CHAPTER 1

General introduction

1.1 Introduction

Almost thirty years ago Hynes (1975) recognised the importance of groundwater to in-stream processes, not just as a source of supplementary flow, but also as a significant contributor to nutrient dynamics and biodiversity. Since then, research into the stream/groundwater interface has flourished, culminating in an extensive literature on the area known as the hyporheic zone (defined in section 1.2, see reviews in Jones and Mulholland 2000, Ward *et al.* 2000). However, until recently, management policies have treated groundwater and surface waters separately, rather than as a continuum, and have overlooked the central role played by the hyporheic zone (Boulton 2000b).

Greater pressure is being placed on freshwater ecosystems to provide water for ever-increasing human demand. Groundwater aquifers and rivers are two of the primary sources of fresh water and the recognition that they are hydrologically linked means that one cannot be managed without consideration of the other (Winter *et al.* 1998, Hancock 2002). For example, excessive pumping of groundwater from an aquifer that feeds a nearby stream may cause the stream to dry. Alternatively, if pollution occurs in a stream that feeds an aquifer, groundwater resources can be contaminated for many years. The establishment of the NSW Groundwater Dependent Ecosystems Policy (Department of Land and Water Conservation 2002) recognises the importance of links between surface and groundwater. It aims to protect groundwater dependent ecosystems (GDEs), such as the hyporheic zone, while achieving efficient and sustainable management of surface and groundwater resources.

1.2 The hyporheic zone

As water moves downstream in a gravel-bed river, it exchanges between the channel and its surrounding saturated sediments. Downwelling surface water is generally rich in oxygen and some nutrients, and enters the sediments at areas of bed inflection, such as the head of riffles or gravel bars (Figure 1.1). During its temporary subterranean residence, the water undergoes a series of transformations and mixes with groundwater, so that when

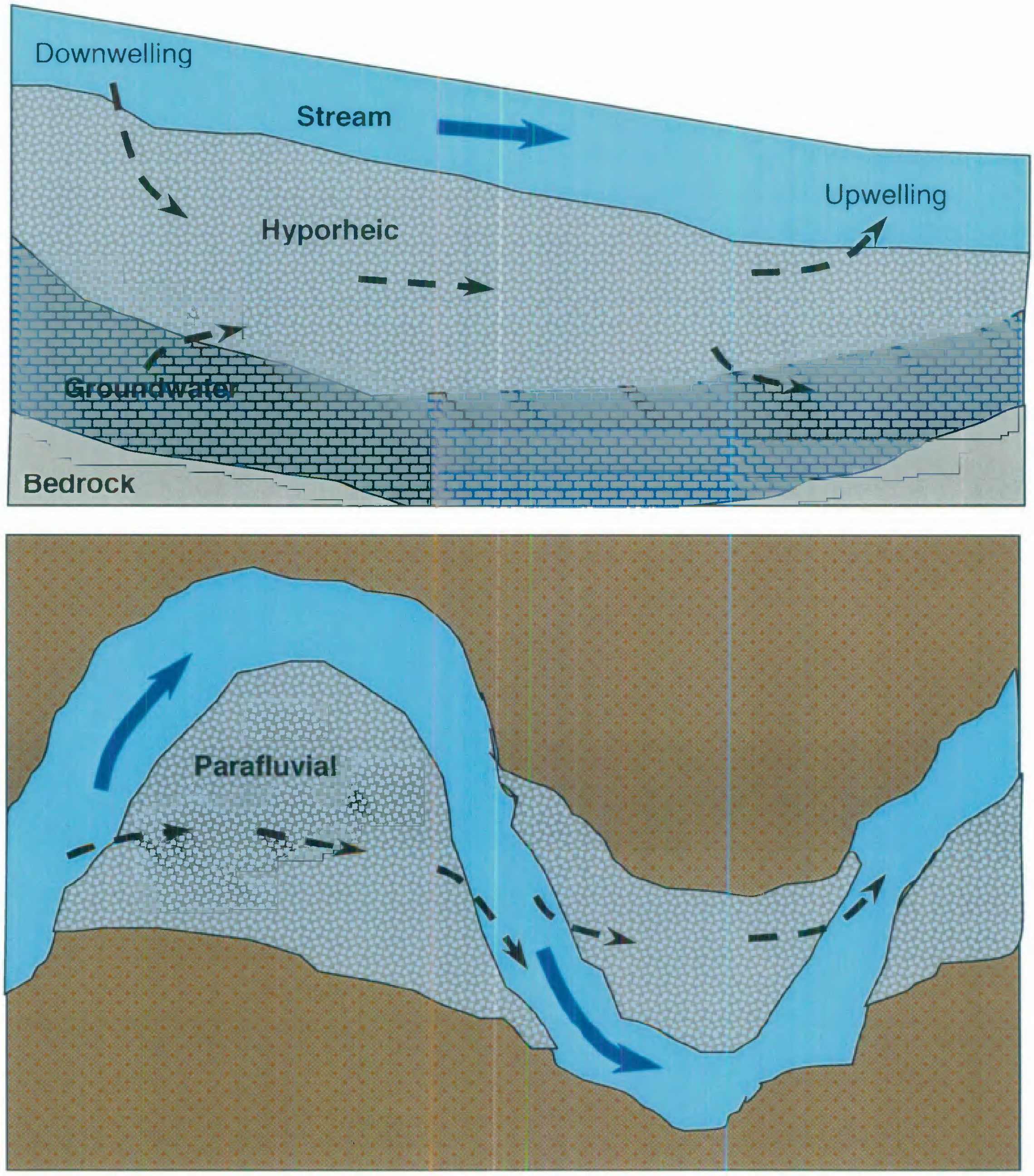

Figure 1.1. Longitudinal cross-section (upper) of a riffle and an aerial view of a lateral bar sequence (lower), showing hyporheic and parafluvial exchanges (dashed arrows). Solid arrows represent flow in the main channel.

it exits it is often chemically different. This area of exchange, which acts as a variable boundary between the stream and the aquifer, is called the hyporheic zone. The hyporheic zone is characterised by intense biogeochemical activity (Morrice *et al.* 2000, Min *et al.* 2003) and transforms the water passing through it (Hancock 2002). In small streams, all of the water in the channel can exchange with the hyporheic pore water within several kilometres (Harvey and Wagner 2000), so it is clear that hyporheic processes have implications for whole-stream ecology. Localised areas of upwelling and downwelling have been found to influence algal growth (Martí *et al.* 1997, Dent and Henry 1999, Henry and Fisher 2003), aquatic plant growth (White *et al.* 1992), and fish spawning sites (Power *et al.* 1999, Malcolm *et al.* 2003).

In large floodplain rivers, such as the Flathead River in Montana (Stanford *et al.* 1994) the Rhône River in France (Marmonier *et al.* 2000), and the Tagliamento River in Italy (Arscott *et al.* 2002), the hyporheic zone can be up to 3 m deep and extend laterally for more than a kilometre. The lateral extension of the hyporheic zone is often referred to as the parafluvial zone (Holmes *et al.* 1994a, 1994b, Claret *et al.* 1999). Globally, these interstitial habitats, and those associated with lakes, wetlands, and groundwater aquifers, house an impressive inventory of species. This biodiversity has been estimated to contain more than 100 000 invertebrate species, and 20 000 species of bacteria and protozoa (Palmer *et al.* 1997, Palmer *et al.* 2000).

This rich biota makes up the biological component of hyporheic filters which, when complemented by the physical and chemical components, enhance stream and groundwater quality (Boulton 1999, Hancock 2002). Stream water entering the hyporheic zone at downwelling zones is oxygen rich, and entrained with nutrients and small particles of organic matter. As it travels through the pore-space, particles become trapped in the sediment matrix (Vervier *et al.* 1992). This is the physical component of the filter (Figure 1.2a). Microbes and small detritivorous invertebrates subsequently decompose the organic fraction of the particles (Figure 1.2b). Water moving through the interstitial pore space travels slower than it does in the stream, and is constantly in contact with a large surface area of microbially-coated sediments. Bacterially-aided nutrient transformations are a key component of the self-purification process in many streams (Claret *et al.* 2000). Where hyporheic oxygen concentrations of a site on the regulated Rhône River were high enough to allow unimpaired microbial activity, concentrations of nitrate-N increased with both depth and travel distance from the surface stream (Claret *et al.* 2000). Conversely, riparian parafluvial zones that are rich in dissolved organic carbon such as those of Contentnea Creek, North Carolina (Spruill 2000) and Nakdong River, Korea, (Min *et al.* 2003) can remove nitrates from agriculturally polluted groundwater through denitrification. Nutrients dissolved in water of surface or subterranean origins are transformed or adsorbed by the microbial film (Vervier *et al.* 1992), which is then grazed by a variety of invertebrates (Borchardt and Bott 1995, Boulton 2000b, Figure 1.2b).

The efficiency of this biological component of filtration is correlated with microbial activity (Marmonier *et al.* 1995), which in turn is stimulated by the presence of invertebrates. By modifying sediment particle distribution and acting as 'ecosystem engineers', invertebrates enhance aerobic and anaerobic microbial activity (Mermillod-Blondin *et al.* 2003). The chemical filtration component relies largely on the prevalent redox conditions of the hyporheic zone, affecting the precipitation of dissolved metals and minerals (Wielinga *et al.* 1994, Harvey and Fuller 1998, Spruill 2000, Figure 1.2c). The precipitants become trapped by the physical filter, and transformed or adsorbed by microbes. The three filtration mechanisms function under fluctuating redox conditions. Many of the microbes require oxygen, although there are some that do not, and these are equally important in filtration processes (Duff and Triska 2000). In particular, anaerobic sediments in the hyporheic zone can be one of the most important areas of denitrification in nitrate-rich streams (Spruill 2000). Generally, oxygen is consumed by the biota of the filter, so even pristine streams have anoxic areas in their hyporheic and parafluvial zones (Boulton *et al.*1998).

The hyporheic zone is a dynamic ecotone, centrally connected to parafluvial zones, riparian habitats, groundwater, and the surface stream (Gibert *et al.* 1990, Figure 1.3). Water and nutrients are exchanged among these habitats in vertical and horizontal directions (Figure 1.4) at different spatial and temporal scales (Boulton *et al.* 1998). Hyporheic and parafluvial waters often display physico-chemical gradients with distance from the surface stream. The strength and direction of exchange, and the steepness of physico-chemical gradients depend on existing hydrological, geomorphological, and biological conditions.

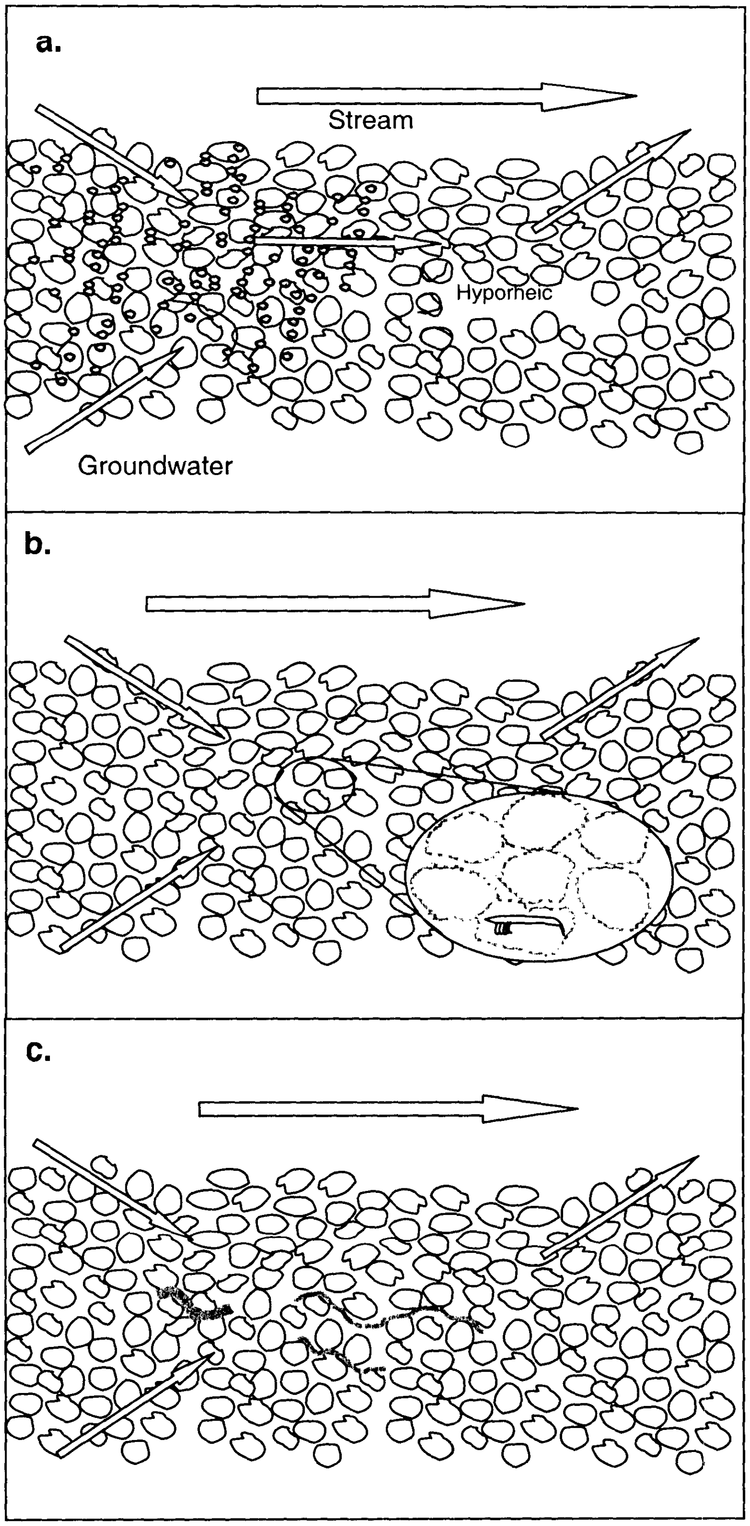

Figure 1.2. The physical (a), biological (b), and chemical (c) components of hyporheic filtration. See text for details (After Hancock 2002).

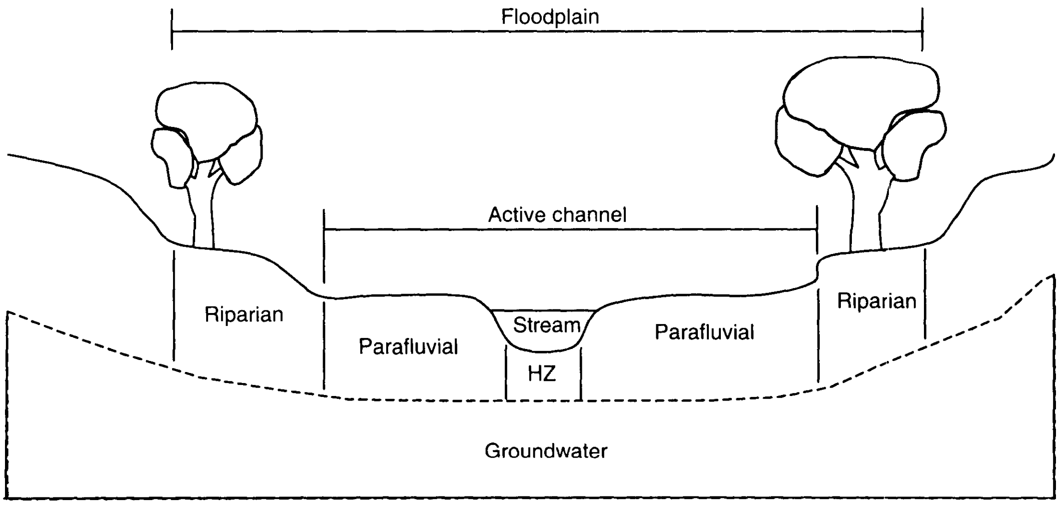

Figure 1.3. Cross section of a river corridor showing the relative location of the stream, hyporheic zone (HZ), parafluvial zone, riparian habitat, and their connection to the groundwater (after Holmes *et al.* 1994a).

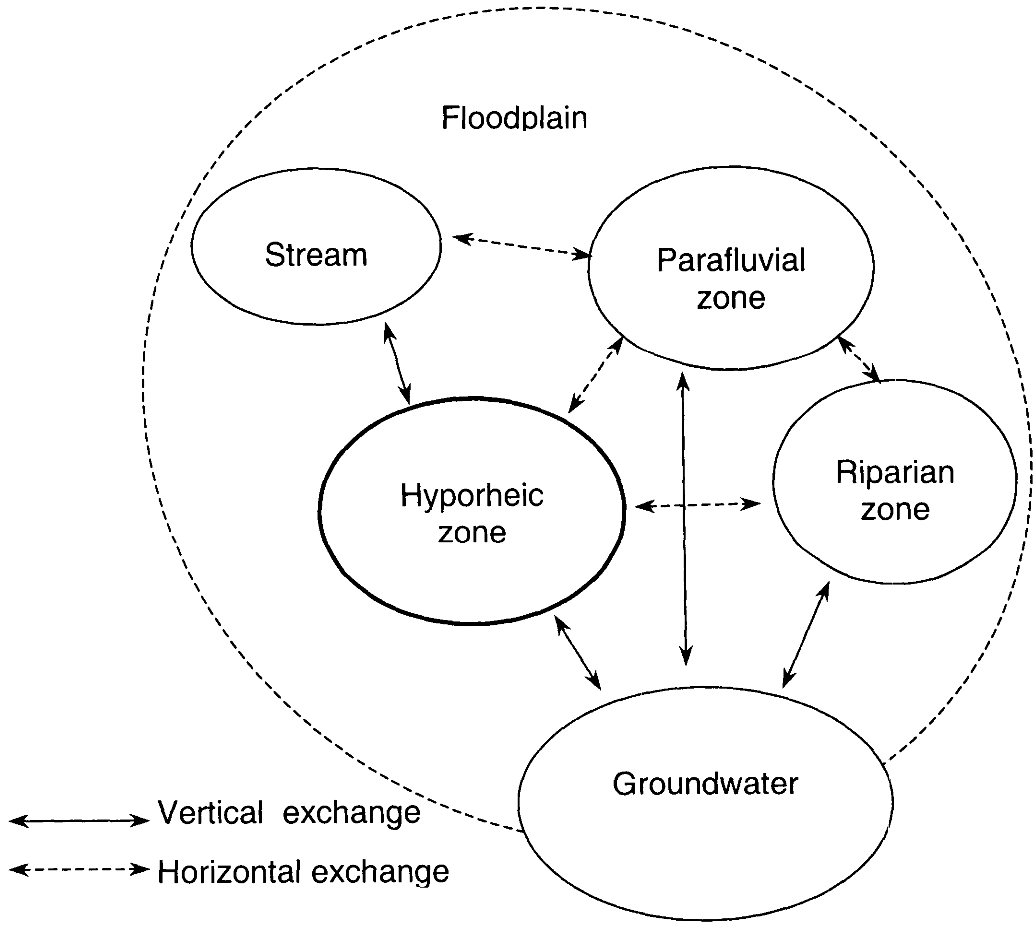

Figure 1.4. The central role of the hyporheic zone in linking the stream and groundwater to floodplain habitats in gravel-bed rivers

1.3 The importance of flow fluctuations to the hyporheic zone

Disturbances are key determinants of community structure (Townsend *et al.* 1997). In rivers, spates constitute one of the main disturbances, re-distributing the components of prior habitats to create new ones (Arscott *et al.* 2002). However, river regulation often reduces the frequency and magnitude of spates (Kingsford 2000, Marchant and Hehir 2002), which can affect the riverine macroinvertebrate fauna (Blinn *et al.* 1995, Humphries *et al.* 1999), riparian vegetation (Jansson *et al.* 2000), and waterbirds (Kingsford 2000). Rivers with large floodplains require regular high flows to maintain linkages between floodplain ecosystems and the river (Arscott *et al.* 2002). The period between these flushing events can increase as a result of river regulation, or links can be lost altogether (Reid and Brooks 2000). Contrasting with this is the situation seen in some dryland rivers in Australia, where regulation maintains flow levels for irrigation when the river would otherwise be dry (McMahon and Finlayson 2003). Geomorphologic processes also become affected by river regulation, reducing the frequency with which river habitats are renewed (Gippel 2001). The reduction in the frequency of high flows downstream of reservoirs can lead to channel migration and bank erosion (Shields *et al.* 2000).

The intermediate-disturbance hypothesis (Connell 1978) predicts that diversity peaks at intermediate levels of disturbance (McCabe and Gotelli 2000). Therefore, disturbances that occur at intervals not too close together, nor too far apart, can have a key role in ecosystem structuring. Medium-sized spates constitute intermediate disturbances and, while not affecting the riverine corridor to the extent of large flows, are still able to re-structure parts of the habitat (e.g., move bed-sediments) without destroying refugia (Townsend *et al.* 1997). Medium-sized flows also wash accumulated small debris from some areas of the stream and distribute it in others, and more rapidly transport nutrients downstream.

Flow fluctuations affect the vertical and lateral connections of rivers. With an increased hydraulic head, stream water penetrates deeper into the sediments, extending both the vertical and lateral dimensions on the hyporheic zone during and after the release (Figure 1.5). A simulated hydroelectricity regime in a Canadian river altered flow pathways and hyporheic water chemistry (Curry *et al.* 1994). There, rising stream water moved the shoreline and rapidly (< 1 day) infiltrated groundwater pathways. The increases in discharge brought about by environmental flow releases have the potential to re-establish or maintain these linkages. In Brenno River, Switzerland, river management, including regulation and abstraction, reduced the number of small to medium flood events (Brunke 1999). As a result, lateral connections to the gravel floodplain decreased strongly while vertical connectivity increased. It was proposed that annual releases to simulate small to medium floods could generate a diversity of disturbances, and re-establish connections to the floodplain (Brunke 1999).

Spates of all magnitudes provide natural hydrologic variations that can prevent hyporheic zones from becoming clogged. The clogging of sediments is termed colmation (Brunke 1999) and can sever the hyporheic zone from the stream. With time at base or low flow, fine particles accumulate in the sediment matrix and pore-space declines, allowing less oxygen-rich water to percolate through the sediments. Low oxygen can restrict invertebrate activity in the sediments (Hakenkamp and Palmer 2000), and therefore the grazing on microbial biofilms. The build-up of biofilms could further contribute to colmation (Battin and Sengschmitt 1999). As redox conditions in the sediments move towards anoxia, anaerobic bacteria take over the filtration processes. If flow in the surface channel continues at base-flow or declines, then many of the filtration processes at downwelling zones that depend on oxygen will potentially cease to function. If it rains or water is released from an upstream reservoir such that there is an increase in water level, then aerobic conditions may once again prevail. Even moderate increases in flow can re-distribute bed-sediments, abrade the microbial coating and wash fine particles rapidly downstream. Hyporheic bacterial activity can respond rapidly to fluctuations in discharge. Bacterial carbon production (BCP) in the bed sediments of the Breitenbach in Germany decreased when biofilm was abraded by a spate (Marxsen 2001). However, one month later BCP was higher than it was before the spate.

Of course, in areas of the river where subterranean water enters the channel, the sediments are not necessarily so prone to colmation. Water exfiltrating from aquifers is relatively free of fine particles (Wright and Symes 1999), and as the hydrological balance in the hyporheic zone shifts to groundwater dominance, particles can be flushed from below.

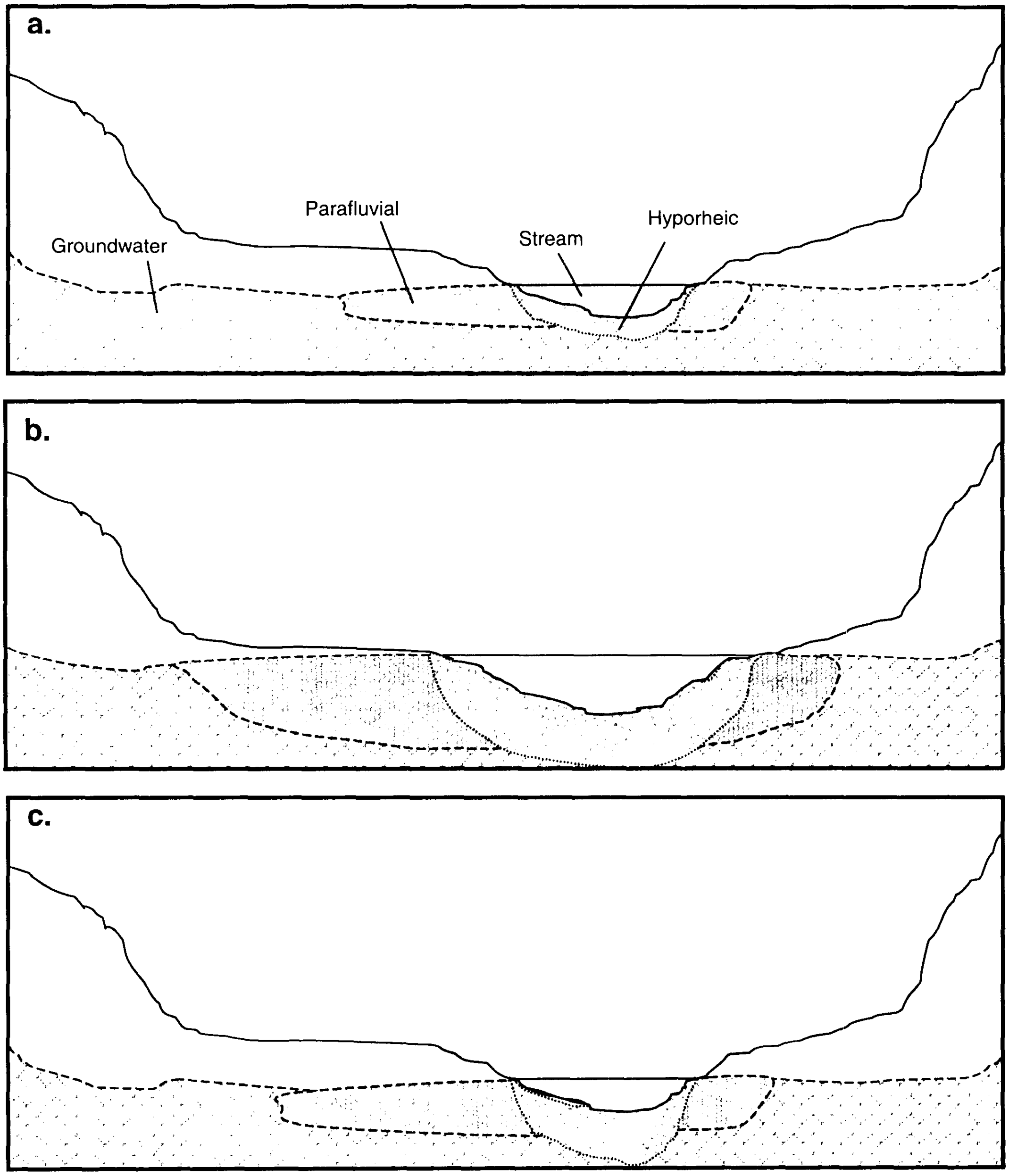

Figure 1.5. The potential spatial dynamics of the hyporheic zone in response to a medium- level flow. At baseflow (a) the hyporheic and parafluvial zones are relatively contracted. An increase in flow (b) causes higher hydraulic pressure and both areas expand laterally and vertically. Sediments are loosened and silt flushed from the pores so that when flow recedes (c) hyporheic and parafluvial zones remain larger than they were initially.

Groundwater is often rich in dissolved organic carbon (Sear *et al.* 1999), which can supply interstitial biofilms, but as long as the connection to the stream is maintained and invertebrates control biofilms by grazing, colmation in these streams can be avoided. In fact, exfiltrating groundwater in the Brenno River, Switzerland, was found to allay the ecological impacts of hydropower flow regulation on the floodplain (Brunke 2002).

1.4 Nutrient dynamics and flow

Nitrogen dynamics in hyporheic zones have been extensively studied (Duff and Triska 2000). Nitrogen entering the hyporheic zone with downwelling water percolates through the sediments. As it does so, dissolved organic nitrogen is mineralised and ammonium is nitrified (Triska *et al.* 1990, Jones *et al.*1995). Inorganic nitrogen can then be immobilised by bacteria, taken up by plants, or returned to the stream (Wondzell and Swanson 1996). Nitrogen transformation is often greatest at the upstream part of the hyporheic or parafluvial zone (Fisher *et al.* 1998). At constant low flows, nitrogen can undergo a series of transformations, shifting from nitrate when sediments are high in oxygen to ammonium or nitrogen gas when oxygen is limiting (Duff and Triska 2000). Even in aerobic hyporheic zones of apparently homogenous sediments, such as in the sand-bed Sycamore Creek, Arizona, internal heterogeneity can lead to small pockets of anoxia, which are key areas for reductive processes (Fisher *et al.* 1998).

This spatial heterogeneity is essential for many hyporheic zone activities. Fluctuations in stream stage can also contribute to hyporheic zone heterogeneity, and have led to increases in the flux of nitrogen (Wondzell and Swanson 1996). The increased hydraulic exchange resulting from higher river stages transports more nitrogen into the sediment, while removing accumulated interstitial nitrate to the stream and enhancing microbial activity (Mulholland *et al.* 1997). In Sycamore Creek, a nitrate-limited desert stream, hyporheic nitrate-N and dissolved oxygen concentrations were relatively high following a spate (Stanley and Boulton 1995). However, as river stage dropped, nutrient and oxygen concentrations decreased in hyporheic sediments below 50 cm deep. In some parafluvial flowpaths of Sycamore Creek, near-stream microbial nitrate production re-established 60 days after the recession of a flash flood (Holmes *et al.* 1998). In the same system, the nitrate retention efficiency doubled following a midsummer flood (Martí *et al.* 1997).

Groundwater can also be another important source of nitrogen, which may be derived from agricultural, geological, or urban activities (Min *et al.* 2003). In some cases (e.g., when there are sufficient supplies of dissolved organic carbon - Dahm *et al.* 2003) the hyporheic and parafluvial zones act as moderators of nitrogen concentration before water enters the stream. At a site at Yongdang, South Korea, the parafluvial zone of the Nakdong River was the site of significant denitrification of agriculturally polluted water before it was intercepted by the main stream (Min *et al.* 2003). Similarly, organic carbon supplied to the hyporheic zone of Contentnea Creek, North Carolina, created reducing geochemical conditions that allowed an estimated 65 – 70 % removal of nitrate through reduction and/or denitrification (Spruill 2000).

Bacteria are important controllers of phosphorus release and uptake in lake sediments (Mitchell and Baldwin 1998) and in streams (Dahm *et al.* 1991). The importance of flow in controlling hyporheic contributions to riverine phosphorus dynamics has been observed in a study on the River Garonne in France, where P was taken up by functional compartments of the river, such as the hyporheic zone, when flow was below 60 m^3s^{-1} (Garay *et al.* 2001). However, suspended matter controlled P retention when flow exceeded 60 m^3s^{-1} (Garay *et al.* 2001).

Aerobic bacterial activity in the hyporheic zone also has three important roles in moderating phosphorus concentrations (Hendricks and White 2000). First, the mineralisation of organic matter by microorganisms transforms large particulate phosphorus into soluble organic forms such as soluble reactive phosphorus. Second, bacteria are able to adsorb inorganic phosphorus, making it available in the food chain. Finally, as bacteria respond to changing nutrient conditions, they alter the redox conditions of the sediment. For these processes to be maintained, the interstitial water often needs to be well-oxygenated.

1.5 Flow and interstitial invertebrate communities

Faunal communities also change in response to increased flow. In fact, there has been considerable debate over the last decade about whether the hyporheic zone acts as a temporary refuge for surface invertebrates (Panek 1991, Matthai and Townsend 2000, Del Rosario and Resh 2000). In the Rhône River, the hyporheic invertebrate community and its ability to recover from a spate depended on the magnitude and duration of the spate, the disturbance regime, and the season (Dole-Olivier and Marmonier 1991). The community composition of three sites along the channel changed with surface flow depending upon the site-specific sediment-stream hydrology (Marmonier and Creuzé des Châtelliers 1991). At a downwelling site, the spate displaced sediment and reduced the abundance and diversity of the fauna that, at low flows, became increasingly dominated by surface-dwelling invertebrates. The two other sites, which were fed mainly by groundwater and had a fauna comprised mostly of stygobites (groundwater specialists that are adapted to subterranean life – Marmonier *et al.* 1993) in times of low flow, became dominated by epigean invertebrates immediately following the spate. The composition of the faunal community in parafluvial and shallow hyporheic habitats of Sycamore Creek was temporarily altered by a spate, but recovery was rapid (1 – 2 days for some taxa, Boulton and Stanley 1995). The community changed from one dominated by cyclopoid copepods and chironomid midge larvae before the spate, to one dominated by microturbellarian flatworms, ceratopogonid midge larve, ostracods, and nematode worms.

1.6 Hyporheic zones in regulated rivers

Many of the principles underlying large river ecology are derived from work on regulated rivers (Ward *et al.* 2001). This can bias our understanding, so that what we know of large river ecology inherently includes the effects of regulation, whether these were the direct focus of the study or not. Some of the rivers from which the above observations have been made are regulated to some degree (e.g., Rhône, Brenno). Nevertheless, this work has been essential to our understanding of the hyporheic zone and its processes, and modest extrapolations of it might provide a model of how the hyporheic zones of large rivers behave under natural flow conditions. Most of these large rivers are in the cooler areas of Europe or North America and many were formed by glacial, rather than alluvial processes, and unlike most rivers in Australia, have a hydrology, geomorphology, and ecology influenced by seasonal snow melt.

Along the coast of New South Wales north of Sydney, several large gravel-bed rivers make their way to the Pacific Ocean. The Mann, Macleay, Bellinger, Hastings, and Hunter Rivers all support significant human activity in their regions. Most of the hyporheic ecological processes in these rivers are unknown. Therefore, if human activity has had any effect on the hyporheic zones of these rivers, it has gone unnoticed. This study investigates the extent of the hyporheic zone in one of these rivers, the Hunter, and explores how river regulation might influence hyporheic nutrients and fauna.

1.7 The Hunter River hyporheic zone and thesis outline

In New South Wales, it is estimated that groundwater-fed baseflow comprises an average of 40% of the flow duration of any river (DLWC 2002). In the Hunter River, although supplemented by releases from Glenbawn Dam, flow often relies on influent groundwater. The river bed and gravel bars that line the river have been recognised as having active hyporheic zones (Boulton 2000a, DLWC 2002) with a diverse fauna (Figure 1.6). These preliminary findings underscore the potential importance of the hyporheic zone as a regulator of surface water quality in the Hunter River. This thesis further assesses the role of hyporheic processes in the Hunter River by examining aspects of interstitial ecology at several stages of the hydrograph (Figure 1.7). In Chapter 3, physical, chemical, and biological data collected from riffles and lateral bars at seven sites over a year are analysed to give a comprehensive perspective of the spatial and temporal trends in the hyporheic ecology of the Hunter River (Figure 1.7).

One of the most-studied hyporheic zones in terms of microbial activity and physico-chemical dynamics is that of Sycamore Creek in Arizona. The bed of Sycamore Creek is predominantly sand. Sand-bed streams, because of their fine sediments, have hyporheic zones that may behave differently to those of streams with coarser substrata (Marxsen 2001, Boulton *et al.* 2002a). Wollombi Brook and the Goulburn River are two sand-bed tributaries of the Hunter River. In Chapter 4, physico-chemical and nutrient data from the hyporheic and parafluvial zone from each tributary is compared to samples from four sites on the Hunter River to determine associations between sediment matrix features, biota, and water chemistry (Figure 1.7).

Flow in the Hunter River changes throughout the year and is regulated to meet demands for mines, irrigation, and domestic purposes. Although extant conditions vary significantly from natural ones, an active hyporheic zone appears to have persisted. With an increased understanding of the role of flow in river ecology, flows that were once controlled

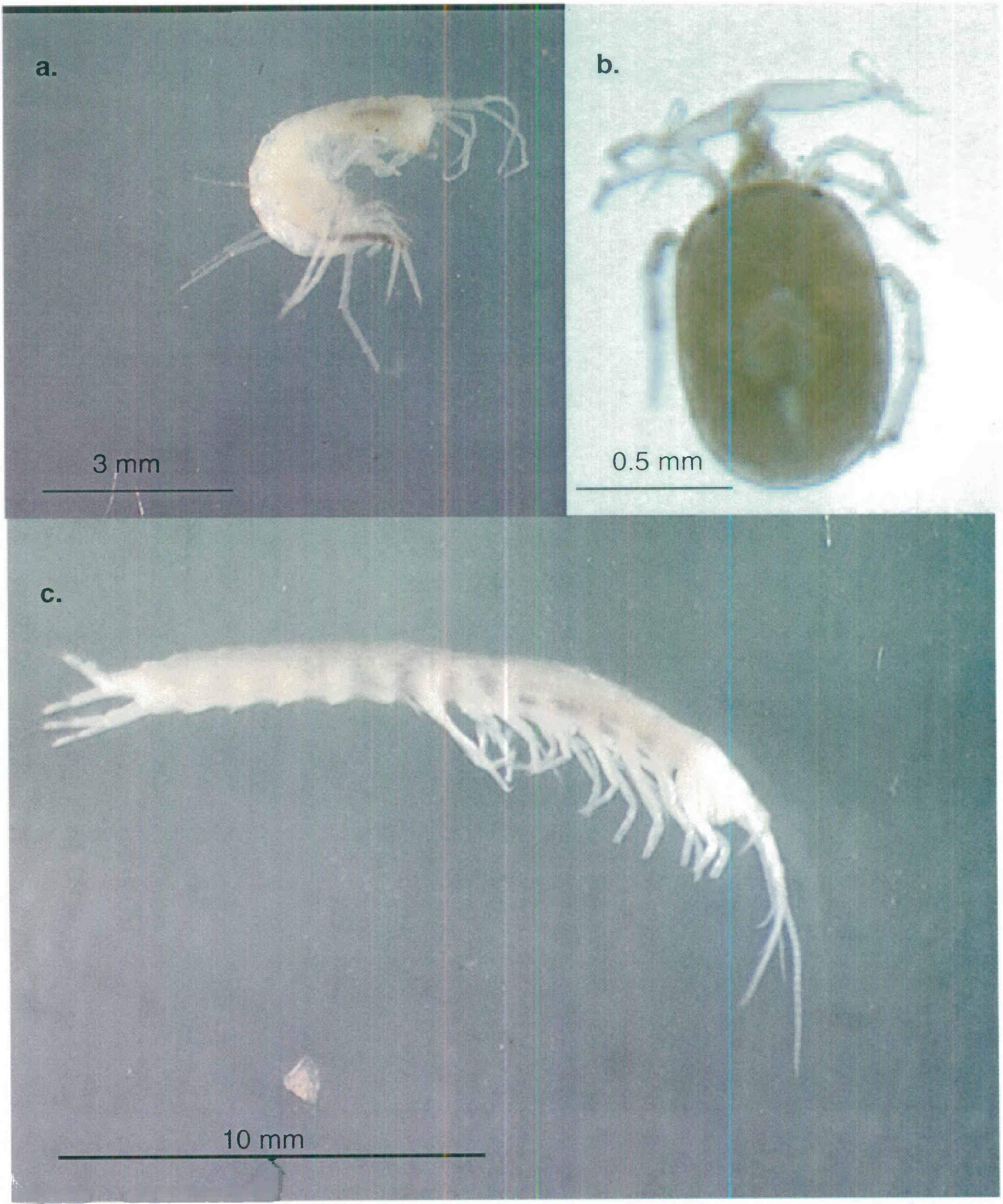

Figure 1.6. Three examples of the hyporheic fauna of the Hunter River. (a) an unknown amphipod, (b) *Partidomomonia* sp. (Momoniidae), (c) an unknown syncarid (Psammaspididae). Photo credits: a and c – Peter Serov, b – Melanie Hancock.

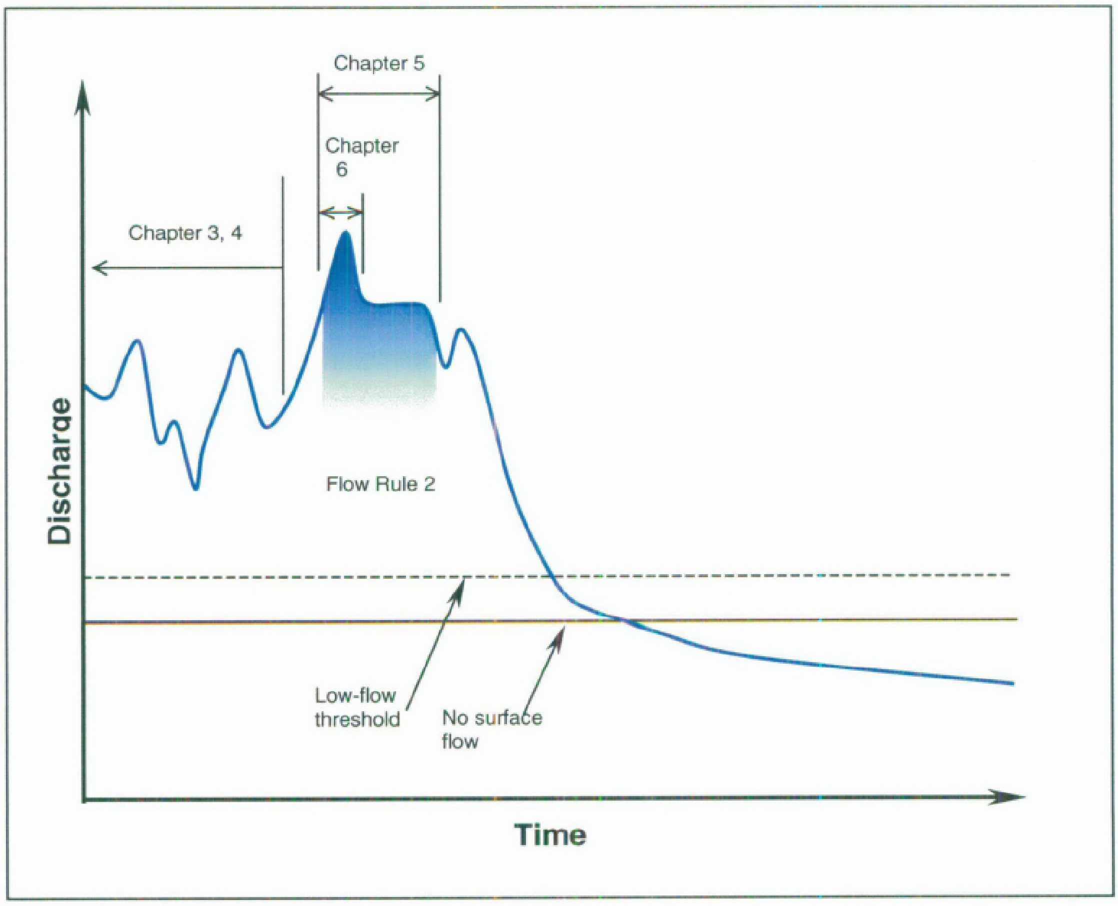

Figure 1.7. Theoretical hydrograph, indicating the various management components of the Hunter River (Flow Rule 2) and the thesis chapters in which they are discussed.

exclusively for human use are now being allocated back to the environment. A series of flow rules specific to the Hunter River was introduced in 2000 as part of the New South Wales Government water reforms agenda. The aim of these flow rules is to achieve long-term river health, maintain biodiversity, and secure sustainable water resources (New South Wales Environmental Protection Authority 1999).

As well as managing flow in the surface channel, the flow rules have the potential to affect the hyporheic zone and its ecology. One rule of particular relevance is Flow Rule 2, which allows the first 12 h of a high flow event to pass without extraction (Figure 1.7). Following the first 12 h, a maximum extraction of 50% is allowed. During high flows, the strength of hydrological exchange with the hyporheic zone potentially increases, as more hydraulic pressure is available to drive exchange. This allows more oxygen-rich water to pass through the sediment, stimulating microbial activity and altering the invertebrate community. It also potentially flushes silt from the interstices and loosens sediment particles. The effects of a medium-level environmental flow on hyporheic filtration are examined in Chapter 5 (Figure 1.7).

A second consequence of Flow Rule 2 is an increase in river stage for at least the first 12 h of a high flow event, and thus, a potential increase in the volume of the hyporheic filters. Chapter 6 examines hyporheic physical, chemical, microbial, and faunal responses to a twelve-hour inundation by a small-scale diversion of river water over two gravel bars (Figure 1.7).

With the advent of the NSW Groundwater Dependent Ecosystem Policy (Department of Land and Water Conservation 2002), it is essential that the future management of the Hunter River and its surrounding groundwater resources gives due consideration to the hyporheic zone. This study provides a preliminary assessment of the hyporheic zones at nine sites in the valley, and of the effects of small and medium sized flows on a subset of sites. In Chapter 7, the main findings of this study are synthesised and discussed, and some implications and recommendations are given for the management of Hunter River hyporheic zones.

CHAPTER 2

Study sites

2.1 Catchment

2.1.1 Geology

The Hunter River is a large, coastal river in north-eastern New South Wales. Rising in the Barrington Tops National Park, and flowing almost 300 km, the river drains an area of approximately 22 000 km^2 before entering the Pacific Ocean at Newcastle. The Liverpool Range in the north, the Great Dividing Range in the west, and a series of dissected limestone plateaux in the south mark the boundary of the catchment. Permian sediments dominate the lower section of the catchment (Chessman *et al.* 1997). These are overlain by Triassic sediments to the south, and Devonian and Carboniferous rocks to the north-east. In the north, Tertiary basalt flows and igneous intrusions are common (Chessman *et al.* 1997). Streams flowing from the north of the catchment supply gravel and cobble sediments to the Hunter River, while bedload from the southern and western tributaries generally consists of sand (Raine 2000).

2.1.2 Land use

European settlement of the valley began in 1804, and since that time most of the native vegetation has been cleared from the central lowlands (Chessman *et al.* 1997). However, in the northern and southern parts of the catchment where the terrain is steeper and less accessible, large tracts of native vegetation remain (Albrecht 2000). This consists of a mixture of rainforest in the north-east, subalpine woodland in the north and north-east, and a variety of wet and dry eucalypt forest. Catchment-wide clearing and the introduction of pest species such as rabbits and prickly pear led to extensive catchment and bank erosion (Chessman *et al.* 1997).

The Hunter Valley now supports a human population of approximately 500 000, mostly living in coastal areas in and around Newcastle. Beef cattle, dairying, egg and poultry production, and horse breeding make up the major agricultural activities in the valley. Other agricultural activities that are economically important to the Hunter Valley rural communities include viticulture, and the production of lucerne, wheat, and hay. Hunter

Valley coalmines produce about two-thirds of NSW's coal (Chessman *et al.* 1997). Much of this coal is used locally in the Liddell and Bayswater Power Stations. There is some concern (Albrecht 2000) about saline water inputs to the river from coalmines and power generation, which supplement natural saline seepages and those increases in salinity that probably followed catchment clearing.

2.1.3 Climate

The majority of the Hunter River catchment has a warm temperate climate, although snow falls at times on the higher peaks (approximately 1200 to 1600 m) in the north and north-east of the catchment (Chessman *et al.* 1997). Rainfall in the upper catchment averages from 600 mm per year near Merriwa to 1200 mm on the Barrington Tops, with the wetter months being from November to March. Rainfall at Scone, upstream from the Aberdeen study site (Figure 2.3), averages 655 mm per year with the wettest months being January and February (Figure 2.1). Air temperature here can range from just above 30 °C in December and January, to 5 °C in July (Figure 2.1). Average rainfall at Jerrys Plains, near the Moses Crossing and Bowmans Crossing sites (Figure 2.3) is 640 mm, with the wetter months also occurring in January and February (Figure 2.2). Temperature patterns at Jerrys Plains resemble those recorded at Scone (Figure 2.2).

2.1.4 The Hunter River

Approximately 17 km upstream of Aberdeen (Figure 2.3), the Hunter River is impounded by Glenbawn Dam (870 000 ML), which provides water for irrigation, industry (mostly coal mining and power generation), and domestic supplies for Aberdeen, Muswellbrook, Denman, and Singleton. The dam also plays a major role in flood mitigation in the valley. The main effect of Glenbawn Dam on the Hunter River has been a reduction in the size and frequency of small to medium spates, and the maintenance of steady low flows when the river might otherwise be dry (Chessman *et al.* 1997). The average annual runoff from the Hunter River catchment is 1 680 000 ML, which mostly comes from the Patterson and Williams basins (Chessman *et al.* 1997).

Prior to European settlement, the Hunter River was lined with red cedar (*Toona ciliata*), river oak (*Casuarina cunninghamiana*), river red gum (*Eucalyptus camaldulensis*) and thick vine brushes, of which no remnants now exist on the floodplain (Raine 2000). Much

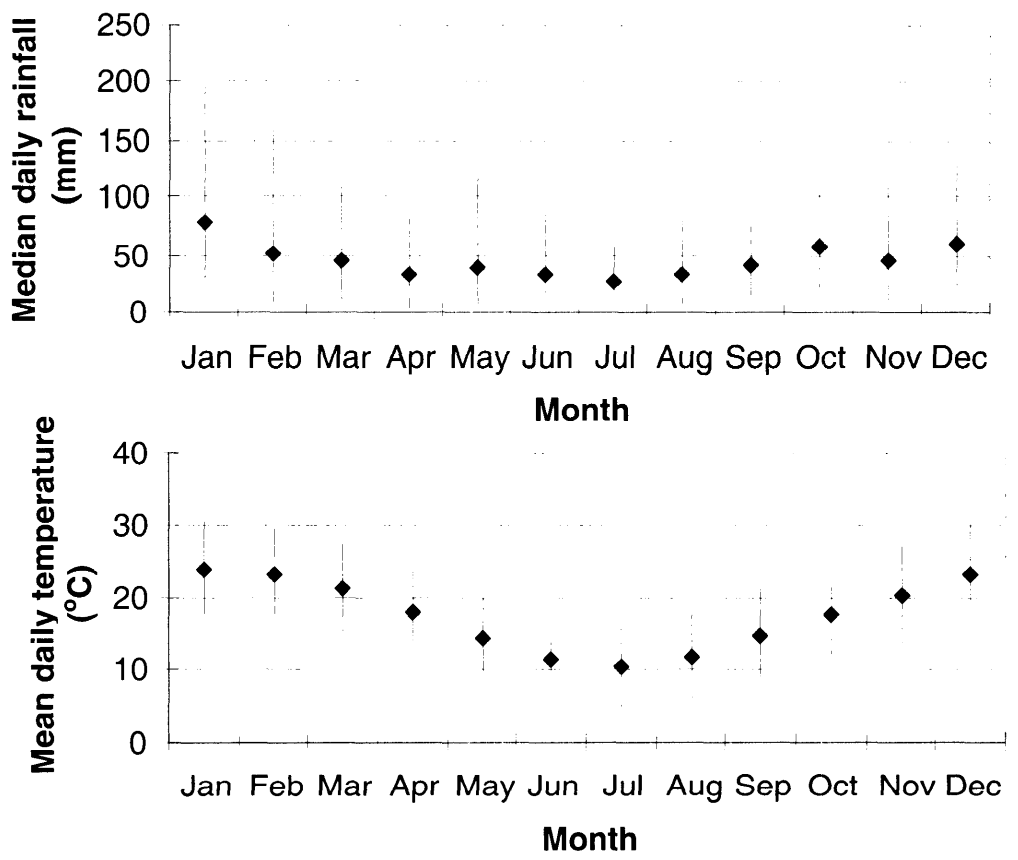

Figure 2.1 Median daily rainfall (upper limit of vertical bars represents the 90th percentile, diamonds represent the 50th percentile, and lower limit represents the 10th percentile) and mean daily temperature (bars represent mean daily maxima and minima) at Scone. Records commenced in 1873. Data courtesy of the Bureau of Meteorology.

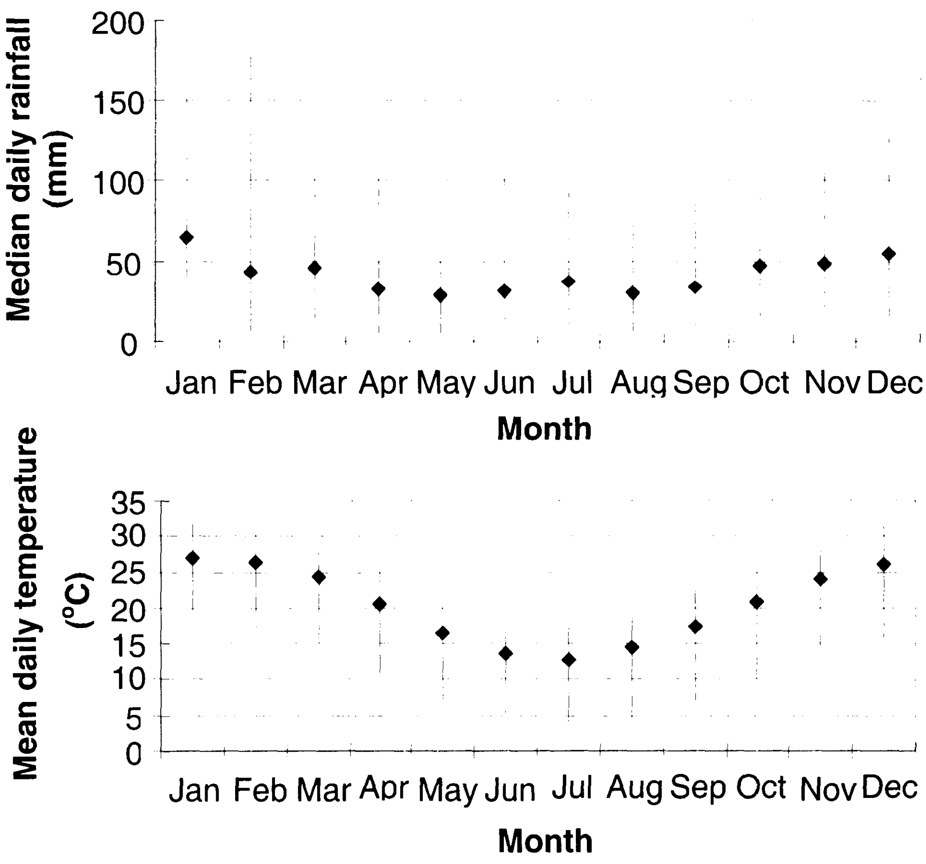

Figure 2.2 Median daily rainfall (upper limit of vertical bars represents the 90th percentile, diamonds represent the 50th percentile, and lower limit represents the 10th percentile) and mean daily temperature (bars represent mean daily maxima and minima) at Jerrys Plains. Records commenced in 1884. Data courtesy of the Bureau of Meteorology.

riparian vegetation has been cleared, leading to major changes in the geomorphology of the Hunter River streams (Raine 2000). Sand and gravel extraction from the Hunter River has also caused significant geomorphological changes with the resultant loss of an armour layer increasing the potential erodability of many parts of the stream-bed (Erskine *et al.* 1985). Of primary concern is the loss of bank stability and subsequent erosion, and the loss of pool-riffle sequences. The Goulburn River, covering almost 40 % of the Hunter River basin, potentially contributes an estimated 58 000 tonnes of sand annually to the Hunter River, leading to a loss of the pool-riffle sequence downstream of its confluence (Raine 2000). However, the Hunter River upstream maintains its natural cobble and coarse gravel bed.

After 1946 a series of large rainfall events resulted in several large floods (Erskine and Bell 1982) that widened the river channel and caused massive erosion of the floodplain and terraces. These floods prompted extensive river training and flood mitigation works, which commenced in 1955 (Erskine 1992) and involved the removal of logs, islands and vegetation from the channel, channel realignment, creation of artificial cutoffs, and the implementation of bank protection measures such as rock placement, brush or wire-mesh fencing, and planting of willow and poplar trees (Chessman *et al.* 1997). These works led to a loss in channel length and sinuosity, and an increase in overall flow velocity (Erskine *et al.* 1992).

On 20 November 2000 a flood exceeding bankful capacity travelled down the Hunter River. At Jerrys Plain more than 109 000 ML passed through the gauging station, equating to a 1 in 5 year flood. This flood peaked at more than 7 m at Aberdeen (DLWC gauging data, Figure 2.5) and caused extensive bed movement at all study sites.

2.2 Study sites

This study initially examined seven sites along a 138-km stretch of river from Aberdeen to upstream of Singleton (Figure 2.3, site details summarized in Table 2.1). Sites were also sampled on the Goulburn River at Sandy Hollow, and Wollombi Brook at Warkworth. Later attention focused on the sites at Aberdeen, Moses Crossing, and Bowmans Crossing to explore patterns in more detail at a finer temporal resolution. These sites were among those recommended by Boulton (2000a), which were initially selected in September 1999

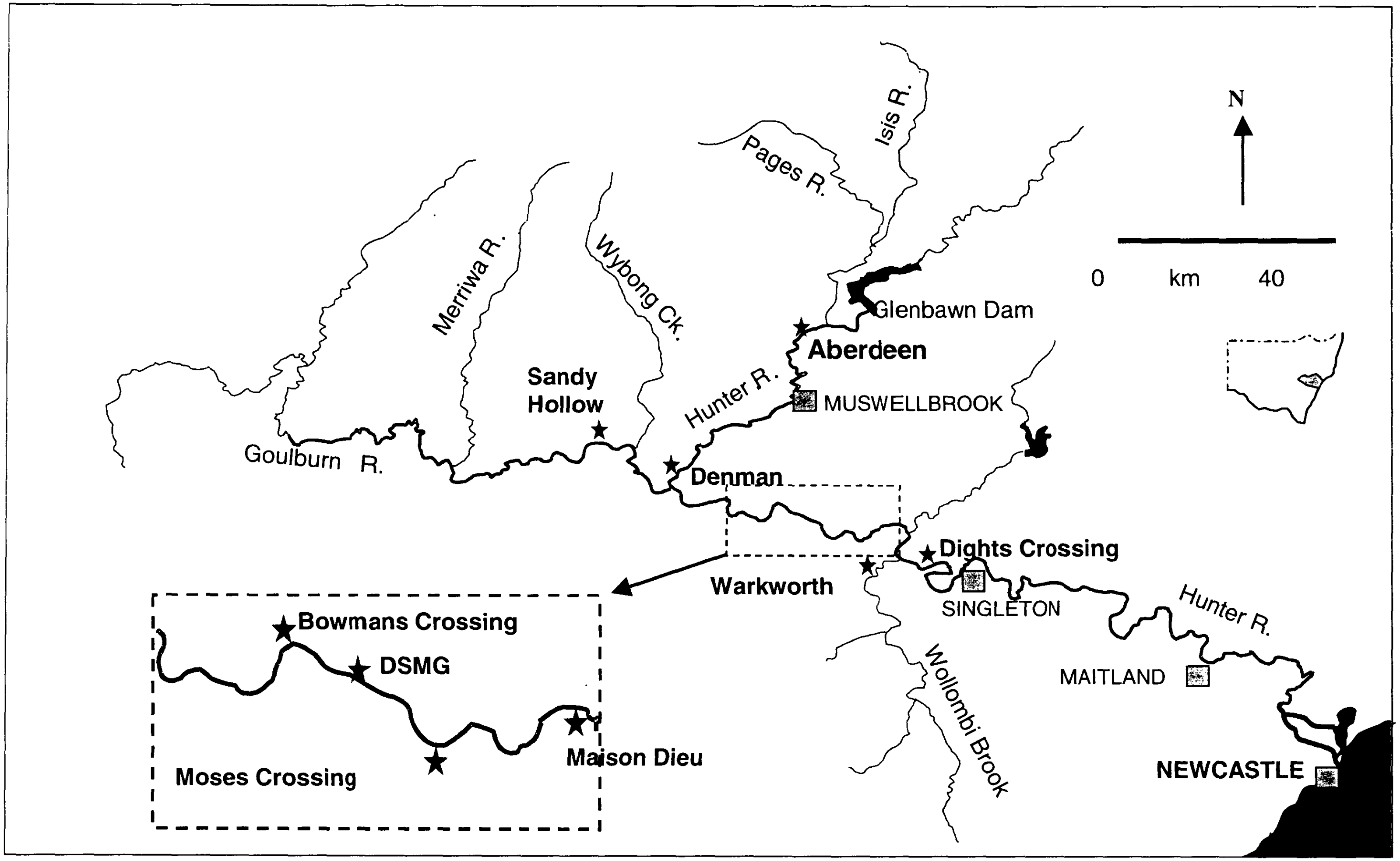

Figure 2.3 Map of the Hunter River showing the location of sampling sites.

Table 2.1 Summary of study sites in the Hunter Valley.

Site	**Distance from Glenbawn Dam (river km)**	**Altitude (m asl)**	**Longitude (E)**	**Latitude (S)**	**Mean surface substrate size - B axis**
Aberdeen	17	167	150°52'58”	32°10'03”	46mm, -5.4ϕ
Denman	66	110	150°42'38”	32°22'58”	36mm, -5.1ϕ
Bowmans Crossing	112	77	150°50'48”	32°27'14”	34mm, -5.1ϕ
d/s Macquarie Generation	119	67	150°55'20”	32^{o3}0'24”	27mm, -4.7ϕ
Moses Crossing	124	64	150°55'10”	32^{o3}1'06”	33mm, -5.0ϕ
Maison Dieu	146	46	151°03'02”	32°31'44”	19mm, -4.2ϕ
Dights Crossing	155	44	151°05'38”	32°33'57”	20mm, -4.2ϕ
Goulburn River		118	150°34'13”	32°20'41”	9mm, -3.1ϕ
Wollombi Brook		55	151°01'09”	32°34'04”	<1mm, 1.5 ϕ

following guidance by Mr Allan Raine, Resource Analysis Manager, DLWC Hunter Region. The following criteria were used: suitability of substrata for a hyporheic study, the presence of a riffle, the presence of either a lateral or central gravel bar, and the ease of access at high flows.

2.2.1 Aberdeen

This is the most upstream site of the study (Figure 2.3) and is situated across the river from the Aberdeen sporting fields and golf course. Land use on the right bank (looking downstream) consists of a dairy farm where cattle have access to both river and bar. Pumping from river and groundwater occurs, with the nearest groundwater pump situated 200 m from the gravel bar. A few *Casuarina cunninghamiana* and *Salix* spp. are present in the riparian vegetation upstream and adjacent to the bar. On the bar, herbaceous *Persicaria decipiens* and sedges (*Juncus* sp.*)* are present during low flows. In spring, filamentous green algae (*Spirogyra* sp.) proliferates along the riffle.

The substrate of the gravel bar is cobble with an organic-rich sand-silt soil matrix (Table 2.1). It appears to have been generated by the erosion of soil from the right bank and subsequent exposure of old alluvial sediments. Until November 2000, the bar ranged from 120 to 150 m in length, and 30 to 50 m in width (Figure 2.4), depending upon river height. In November, a large flood (Figure 2.5) extended the bar by approximately 170 m at the downstream edge. Apart from a small amount of deposition, this flood caused little visible morphological change in shape or sediment particle size at the upstream section of the bar where sampling occurred.

Riffle width ranges from 25 to 30 m and falls 50 cm over 170 m along the edge of the bar. The riffle has a cobble/sand substrate with high amounts of silt and fine sediments relative to other sites (Table 5.4).

2.2.2 Denman

The absence of a suitable lateral bar at this site meant that an exposed central bar was chosen for sampling (Figure 2.6). This bar has a coarse gravel/fine sand substrate (Table 2.1), is 110 m long and 20 m wide. The slope across the bar fell 20 cm from right to left (looking downstream), and the sediments had good hydraulic conductivity. Vegetation on

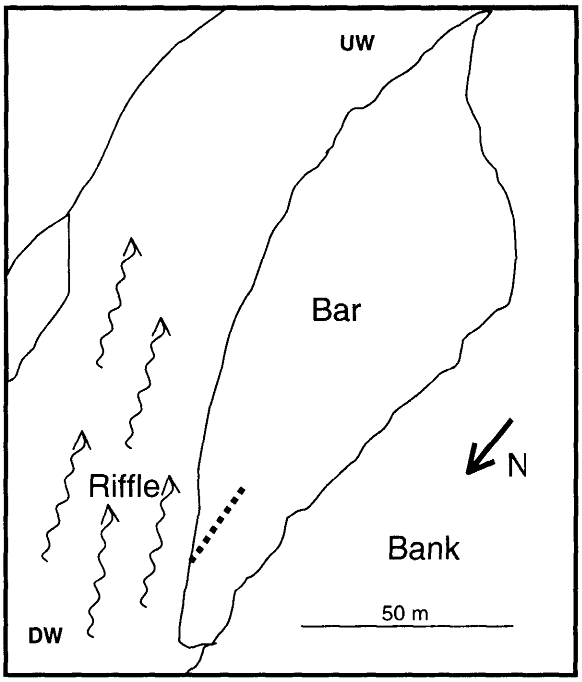

Figure 2.4. Study site at Aberdeen. DW = downwelling area, UW = upwelling area. Dotted line indicates the sampled flow path (Chapter 3).

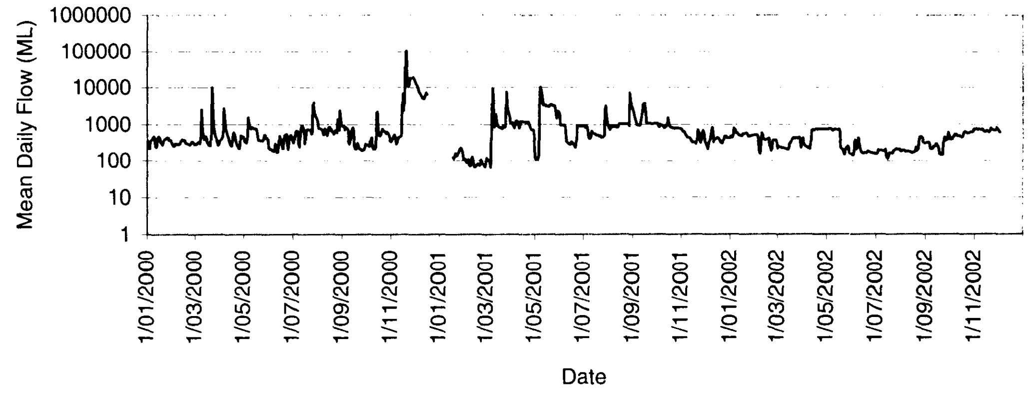

Figure 2.5. Hydrograph for Aberdeen from January 2000 to December 2002. Note the logarithmic scale on the y axis (Department of Land and Water Conservation).

the bar was dominated by *Persicaria decipiens* and on the banks by willows (*Salix* spp.) and *Casuarina cunninghamiana*. Bar vegetation was totally removed by the November 2000 flood.

2.2.3 Bowmans Crossing

This large sand and gravel bar extends approximately 700 m upstream from Bowmans Bridge, with the sampling site being 400 m upstream of the bridge (Figure 2.3). At low flows and at its widest, the bar extends 150 m laterally from the right bank (Figure 2.7). Bar grade at this site is low, with a 20 cm rise in water level advancing the shore-line by up to 13 m. Consequently the sampled sections of both the riffle and bar necessarily changed with river height. The depth to the hyporheic water restricted sampling on the lateral bar. The low flow sampling location was approximately 10 – 20 m to the north, and 50 – 60 m upstream of where sampling occurred at high flows. The November flood (Figure 2.8) deposited up to 1 m of sand over most of the leading edge of bar-section, covering the both high and low flow sampling areas.

Cobblers Peg (*Conyza sp.*) and Hunter Burr (*Xanthium italicum*) dominate vegetation on the gravel bar. Willows (*Salix* spp.), which are prevalent on the left bank, have also recently become established in low numbers and are the only trees present on the bar.

2.2.4 Downstream of Macquarie Power Generation

At this site, a low bar extends for 80 m along the left edge of the river (Figure 2.9). The river is 20 - 35 m wide at the sampling site and a 100-m riffle, starts 80 m upstream of the leading edge of the bar. Because the bar was low, riffle depth and water velocity prevented sampling at medium and high flows. The sampled bar comprises mainly sand and coarse gravel (Table 2.1), and is devoid of vegetation. However, the near bank is grassed with exotic pasture species and the opposite bank has a well vegetated riparian strip dominated by willows. The offtake for the Macquarie Power Generation water storage is approximately 800 m upstream. Cattle have access to the river and bar, and on most sampling occasions were seen walking on both habitats.

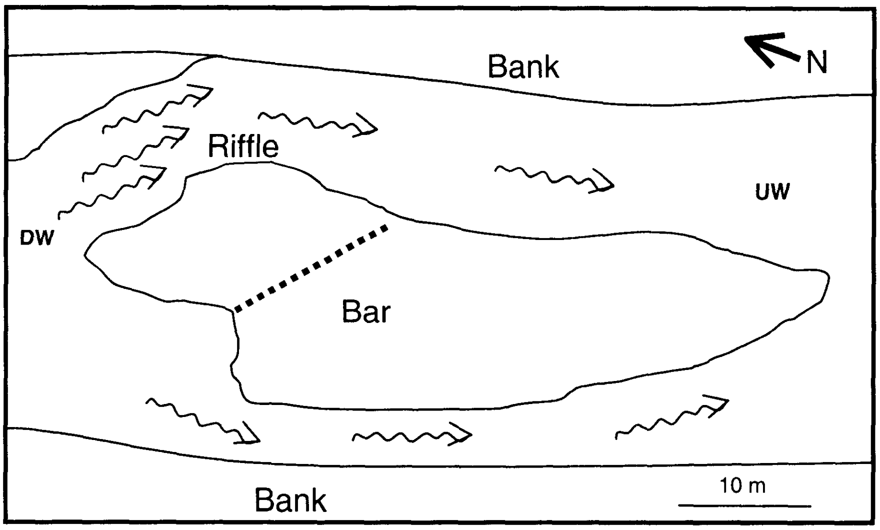

Figure 2.6. Study site at Denman. DW = downwelling area, UW = upwelling area. Dotted line indicates the sampled flow path (Chapter 3).

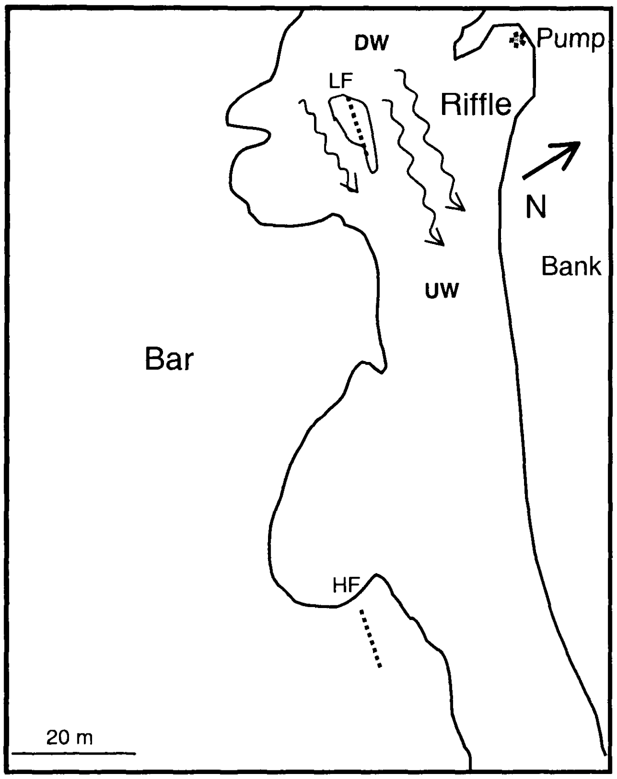

Figure 2.7. Study site at Bowmans Crossing during medium flow. LF = area of bar sampled in low flows, HF = area of bar sampled in high flows. DW = downwelling area, UW = upwelling area. Dotted line indicates the sampled flow path (Chapter 3).

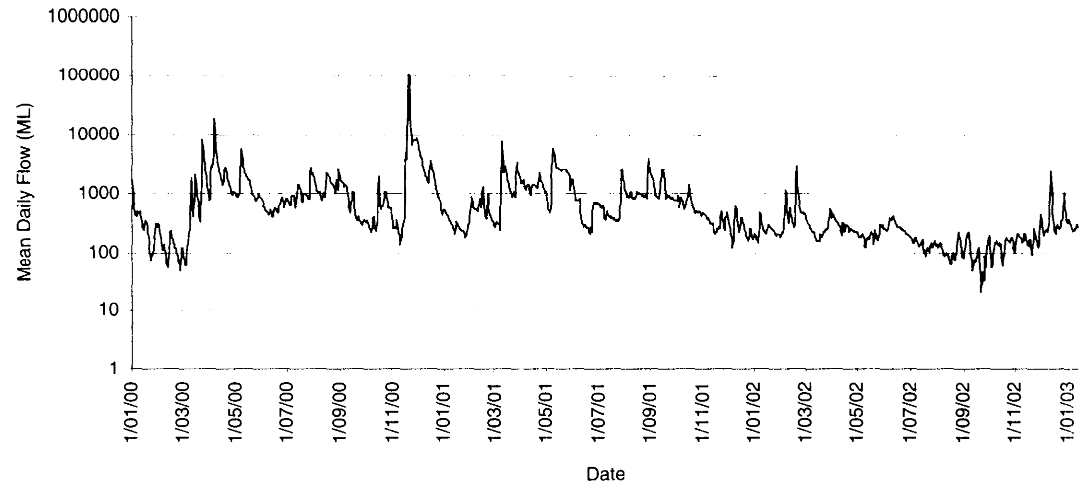

Figure 2.8. Hydrograph for Jerrys Plains from January 2000 to January 2003. (Department of Land and Water Conservation).

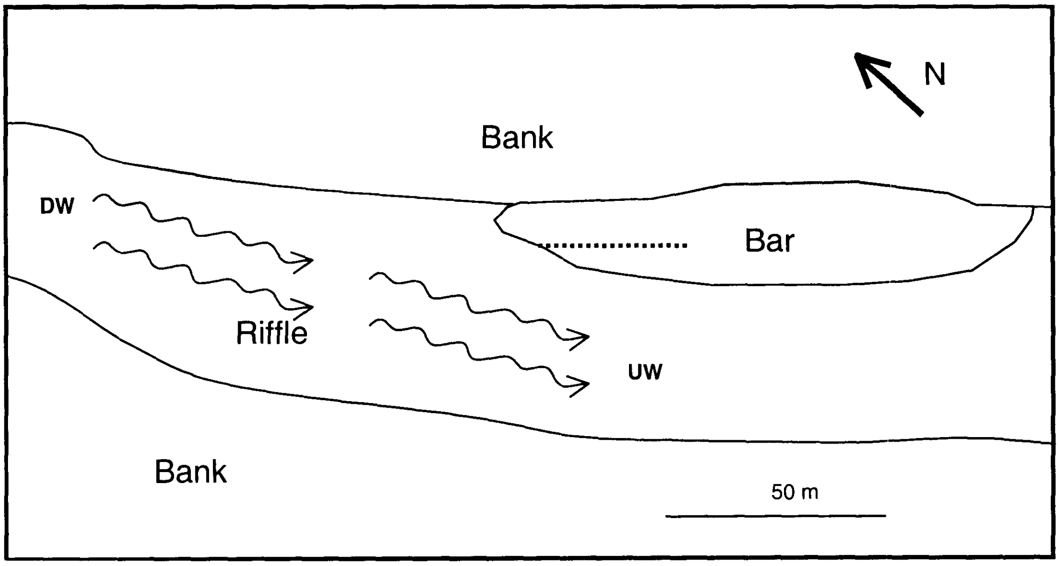

Figure 2.9. Study site at Downstream Macquarie Power Generation. DW = downwelling area, UW = upwelling area. Dotted line indicates the sampled flow path (Chapter 3).

2.2.5 Moses Crossing

This is a large bar extending more than 1 km along the left side of the river (Figure 2.10) upstream from Moses Crossing Bridge. At low flow, the leading edge of the bar is preceded by a series of small central gravel bars. A 3-m long riffle cuts between the head of the lateral bar and the downstream edge of the first central bar. It is this riffle and the first 25 m of the lateral bar that were sampled. The active channel is approximately 110 m wide and it is lined with willows (*Salix* spp.) on the right bank, and *Casuarina cunninghamiana* on the left bank. Agricultural weeds (*Bidens* sp., *Conyza* sp., *Ricinus cummunis, Xanthium italicum* and *Foeniculum vulgare*) dominate the understorey and vegetate the bar. The bar extends from an incised bank (15 m high) and consists of coarse sand/ medium gravel (Table 2.1). The November 2000 (Figure 2.8) flood scoured and subsequently deposited sand and gravel over the entire bar. At the section of bar and riffle that was sampled, this deposition ranged in depth from 30 to 60 cm.

2.2.6 Maison Dieu

At Maison Dieu, the steeply incised banks (20 m) of the river are approximately 100 m apart and vegetated with willows (*Salix* spp.) and *Casuarina cunninghamiana.* The understorey and bar are covered by agricultural weeds (*Bidens* sp., *Conyza* sp., *Ricinus cummunis, Xanthium italicum,* and *Foeniculum vulgare*). Samples were taken from the leading edge of the lateral bar, which extends for approximately 800 m along the right bank of the river and the 20-m long riffle that runs across the upstream edge and along the first 12 m of the bar (Figure 2.11). At its widest, the bar at the sampling location is approximately 25 m wide. Sediment of the bar consists of medium to coarse gravels and sand (Table 2.1).

2.2.7 Dights Crossing

This large bar extends for 1.2 km along the inside of a large left hand bend in the river. Sampling was conducted where the bar juts out into the main river, approximately 300 m upstream of a low bridge and just downstream of a riffle (Figure 2.12). The riffle runs transversely across the stream and is approximately 20 m long. Vegetation on the bar consisted mostly of pasture grasses and the same species of agricultural weeds as Maison Dieu.

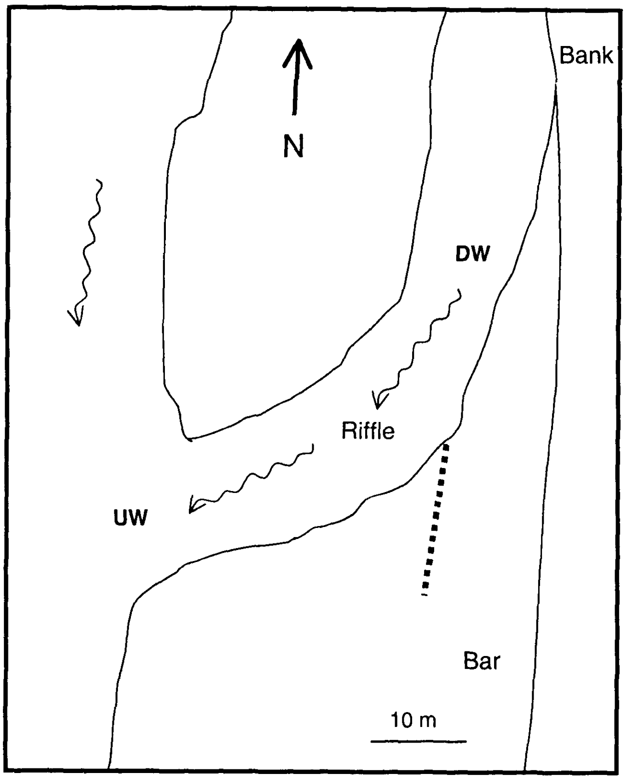

Figure 2.10. Study site at Moses Crossing. DW = downwelling area, UW = upwelling area. Dotted line indicates the sampled flow path (Chapter 3).

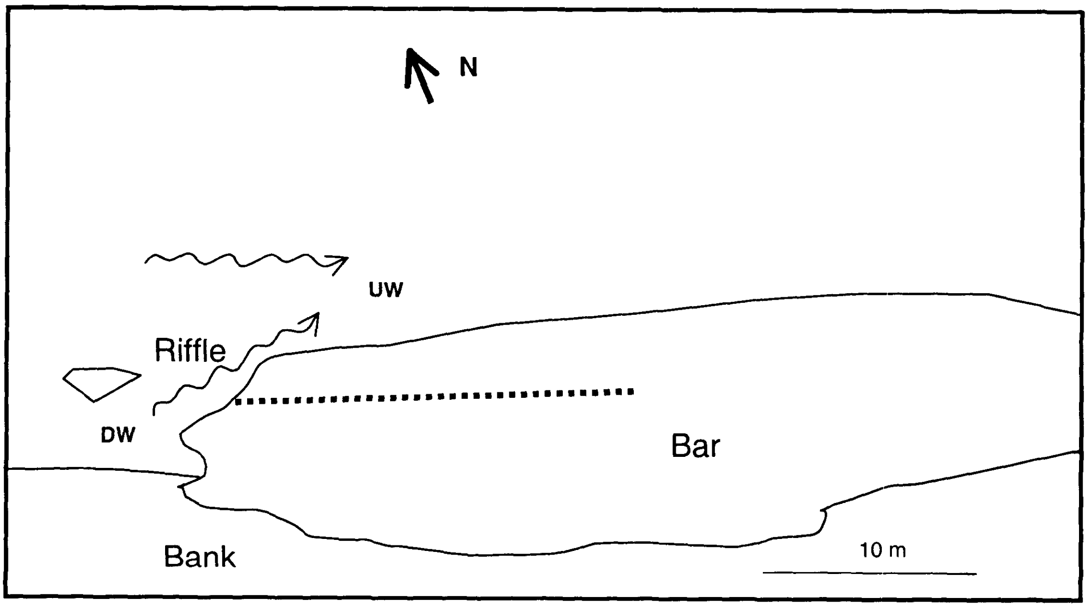

Figure 2.11. Study site at Maison Dieu. DW = downwelling area, UW = upwelling area. Dotted line indicates the sampled flow path (Chapter 3).

2.2.8 Goulburn River at Sandy Hollow

The catchment of the Goulburn River covers approximately 8 300 km^2 and drains mostly agricultural land before entering the Hunter River downstream of Denman. In February 1955 a flood 43.4 times greater than the annual flood event caused massive erosion and deposited an estimated 10 million cubic metres of sand into the river (Raine 2000). Erosion in the Goulburn catchment contributes about 58 000 tonnes of sand per year to the Hunter River, increasing the rate of sediment in the river at Bowmans Bridge to 81 000 tonnes, which is about 5 times the volume of sediment transported upstream of the Goulburn confluence (Parfait 1988).

The Goulburn River at Sandy Hollow consists of a 1-km long, low bar on the right hand side of the river (Figure 2.13). A shallow riffle with only a slight gradient extended for 30 to 45 m along the sampled section of bar. The substrate of the bar and riffle consists of medium to coarse sand (Table 2.1). Apart from occasional grasses, this exposed bar remained devoid of vegetation during the study. Spear-point pumping inlets, used for irrigation, are present within the bar. Gauging data at this site for the period of study is displayed in Figure 2.14.

2.2.9 Wollombi Brook at Warkworth

Wollombi Brook drains an area of some 2 000 km^2 and joins the Hunter River upstream of Singleton. In 1949 a large flood deposited massive amounts of sand in the channel of Wollombi Brook (Erskine 1996). It is estimated that Wollombi Brook transports 215 000 tonnes of sand into the Hunter River per year, increasing the sediment load of the river to 300 000 tonnes per year at Elderslie (Parfait 1988).

The bar sampled on Wollombi Brook is 50 m upstream of Cockfighters Bridge at Warkworth (Figure 2.15). It consists almost entirely of fine sand with a mean sediment size of 0.24 mm (Erskine 1996). This bar is vegetated with *Juncus acutus*, and dense stands of *Phragmites australis. Casuarina cunninghamiana* is the dominant riparian species. Riffle samples were collected from a 10 – 20 m riffle with a grade of 20 cm falling over 20 m. The riffle occurs to the left of the lateral bar and has a substrate consisting mostly of fine sand and fine to medium gravels (Table 2.1). The hydrograph for this site is displayed in Figure 2.16.

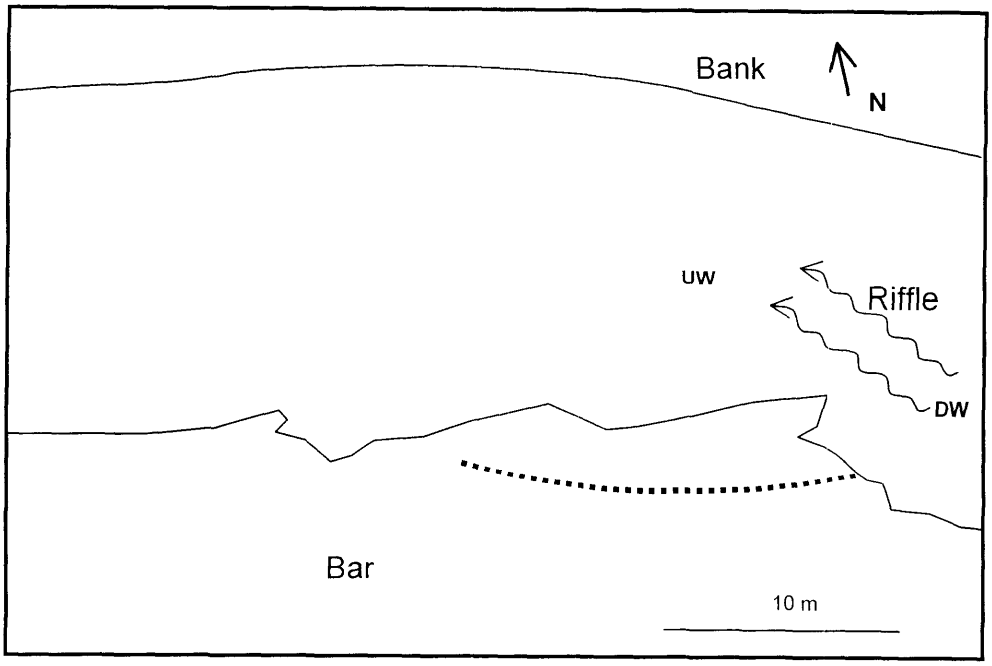

Figure 2.12. Study site at Dights Crossing. DW = downwelling area, UW = upwelling area. Dotted line indicates the sampled flow path (Chapter 3).

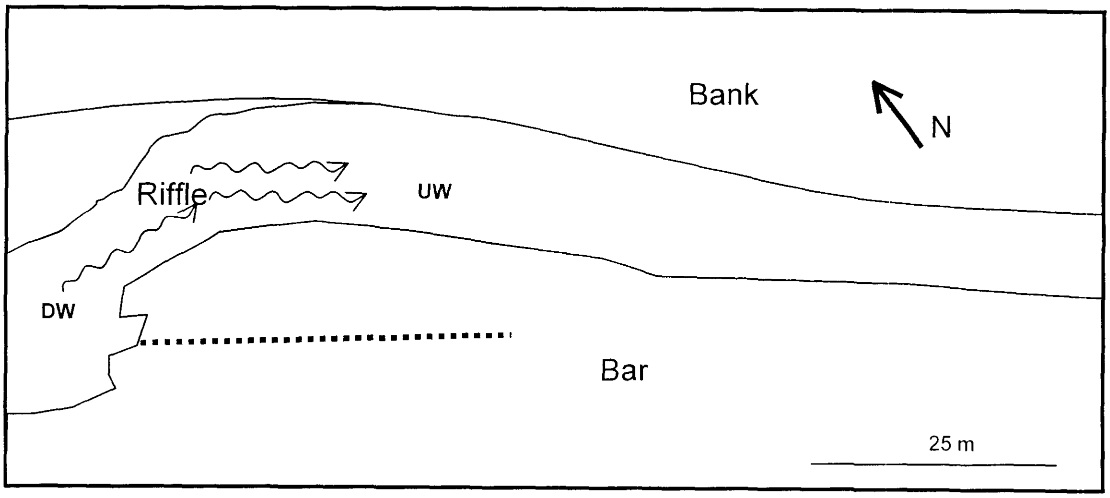

Figure 2.13. Study site at Sandy Hollow. DW = downwelling area, UW = upwelling area. Dotted line indicates the sampled flow path (Chapter 4).

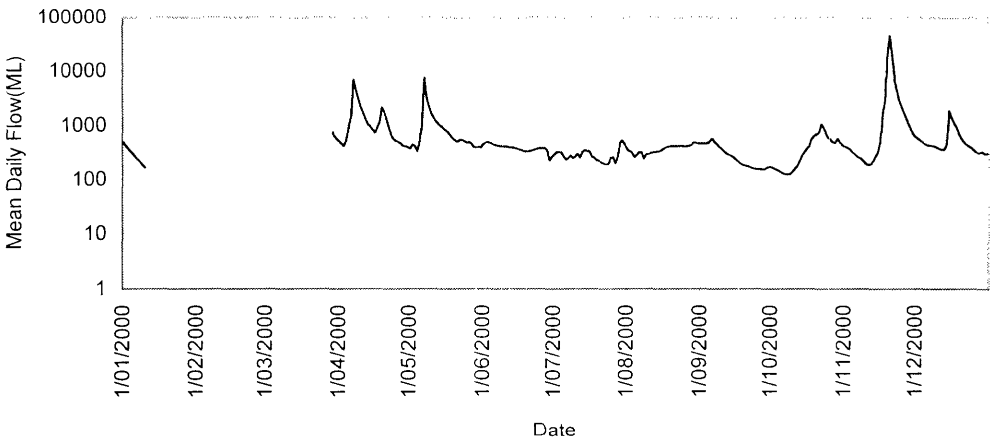

Figure 2.14. Hydrograph for the Goulburn River at Sandy Hollow from January 2000 to December 2001. Note the logarithmic scale on the Y-axis (Department of Land and Water Conservation).

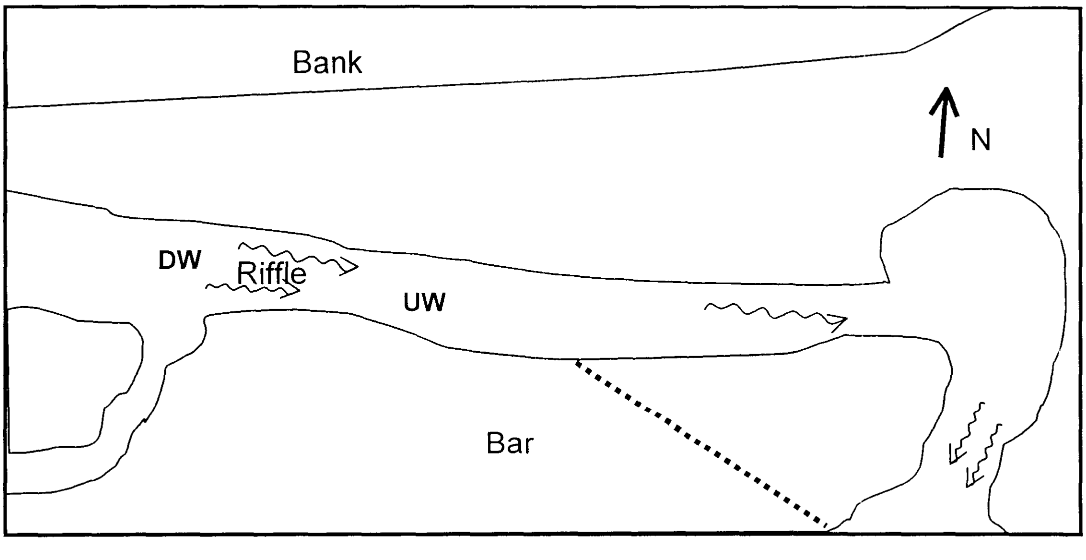

Figure 2.15. Study site at Warkworth. DW = downwelling area, UW = upwelling area. Dotted line indicates the sampled flow path (Chapter 4).

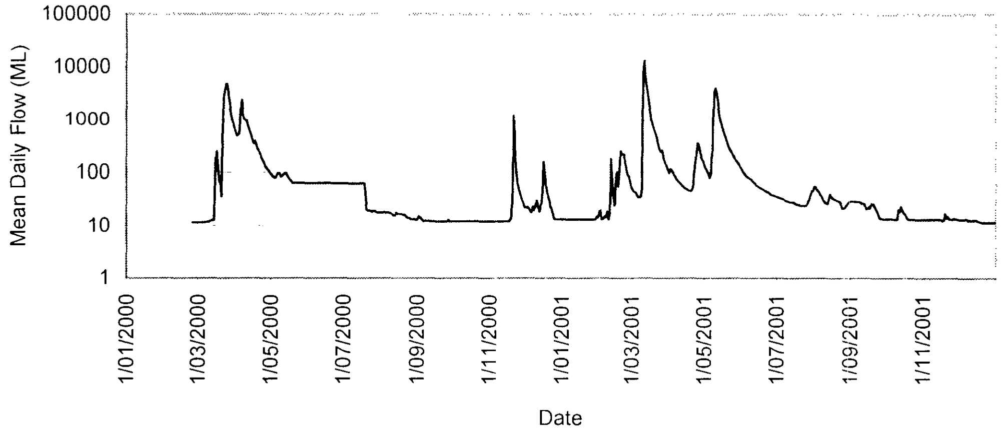

Figure 2.16. Hydrograph for Wollombi Brook at Warkworth from January 2000 to December 2001. Note the logarithmic scale on the Y-axis (Department of Land and Water Conservation).