DOI: 10.1007/s00267-001-0064-5

Human Impacts on the Stream–Groundwater Exchange Zone

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ABSTRACT / Active exchanges of water and dissolved material between the stream and groundwater in many porous sand- and gravel-bed rivers create a dynamic ecotone called the hyporheic zone. Because it lies between two heavily exploited freshwater resources—rivers and groundwater—the hyporheic zone is vulnerable to impacts coming to it through both of these habitats. This review focuses on the direct and indirect effects of human activity on ecosystem functions of the hyporheic zone. River regulation, mining, agriculture, urban, and industrial activities all have the potential to impair interstitial bacterial and invertebrate biota and disrupt the hydrological connections between the hyporheic zone and stream, groundwater, riparian, and floodplain ecosystems. Until recently, our scientific ignorance of hyporheic processes has perhaps excused the inclusion of this ecotone in river management policy. However, this no longer is the case as we become increasingly aware of the central role that the hyporheic zone plays in the maintenance of water quality and as a habitat and refuge for fauna. To fully understand the impacts of human activity on the hyporheic zone, river managers need to work with scientists to conduct long-term studies over large stretches of river. River rehabilitation and protection strategies need to prevent the degradation of linkages between the hyporheic zone and surrounding habitats while ensuring that it remains isolated from toxicants. Strategies that prevent anthropogenic restriction of exchanges may include the periodic release of environmental flows to flush silt and reoxygenate sediments, maintenance of riparian buffers, effective land use practices, and suitable groundwater and surface water extraction policies.

As global exploitation of both stream water and groundwater increases, it is becoming more evident that managers need to develop an awareness of the linkages between these two systems, the roles that these linkages play in maintaining water quality, and how human activities may impair them. The impact of human activity on surface stream habitats has been extensively studied throughout the world (Hynes 1960, Johnson and others 1997, Townsend and others 1997, Parker and others 2000), and this scientific information is now the basis for many stream restoration efforts (Stanford and others 1996, Wissmar and Beschta 1998). However, the surface stream forms only the visible part of a continuous freshwater ecosystem that includes the groundwater, alluvial, and riparian systems (Gibert and others 1990). Central to all of these is the area of exchange called the hyporheic zone (Figure 1), which occurs in the sediments of many gravel- or sand-bed streams. The hyporheic zone is a dynamic ecotone between streams and groundwater and, as well as hosting a unique and diverse invertebrate fauna (Marmonier and others 1993), is frequently the site of intense biogeochemical activity (Morrice and others 2000).

Exchanges between the hyporheic and surrounding surface, groundwater, riparian, and alluvial floodplain habitats occur over a wide range of spatial and temporal scales (Boulton and others 1998). The volume and rapidity of these exchanges varies greatly, governed by surface water discharge, bed structure, and ambient conditions. Exchanges are necessary, as inflowing water brings with it material to support the resident bacteria and invertebrates that play a role in the "biological filter" of the hyporheic zone. However, this reliance on exchange also makes the hyporheic zone vulnerable to contaminants that impact on subsurface processes. As the hyporheic zone and its linkages to other habitats are seldom considered in planning decisions, the potential for disturbance originating from human activity (Table 1) is substantial. This paper synthesizes scattered ecological literature to illustrate how instream and catchment scale human activity impacts on the hyporheic zone. As the focus is from a river management and restoration perspective, the paper concludes with several recommendations for the effective management of streams where the hyporheic zone is an important ecosystem component.

KEY WORDS: Human impacts; Hyporheic zone; Mining impacts; Agricultural impacts; Urban impacts; Industrial pollution; River regulation; Sedimentation; Stream restoration; Stream management

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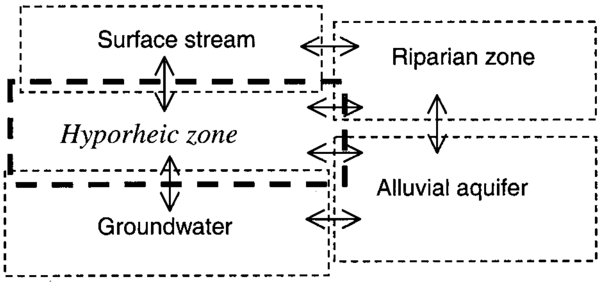

Figure 1. The hyporheic zone as a modulator for linkages between the stream, groundwater, riparian, and alluvial aquifer systems (after Boulton 2000a).

The Hyporheic Zone

Exchanges between surface and groundwater in porous-bed streams create a transitional ecotone called the hyporheic zone (Orghidan 1959, Schwoerbel 1961, Gibert 1991, Sabater and Vila 1991). It is characterized by the presence of water moving into, through, and out of the sediment interstices in a downstream direction (Figure 2). In many rivers the hyporheic zone contains a unique invertebrate fauna, termed the hyporheos (Williams and Hynes 1974), which is composed of surface and subsurface species. It also contains many forms of fungi and microbes that transfer, release, and stabilize some forms of transient nutrients. The size of the hyporheic zone depends on the extent and strength of the surface water–groundwater interactions, which are a function of sediment porosity, channel morphology, strength of groundwater upwelling, and stream discharge (Dahm and others 1998). However, although it has been more than 65 years since hyporheic research began (Karaman 1935), a specific set of quantitative defining criteria for this zone is difficult to find (Findlay 1995). Its boundaries have been described using gradients in temperature (White and others 1987), discontinuity break-lines in alkalinity and oxygen (Williams 1989), and the composition of the hyporheos (Williams 1989, Boulton and others 1992, Bretschko 1992), but with limited success. Triska and others (1989) used chemical tracers to define the hyporheic zone as being the area where 98%–10% of water originated from the surface stream. This definition goes some way toward quantifying and illustrating the variability of hyporheic boundaries and is a suitable definition for this review. As well as extending vertically below a stream, the hyporheic zone reaches laterally into the sediments beside the stream and the floodplain (Figure 2). This lateral extension is often referred to as the parafluvial zone (Holmes and others 1994, Claret and others 1999).

Exchange between surface and subsurface water may be the most important regulator of biological activity in the hyporheic zone. Without flow to renew nutrients and oxygen and to flush wastes, the sediments become unsuitable for the majority of life that inhabits them. The importance of hydrologic fluctuations in controlling water and nutrient exchange between the hyporheic zone and surface, groundwater, riparian, and floodplain habitats is recognized in the dynamic ecotone model of the hyporheic zone (Gibert and others 1990, Vervier and others 1992). Fluctuations in hydraulic and geomorphological variables mean that the boundaries and flow paths of water through the interstices of the hyporheic zone are constantly changing. In some large floodplain rivers the hyporheic zone can extend laterally for several kilometers [e.g., Flathead River in Montana, USA (Stanford and Ward 1988, Stanford and others 1994)], vertically for some meters [e.g., Rhône River in France (Marmonier and others 1992)], and have a volume that is several times greater than that of the surface stream (Valett and others 1990). Hyporheic zones in upland streams tend to be less extensive, but still make important contributions to some stream ecosystem processes (Boulton and Foster 1998, Morrice and others 2000).

Importance of the Hyporheic Zone

In terms of biodiversity, the hyporheic zone may not harbor as great a number of invertebrate species as other ecotones (Gibert and others 1990). However, as an area of intermediate biodiversity between the stream and groundwater, it is relatively species-rich, especially in evolutionarily ancient taxa (Boulton 2001). Its role as a refuge for surface invertebrates has been well documented (Grimm and others 1991, Boulton and Stanley 1995, Brunke and Gonser 1997), as has the occurrence of groundwater dwelling Crustacea (Marmonier and others 1992) and other groups that occur exclusively in the hyporheic zone (Vervier and others 1992). Relatively short food webs and a low diversity of food sources make these organisms sensitive to environmental change (Marmonier and others 1993) and have led to some suggestions that hyporheic fauna could be used as biological indicators (Malard and others 1994, Plénet 1995).

For some species of salmonids, the hyporheic zone is used for spawning and egg incubation (Geist and Dauble 1998, Dauble and Geist 2000, Woessner 2000). These processes require loose gravel and an adequate oxygen supply (Kondolf 2000), as well as the buffered temperatures (Shepherd and others 1986) that are provided by the interstitial habitat of the hyporheic zone.

Table 1. Human activities with potential to directly or indirectly impact the hyporheic zone

Activity	Potential impact
Dam construction	Creation of upstream no-flow areas, downstream sediment starvation, barriers for migration of fauna and river channel
Release of cool water from dams, or warm water from hydrothermal dams	Change in physicochemical conditions in the hyporheic zone, alteration of exchanges through instream macrophytes
Channelization and embankments	Removal of river bends, which slow water and allow down-welling, isolation of river from floodplain
River regulation and surface water extraction	Alteration of natural hydrological exchanges between hyporheic zone and surrounding habitats
Groundwater extraction on alluvial floodplain	Rapid influx of surface water pollutants, decreased residence time for hyporheic water
Gravel extraction or mining on floodplain	Lowering of alluvial water table, disruption of parafluvial flowpaths
Instream gravel, rock, or mineral extraction	Direct removal of hyporheic habitat, disruption of flowpaths, resuspension of silt, destabilization of river channel
High silt loads in runoff from agriculture, forestry, roads, mining, and urban areas	Clogging of sediment interstices, creating anaerobic conditions
Increased nutrients from fertilizers, effluent, burning, livestock, etc.	Enhanced algal growth in surface water, leading to colmation of the surface sediments
Failure to fence stock from river	Increased nutrients and particulate matter, resuspension of silt, gravel compaction, destruction of riparian plants, introduction of weeds
Permeable irrigation ditches and channels	Increase risk of contaminants entering groundwater, loss of groundwater or influx of surface water
Instream and groundwater salinity from agriculture and mining	Changes in physicochemical hyporheic conditions, potentially affecting biofilm and making conditions unsuitable for invertebrates
Introduction of exotic plant species	Change distribution of gravel bar, change in nutrient inputs and out takes from stream
Clearing of riparian vegetation for agriculture, forestry, and urban beautification	Removal of riparian regulation of groundwater fluxes, increased sunlight on stream leading to more algal growth and higher hyporheic temperatures
Herbicide and fungicide pollution	May poison interstitial bacteria, riparian vegetation, or the benthic algae or plants which assist with exchanges
Pesticide pollution	Poisoning of hyporheic invertebrates and microbes
Heavy metal and chemical pollution from industrial, urban, and mining sources	Poisoning of hyporheic invertebrates and microbes
Increased acidity from acid rain and mine drainage	Alter hyporheic physicochemical conditions and reduce precipitation of dissolved metals, may make habitat unsuitable for fauna

Once the eggs hatch, the larvae of some species may stay in the sediments for up to a month (Dent and others 2000).

The porous sediments in banks adjacent to streams can act as buffers to rising water levels and reduce, delay, or even prevent the occurrence of flooding (Gardner 1999). This process is known as bank storage (Brunke and Gonser 1997). The ability of the sediments to absorb a flood through bank storage depends upon the extent and porosity of the riverbed and its alluvial floodplain, and the extent of sediment saturation already present.

The ecological importance of the hyporheic zone is starting to be recognized by water managers in some parts of the world (Winter and others 1998, Boulton 2000a). A primary reason for this recognition is the realization of the significance of the links between two of the main exploitable sources of fresh water in maintaining water quality by biological filtration, supporting biodiversity and providing buffers for floods.

Physical, chemical, and biological conditions of the hyporheic zone allow it to have a filtering effect on the water that travels through it (Vervier and others 1992). In the Rhône River the first meter of bed sediments functions as a filter between surface and interstitial water, changing the chemistry of the pore-water, metal distribution, and the hyporheic faunal composition (Gibert and others 1995). Three filtration mechanisms can occur concurrently or consecutively in most hyporheic zones. The most obvious is the physical mecha-

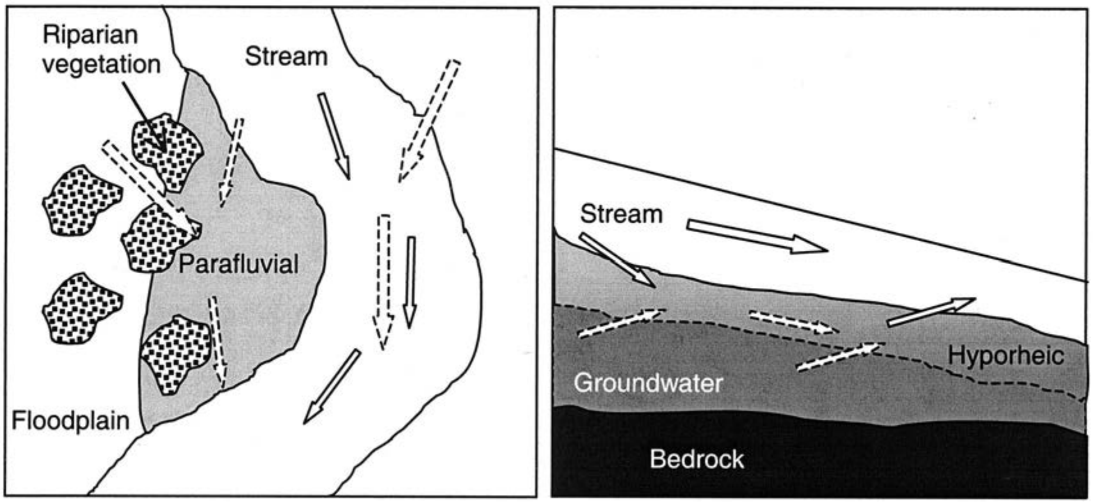

Figure 2. Aerial and side view of the hyporheic and parafluvial zones showing connections with the stream, groundwater, riparian, and floodplain systems. Dashed arrows show subsurface flow.

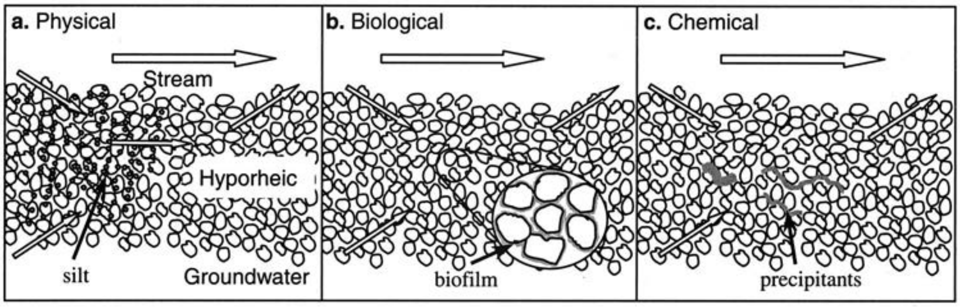

Figure 3. Three filtration processes that occur concurrently in the hyporheic zone: (**a**) physical filtration by the sediment matrix, (**b**) biological filtration by the microbial biofilm, and (**c**) chemical filtration by reactions such as mineral and redox processes

nism (Figure 3a), where the sediment particles impede the flow of silt and particulate matter as water enters and moves through the hyporheic zone (Vervier and others 1992). A second, biological filtering mechanism (Figure 3b) works in a manner similar to the trickle filters of sewage treatment plants (Ward and others 1998). Nutrients dissolved in either ground- or surface waters are taken up or transformed by microbial biofilms coating the sediments (Vervier and others 1992, Boulton 1999). The efficiency of biological filtration is correlated to microbial activity (Marmonier and others 1995). Subsurface invertebrates then feed upon the biofilms, and the nutrients enter the food chain. A third filtering mechanism (Figure 3c) is provided primarily by the chemical conditions prevalent within the hyporheic zone, which allow the precipitation of dissolved minerals and metals (Wielinga and others 1994, Harvey and Fuller 1998). The precipitate is then trapped by the physical filter, where it may be degraded biologically (Gibert 1990). Therefore, by increasing solute residence time and contact time with substrates in environments with spatial gradients in dissolved oxygen and pH, the hyporheic zone influences the biogeochemistry of stream ecosystems (Bencala 2000). In Sycamore Creek, Arizona, USA, the influence of patchy subsurface processes was found to effect surface nutrient patterns for up to several kilometers downstream (Dent and others 2001).

Human Activities

Human activities impact the hyporheic zone in two general ways (Boulton 2000a, Dent and others 2000). The first affects transfers between the component systems by impairing water exchange, and the second impairs biological activity directly through the poisoning of invertebrates and bacteria. Often the occurrence of one will lead to the other. When exchanges between the surface and hyporheic zone are disrupted by colmation (i.e., the blocking of interstitial spaces), conditions can become anoxic, inhibiting faunal and aerobic microbial activity (Brunke and Gonser 1997). Colmation is caused by physical (e.g., inputs of silts and fine sediments, compaction of sediment), biological (e.g., overgrowth of microbial biofilms and surface algae), or chemical processes (e.g., clogging by precipitants). In general, a high level of colmation leads to decreased oxygen and nitrate concentrations and increases in ammonification. Apart from direct hydrologic disruptions, the poisoning of the invertebrate fauna from an inwelling toxicant may lead to a blocking of the sediments, as there would be no regulators to prevent their clogging through microbial biofilm grazing (Gibert and others 1994), burrowing (Palmer and others 1997), and pelletization of fine particles (Danielopol 1989).

The following sections are separated into categories of human activity, with each section investigating an activity's potential impact on the hyporheic zone. Many activities share impacts. For example, mining, agriculture, and urbanization all may contribute silt to the hyporheic zone and lead to colmation.

Mining

Heavy metals associated with mining can pollute surface streams, groundwater, and alluvial aquifers (Paulson 1997), which in turn may limit both the hydrological exchange and biological activity of the hyporheic zone. Runoff that contains silt may lead to colmation, but it may also contain high levels of heavy metals (Ciszewski 1998, Soares and others 1999). More directly, gravel mining (Kondolf 1997, Boulton 1999) and alluvial gold and gem mining disturbs and removes sediments and resuspends silt, allowing it to block the interstices of hyporheic zones downstream. In-stream mineral extraction can also cause deepening of the channel, leading to a loss of pool–riffle sequence, bank slump (Bravard and Petts 1996), and a lowering of floodplain water levels (Kondolf 1997). All of these have the potential to disrupt hyporheic exchanges both laterally and vertically.

The influx of acid or saline groundwater into the mine excavation (Bochenska and others 2000), has the potential to lower the groundwater table through increased drainage or evaporation and might also impact on the hyporheic zone if it enters a nearby stream. Increasing the acidity and salinity of down-welling surface waters is likely to lead to a general failure in one or more of the hyporheic filtering mechanisms.

In some cases the hyporheic zone can be a barrier between surface and groundwater, preventing or slowing down the release of pollution from one habitat to the other. Wielinga and others (1994) found that the hyporheic zone of Silver Bow Creek, Montana, USA, acted as an intermediate boundary between groundwater, with low pH and high metal (iron and manganese) concentrations, and surface water, with high pH and low metal concentrations (Figure 4). The mixing of hyporheic water and groundwater formed a 10-cm-thick layer where bacteria and pH dropped substantially and a dense band of precipitated metals formed. In this case, the specific geochemical conditions provided by the hyporheic zone slowed the rate of release of mine-originated pollution into the surface stream.

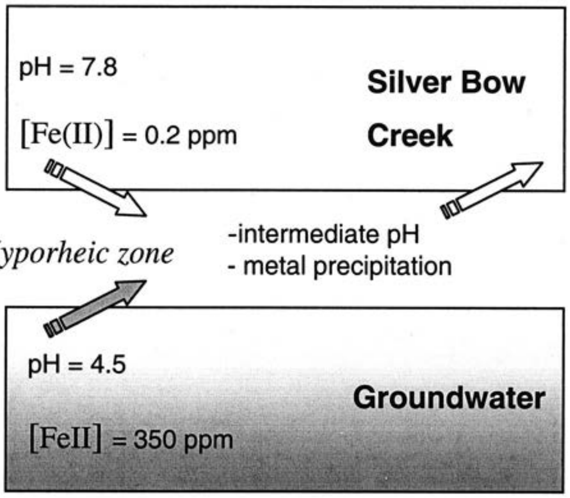

Figure 4. Precipitation of metals in the hyporheic zone of Silver Bow Creek, Montana, using Fe(II) as an example (after Wielinga and others 1994).

In the Pinal Creek basin, Arizona, USA, sediment-borne microbial oxidation removed approximately 20% of the dissolved manganese pollution resulting from copper mining (Harvey and Fuller 1998). The rate of the manganese uptake depends on a balance between chemical reaction rates, hyporheic residence time, and the turnover of stream water through the hyporheic zone. Associated with this increase in manganese oxides were decreases in the concentrations of other metals (cobalt, nickel, zinc), which were taken up during the oxide formation (Fuller and Harvey 2000). An experiment conducted specifically to test the ability of subsurface gravel (limestone and river gravel) in removing manganese from acid mine drainage found that a pH of between 6.8 and 7.2, dissolved oxygen (DO) concentration ranging from 3 to 5 mg/liter, and a redox greater than 500 mV provided ideal conditions for precipitation (Sikora and others 2000).

The ability of the hyporheic zone to act as a physicochemical filter should not be taken as an invitation for complacency, as the filter may break down if the chemical conditions change too excessively or if they are not able to fluctuate. For example, if water drained from a mine increased the acidity of the hyporheic water, contaminants such as metals could remain dissolved and toxic to the fauna. Without fluctuations in the locations of conditions that favor the precipitation of metals, the sediments risk becoming clogged. If fluctuations in both hydrological and chemical conditions do occur, the distribution of precipitants may be dispersed over a broader spatial scale, allowing more time for microbial breakdown.

Changed hyporheic conditions can also lead to the poisoning of invertebrates from contaminants. Arsenic and iron from a stream in Montana occurred in higher concentrations in the hyporheic zone than in the surface and groundwater (Nagorski and Moore 1999). Furthermore, the dissolved arsenic existed in the hyporheic zone as As(III), which is more toxic to invertebrates. It was thought that the physical and chemical conditions of the hyporheic zone (pH between 6 and 7, DO levels of 0–3 mg/liter) allowed sediment-bound arsenic to occur in its dissolved form of As(III), where it then reentered the stream. In this case, the hyporheic zone acts as a source of toxicant to the surface stream, which was derived from a less toxic sediment-bound form. Heavy metals from mining can occur in high concentrations in river bottom sediments (Ciszewski 1998, Soares and others 1999), where they affect benthic community structure (Clements and others 2000). Heavy metals such as zinc and copper (Plénet and Gibert 1994) are also toxic to groundwater invertebrates. Losses in the hyporheic invertebrate fauna may impair processes in the rest of the hyporheic zone, as they would not be present to stimulate bacterial activity and maintain interstitial porosity (Ward and others 1998, Boulton 2000b).

Urban and Industrial Impacts

Surface Water

Streams flowing through urban areas are usually subject to river training works and receive substantial inputs of effluent, stormwater, and industrial discharge (Laws 1993, Williams 1999). Removal of surface water for domestic or industrial use can lower the river level, the effects of which may be especially pronounced in arid or semiarid areas. Lower water levels often diminish the volume of the hyporheic zone by decreasing the area of sediment that is covered by water and by lowering the hydraulic gradient, reducing the penetration of downwelling water into the sediments (Stanley and Valett 1991).

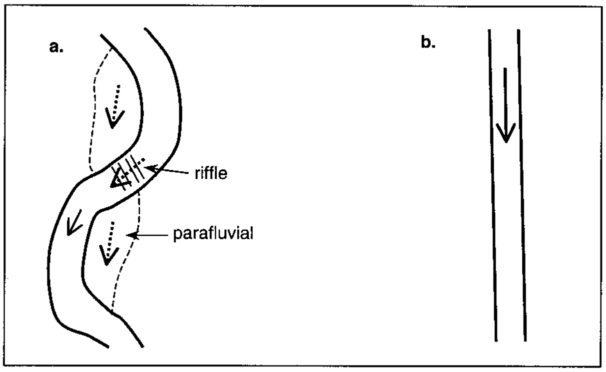

Figure 5. Before channelization the sinuosity and gradient of a river allows hyporheic exchange at riffles and parafluvial zones (**a**). Channelization reduces sinuosity and increases stream velocity, removing hyporheic exchange (**b**).

River training is not unique to urban environments, and the straightening and enlarging of river channels have often been used to reduce the frequency of flooding (Erskine 1992). This increases flow velocity, causing erosion and removal of bed and bank material (Erskine 1992) and a loss of the natural pool–riffle sequence (Clifford 1993) that creates the hydraulic conditions conducive to hyporheic exchange. The loss of sinuosity in the river reduces the amount of water flowing through the parafluvial zone (Figure 5). Increased impermeable areas, such as buildings, car parks, and roads, raise the volume of runoff. Without hyporheic bank storage, the frequency of flash flooding increases and enhances scouring of sediments. Runoff may also contain a number of contaminants that affect the hyporheic zone. Stormwater from an urban area in Maricopa County, Arizona, USA, carried sediments containing cadmium, copper, lead, zinc, and arsenic as well as the organic compounds chlordane, dieldrin, polychlorinated biphenyls (PCBs), and toxaphene (Parker and others 2000). These sediments can clog the interstitial spaces, while the contaminants poison microbes and invertebrates.

Embanking in some larger rivers (e.g., Danube, Rhône, and Rhine) has long been used to improve channels for shipping and provide protection against erosion and flooding (Bravard and Petts 1996). This has often involved separating the channel from its floodplain via the construction of longitudinal dikes, low submersible embankments, and other structures. The isolation of the river from the floodplain severs links with the lateral parafluvial zone as down-welling oxygen rich water is prevented from entering the sediments. Disruptions such as these, which alter the connectivity of interactions that structure ecotones, invariably lead to reductions in biodiversity (Ward and others 1999).

Channel diversion removes flow going over and through the sediments. The effects of diversion are particularly prominent in riffles. Without surface flow, there is no deposition or erosion in the riffle area, and in a bypassed channel of the Rhône River these processes were found to have a large role in determining hyporheic community structure by influencing interstitial water circulation (Creuzé des Châtelliers and Reygrobellet 1990). Although water may still flow through the sediment when surface flows are diverted, causing the hyporheic zone to become parafluvial, the requirement for regular flushing flows to prevent the sediments becoming clogged are not met (Schälchi 1992). This can lead to the formation of an impermeable surface layer, uncoupling the stream and hyporheic zone. Depending upon the extent of the diversion, flushing flows may only occur during flooding, or not at all.

Effluent can be a major source of nutrients downstream of urban environments, resulting in eutrophication, algal blooms, and colmation (Boulton 2000a). However, the hyporheic zone is often able to transform some of these nutrients. In the South Platte River downstream of Denver, Colorado, USA, where 95% of the base flow consisted of effluent from a treatment plant, denitrification in the anaerobic zone of the sediments was a key process (Bradley and others 1995). When this was combined with the nitrification of ammonium in the oxygen-rich area, the predominantly coarse-sand bed was found to be an effective method of removing anthropogenic nitrogen. This example further illustrates the role of hyporheic zone filtration.

Waterborne pollution from industrial sources can contribute metal contaminants that alter hyporheic invertebrate communities. Surveys of hyporheic invertebrates from the Rhône River upstream (Plénet and Gibert 1994) and downstream (Plénet and others 1996) of the city of Lyon, France [with moderate pollution from chemical and metallurgic industries as well as water-purification stations (Plénet 1995)] revealed that the invertebrate community was affected by metal contamination of the sediments, especially iron, chromium, and nickel.

Groundwater Extraction and Pollution

Pumping groundwater from wells close to streams can draw stream water through the hyporheic zone and reduce its residence time, impacting on biological and hydrological activity and thus reducing the efficiency of the biochemical and physical filters. In an alluvial aquifer of the Rhône River, Mauclaire and Gibert (1998) monitored variations in physical and chemical conditions (water table, temperature, pH, redox potential, conductivity and dissolved oxygen). They observed that pumping from a 200 m^3/h capacity pump for a mean of three hours every day reduced the amount of time it took for surface water to influence the aquifer from two days to two hours. This rapid influx of surface water made the hyporheic zone more vulnerable to surface water pollution, and the reduced contact time between sediments and water probably reduced the effectiveness of biological filtration. Alternatively, Bourg and Bertin (1993) suggested that by careful positioning of bores in alluvial aquifers, some pollutants could be filtered from the water. It was found that the alluvial sediments of the Lot River, France, effectively filtered out zinc within the first 10–15 m of sediment. However, they also note that in some sediments, biological activity can have detrimental effects, such as the release of iron and manganese due to the dissolution of their respective oxides.

Pollution of groundwater by human effluent is of concern in aquifers where septic tanks are in use or where the sewer piping is old and prone to leaks. While the hyporheic zone can intercept effluent-polluted groundwater and remove some of the nutrients before it enters the stream, its ability to effectively remove coliform bacteria is uncertain. Sinton (1986) investigated the effects of two septic tank effluent disposal methods (deep soakage pits and injection bores) on the microbial quality of an alluvial gravel aquifer in New Zealand. A 5.5-m-deep soakage pit allowed approximately 80% of the effluent to percolate into an unconfined aquifer where fecal coliform bacteria were found 9 m from the pit. An 18-m-deep injection bore leaked effluent into a confined aquifer, where coliform bacteria dispersed up to 42 m from the bore. A separate study (Sinton and others 1997) found bores situated on an alluvial aquifer near Christchuch, New Zealand, to be contaminated with bacteria originating from effluent irrigation up to 445 m upslope. Coliform dispersal over these distances indicates that bacteria may still be able to reach the hyporheic zone via its linkages with the alluvial floodplain, and perhaps then enter the stream.

Not much work has been done on the specific effects of groundwater sewage on the hyporheos, but there have been several studies of its impact on groundwater invertebrates that indicate high levels of sewage pollution do impact on the structure of associated faunal communities. Epigean organisms dominated the groundwater fauna of the Terrieu area in France during low water periods when there was a high sewage

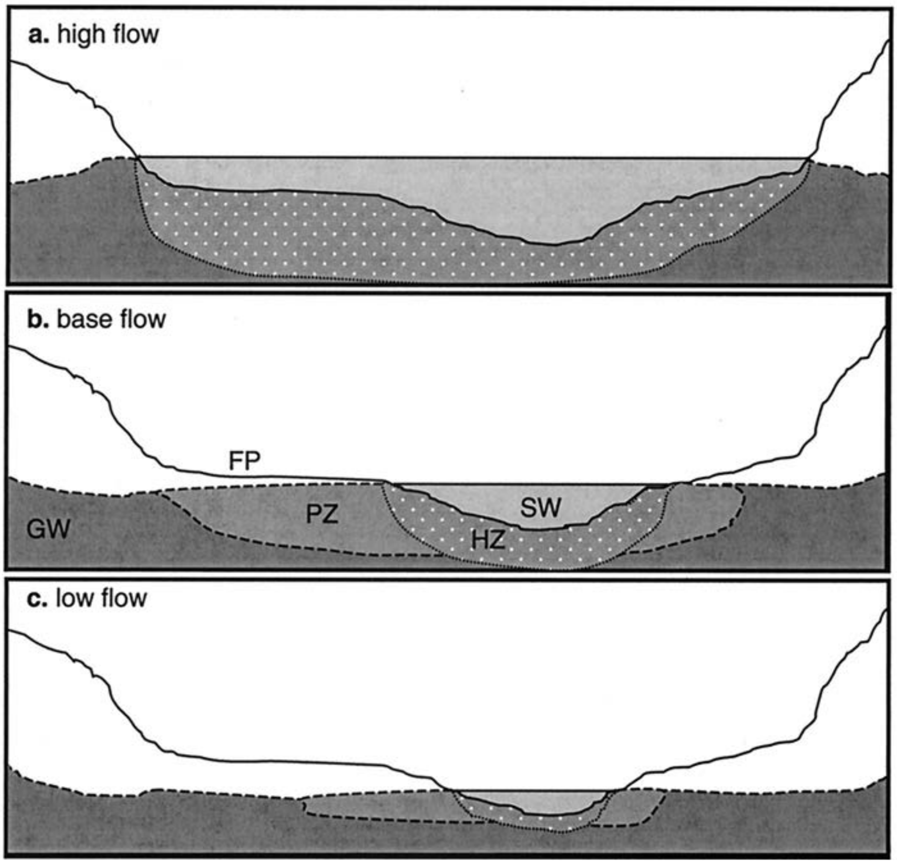

Figure 6. Expansion and contraction of the parafluvial zone (PZ) and hyporheic zone (HZ) with changes in surface water (SW) stage: (**a**) high flow increases saturated the hyporheic zone (HZ); (**b**) base flow maintains HZ below the stream and PZ below the floodplain (FP); and (**c**) low flows reduce PZ and HZ as groundwater infiltrates more freely.

infiltration rate (Malard and others 1994). When groundwater recharge from the sewage-polluted Terrieu Stream was high, these epigean organisms were displaced downstream and the fauna temporarily became dominated by hypogean taxa. Sinton (1984) found a depauperate fauna (98% were three crustacean species) in a sewage-contaminated aquifer in New Zealand. However, a lack of background knowledge has not made it clear if this difference was natural or due to the pollution. About 10% of the crustaceans contained coliform bacteria and high sewage contamination corresponded with high crustacea mortality rates. Wilson and Fenwick (1999) also suggest that effluent-polluted groundwaters may create a suitable habitat for the isopod *Phreatoicus typicus*. The high death rates found by Sinton (1984) may be a result of some detrimental effect of the bacteria on groundwater invertebrates and the organic matter, low oxygen, and enriched nutrient levels often associated with effluent. Because of the overlap between the groundwater fauna and the hyporheos, it is likely that they share similar responses to effluent pollution. Groundwater invertebrates may use the hyporheic zone as a refuge when conditions deeper down become unsuitable.

River Regulation

Changes in Flow Regime

Rivers are regulated to provide water for various catchment land uses, for hydroelectricity generation, or for flood control or mitigation. Fluctuations in water level alter the strength of hydrological interactions and the amount of bed exposed to below-stream hyporheic or parafluvial activity (Figure 6). In a Canadian stream, fluctuations in river discharge simulating a hydroelectricity regime altered the flow pathways and chemistry of hyporheic water at trout spawning and incubation sites (Curry and others 1994). Although detrimental to trout reproduction in this case, fluctuating water levels may be essential for the hyporheic zone to function effectively (Brunke and Gonser 1997, Boulton and others 1998). Natural fluctuations often differ in timing, magnitude, and duration from those induced anthropogenically. Stream organisms tend to be linked to the natural disturbance and flow regimes with which they evolved (Jones and others 2000) and, as a result, may be vulnerable to any changes in these.

As river regulation alters flow regime, it potentially has far-reaching and permanent spatial and temporal effects on the hyporheic zone. Under high stream flows (Figure 6a), water enters and travels through the sediments with relative ease. However, if it moves too rapidly, there will be little time for biological and chemical filtration to take place (Grimaldi and Chaplot 2000). As the surface flow decreases (Figure 6b, c), so too does the volume of water moving through the sediment. Because the water is moving slowly, it deposits silt and fine particulate matter in the sediment interstices, causing colmation (Milan and Petts 1998, Brunke 1999). For some processes, especially reduction, low flows could be as important to the hyporheic zone as high flows because they provide conditions favorable to anaerobes in saturated areas. After a period of low flow, a greater hydraulic pressure, resulting from high flows, is needed to resuspend the silt and move it rapidly downstream. The cyclical wetting and drying of sediment in lateral and mid-channel bars may aid in their oxygenation, since when they are dry, air is able to penetrate the interstices. When river flow levels are to be regulated, the reliance of hyporheic and other fluvial habitats on fluctuations in discharge needs to be recognized in order to sustain natural rates of filtration.

Dam Construction

The concept of the hyporheic zone acting as a corridor for the migration of interstitial fauna incorporates channel-aquifer interactions into river continuum models (Stanford and Ward 1993). Connections between interstitial communities are often only present through alluvial aquifer systems. The Global Interstitial Highway Model (Ward and Palmer 1994) views the alluvial aquifer as the center of a spatially continuous hypogean habitat, which follows a river along its length and connects it through groundwater linkages to alluvial aquifers in other catchments. The construction of dam walls can sever parts of the interstitial highway by drowning alluvial aquifers upstream of the wall and isolating those downstream to downstream migration of hyporheic fauna, many of which do not have the aerially dispersing stages that are present in surface-dwelling invertebrates. Dams also act as barriers for the downstream transport of sediment and movement of channel change in up- and downstream directions (Kondolf 1997, Shields and others 2000). Releasing sediment from a reservoir to compensate for its accumulation within the profundal zone is one method that is adopted by some managers to prevent the reservoir silting up. Below the Guernsey Reservoir, on the North Platte River in Wyoming, USA, sediment releases correlated with fluctuations in benthic invertebrate communities (Gray and Ward 1982). Some groups decreased initially and then recovered or even increased in density after cessation of sediment release. The impact of such releases on the hyporheic zone would depend upon the size distribution of the sediments released, the rate of release (gradual steady release versus pulse releases), bed porosity and roughness, and the energy of the water used to transport them. Compensating for the hyporheic zone when planning for sediment release is complicated by many factors. If too little sediment is released, or the water is too fast, then sediment starvation may occur. If the opposite occurs, existing hyporheic zones could be colmated and smothered, or there would be too little water to properly sort the sediments.

Reservoirs that reduce the frequency and durations of high flows can lead to channel migration and bank erosion (Shields and others 2000). As the channel moves away from its original course, it abandons the original hyporheic zone. Because high flows have been reduced, there is little down-welling water to flush out silt to create new interstices for hyporheic colonisation. Lentic areas that occur immediately upstream of dam walls can inundate sediment and remove any moving water that might allow exchange with the hyporheic zone. Alternatively, continuous erosion downstream of the wall could scour the bed sediments to such an extent as to expose bedrock (Kondolf 1997), thereby removing the hyporheic zone.

With many dams there is often a temperature difference between the stream above the reservoir and the water being released. In the Dyje River in the Czech Republic, the water temperature regimes were recorded upstream and downstream of the Vranov Reservoir (Helešic and others 1998). Fluctuations of 0–23°C above the reservoir fell to 2–14°C downstream of the wall. A decrease in temperature may encourage surface-dwelling fauna to take refuge in the hyporheic zone (Šterba and others 1992) potentially changing the composition of the fauna through competition or predation. Cooler hyporheic temperatures will slow bacterial activity (Hill and others 2000), and the lower oxygen levels often associated with hypolimnic water would change the predominant biogeochemical processes to reductive ones. Changes in temperature can alter the composition of instream macrophytes, affecting the exchanges that occur between their surface leaf and subsurface root regions (White and Hendricks 2000). Reservoirs may also increase the amount of water flowing through the hyporheic zone by preventing the river from freezing in winter. Regulated flows from Hungry Horse Dam on the Flathead River, Montana, USA, combined with warm water from the Kalispell Valley aquifer allow hyporheic activity to continue throughout the

Table 2. Potential impacts of agricultural activity and forestry on the hyporheic zone and their causes

Impacts	Agricultural causes	Forestry causes
Nutrients	Fertilization, erosion	Ash from burning, erosion
Silt	Erosion, resuspension of instream silt by stock	Erosion of exposed postharvest soil
Riparian linkages	Clearing and grazing streamside vegetation	Clearing
Toxic chemicals	Seepage from stock dips; herbicides and pesticides	Herbicides and pesticides
Instream and bar disturbances	Unfenced stock; road crossings	Road crossings
Hydrological	Increased runoff in some cases, decreased runoff due to dams in others; higher groundwater tables; salinization	Increased runoff after logging; higher groundwater tables

winter despite air temperatures of −30°C (Stanford and others 1994).

Agricultural and Forestry Impacts

In many regions agricultural and forestry activities bring about catchment-wide alterations to the landscape, potentially affecting the hyporheic zone (Table 2). These impacts result from excessive nutrients, livestock trampling and grazing, the modification of natural riparian buffers, increased silt load, pesticides and herbicides, salinization, and hydrological alterations caused by landscape modification, and groundwater and surface water extraction. As many of these impacts act in concert, the effects of individual adverse processes are hard to isolate.

Excessive Nutrients

Agriculture is a major source of nitrogen and phosphorus in aquatic ecosystems. The sources of these nutrients may be diffuse and originate from animal waste, fertilizers, or the ash of forestry waste or stubble burned after harvest. High nutrient levels can lead to algal blooms, loss of oxygen, and other problems that affect surface waters (Carpenter and others 1998). They also impact on the hyporheic zone (Table 2).

Anoxic down-welling water impairs interstitial biological oxidation and in doing so reduces the efficiency with which the biochemical filters are able to deal with an excess in some nutrients. Bacterial nitrification requires oxygen, as do the invertebrates that graze the bacteria, preventing clogging and stimulating growth (Ward and others 1998, Boulton 2000b). However, processes such as ammonification may increase under anoxic conditions, accelerating nitrogen removal in this way. Phosphorus tends to accumulate in hypoxic areas of the hyporheic zone. If oxygen levels become too low, the sediment-bound phosphorus is freed and can be released into the stream or absorbed by periphytic biofilm on the surface of upwelling zones (Hendricks and White 2000). Algal blooms brought about by high nutrient levels can lead to a clogging of the surface sediments at down-welling zones, preventing exchange between the stream and hyporheic zone (Schälchi 1992, Boulton 2000a).

Filtration of nutrients in the hyporheic zone can be relatively successful in agricultural catchments if conditions are suitable. A study of two moderate-intensity agricultural catchments in France (La Roche and Moulinet) found that substrate origin governed how rapidly the hyporheic zone was able to process nitrate (Grimaldi and Chaplot 2000). Granite-derived substrate, which had a sandy or peaty texture, allowed the inflow of nitrate-rich stream water to regions of denitrification in the hyporheic zone. As a result, stream nitrate concentrations decreased in a downstream direction. This was not the case when the substrate is derived from schist, and it is thought that the redox conditions due to low hydraulic conductivity are a key contributing factor for this (Grimaldi and Chaplot 2000).

Livestock

Failure to fence stock out of streams can lead to direct inputs of particulate organic matter and nutrients from waste (Harding and others 1999). Large stock such as cattle and horses can also resuspend silt (Fritz and Dodds 1999), compact the gravel in lateral bars and in the bed, and graze or trample riparian vegetation. Stock act as vectors for weeds, which establish themselves on gravel bars, out-compete native species, and affect processes such as evapotranspiration and bar stability.

Intensive livestock industries (e.g., feedlots, piggeries) have the potential to contribute large amounts of nutrients and silt to a stream if not managed properly.

Chemicals leaching from stock dips and drenches near streams may also poison hyporheic invertebrates and bacteria.

Land Clearing and Modification of Riparian Habitat

Riparian ecosystems are important filters for stream water quality, removing excessive nutrients and silt from overland flows and regulating groundwater discharge and chemistry before it enters the stream (Vought and others 1994, Hill 2000). In the Walker Branch, Tennessee, USA, the riparian zone is a source of ammonium and phosphorus to hyporheic water when the dissolved oxygen content is low, but acts as a sink for phosphorus when dissolved oxygen levels are high (Mulholland 1992), underscoring the links between the hyporheic and riparian habitats. Removing riparian vegetation during land clearing can lead to an increased likelihood of bank collapse, burying the lateral bars and parafluvial zones (Boulton and others 1997) and allowing more silt to enter the stream from up-slope agriculture (Mulholland 1992, Maridet and others 1996). In addition, greater amounts of light and nutrients can enhance algal growth (Townsend and others 1997). All of these processes can lead to colmation.

Land use was correlated with the composition of hyporheic fauna in several New Zealand streams near Hamilton, North Island (Boulton and others 1997). Streams draining native forest contained a diverse invertebrate fauna of mostly temporary hyporheic taxa (i.e., those which spend only a part of their life cycle in the hyporheic zone). In streams flowing through pasture and in exotic pine forests, the fauna was less abundant and lower in taxonomic richness. The shading effect of the trees in pine and native forests meant that hyporheic water at these sites was cooler than at the pasture sites, while burial of lateral bars reduced dissolved oxygen levels in pasture sites.

Exotic plant species could also cause problems for the hyporheic zone. In Australia, various species of introduced willow (*Salix* spp.), which have a matrix of fine filamentous roots, probably impede the subsurface flowpaths of water traveling through the hyporheic zone. Due to their deciduous nature, the contribution of willow organic matter to the stream is greater in autumn than the contribution made by the native evergreen eucalypts. This, when combined with less shaded water, can lead to increased growth in epilithic algae throughout autumn and winter (Read and Barmuta 1999). As well as changing the timing of dissolved organic carbon (DOC) inputs into the hyporheic zone and the surface stream, this can also change the type of DOC, which is required as a source of carbon and energy for hetertrophic organisms. A change in the timing, type, or amount of DOC can have detrimental effects on hyporheic filtration and stream ecosystem metabolism. In some areas where eucalypts are introduced (e.g., Spain and California) the various impacts mentioned above would be expected to differ predictably.

Silt and Sediment

Forestry and agriculture can be major sources of the silt and fine sediments that clog interstices and cause colmation. Cattle farming and forestry in two French catchments increased erosion so that silt accumulated in the sediments (Maridet and others 1996). Fine sediment was found to accumulate in the hyporheic areas of Bear Valley Creek in Idaho, USA, where it influenced the invertebrate colonisation rates and assemblages (Richards and Bacon 1994). Roads associated with forestry can act as conduits for silt and water. They also create regions of instability which can act as sources for landslides (Jones and others 2000). The clogging of sediments with silt will reduce the numbers and activity of hyporheic invertebrates, in turn affecting the porosity of interstitial sediments through the absence of their feeding and burrowing (Brunke and Gonser 1997). Due to their sensitivity to elevated silt levels, hyporheic communities may be potential indicators of poorly managed land use practices (Mary and Marmonier 2000, Govedich and others 1996).

Agricultural development in the Ozarks area of the United States has contributed gravel-sized sediments to the Current River, Missouri (Jacobson and Gran 1999). Superficially, this could be good for the hyporheic zone, as it provides sediments and goes some way to offset the losses of gravel from extraction. However, accumulations of instream sediment can lead to channel instability and a decrease in channel storage, leading to the resuspension of silt stored in the floodplain sediments (Jacobson and Gran 1999) and predictable impacts on the hyporheic zone. Furthermore, the smothering of surface stream habitats may have important implications for hyporheic ecology. Siltation of salmonid spawning beds impedes fish breeding success (Milan and Petts 1998). To combat this, managers seek methods to clean fine particles from the gravel. Of three such methods investigated in four rivers in southern England, pump-washing was found to be more suitable than both high-pressure jet washing and tractor rotovating (Shackle and others 1999), although the authors suggest that an overall reduction in silt may be more beneficial. The ensuing loosening of the gravel from all these methods could lead to a spatial shift or alterations in the chemistry of the upwelling hyporheic

Table 3. Pesticides in Dutch aquifer detected or modelled at levels exceeding the risk boundaries for pesticides in groundwater set by the European Community[a]

Exceed risk boundaries (detected)	Expected to exceed risk boundary (modeled)
aldicarb	cypermethrin
1,3-dichloropropene	1,3-dichloropropene
ethoprophos	fenpropathrin
	pendimethalin
	pirimicarb
	pirimiphos-methyl
	propoxur
	terbufos
	thiram
	trichlorphon

[a] Risk boundaries: 0.1 mg/liter for separate compounds, and 0.5 mg/liter for mixtures (based on Notenboom and van Gestel 1994).

area, which is generally typified by low oxygen conditions. Resuspended silt or sediment may cause colmation in downwelling zones downstream.

Agricultural Chemicals

Pesticides impact on invertebrate communities both in surface (Liess and Schulz 1999) and groundwaters (Notenboom and van Gestel 1992) and can enter the hyporheic zone via either of these pathways. Levels of the pesticides atrazine, deethylatrazine, and deisopropylatrazine in stream water infiltrating an alluvial aquifer of Walnut Creek, Iowa, USA, reached levels between 270 and 3060 (μg/day)/m^2 where average vertical hydraulic conductivity through the streambed ranged from 35 to 90 m/day (Squillace and others 1993). Pesticides also entered the groundwater through leaching, but were recorded at levels two to five times less and moved at a slower rate than those in surface water.

A preliminary investigation comparing the estimated groundwater concentrations of several pesticides to toxicity data of several species of groundwater crustaceans was carried out in a Dutch aquifer (Notenboom and van Gestel 1992). Aldicarb, 1,3-dichloropropene, and ethoprophos were at concentrations high enough to exceed European Community risk boundaries, while modeling indicated that nine others were at sufficient levels to pose a potential risk to groundwater ecosystems (Table 3).

Concentrations of the lamprey pesticide 3-trifluoromethyl-4-nitrophenol (TFM) in the hyporheic zone of Dam Creek, Ontario, Canada, were found to be greatest at a depth of 55 cm one day after treatment (Jeffrey and others 1986). At concentrations high enough to kill juvenile lampreys, TFM has been found to be toxic to a number of surface-dwelling microinvertebrate species (Smith 1967). However, of eight taxa that occurred in the hyporheic zone, only tubificid worms decreased in abundance after its application. Although the hyporheic zone is not impermeable to TFM, it may act as a refuge for surface invertebrates during treatment and as a source for recolonization after surface concentrations return to normal. There appears to be no literature on the impacts of herbicides or fungicides on the hyporheic zone. However, linkages with riparian and instream plants and algae imply that further work in this area may reveal some such impacts.

Salinization

The concentration of salt in running waters is a function of surface flow regime, catchment conditions, and groundwater discharge patterns (Schofield and Ruprecht 1989). In 13 streams in south Western Australia, hyporheic salt levels at depths of only 20–40 cm often differed significantly from those in the surface water (Boulton and others 1999). In some of the streams, hyporheic salinity was lower than surface concentrations by 20%; in others it was 20% greater. Differences in salinity between hyporheic and surface water could affect the chemical processes of each habitat and create toxic conditions for invertebrates. In the streams with saline subsurface water, hyporheic species richness was much lower (A. Boulton and P. Marmonier unpublished data).

Hydrological Effects

Agricultural and forestry practices alter the hydrology of a catchment. Large-scale land clearing decreases the evapotranspiration, increases stormwater runoff and erosion, and decreases groundwater infiltration and base flow in streams (Winter and others 1998). Pumping for irrigation from groundwater lowers the water table and may change the extent and efficiency of the hyporheic zone. Pumping from the stream, either directly onto crops or pasture or into storage dams or irrigation ditches, reduces the hydraulic pressure with which water is pushed into and through the hyporheic zone. The lowering of the river height may also reduce the areal extent of hyporheic exchange sites and of the lateral parafluvial zone (Figure 7).

Irrigating from groundwater with pumps situated near rivers can induce rapid streamwater infiltration of the hyporheic zone (Mauclaire and Gibert 1998). Even when pumping is not carried out near streams, inappropriate groundwater irrigation can lead to problems such as salinity and lower water tables for the hyporheic zone (Boulton and others 1999). In recharge areas, increasing groundwater exploitation could lead to in-

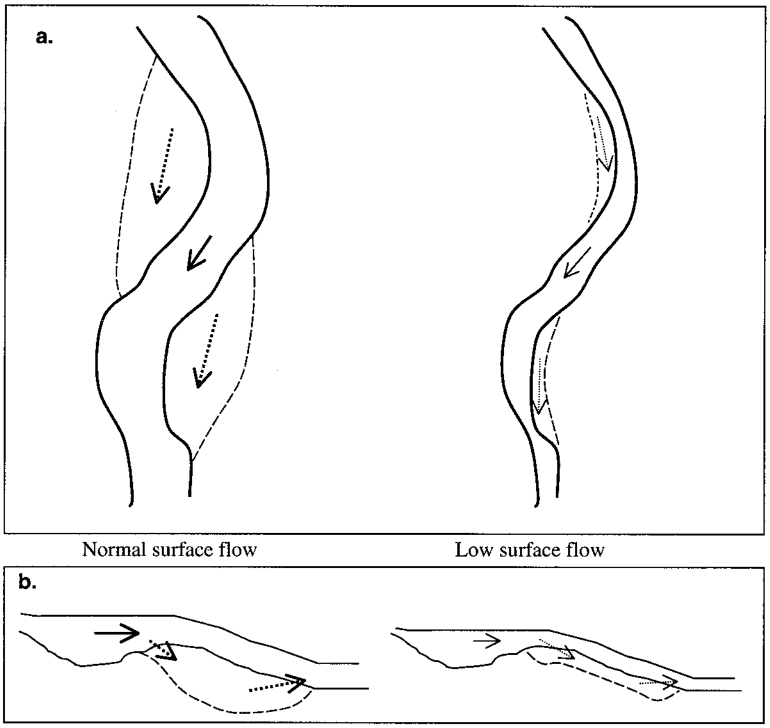

Figure 7. (**a**) Plan view and (**b**) longitudinal cross section showing the effects of low surface flows on hyporheic boundaries (dashed lines).

creases in groundwater pollution along shallow flow paths (Hobma 1997), which could flow into the hyporheic zone.

Irrigation ditches can increase the area of surface water–groundwater interactions, leading to the infiltration of water into the groundwater system. In the Kara-Kum canal in the Turkmenistan region of Russia, it is estimated that 45%–55% of water is lost through seepage from permeable irrigation ditches (Zaletaev 1997). In these cases, irrigation ditches probably accelerate the entry of agricultural chemicals to the groundwater and then the hyporheic zone. Conversely in arid areas irrigation ditches can increase the loss of groundwater by evaporation (Zaletaev 1997).

Global Issues

Since stream morphology and hydrology are important determinants of hyporheic processes and because these are largely determined by climatalogical variables, the hyporheic zone is likely to be affected by climate change (Meyer and others 1999). The predicted increase in temperatures and changes in precipitation patterns linked with global warming are expected to result in an increase in the influence of groundwater volume in streams (Winter 2000). In some regions this could lead to permanent streams becoming temporary and to current flow duration in temporary streams becoming even briefer (Stanley and Valett 1991). Streams fed by groundwater may experience an increase in the influence of subsurface flow. This will result in a diminished hyporheic zone, since exchange with the surface stream will be less.

It appears that the vulnerability of a stream to climate change depends upon whether its dominant source of water is through direct precipitation or from groundwater recharge. Because of the buffering capacity of large groundwater flows, it is thought that the latter will be more stable (Winter 2000). A greater frequency and magnitude of spates and drying in surface waters could render the more stable hyporheic zone increasingly important as an invertebrate refuge. Within the hyporheic zone itself, the effects of increased periods of drying in the surface stream will lead to lower levels of exchange of down-welling waters, with the repercussions identified earlier.

Hyporheic pH and redox conditions can also be changed by acid precipitation, resulting from atmospheric concentrations of chemicals like sulfate and nitrate. If the acidic water first leaches through to the groundwater, there is a chance that it will become neutralized before entering the groundwater–stream ecotone (Winter and others 1998). However, neutralization is less likely for water that enters the hyporheic zone across the stream interface, and over time could result in chronic changes in pH and redox conditions.

Management Suggestions

Our knowledge of the hyporheic zone has increased substantially over the past two decades. However, we do not understand hyporheic processes as we do those in surface and riparian ecosystems. Effective management requires decisions to be based on the best scientific information, and close collaboration between managers and hyporheic ecologists is a necessary step in achieving this. We must have river rehabilitation and protection strategies that consider all the interactions between stream, hyporheic, floodplain, and groundwater components. Strategies that prevent anthropogenic restriction of exchanges may include the periodic release of environmental flows to flush silt and reoxygenate sediments, the planting and maintenance of riparian buffers consisting of native species, effective land use practices, and suitable groundwater and surface water extraction policies. In many cases these policies are already in place, mostly for the benefit of the surface stream, and it is only a matter of extending their boundaries to incorporate subsurface processes. However some, such as gravel extraction policies in Australia, do not acknowledge the potential effects on the hyporheic zone.

Rehabilitation of a degraded hyporheic zone may not be too difficult a task in a stream that is undergoing rehabilitation for its surface component. For example, a stream that has a well planted riparian zone in a catchment where land use practices minimize silt, nutrient, and chemical runoff to the stream may only require a surge of water to flush silt from the sediment in order to establish a suitable hyporheic zone for subsequent recolonization of invertebrates. Some streams will require more work, including the careful introduction of gravel, the loosening of existing gravel by mechanical means, and the reintroduction of bends, large boulders, and logs to induce down-welling and sediment deposition. However, since it is often not possible to ascertain what hyporheic conditions were like before the river became degraded, it may be difficult to determine a restoration aim. This may be achieved using a combination of upstream conditions, conditions in similar but unimpacted systems, and the latest scientific information.

Although increasing numbers of scientists and managers are becoming aware of the hyporheic zone, the awareness of the general community does not seem to be growing. Raising public consciousness should be considered as an important step in hyporheic zone restoration and preservation. A way of achieving this is through the inclusion of river users (e.g., rural and urban stream care groups, mining companies, etc.) in monitoring and rehabilitation programs that incorporate the hyporheic zone as an essential part of a healthy river (Boulton 2000a). The establishment of a community-based hyporheic monitoring protocol may include sampling for microbial activity using the cellulose breakdown potential through loss in tensile strength of the standard sized strips of cotton (Boulton and Quinn 2000). Sampling for fauna and nutrients will also give useful monitoring data. Karaman-Chappuis pits (Mathieu and others 1991) and the pump method (Boulton and others 1992) are two simple techniques that can be used for this. The field methods described above are relatively cheap and should well be within the budget of most community stream care groups. However, as the fauna are small and nutrient measurements require expensive equipment and chemicals, the samples may need to be sent away for analysis. The establishment of government funded "hyporheic monitoring centers" at the state level may be one way of minimizing the cost here. It is hoped that once people are conscious of the existence of the hyporheic zone and its importance in river ecology, there will be a wider understanding of any management decisions required.

Our lack of knowledge on the inhibition of invertebrate and microbial activity by toxic levels of chemicals such as petrochemicals and agricultural chemicals needs to be addressed. More research is required into specific pollutants, the mechanism by which they reach the hyporheic zone, and the impact they have on species.

Many of the examples given in this review come from studies that span either a short temporal or small spatial scales. Impacts from human activity are not so confined. They may be immediate or take years to decades to show any effects. Similarly they may affect the hyporheic zone of a single gravel bar or that of an entire river catchment. To assess the true impact of human activity, more long-term studies are required over large stretches of river (catchment or trans-catchment). Appropriate hyporheic monitoring programs could go some way toward increasing this knowledge.

Conclusion

The hyporheic zone is a central part of most sand- and gravel-bed rivers. Its location at the interface between stream surface water and groundwater exposes it to a variety of anthropogenic pressures. Impacts on the hyporheic zone potentially jeopardize the quality of water in rivers and groundwater. The hyporheic zone is able to withstand natural levels of disturbance and is able to transform nutrients, stabilize metals, and recover from drying and floods. However, many human activities have the potential to disturb hydrological exchange and biological activity beyond the threshold where recovery is possible. Managers must recognize the importance of links between the hyporheic zone and the surrounding habitats and incorporate this into their restoration and management plans.

Acknowledgments

I would like to thank the NSW Department of Land and Water Conservation, the River Basin Management Society, and the University of New England (UNE) for funding. Much of the research for this document was undertaken as part of a Masters of Resource Science at UNE. I would like to thank two referees for their remarks. This manuscript benefited from comments by Professor Pierre Marmonier (University of Rennes), Associate Professor Andrew Boulton (UNE), Melanie Pearson (Murray Darling Freshwater Research Centre), and Jodie Reseigh (UNE).

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