Second Australian Stream Management Conference
8-11 February 1999, Adealaide, South Australia

The role of subsurface biological filters in gravel-bed river rehabilitation strategies

Andrew Boulton

SUMMARY: Many stream rehabilitation programs aim to stabilise river banks and reduce erosion or channel cutting, judging the effects of these practices from the state of visible parts of the stream such as the banks and the streambed. However, few strategies specifically target the importance of the maintenance of water exchange between the surface stream and the subsurface "hyporheic zone". Large volumes of water may flow through gravel bars and in the hyporheic zone, and during the dry season when surface flows are low, most stream-flow may be below the surface. This subsurface flow affects water quality because the gravel beds act like biological filters, similar to gravel in a fish tank. Microbial biofilms on the surfaces of the stones transform nutrients while the gravels retain particles of organic matter (e.g., leaf fragments, dead algae) drifting downstream. In turn, the biofilms and organic matter are eaten by subsurface invertebrates. Recent work in several Australian streams and rivers has revealed the extent of this subsurface ecosystem compartment and its fauna, and the importance of hydrological exchange for sustaining the hyporheic zone. Human activities can restrict this exchange through sedimentation from bank erosion, gravel extraction, or poorly-managed catchment land-uses. Flow regulation can prevent natural flushing flows that periodically cleanse the biological filters of silt and fine sediments. Stream rehabilitation programs should consider ways to prevent clogging of the upper sediments of gravel-bed rivers and bars, or if necessary, remove the fine material by carefully controlled aspiration.

THE MAIN POINTS OF THIS PAPER

- The hyporheic zone is the saturated interstitial habitat below the stream bed and into the banks, and can act as a biological filter to improve water quality.
- In many gravel-bed rivers, exchange of water, nutrients, organic matter, and other material between the surface and the hyporheic zone influences ecological processes in the surface stream.
- Strategies for rehabilitating rivers seldom specifically consider the role of the hyporheic zone.
- Human activities may restrict this exchange, often through sedimentation from erosion, gravel extraction, or poorly-managed catchment land-uses.
- River management strategies to restore exchange processes could include removal of silt by aspiration or flushing, and prevention of events that lead to excessive sedimentation and soil-loss into the river.

1. INTRODUCTION

Stream ecologists have known for at least 40 years (Orghidan 1959) of the existence of a distinct zone - the hyporheic zone - that lies between the river above, the groundwater below, and often the lateral alluvial aquifers under river banks, vegetated riparian zones and floodplains (Figure 1). The boundaries of this zone are difficult to define because they vary in response to surface discharge, bed porosity, channel shape and other factors. However, the real significance of the hyporheic zone lies in its role as a dynamic ecotone between the river and the ground-water (Gibert et al. 1990), acting to filter sediments, nutrients, organic matter and invertebrates exchanged between surface and subsurface compartments (Vervier et al. 1992). Thus, it has really only been in the last decade that we have fully appreciated the functional significance of the hyporheic zone (reviews in Brunke and Gonser 1997; Boulton et al. 1998) to the whole river ecosystem.

These rapid advances in our scientific knowledge of the hyporheic zone have seldom been effectively communicated to river managers or specifically adopted in stream rehabilitation strategies or policies aimed at protecting river values. For example, the "NSW Sand and Gravel Extraction Policy for Non-tidal Rivers" released in 1992 makes no mention of potential impacts of sedimentation or gravel extraction on the faunal and microbial components of the hyporheic zone. At that time, little work had been done in Australia on the hyporheic zone. We now have data from the hyporheic zones of streams and rivers in several states of Australia that indicate a rich invertebrate fauna and active water exchange with the surface stream. Although these data are sparse, it is time to include the hyporheic zone in river

Division of Ecosystem Managament, University of New England, Armidale 2350 NSW
Telephone: (02) 6773 3760, Fax (02) 67732769, email: aboulton@metz.une.edu.au

rehabilitation strategies that attempt to recover or protect key ecosystem linkages.

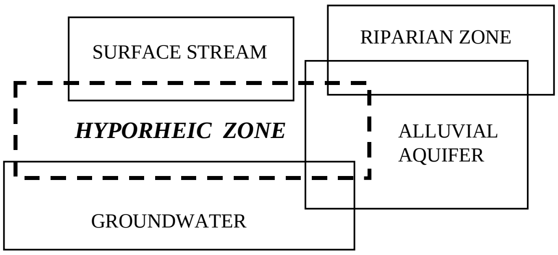


Figure 1. The hyporheic zone acts as an ecotone between a number of compartments of a river ecosystem. The broken line symbolizes the flexibility of these boundaries and the degree of overlap.

This paper briefly describes current knowledge of the significance of the hyporheic zone and reviews the Australian research. It is suggested that processes limiting exchange between the surface stream and the hyporheic zone are the most detrimental to river health, impairing the key filtration role of gravel beds in many rivers. River rehabilitation strategies that minimize or control input of fine sediments and that enable gravel bars and streambeds to maintain natural levels of mobility are most likely to protect the hyporheic zone.

Downwelling surface streamwater carries oxygen, nutrients, organic matter and other material into the sediments. These supply the rich microbial biofilms that coat the large surface area of the sediments (Bärlocher and Murdoch 1989). The biofilms are capable of transforming nutrients, respiring oxygen, degrading organic matter, and carrying out many other key ecosystem processes. The extent of their activities depends on the rate of exchange of water, the temperature, local physical and chemical conditions, and many other factors (Findlay 1995; Boulton et al. 1998). In turn, these biofilms provide the main food resource for many hyporheic invertebrates whose grazing may also control microbial activity (Boulton in press).

Water from the hyporheic zone that upwells into the surface stream is usually altered according to its subsurface residence time and the relative volumes of surface and hyporheic water. For example, in Sycamore Creek, a desert stream in Arizona, the metabolically active hyporheic zone generates nitrate (Grimm et al. 1991) that upwells into the surface stream where, because nitrate is the main nutrient limiting algal growth, it creates a longitudinal gradient in benthic algal composition (Valett et al. 1990). Other examples of the influence of hyporheic water on the distribution of algae, macrophytes and benthos in streams are given by Boulton (1993) and

2. THE FUNCTIONAL SIGNIFICANCE OF THE HYPORHEIC ZONE

Some streams flow over bedrock or extremely fine sediments and for these, the hyporheic zone is either absent or there is so little exchange of water that it is not an important component. However, many rivers have sections of sand, gravel or cobble beds, and water exchange may extend several metres depending upon the porosity and permeability of the bed, the shape of the channel, and the flow of the surface water. Water exchange potentially occurs in three dimensions: vertically and longitudinally as sequences of upwelling and downwelling along a stream reach (Figure 2), and laterally as exchange across gravel bars and alluvial aquifers (Findlay 1995).

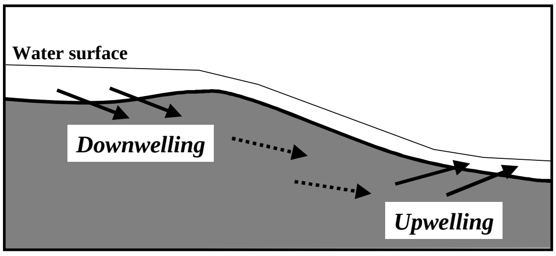


Figure 2. Water can downwell vertically from the surface stream at the head of a riffle, travel in the hyporheic zone longitudinally, and then upwell into the surface stream. Findlay (1995). Downwelling also governs the distribution of many hyporheic organisms (Brunke and Gonser 1997).

The hyporheic zone has been proposed as a refuge for many surface invertebrates from drought, flooding, and poor surface water quality (see Dole-Olivier et al. 1997 for review). Although support for this refuge hypothesis is equivocal and needs more experimental testing (Boulton et al. 1998), individuals of many species of Australian surface invertebrates spend part of their life cycle in the sediments (Marchant 1988, 1995; Cooling & Boulton 1993). Thus, a reasonable degree of physical stability and the existence of sufficiently large interstitial spaces free of silt appears to be important.

At the reach scale, the hyporheic zone also acts as a retentive device in many streams (Figure 3), and is capable of storing large amounts of organic matter (Naegeli et al. 1995; Boulton and Foster 1998). This organic matter is available for breakdown by hyporheic invertebrates in some streams (Smith and Lake 1993). Even at a fine scale, sediment particles retain huge amounts of dissolved organic matter because it is actively trapped by the microbial biofilms (Younger et al. 1993).

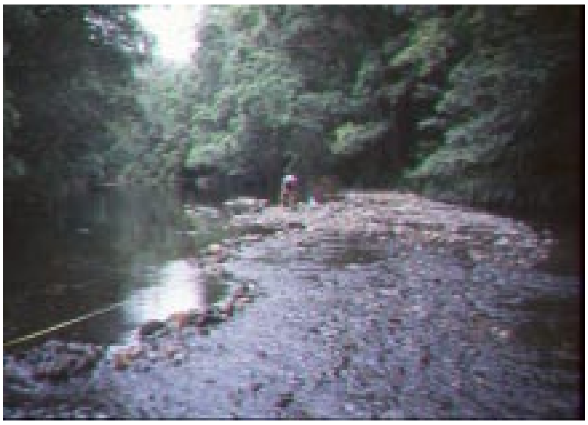


Figure 3. A riffle in a gravel-bed river, the Never-Never River in NSW. At this site, there was up to 72 g of particulate organic matter in every litre of bed sediment (Boulton and Foster 1998).

Thus, the hyporheic zone is functionally important because it is a metabolically-active zone where streamwater may be transformed and after upwelling, influence the distribution of surface stream plants and animals. It also provides an important habitat for many invertebrates, and acts as a retentive device for organic matter such as sticks, leaves, and fragments of plants that would otherwise be swept downstream. The linkage between the hyporheic zone and the surface water influences ecosystem processes in both compartments of the stream. Disruption of this linkage potentially starves each component of critical nutrients, organic matter, or fauna.

3. DISRUPTION OF THE LINKAGE

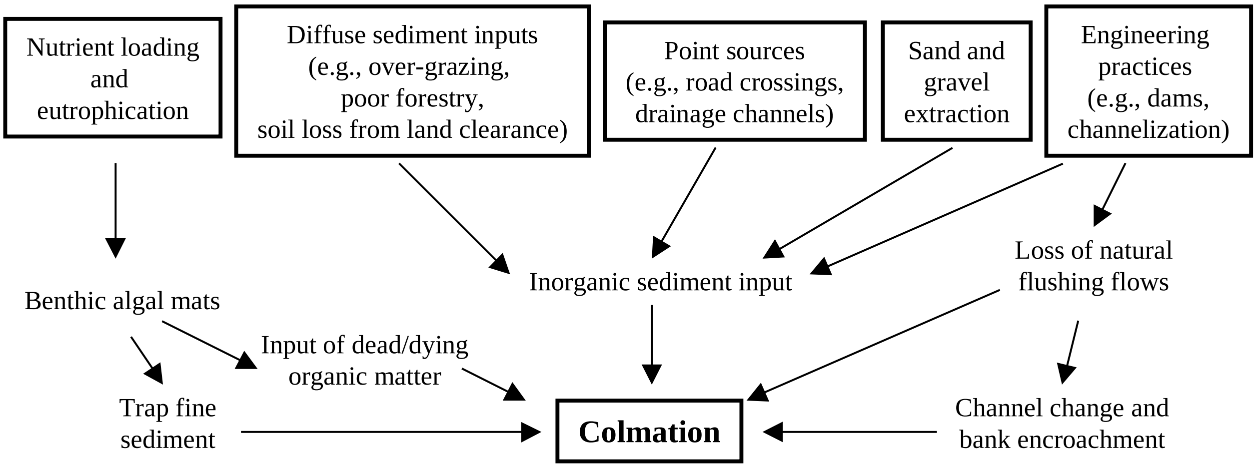
The organisms and the functioning of the hyporheic zone is prone to damage from toxicants, acidity, and the suite of pollutants that adversely affect surface biological processes. It can also be disrupted by excessive groundwater extraction that removes water more rapidly than it is supplied to the hyporheic zone by the overlying river. However, the most common form of damage arises from the uncoupling of the hydrological linkage between the surface stream and the hyporheic zone. Although this can happen naturally when surface waters dry (e.g. Stanley and Boulton 1995), it is usually a result of a process termed *colmation*. This refers to clogging of the upper layer of the streambed sediments that leads to a reduction of pore volume, consolidation of the sediments, and reduced bed permeability (Brunke and Gonser 1997).

Colmation can arise from several sources (Figure 4). Increased loading with nutrients (e.g., from sewage input) and eutrophication promote the formation of dense algal mats on the stream bed that enhance rates of sediment deposition. Organic matter from dead and dying algae may also block the interstitial spaces in downwelling zones. Inorganic sediments can come from diffuse sources such as poorly-managed land-uses (e.g., agriculture, over-grazing, forestry) (Finlayson and Silburn 1996) and from point sources such as badly-designed road crossings and drainage channel inputs (Stout and Coburn 1989). Engineering activity in the catchment or in the river itself (e.g., instream gravel extraction, damming, channel-straightening) may also generate excessive amounts of silt (Petts et al. 1993) as well as potentially reducing the likelihood of natural flushing flows or floods (Sherrard and Erskine 1991, Figure 4).

Colmation may partially or completely inhibit the hydrological exchange between surface water and the hyporheic zone. Once the process commences, it tends to self-perpetuate. Initially, dissolved oxygen levels in the hyporheic zone are likely to fall, leading to a change in redox potential and an alteration in the microbial and biochemical transformations occurring in the sediments. Many subsurface invertebrates will also disappear although some are able to tolerate quite low levels of dissolved oxygen (Strayer et al. 1997).

As the interstitial spaces fill, the strength of the upwelling and downwelling zones tends to decline, and soon silt settles in areas that were once upwelling. The surface stream is deprived of water transformed in the hyporheic zone, and the substratum becomes more homogenous, reducing the availability of niches for surface organisms. Water temperature patterns in both zones are also likely to be altered, and this, combined with reduced oxygen levels, has serious implications for fish that spawn in gravel (Zeh and Dönni 1994). In the final stages of colmation, potential refuges for surface invertebrates and juvenile fish are removed, and the impacts of toxicants and natural disturbances in the stream are magnified (Brunke and Gonser 1997). Flow patterns are also changed, and may lead to local flooding and channel adjustment (Finlayson and Silburn 1996).

Figure 4. Processes potentially leading to colmation in gravel bed rivers. These causes are often cumulative.



4. WORK ON THE BIOTA OF THE HYPORHEIC ZONE IN AUSTRALIA

Before getting too concerned about the effects of colmation in Australian streams and rivers, we must establish whether the hyporheic zone is likely to be particularly important. Thus far, there have been no detailed studies of filtration processes, microbial activity, or rates of metabolism of hyporheic sediments in any Australian streams. Although most studies of the fauna have been broadly descriptive, invertebrates have been reported from the hyporheic zones of streams in South Australia (Williams 1983; Cooling and Boulton 1993), Victoria (Marchant 1988, 1995; Boulton 1989; Smith and Lake 1993), New South Wales (Boulton and Foster 1998), the Northern Territory (Paltridge et al. 1997) and south-western West Australia (Trayler and Davis 1998). Interstitial crustaceans have also been collected from below riverbeds in Tasmania (see Williams 1980).

Given this, it is reasonable to assume that most Australian rivers with coarse sediments harbour interstitial invertebrates, and that these play some role in natural river ecosystem processes. Many of the studies above have collected new species (e.g., Harvey 1998), some of which are obligate inhabitants of the interstitial zone. These taxa are important components of our national biodiversity (cf. Marmonier et al. 1993) and our knowledge is too limited to speculate about their vulnerability.

While there has been little research on the effects of colmation on Australian hyporheic zones, parallels justifiably can be drawn with results from overseas work (e.g., Boulton et al. 1997). It is therefore appropriate that river rehabilitation strategies specifically include some consideration of the hyporheic zone and adjacent alluvial aquifers.

5. POTENTIAL RIVER REHABILITATION STRATEGIES TO OVERCOME COLMATION

Most river rehabilitation strategies aimed at preserving or rehabilitating surface plants and animals are likely to also address threats to water exchange with the hyporheic zone. Approaches that control soil erosion (e.g., Freebairn et al. 1996) and other inputs of fine sediments are obviously important. Prevention of excessive benthic algal growth capable of trapping silt and leading to organic colmation is necessary in streams receiving high inputs of nutrients. Bank stabilisation, the use of riparian buffer strips, and other stream management practices are similarly effective.

Removal of interstitial silt already present in the hyporheic zone is more problematic. Flushing flows may be of local benefit but often simply shift the problem downstream (e.g., Marmonier et al., this volume) and are not a realistic long-term solution. Increased current velocity may flush fine material only from the surface layers, and it may require actual bedload movement to effectively renew hydrological exchange. Other options include the use of dredges and aspirators that remove the silt from the river completely. Not only might these prove expensive and only locally effective, the timing of the silt removal is probably important. At present, we know little about the seasonality of life histories and recolonization abilities of hyporheic invertebrates, and such rehabilitation practices would need to be timed to avoid disruption of the existing stream fauna. The likely side-effects of suction dredging need evaluation (see Harvey and Lisle 1998) before using this approach.

Many gravel bed rivers naturally have dynamic beds that move in a constant process of aggradation and degradation in response to changes in flow regime (Giberson and Casey 1998). Large floods may create new lateral gravel bars (Figure 5) that slowly become vegetated unless reworked by subsequent major floods. Constraints on the flow regime, particularly of high flows, by river regulation and water abstraction may reduce channel mobility and lead to colmation. For example, the construction of Mangrove Creek Dam in NSW reduced floods (up to 94%) and nearly 100% of the sediment supply to the downstream section. Longer term effects were predicted to be the conversion of a broad, active sand-bed channel into a small, sinuous, well-vegetated stream (Sherrard and Erskine 1991).

Figure 5. A lateral gravel bar on the Macleay River, northern NSW. Such bars resist most floods but may be modified by immense spates that initiate substantial bedload movement.

6. CONCLUSIONS

River rehabilitation strategies aimed specifically at protecting or rehabilitating the hydrologic exchanges between the hyporheic zone and the surface stream are in their infancy. This partly reflects the limited information that exists about the hyporheic zone and the lack of communication between stream ecologists working on this topic and river managers. It may also reflect the fact that we have only recently become aware of the implications to stream ecosystem function of this linkage between the hyporheic zone and the surface. More subtle linkages with the riparian zone and lateral alluvial aquifers await clarification.

The effects of colmation are severe and, to some degree, predictable. Many river rehabilitation strategies currently directed at river bank stabilisation, reduction of sediment input, and restoration of a nearly-natural flow regime are likely to have beneficial effects for the maintenance of a functional hyporheic zone. However, recognition of the importance of the hyporheic zone and a specific focus on the problems of colmation may ensure that river rehabilitation strategies are more effective at protecting or rehabilitating the entire river ecosystem. So next time you look at a river, ask yourself "is the hyporheic zone adequately linked to the surface stream"?

7. ACKNOWLEDGEMENTS

I thank an anonymous referee for some useful comments and additional references, and Ian Rutherfurd and Rebecca Bartley for editorial assistance. Preparation of this work was funded by the Australian Research Council.

8. REFERENCES

Bärlocher, F. and Murdoch, L.H. (1989). "Hyporheic biofilms - a potential food source for interstitial animals." Hydrobiologia 184: 61-67.

Boulton, A.J. (1989). "Over-summering refuges of aquatic macroinvertebrates in two intermittent streams in central Victoria." Transactions of the Royal Society of South Australia 113: 23-34.

Boulton, A.J. (1993). "Stream ecology and surface-hyporheic hydrologic exchange: implications, techniques and limitations." Australian Journal of Marine and Freshwater Research 44: 553-564.

Boulton, A.J. (in press). "The functional role of the hyporheos." Verhandlungen der Internationalen Vereinigung für Limnologie 27: in press.

Boulton, A.J. and Foster, J.G. (1998). "Effects of buried leaf litter and vertical hydrologic exchange on hyporheic water chemistry and fauna in a gravel-bed river in northern New South Wales, Australia." Freshwater Biology 40: 229-243.

Boulton, A.J., Findlay, S., Marmonier, P., Stanley, E.H. and Valett, H.M. (1998). "The functional significance of the hyporheic zone in streams and rivers." Annual Reviews of Ecology and Systematics 29: 59-81.

Boulton, A.J., Scarsbrook, M.R., Quinn, J.M., and Burrell, G.P. (1997). "Land-use effects on the hyporheic ecology of five small streams near Hamilton, New Zealand." New Zealand Journal of Marine and Freshwater Research 31: 609-622.

Brunke, M. and Gonser, T. (1997). "The ecological significance of exchange processes between rivers and groundwater." Freshwater Biology 37: 1-33.

Cooling, M.P. and Boulton, A.J. (1993). "Aspects of the hyporheic zone below the terminus of a South Australian arid-zone stream." Australian Journal of Marine and Freshwater Research 44: 411-426.

Dole-Olivier, M.-J., Marmonier, P. and Beffy, J.-L. (1997). "Response of invertebrates to lotic disturbance: is the hyporheic zone a patchy refugium?" Freshwater Biology 37: 257-276.

Findlay, S. (1995). "Importance of surface-subsurface exchange in stream ecosystems: the hyporheic zone." Limnology and Oceanography 40: 159-164.

Finlayson, B. and Silburn, M. (1996). "Soil, nutrient and pesticide movements from different land use practices, and subsequent transport by rivers and streams." In H.M. Hunter, A.G. Eyles and G.E Rayment (Eds) "Downstream Effects of Land Use", p. 129-140, Department of Natural Resources, Queensland, Australia.

Freebairn, D.M., Truong, P., Miles, R.L., Ciesiolka, C.C.A., Titmarsh, G. and Norrish, S. (1996). "Practical measures to counter soil erosion". In H.M. Hunter, A.G. Eyles and G.E Rayment (Eds) "Downstream Effects of Land Use", p. 213-219, Department of Natural Resources, Queensland, Australia.

Giberson, D.J. and Caissie, D. (1998). "Stream habitat hydraulics: interannual variability in three reaches of Catamaron Brook, New Brunswick." Canadian Journal of Fisheries and Aquatic Sciences 55: 485-494.

Gibert, J., Dole-Olivier, M.-J., Marmonier, P. and Vervier, P. (1990). "Surface water-groundwater ecotones". In R.J. Naiman and H. Décamps (Eds) "The Ecology and Management of Aquatic-terrestrial Ecotones, Man and the Biosphere Series" p. 199-225, Park Ridge, New Jersey: UNESCO and the Parthenon Publishing Group.

Grimm, N.B., Valett, H.M., Stanley, E.H. and Fisher, S.G. (1991). "The contribution of the hyporheic zone to the stability of a desert stream." Verhandlungen der Internationalen Vereinigung für Limnologie 24: 1595-1599.

Harvey, B.C. and Lisle, T.E. (1998). "Effects of suction dredging on streams: A review and an evaluation strategy." Fisheries 23: 8-17.

Harvey, M.S. (1988). "Unusual new water mites (Acari: Hydracarina) from Australia, Part 1." Records of the Western Australian Museum 19:91-106.

Marchant, R. (1988). "Vertical distribution of benthic invertebrates in the bed of the Thomson River, Victoria." Australian Journal of Marine and Freshwater Research 39: 775-784.

Marchant, R. (1995). "Seasonal variation in the vertical distribution of hyporheic invertebrates in an Australian upland river." Archiv für Hydrobiologie 134: 441-457.

Marmonier, P., Vervier, P., Gibert, J. and Dole-Olivier, M.-J. (1993). "Biodiversity in groundwater." Trends in Ecology and Evolution 8: 392-395.

Marmonier, P., Claret, C. and Dole-Olivier, M.-J. (this volume). "Restoration of alienated floodplain channels: effects on interstitial assemblages." This proceedings.

Naegeli, M.W., Hartmann, U., Meyer, E.I. and Uehlinger, U. (1995). "POM-dynamics and community respiration in the sediments of a flood prone prealpine river (Necker, Switzerland)." Archiv für Hydrobiologie 133: 339-347.

Orghidan, T. (1959). "Ein neuer Lebensraum des unterirdischen Wassers, der hyporheische Biotop." Archiv für Hydrobiologie 55: 392-414.

Paltridge, R.M., Dostine, P.L., Humprey, C.L. and Boulton, A.J. (1997). "Macroinvertebrate recolonization after re-wetting of a tropical seasonally-flowing stream (Magela Creek, Northern Territory, Australia)." Marine and Freshwater Research 48: 633-645.

Petts, G.E., Armitage, P. and Castella, E. (1993). "Physical habitat changes and macroinvertebrate response to river regulation: The River Rede, UK." Regulated Rivers 8: 167-178.

Sherrard, J.J. and Erskine, W.D. (1991). "Complex response of a sand-bed stream to upstream impoundment." Regulated Rivers 6: 53-70.

Smith, J.J. and Lake, P.S. (1993). "The breakdown of buried and surface-placed leaf litter in an upland stream." Hydrobiologia 271: 141-148.

Stanley, E.H. and Boulton, A.J. (1995). "Hyporheic processes during flooding and drying in a Sonoran Desert stream. I. Hydrologic and chemical dynamics." Archiv für Hydrobiologie. 134: 1-26.

Stout, B.M. and Coburn, C.B. (1989). "Impact of highway construction on leaf processing in aquatic habitats of eastern Tennessee." Hydrobiologia 178: 233-242.

Strayer, D.L., May, S.E., Nielsen, P., Wolheim, W. and Hausam, S. (1997). "Oxygen, organic matter, and sediment granulometry as controls on hyporheic animal communities." Archiv für Hydrobiologie 140: 131-144.

Trayler, K. and Davis, J.A. (1998). "Forestry impacts and the vertical distribution of stream invertebrates in south-western Australia." Freshwater Biology 40: 331-342.

Valett, H.M., Fisher, S.G. and Stanley, E.H. (1990). "Physical and chemical characteristics of the hyporheic zone of a Sonoran Desert stream." Journal of the North American Benthological Society 9: 201-215.

Vervier, P, Gibert, J., Marmonier, P. and Dole-Olivier, M.-J. (1992). "A perspective on the permeability of the surface freshwater-groundwater ecotone." Journal of the North American Benthological Society 11: 93-102.

Williams, W.D. (1980). "Australian Freshwater Life." Second Edition, Macmillan, Melbourne.

Williams, W.D. (1983). "Life in Inland Waters." Blackwell Scientific Publications, Melbourne.

Younger, P.L., Mackay, R.J. and Connorton, B.J. (1993). "Streambed sediment as a barrier to groundwater pollution: insights from fieldwork and modelling in the River Thames basin." Journal of the Institute of Water and Environmental Management 7: 577-585.

Zeh, M. and Dönni, W. (1994). Restoration of spawning grounds for trout and grayling in the River High-Rhine." Aquatic Sciences 56: 59-69.