strategy (Chapter 5) was designed to complement the hydrological and ecological sampling activities. This was acceptable because the principal objective was to link water source dynamics with stream communities (sampled fortnightly). However, more frequent hydrochemical sampling at the sites in the lower Vallée would have afforded additional insights into water source variability between macroinvertebrate sampling dates, allowing a more comprehensive assessment of catchment hydrological functioning and influences upon benthic communities. In addition, more frequent (i.e. 15 min) sampling during precipitation events may have enabled storm flow pathways in the catchment to be determined (e.g. Soulsby *et al.*, 2003) to increase understanding of water source contributions and associated stream physico-chemical variables during these intermittent events.

2. The Taillon Glacier 'Distributed' system end-member was estimated from relationships between stream discharge and solute concentrations (Tranter and Raiswell, 1991). A more preferable method would have been to collect direct measurements by drilling boreholes from the glacier surface to the glacier-bed (e.g. Lamb *et al.*, 1995). However, the glacier's location in the Parc National des Pyrénées prevented such a study, whilst the wide hydroecological scope made this additional work logistically and practically unfeasible. To improve discharge–solute relationships for the method employed (Chapter 5), ideally more samples would have been collected at the Upper site between low and high flows on sampling days to improve the strength of regression relationships. In addition to snowpack solute assessment at

the beginning of the melt season, weekly samples of snow would have provided a better understanding of elution processes occurring within the catchment (Hodson *et al.*, 2002). This would have allowed for more detailed temporal variability within the 'Quickflow' end member.

3. The length of the study period (i.e. melt season) provided an insight into hydroecological patterns and processes occurring within discrete 'windows' in 2002 and 2003. Given future climate change scenarios and potential changes in the timing of peak snow- and ice-melt (McGregor *et al.*, 1995a), it would be preferable to commence sampling during late May (as opposed to late June as conducted herein) to document the influence of early-peak snowmelt episodes upon stream physico-chemical habitat conditions (e.g. stream discharge, hydrochemistry during snowpack elution). Hydroecological functioning of the catchment in the autumn-early winter could be understood by extending the field-season into late September-early October when climate conditions become cooler and meltwater sources reduce.

4. Although this study has demonstrated clear differences in water source contributions, stream physico-chemical habitat, and stream ecological community variability between two consecutive melt seasons, there is a clear need for longer-term studies (e.g. Chapter 8) to place this inter-annual variability into a longer time frame. This would enable identification of longer-term trends in water source dynamics in addition to highlighting atypical melt season patterns (e.g. Hannah *et al.*, 2000b; Smith *et al.*, 2001). Furthermore, although stream physico-chemical variables for individual stream classifications have been quantified for the headwater Taillon-Gabiétous catchment, further research is necessary within other alpine areas to extend the physico-chemical and ecological database for each category.

5. Most ecological work in alpine streams has focused on benthic macroinvertebrate community variability, since these fauna are numerous, easy to collect and identify, and their

ecology is typically well studied in comparison with other faunal groups. However, analysis of feeding trait dynamics in this study suggests that other members of the stream community (i.e. diatoms, algae) may play an important role influencing macroinvertebrate populations, in addition to abiotic factors, in these harsh environments. However, there are few studies of biotic interactions, in addition to minimal knowledge of stream food web responses to habitat variability in alpine streams (Zah *et al.*, 2001; Füreder *et al.*, 2003a, b). Further research should also consider the implications of dynamic water source contributions, stream habitat variability and biotic interactions influencing benthic macroinvertebrate life histories.

9.3.2. Data analysis

1. By integrating the spatio-temporally distributed data collected in this thesis with previous knowledge of hydroclimatological functioning of the Taillon-Gabiétous catchment (Hannah, 1997; Smith *et al.*, 2001), it may be possible to model water source contributions to streamflow. 'Quickflow' and 'Distributed' water source contributions may be estimated reliably using a simple linear reservoir runoff model (Hannah and Gurnell, 2001) driven by climatological data. An additional groundwater component (karstic and hillslope) incorporating recharge and discharge would be required for predicting water source contributions at sites lower in the catchment. Model output could readily be validated against stream discharge and hydrochemical water source separation estimates, and may be useful in providing information about catchment water source responses under future climate change scenarios. A challenge would be to expand such a model to predict stream physico-chemical variables and ecological responses to changes in water source contributions.

2. The stream discharge data collected as part of the study may have allowed estimates of water source contributions to streamflow to be made based upon hydrograph separation techniques (e.g. Jenkins *et al.*, 1994). Water source contributions estimates obtained using such methods could be compared with those based upon the EMMA hydrochemical separations. If the results obtained by both methods were comparable, it may have been

possible to examine in greater detail temporal variations in water source dynamics based upon the 15 min gauging station discharge data collections. However, such detailed hydrograph analyses were beyond the scope of this study.

3. The automatic weather station deployed as part of the study (Chapter 4) was used to collect a range of climatological measurements in addition to the variables analysed in this study. A fuller examination of the energy exchanges (Evans *et al.*, 1998; Hannah *et al.*, 2004) driving alpine stream thermal dynamics would also have increased understanding of the processes responsible for thermal heterogeneity in these headwater catchments. The collection of water column temperatures at a range of sites throughout the catchment (Chapter 4) also provides a basis for an investigation into thermal variability over longer time-scales, as these data could be compared with results from 1995-1997 (Hannah, 1997; Smith, 1999; Snook, 2000) and ongoing data collections since 2003.

4. Streambed temperature response to discharge variations over seasonal time-scales were found to be inconsistent. Further work could be undertaken to examine correlations at a range of time-scales (e.g. Webb *et al.*, 2003), particularly during precipitation events when peak discharge often occurs at the same time as sharp decreases in stream temperature. Streambed temperature measurements should also be integrated with continuously monitored measurements of hydraulic head using piezometer nests, to elucidate the role of groundwater-surface water interactions upon streambed thermal dynamics (Malcolm *et al.*, 2003).

5. The ecological data only considered benthic macroinvertebrate community dynamics at the reach scale. All reach scale samples were composed of five replicate Surber samples, thus, analysis of individual sample data may increase understanding at smaller spatial scales (i.e. patch; Townsend, 1989; Lake, 2000). Reach scale habitat variables could be partitioned out within multivariate analyses to identify patch scale influences (e.g. substrate composition,

hydraulic stress, POM), increasing understanding of sub reach-scale habitat variables upon stream communities (Figure 9.6).

6. Due to the difficulties of assessing water source contributions to stream discharge within the field, some of the stream classification categories (e.g. Nival, Nivo-krenal) are currently poorly replicated in terms of typical ecological communities (Figures 9.3 and 9.4). Larger data sets are required to increase understanding of ecological communities associated with these alpine stream classifications. This could be accomplished through additional studies in the Taillon-Gabiétous or comparative catchments.

7. Alpine stream habitat categories were based upon an *a priori* division of the ternary diagram with respect to mixtures of water source contributions. Alternative approaches subdividing classes using similarity of stream environmental variables or the use of known habitat preferences of benthic communities could have been undertaken with the available datasets. However, these approaches were outside the scope of this research project due to time constraints and the thesis word limit. These approaches should be examined in more detail in future studies to refine the classification boundaries and compare and contrast different approaches.

9.3.3. Future research directions

1. The conceptual models presented in this chapter have so far been tested only within the Taillon-Gabiétous catchment over two melt seasons. To fully examine their accuracy and transferability, further studies are required to increase replication of benthic macroinvertebrate community data for each classification category. The model needs to be tested in other alpine glacierized catchments with different hydrological functioning, and where additional macroinvertebrate taxa may be found, to identify general relationships between water source contributions and groups of taxa (family/genera). The ecological 'database' for each classification category could also be extended to include algae, diatoms, fish and amphibians, and how these populations are linked within food webs to understand the

potential impacts of changes in hydrological functioning for entire stream communities. This would provide a more complete understanding of the influence of predicted changes in the timing and magnitude of peak water source contributions under future climate change scenarios.

2. There is currently a paucity of data on primary production in alpine streams, with only a few limited spatial and temporal studies. Furthermore, there have been no attempts to relate water source and physico-chemical habitat conditions to algae and diatom community dynamics. This is despite the importance of these food resources for benthic macroinvertebrate communities in headwater alpine streams (Füreder *et al.*, 2003a), due to the lack of allocthonous inputs to provide energy to support secondary production. There should be a major research focus to integrate spatial (longitudinal, between stream types) and temporal variability in algal and diatom communities with benthic macroinvertebrate community dynamics in alpine streams.

3. Current knowledge of alpine stream hydrological and ecological functioning is highly biased towards the summer melt season. This is understandable given the logistical constraints of sampling during winter in these harsh environments. However, understanding of how alpine stream systems function would be greatly enhanced by gaining information on water source contributions, stream habitat conditions (stream discharge, water column and streambed temperatures; hydrochemistry) and benthic community structure during winter periods. Future research programmes should aim to find ways to resolve the difficulties of accessibility and maintaining reliable data collection during winter months.

9.4. KEY CONTRIBUTIONS TO HYDROECOLOGICAL UNDERSTANDING

The major aim of this thesis was to conduct a truly interdisciplinary study to improve understanding of hydroecological relationships within alpine river catchments. This aim has been met by:

1. increasing our understanding of the spatio-temporal dynamics of snowmelt, icemelt and groundwater contributions to streamflow;
2. relating water source contributions to stream physico-chemical habitat conditions within the framework of an alternative alpine stream classification approach, and;
3. using this classification approach as a conceptual basis for linking hydrological (water source and stream physico-chemical variability) and ecological (stream benthic macroinvertebrate communities) sciences.

This integrated hydroecological approach provides a framework for understanding the impacts of potential changes in alpine catchment water source contributions upon stream communities. To fully predict the effects of future climate change on alpine streams, and, thus, realise the full potential of these ecosystems as indicators of change, research to produce a full holistic understanding of climate-hydrology-ecology linkages is required. In the Taillon-Gabiétous catchment, Hannah *et al.* (1999b) have previously demonstrated the ability to link large scale atmospheric circulation patterns with meltwater production, and this present study has demonstrated hydroecological (water source-macroinvertebrate community) relationships. A challenge for future research projects will be to link hydroclimatological and hydroecological processes, to accurately predict stream community dynamics from climate data.

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APPENDIX A. TAXONOMIC REFERENCES USED FOR MACROINVERTEBRATE IDENTIFICATION

Order	References
Chironomidae	(Goetghebuer, 1927, 1928a, b; Ferrarese and Rossaro, 1981; Cranston, 1982; Serra-Tosio, 1983; Wiederholm, 1983; Kowalyk, 1985; Soponis, 1990; Langton, 1991; Schmid, 1993; Rieradevall and Brooks, 2001)
Trichoptera	(Coineau and Jacquemart, 1963; Décamps, 1965, 1966, 1970a, b; Giudicelli, 1971; Décamps and Pujol, 1975; Verneaux and Faessel, 1976; Faessel, 1985; Wallace *et al.*, 1990; Edington and Hildrew, 1995; Sipahiler, 2002)
Ephemeroptera	(Berthélemyi and Thomas, 1967; Thomas, 1968a, b; Müller-Liebenau, 1969; Thomas, 1970; Thomas and Sowa, 1970; Thomas, 1986; Elliott *et al.*, 1988; Studemann *et al.*, 1992)
Plecoptera	(Despax, 1951; Aubert, 1959; Berthélemyi, 1969; Hynes, 1977; Zwick and Vincon, 1993; Pardo and Vincon, 1995; Vinçon and Ravizza, 2001)
Other taxa	(Holland, 1972; Friday, 1988; Smith, 1989)

APPENDIX B. REFERENCES USED TO CHARACTERISE MACROINVERTEBRATE TRAITS

Taxa Order	References/Communications
Diptera	(Lavandier, 1979; Wiederholm, 1983; Lavandier and Décamps, 1984; Armitage *et al.*, 1995; Franquet, 1996) (R. Céréghino, P. Langton & C. Pinder – *pers. comm.* with D. Snook)
Ephemeroptera	(Lavandier, 1979; Olechowska, 1981; Lavandier and Décamps, 1984; Elliott *et al.*, 1988; Studemann *et al.*, 1992; Brietenmoser-Würsten and Sartori, 1995; Céréghino, 1997; Céréghino and Lavandier, 1998; Sartori and Landolt, 1999) (M. Sartori – *pers. comm.* D. Snook)
Plecoptera	(Despax, 1951; Aubert, 1959; Hynes, 1977; Lavandier, 1979; Céréghino, 1997; Céréghino and Lavandier, 1998) (R. Céréghino, G. Vinçon – *pers. comm.* D. Snook)
Trichoptera	(Giudicelli, 1971; Décamps and Pujol, 1975; Lavandier and Pujol, 1975; Pujol, 1975; Verneaux and Faessel, 1976; Lavandier, 1979; Wallace *et al.*, 1990; Lavandier, 1992; Tachet *et al.*, 1994; Edington and Hildrew, 1995; Faessel, 1995; Lavandier and Céréghino, 1995; Céréghino, 1997; Céréghino *et al.*, 1997; Sipahiler, 2002)

APPENDIX C. MEAN ABUNDANCE OF MACROINVERTEBRATE TAXA FOR SIX SAMPLING DATES DURING 2002

Taxa		A1/2002	A2/2002	A3/2002	A4/2002	A5/2002	A6/2002	B1/2002	B2/2002	B3/2002	B4/2002	B5/2002	B6/2002	C1/2002	C2/2002	C3/2002	C4/2002	C5/2002	C6/2002
Baetis	*alpinus*	0	3	3	6	6	112	301	74	141	599	190	290	266	174	116	15	53	134
Baetis	*gadeai*	0	0	0	0	0	0	6	0	13	4	0	3	0	0	0	0	0	0
Rithrogena	*loyolaea*	9	12	21	17	7	7	47	103	339	247	205	271	127	134	324	167	59	74
Rithrogena	*semicolorata*	2	0	1	0	0	0	20	14	35	19	7	4	26	51	43	15	3	1
Habroleptoides	*berthelymni*	0	0	0	0	0	0	5	88	132	74	67	84	0	0	2	0	1	0
Seratella	*ignita*	0	0	0	0	0	0	0	0	1	3	4	1	0	0	0	0	0	0
Ecdyonurus	*venosus*	0	0	0	0	0	0	2	16	10	11	6	1	1	5	3	4	1	0
Leuctra	sp1	0	1	0	0	0	0	3	3	5	3	1	0	3	3	5	3	2	3
Leuctra	*kempnyi*	1	0	0	0	0	0	0	0	0	0	0	0	1	2	5	1	0	1
Leuctra	sp	0	0	0	0	0	0	6	29	41	28	38	22	1	2	16	7	11	4
Chloroperla	*breviata*	0	1	0	0	0	0	30	23	5	10	8	18	10	4	4	0	0	0
Chloroperla		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Isoperla		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Perlodes	*intricatus*	1	4	4	1	3	2	3	8	7	11	7	13	2	10	10	3	3	1
Perla	*grandis*	0	1	0	0	0	0	21	37	51	48	62	59	3	12	29	43	14	21
Capnioneura	*brachyptera*	1	4	10	15	11	10	7	0	1	28	25	34	0	4	0	5	4	4
Protonemoura		0	0	0	0	0	0	15	2	13	33	26	31	0	6	12	7	0	0
Rhyacophila	*angelieri*	48	106	65	91	40	50	0	1	0	0	1	0	14	19	20	8	9	12
Rhyacophila	*intermedia*	1	2	0	1	0	11	1	0	0	0	0	0	0	1	1	1	2	1
Rhyacophila	*eatoni*	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Thremma	*gallicum*	0	0	0	0	0	0	13	16	3	0	0	3	0	1	3	0	0	0
Chaetopterygini	spp	0	0	1	0	0	0	9	7	14	5	3	11	1	4	4	2	5	1
Hydropsyche	*pellucidula*	0	0	0	0	0	0	2	0	1	0	3	11	0	0	0	1	1	0
Drusus	*rectus*	1	2	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
Sericostoma	*personatum*	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Agapetus	*fuscipes*	0	0	0	0	0	0	1	4	1	0	2	2	0	0	0	0	0	0
Micrasema	*longulum*	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Lepidostomatidae		0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0

Taxa		A1/2002	A2/2002	A3/2002	A4/2002	A5/2002	A6/2002	B1/2002	B2/2002	B3/2002	B4/2002	B5/2002	B6/2002	C1/2002	C2/2002	C3/2002	C4/2002	C5/2002	C6/2002
Polycentropus		0	0	0	0	0	0	0	2	0	4	1	0	0	0	0	0	0	0
Esolus	*angustatus*	2	0	2	0	0	1	207	309	247	216	99	99	200	36	83	166	45	42
Oulimnius		0	0	0	0	0	0	3	11	15	8	14	19	1	0	0	0	0	0
Elmis		0	0	0	0	0	0	2	0	0	0	1	3	5	4	3	5	4	8
Helophorus		1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Esolus/Oulimnius		1	1	5	1	0	0	288	191	358	323	273	186	165	68	106	45	15	28
Elmis		0	0	0	0	0	0	1	3	13	8	6	7	0	2	5	0	0	4
Ceratopogonidae		1	0	0	2	5	2	6	5	3	10	6	13	2	15	25	12	6	5
Limoniinae		6	1	0	0	2	0	11	18	24	18	34	36	2	2	2	3	7	6
Dixidae		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Empididae		6	44	18	11	7	10	10	2	1	3	2	3	3	4	8	3	5	0
Psychodidae		2	14	4	4	1	6	5	0	0	0	0	0	2	9	22	2	0	0
Tipulidae		0	8	3	10	3	2	5	4	3	1	2	3	1	5	8	10	0	0
Tabanidae		0	0	1	0	0	0	2	0	0	0	1	0	0	0	0	0	0	0
Simuliidae		13	19	8	15	2	10	84	32	72	59	10	56	46	48	87	7	17	82
Thaumaleidae		0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Blepharoceratidae		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Stratiomyidae		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Polycelis		0	0	0	0	0	2	26	168	94	229	272	285	6	12	24	25	14	12
Crenobia	*alpina*	6	8	3	2	5	7	1	0	0	1	4	4	3	2	0	0	1	0
Planorbiidae		0	0	3	1	2	2	0	0	0	0	0	0	0	1	1	1	0	3
Valvata		0	0	0	0	0	0	1	0	3	0	0	0	0	0	2	1	0	0
Ancylidae		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oligochaeta		0	1	0	1	0	1	9	2	15	3	15	1	0	0	3	1	4	1
Hydrachnellae		0	0	0	0	0	0	0	10	0	6	5	1	10	0	1	0	0	1
Nematocera		0	0	0	0	0	0	2	0	2	0	2	0	0	0	0	0	0	0
Cyclorrhapha		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hemiptera		0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Diamesa	*latitarsis (sp1)*	385	42	5	0	2	0	14	0	0	0	0	0	22	28	4	0	3	0

Taxa		A1/2002	A2/2002	A3/2002	A4/2002	A5/2002	A6/2002	B1/2002	B2/2002	B3/2002	B4/2002	B5/2002	B6/2002	C1/2002	C2/2002	C3/2002	C4/2002	C5/2002	C6/2002
Diamesa	*latitarsis (sp2)*	114	31	10	7	0	8	26	0	0	0	0	0	22	34	19	8	7	0
Diamesa	*cinerella*	4010	224	34	65	43	76	145	6	0	71	0	195	384	209	26	28	16	333
Diamesa	*zernyi*	347	2	0	0	0	0	3	0	0	0	0	7	0	4	0	0	0	0
Diamesa	*cinerella/zernyi*	761	118	15	34	3	12	64	0	0	0	0	27	26	192	21	3	7	15
Diamesa	*aberatta*	199	20	0	0	0	0	3	0	0	0	0	0	0	4	0	0	0	0
Diamesa	*bertrami*	41	19	4	0	0	0	26	0	0	0	0	0	6	22	3	0	0	0
Diamesa	*dampfyi*	19	9	0	0	0	0	3	0	0	8	0	0	0	11	0	0	0	0
Diamesa spp.		129	21	4	0	3	4	13	0	0	36	0	0	11	7	3	2	1	9
Pseudodiamesa	*branickii*	0	0	1	0	0	0	0	0	0	0	0	0	0	6	0	1	0	0
Pseudokiefferiella		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Corynoneura		0	0	0	0	3	15	3	42	40	62	156	23	0	10	0	0	14	13
Eukiefferiella	*minor/fittkaui*	0	6	2	58	42	129	50	46	80	149	76	150	9	0	2	16	8	33
Eukiefferiella	*claripennis*	0	2	0	4	1	8	0	19	43	79	112	8	0	4	3	3	0	0
Eukiefferiella	*cyanea*	166	31	6	4	0	0	8	0	0	0	12	27	7	13	2	5	9	52
Orthocladius (Eud)		0	0	4	0	6	1	15	0	0	0	0	0	2	5	0	2	0	0
Orthocladius (End)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Orthocladius	*frigidus*	75	25	81	208	58	180	51	29	40	24	2	142	10	22	32	60	50	123
Orthocladius	*rivulorum*	0	0	0	0	4	4	0	0	0	0	0	21	0	0	0	5	6	30
Orthocladius	*ashei/rivicola*	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	0
Parorthocladius		0	0	15	216	42	118	336	1646	2027	1622	642	554	88	700	42	54	45	126
Pseudokiefferiella	*parva*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Orthocladiinae		0	0	3	12	1	8	2	27	0	11	36	7	4	17	10	4	6	12
Tvetenia	*bavarica*	0	0	0	0	0	0	0	0	12	131	53	17	0	3	7	17	1	0
Parametriocnemus	*stylatus*	0	7	52	108	13	1	124	72	89	51	22	12	165	108	218	141	30	10
Harnischia		0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
Stempellinella		0	0	0	0	0	0	2	0	7	0	0	0	0	0	0	0	0	0
Micropsectra		0	0	1	0	1	0	8	3	179	561	693	639	0	8	7	52	52	33
Pentaneuriini		0	0	0	0	0	0	0	0	0	20	0	0	0	0	4	0	0	0
Pentaneurella		0	0	0	0	0	0	0	7	0	20	0	0	0	0	0	0	0	0
Macropelopia		0	0	0	0	0	0	3	0	7	28	0	0	0	0	0	0	0	0
Nilotanypus		0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0

Taxa		*A1/2002*	*A2/2002*	*A3/2002*	*A4/2002*	*A5/2002*	*A6/2002*	*B1/2002*	*B2/2002*	*B3/2002*	*B4/2002*	*B5/2002*	*B6/2002*	*C1/2002*	*C2/2002*	*C3/2002*	*C4/2002*	*C5/2002*	C6/2002
Rheotanytarsus		0	0	1	0	3	5	26	3	166	248	274	23	0	0	9	4	5	4
Rheocrictopus	*effusus*	0	0	2	0	7	34	10	0	69	20	6	4	0	4	12	30	15	19
Tanytarsus		0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Chironominae		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thienemanniola		0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	1	45
Metriocnemus	*hygrocriptus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Microtendipes		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parochlus		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX D. MEAN ABUNDANCE OF MACROINVERTEBRATE TAXA FOR SIX SAMPLING DATES DURING 2003

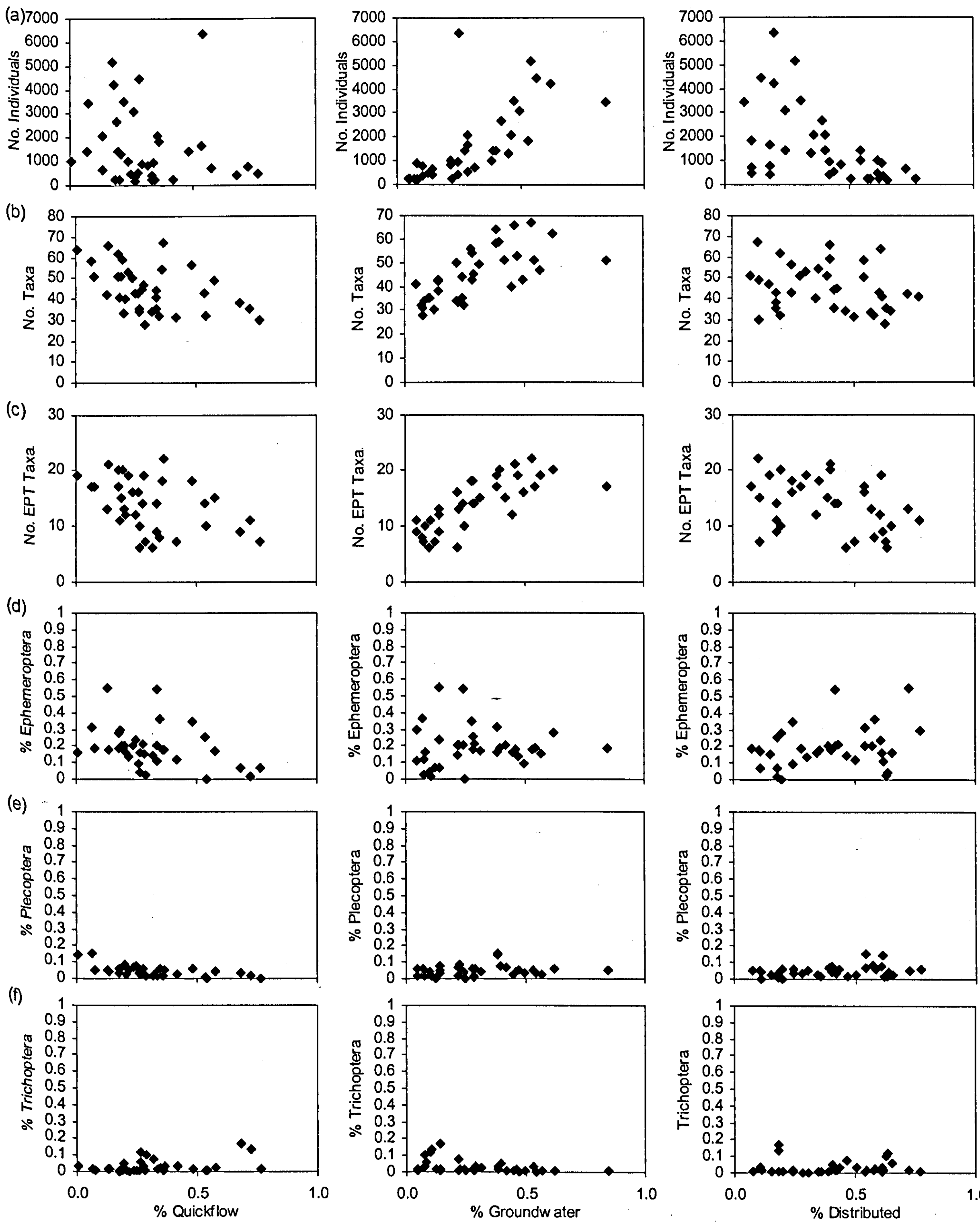
Taxa		A1/2003	A2/2003	A3/2003	A4/2003	A5/2003	A6/2003	B1/2003	B2/2003	B3/2003	B4/2003	B5/2003	B6/2003	C1/2003	C2/2003	C3/2003	C4/2003	C5/2003	C6/2003
Baetis	*alpinus*	10	1	1	3	52	75	167	100	55	307	387	917	77	39	14	68	241	436
Baetis	*gadeai*	0	0	0	0	1	1	1	2	0	1	0	1	2	3	0	1	2	8
Rithrogena	*loyolaea*	8	3	11	1	1	4	98	95	76	106	118	211	26	42	27	37	103	70
Rithrogena	*semicolorata*	18	22	19	21	18	14	34	32	5	3	1	0	16	6	11	5	8	3
Habroleptoides	*berthelymni*	0	0	0	0	0	0	20	23	22	19	28	29	1	0	1	1	0	0
Seratella	*ignita*	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0
Ecdyonurus	*venosus*	0	0	0	0	0	0	6	12	4	2	7	9	0	0	0	0	2	0
Leuctra	sp1	0	0	0	0	0	0	1	1	1	0	6	0	0	0	0	0	0	0
Leuctra	*kempnyi*	0	1	0	0	1	0	7	0	1	0	0	2	1	1	0	0	0	2
Leuctra	sp	0	4	2	1	4	0	14	36	48	20	31	10	7	7	11	13	5	3
Chloroperla	*breviata*	0	0	0	0	2	0	7	4	0	0	0	0	1	2	0	1	9	0
Chloroperla		0	0	0	0	0	0	11	0	0	0	0	0	11	0	0	0	0	0
Isoperla		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Perlodes	*intricatus*	1	0	0	0	0	1	1	0	1	0	0	0	1	0	1	0	0	1
Perla	*grandis*	0	0	0	0	0	0	35	61	78	116	109	145	5	4	8	13	7	18
Capnioneura	*brachyptera*	0	0	2	1	7	14	2	5	5	20	11	13	0	2	1	6	7	5
Protonemoura		0	0	1	2	1	0	21	4	12	56	30	72	5	1	1	2	3	1
Rhyacophila	*angelieri*	4	3	3	2	2	5	4	1	0	0	0	5	0	1	1	0	3	4
Rhyacophila	*intermedia*	3	4	7	1	0	1	0	0	0	0	0	1	2	1	2	0	2	2
Rhyacophila	*eatoni*	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0
Thremma	*gallicum*	0	0	0	0	0	0	17	25	17	2	1	2	2	0	1	1	0	0
Chaetopterygini	spp	0	0	1	0	1	0	34	37	11	5	3	9	12	3	0	1	4	3
Hydropsyche	*pellucidula*	0	0	0	0	0	0	3	1	1	11	4	10	0	1	1	0	0	0
Drusus	*rectus*	0	0	0	0	0	0	0	1	2	1	0	14	0	0	0	0	0	0
Sericostoma	*personatum*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Agapetus	*fuscipes*	0	0	0	0	0	0	5	1	2	3	10	9	0	0	0	0	0	0
Micrasema	*longulum*	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	2

Taxa		*A1/2003*	*A2/2003*	*A3/2003*	*A4/2003*	*A5/2003*	*A6/2003*	*B1/2003*	*B2/2003*	*B3/2003*	*B4/2003*	*B5/2003*	*B6/2003*	*C1/2003*	*C2/2003*	*C3/2003*	*C4/2003*	*C5/2003*	*C6/2003*
Lepidostomatidae		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Polycentropus		0	0	0	0	0	0	2	1	2	0	1	0	0	0	0	0	0	0
Esolus	*angustatus*	0	13	3	2	1	0	364	463	147	90	21	10	44	43	4	128	47	51
Oulimnius		0	0	0	0	0	0	5	12	3	10	2	6	1	4	0	10	0	0
Elmis		0	0	0	0	0	1	3	1	1	0	2	2	0	0	0	0	0	0
Helophorus		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Esolus/Oulimnius		0	5	0	2	1	3	246	108	108	221	133	114	66	32	3	21	21	37
Elmis		0	0	0	0	0	0	2	0	4	3	7	0	1	1	2	2	0	0
Ceratopogonidae		0	0	0	0	1	1	4	2	0	0	0	1	6	0	0	1	0	0
Limoniinae		1	0	2	3	4	1	5	14	17	17	32	20	4	7	7	9	12	11
Dixidae		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Empididae		5	3	12	12	7	8	2	4	4	1	3	3	4	5	2	3	4	2
Psychodidae		3	3	4	14	6	4	2	0	0	0	0	8	3	0	3	1	2	0
Tipulidae		4	0	1	2	3	3	9	4	6	11	15	21	3	1	1	13	12	1
Tabanidae		0	0	0	1	0	0	1	0	0	0	0	0	1	0	2	0	1	1
Simuliidae		0	22	4	5	14	17	24	22	37	23	35	23	19	58	19	27	52	43
Thaumaleidae		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Blepharoceratidae		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stratiomyidae		0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Polycelis		0	0	0	0	0	0	180	83	110	88	120	149	9	6	5	16	3	4
Crenobia	*alpina*	5	4	12	12	5	2	2	4	4	4	0	0	0	1	0	0	0	0
Planorbiidae		0	0	0	1	0	0	1	0	1	1	1	1	0	0	0	1	0	0
Valvata		0	0	0	0	0	0	2	1	0	1	0	0	0	0	0	0	0	0
Ancylidae		0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
Oligochaeta		2	1	1	2	5	1	7	5	12	3	4	3	3	0	0	3	2	2
Hydrachnellae		0	0	0	0	0	0	6	5	15	6	0	6	3	1	0	0	1	0
Nematocera		0	0	0	0	0	0	0	0	4	1	0	2	0	0	0	0	0	0
Cyclorrhapha		0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Hemiptera		0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0

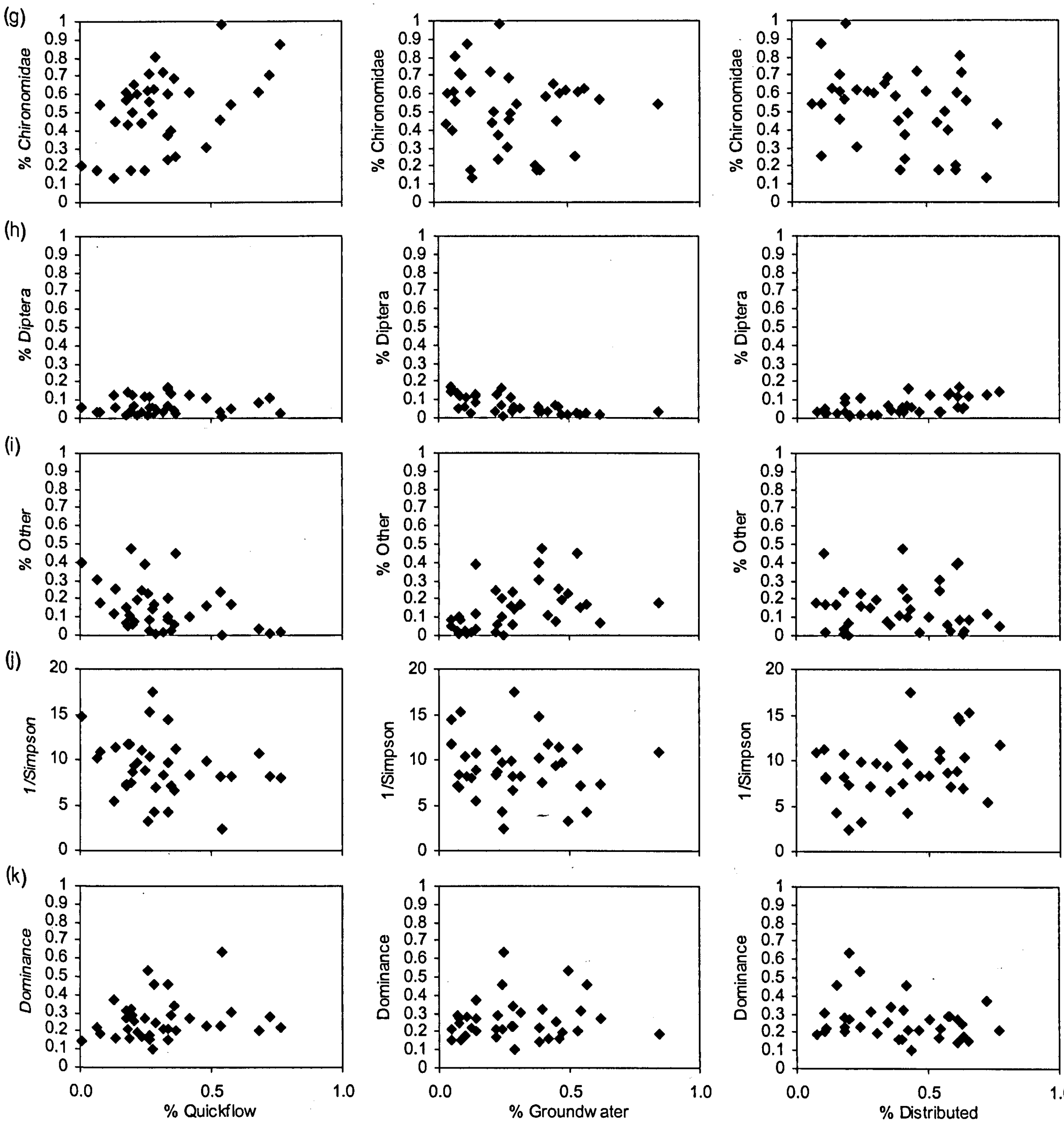
Taxa		A1/2003	A2/2003	A3/2003	A4/2003	A5/2003	A6/2003	B1/2003	B2/2003	B3/2003	B4/2003	B5/2003	B6/2003	C1/2003	C2/2003	C3/2003	C4/2003	C5/2003	C6/2003
Diamesa	*latitarsis (sp1)*	30	8	3	4	3	0	0	0	0	0	0	0	8	0	0	2	0	0
Diamesa	*latitarsis (sp2)*	85	62	30	30	15	3	6	0	2	0	0	0	222	93	75	11	5	6
Diamesa	*cinerella*	86	4	8	1	2	0	7	0	4	8	429	178	0	3	0	7	8	3
Diamesa	*zernyi*	13	2	6	1	0	0	4	1	5	4	275	37	11	1	0	4	3	4
Diamesa	*cinerella/zernyi*	111	8	13	9	3	2	12	1	3	6	243	126	19	11	1	12	11	13
Diamesa	*aberatta*	52	34	23	7	2	2	0	0	0	0	0	20	16	1	0	0	1	2
Diamesa	*bertrami*	1	3	1	0	0	0	0	0	0	0	0	0	7	0	3	1	0	0
Diamesa	*dampfyi*	1	3	7	1	1	0	0	0	0	1	8	0	2	0	0	0	0	0
Diamesa spp.		19	5	3	3	3	2	1	1	1	2	3	12	39	12	15	2	6	6
Pseudodiamesa	*branickii*	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2
Pseudokiefferiella		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Corynoneura		0	1	0	1	0	0	76	39	9	29	112	28	0	0	0	0	0	0
Eukiefferiella	*minor/fittkaui*	0	0	1	8	13	36	18	22	18	60	34	130	0	0	0	4	11	16
Eukiefferiella	*claripennis*	1	0	0	0	0	0	3	1	0	6	21	29	0	0	0	0	0	0
Eukiefferiella	*cyanea*	4	1	1	6	3	5	5	2	5	9	3	25	0	0	0	2	4	39
Orthocladius (Eud)		0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0
Orthocladius (End)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Orthocladius	*frigidus*	2	0	7	17	36	43	38	7	20	33	268	1140	15	0	8	11	27	57
Orthocladius	*rivulorum*	0	0	0	1	0	1	0	0	1	4	23	335	0	0	0	2	0	67
Orthocladius	*ashei/rivicola*	0	1	1	2	1	0	3	2	0	0	0	0	1	0	0	0	0	1
Parorthocladius		0	0	0	0	7	0	28	38	8	7	11	21	3	0	0	0	0	0
Pseudokiefferiella	*parva*	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Orthocladiinae		2	0	0	1	5	3	29	11	9	1	0	71	11	5	8	0	2	6
Tvetenia	*bavarica*	0	0	0	3	4	0	0	0	0	1	0	0	3	0	0	5	1	1
Parametriocnemus	*stylatus*	27	3	5	34	5	2	117	81	69	20	14	79	33	35	18	20	7	1
Harnischia		0	0	0	0	0	0	0	4	1	0	0	5	0	0	0	0	0	0
Stempellinella		0	0	0	0	0	0	25	12	0	0	0	0	0	0	0	0	0	1
Micropsectra		0	0	0	0	0	0	52	6	17	13	60	45	5	1	0	1	1	1
Pentaneuriini		0	0	0	0	0	0	1	7	2	2	4	0	0	0	0	0	0	0
Pentaneurella		0	0	0	0	0	0	1	4	3	0	8	4	0	0	0	1	0	0

Taxa		A1/2003	A2/2003	A3/2003	A4/2003	A5/2003	A6/2003	B1/2003	B2/2003	B3/2003	B4/2003	B5/2003	B6/2003	C1/2003	C2/2003	C3/2003	C4/2003	C5/2003	C6/2003
Macropelopia		0	0	0	0	0	0	0	0	2	0	3	0	0	0	1	0	0	0
Nilotanypus		0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Rheotanytarsus		0	1	1	3	0	0	3	1	6	1	0	17	1	0	0	0	1	0
Rheocrictopus	*effusus*	3	1	0	1	0	1	18	13	14	45	36	57	0	0	2	0	1	1
Tanytarsus		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chironominae		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thienemanniola		0	0	0	0	0	0	0	0	4	3	11	12	0	0	0	0	0	0
Metriocnemus	*hygrocriptus*	0	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
Microtendipes		0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Parochlus		0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0

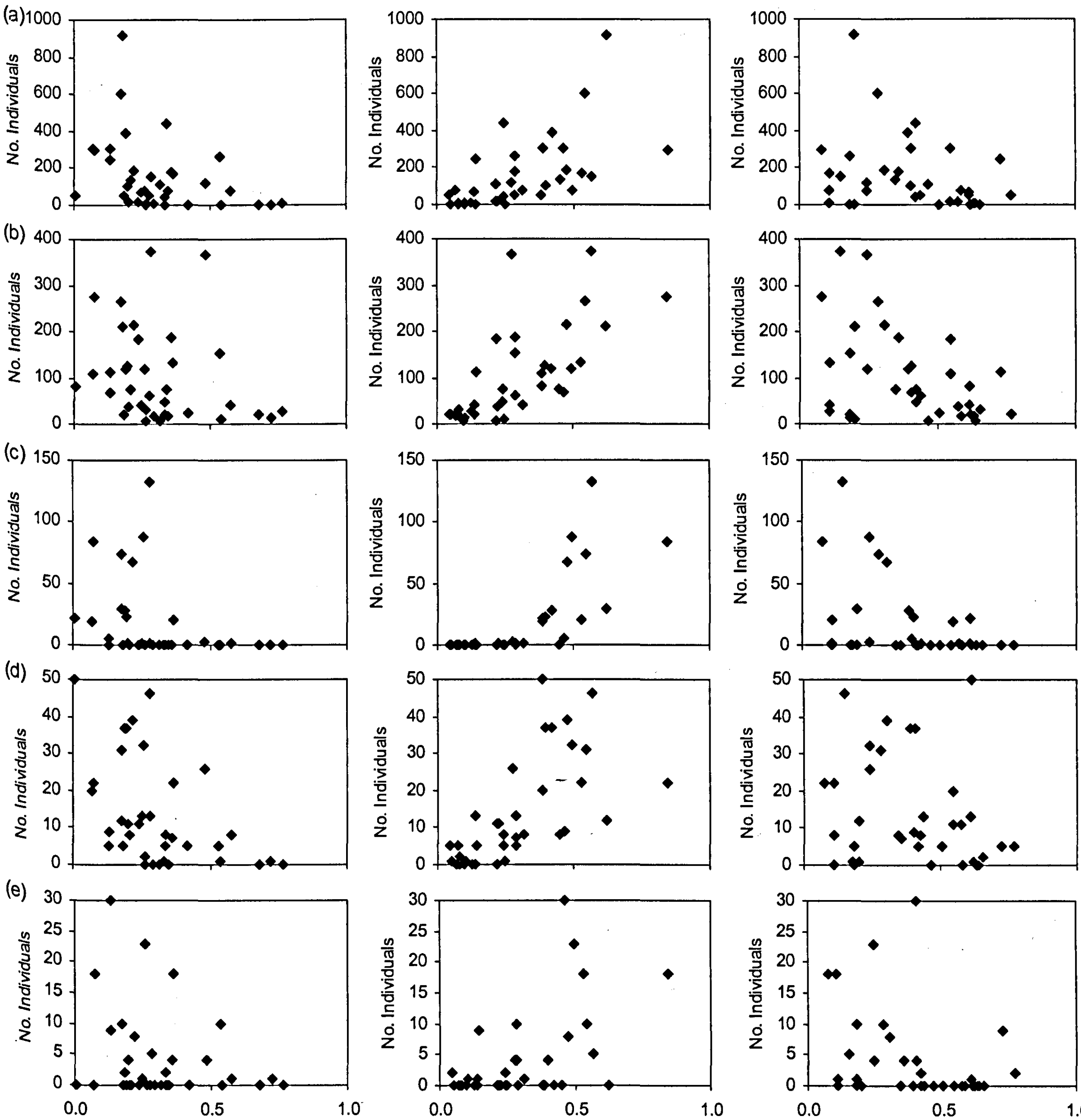
APPENDIX E. RELATIONSHIPS BETWEEN BENTHIC COMMUNITY DESCRIPTIVES AND WATER SOURCE CONTRIBUTIONS



APPENDIX E. CONTINUED

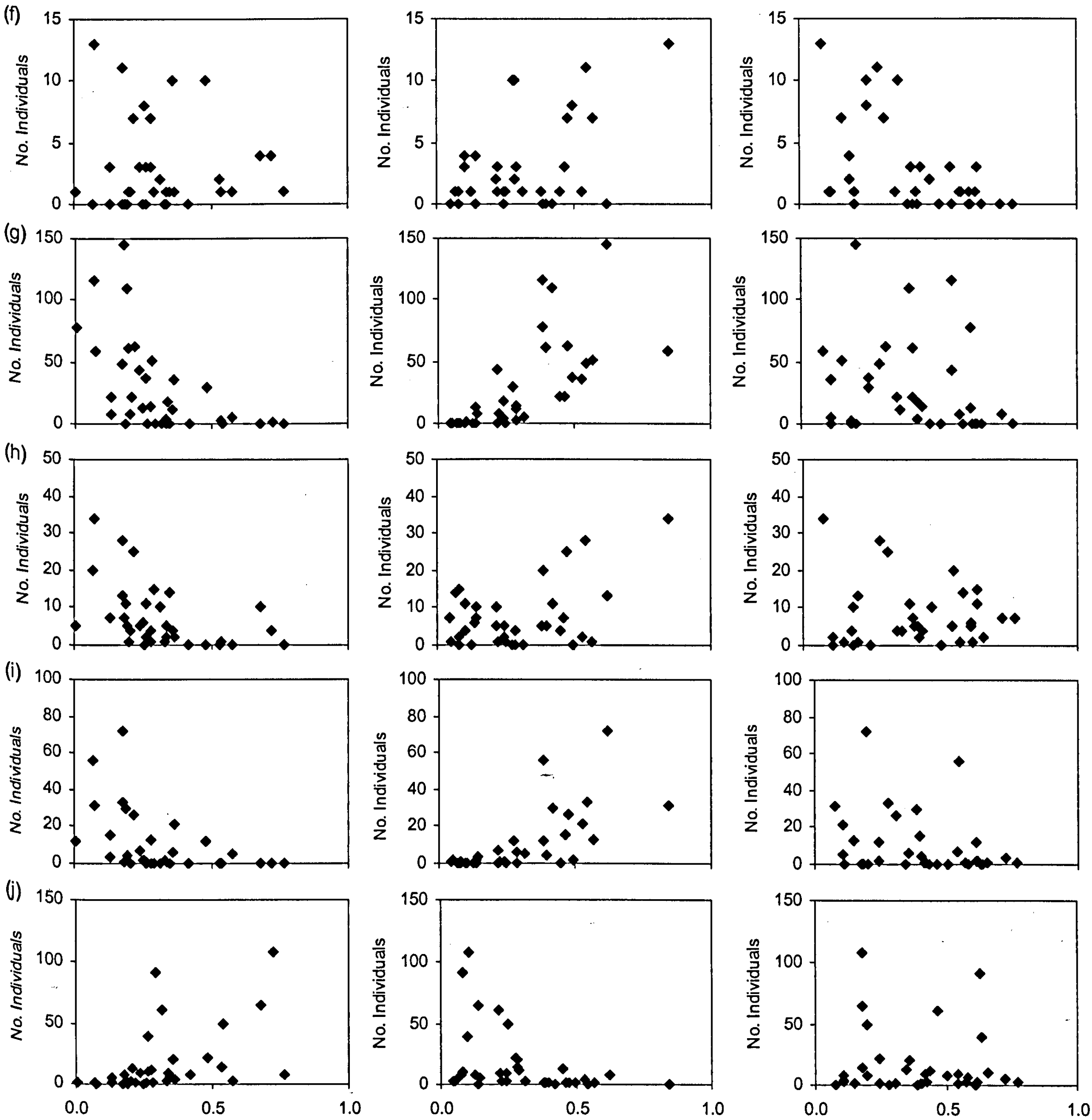


APPENDIX F. RELATIONSHIPS BETWEEN TAXA ABUNDANCES AND WATER SOURCE CONTRIBUTIONS



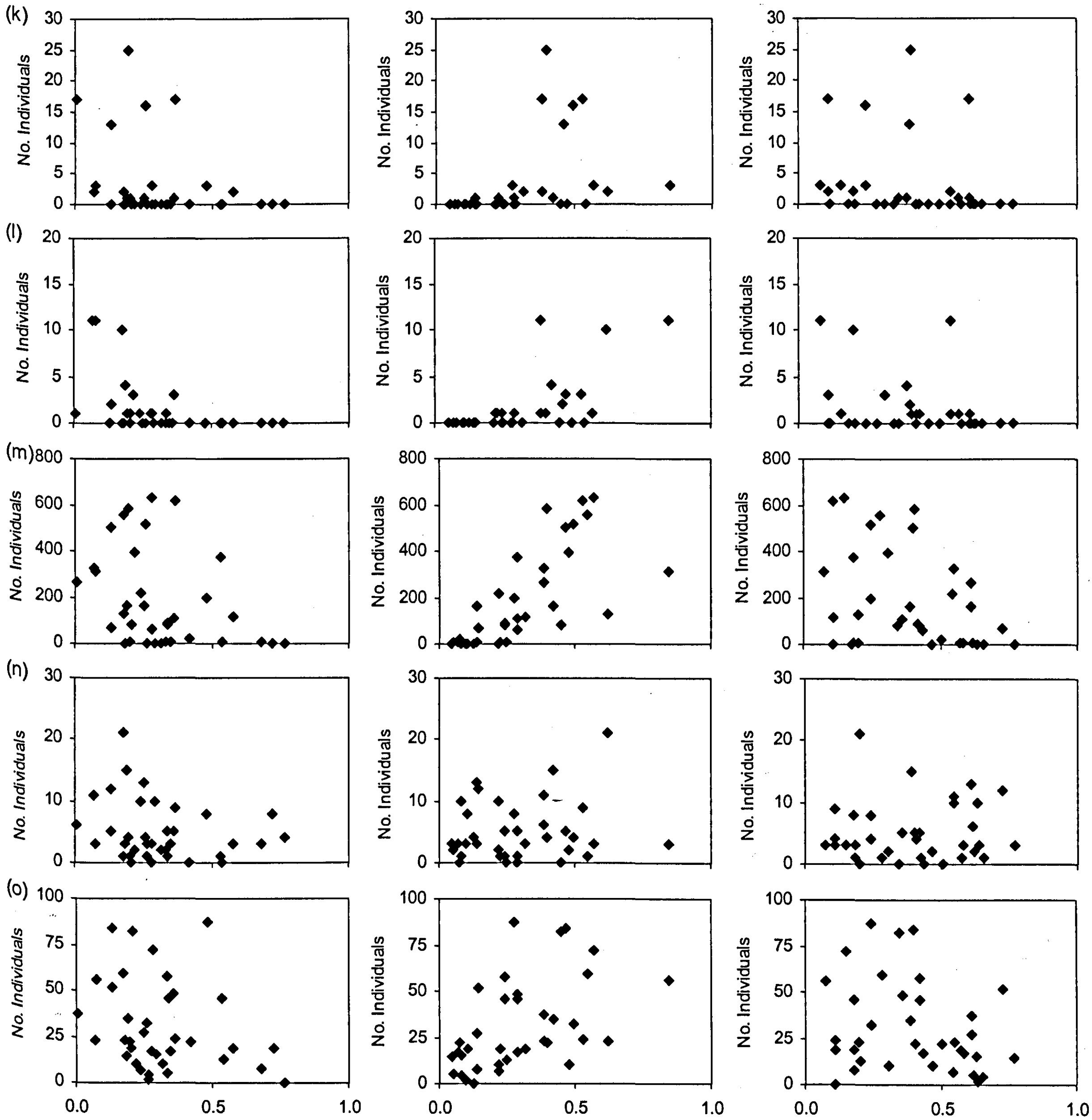
(a) ***Baetis*****; (b)** ***Rithrogena*** **(c)** ***Habroleptoides berthelemyi;*** **(d)** ***Leuctra*****; (e)** ***Chloroperla***

APPENDIX F. CONTINUED



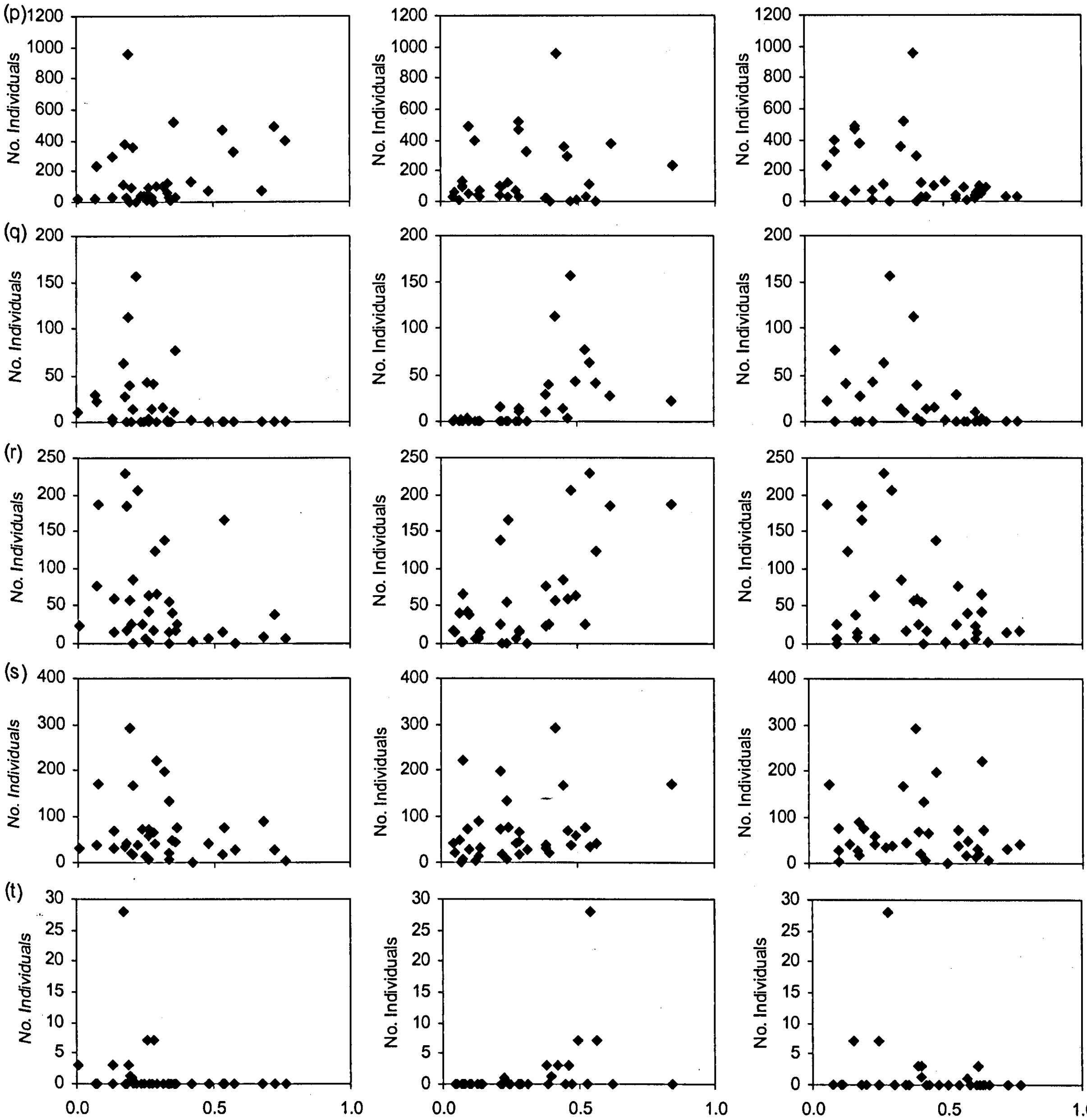
(f) ***Perlodes*****; (g)** ***Perla grandis*****; (h)** ***Capniidae*****;**
(i) ***Protonemoura*****; (j)** ***Rhyacophila***

APPENDIX F. CONTINUED



(k) *Thremma gallicum*; (l) *Hydropsyche*; (m) Coleoptera; (n) Tipulidae; (o) Simuliidae

APPENDIX F. CONTINUED



(p) ***Diamesa*****; (q)** ***Corynoneura*****; (r)** ***Eukiefferiella*****; (**
Orthocladiinae; (t) Tanypodinae