Long-term land treatment constraints for hyporheic zone management

Alana Bowmar [A,C], Katy Grant [A], Azam Khan [A]

[A] Pattle Delamore Partners Limited, PO Box 9528, Newmarket, Auckland 1149
[C] Corresponding author. Email: Alana.Bowmar@pdp.co.nz

ABSTRACT

The introduction of the National Policy Statement for Freshwater Management (NPSFM) is requiring regional councils to start developing the framework for addressing the implementation of freshwater management units for all catchments under their control (Ministry for the Environment [MfE], 2017). This in turn is creating additional elevated regulatory pressure to improve water quality, especially for catchments that drain agricultural farmland.

When wastewater is applied on the same land, as part of a land treatment system, the controls required are increased to ensure the outcomes sought for the NPSFM are maintained at all times.

As land treatment systems have been progressively established, there has undoubtedly been some examples of poor land treatment practices that have the potential to quickly result in negative environmental impacts. Particularly, if the shallow groundwater below the land treatment is in close proximity and/or directly connected to hyporheic zone where the groundwater and surface waters interact.

Surface water quality in the vicinity of an existing long-term land treatment system showed direct connection between shallow groundwater and surface water, resulting in a comprehensive review of current practices and significant tightening of nitrogen loading onto land. There has been a re-think of the likely sustainable level of nitrogen application despite nutrient modelling supporting a continued moderate to higher nitrogen application.

This paper discusses the importance of hyporheic zone management. It also assesses and discusses how an existing land treatment system receiving treated wastewater and other nitrogenous product inputs has quickly become a considerable water quality issue in the hyporheic zone and downstream surface water receiving environment.

Keywords: nitrogen; hyporheic; groundwater; land treatment.

INTRODUCTION

Land treatment of wastewater is becoming increasingly more common for industrial and municipal wastes where nearby agricultural land is available. Many regional councils throughout New Zealand are promoting the use of land treatment as a preferential method of wastewater disposal. Land treatment has shown success in attenuation of a wide range of pollutants in the agricultural (soil, plant, animal) system (Katz *et. al.*, 2009).

While land treatment is generally a successful pollutant management system, certain pollutants that do not typically undergo sorption processes, and are in excess of agricultural requirements at any one time can be mobilised into groundwater. Of particular concern in New Zealand land treatment systems is nitrate-nitrogen.

Management of resources in New Zealand is on an environmental effects basis. In the case of land treatment, water quality effects assess impacts on groundwater quality as it impacts human and animal health as a drinking water resource. For land treatment systems where there is no connection to drinking water bores, water quality effects are assessed as they enter stream water and impact surface water ecology. This approach ignores the hyporheic zone, where groundwater and surface water interact beneath a stream (Biddulph, 2015). Depending on the level and type of nutrients present, land treatment systems can become a considerable contributor to diffuse pollution source and its negative impacts realised in the receiving waterbodies.

This zone is often described as an ecotone; where a gradient of physical, chemical and biological characteristics exist. The gradients are a reflection of the relative influence of groundwater and surface water spatially and temporally (Marmonier *et. al.*, 2012). This zone in itself is an integral part of the overall stream function, and a significant ecosystem on its own (Marmonier *et. al.*, 2012). Disruption of damage to this zone can result in changes to stream biogeochemical processes, water chemistry and ecology (Hancock, 2002).

This paper looks at available information on the hyporheic zone, and considers it within a land treatment context. A case study is considered, where poor land treatment management practices occurred resulting in elevated nitrate-nitrogen in groundwater that was shown to be directly connected to surface water via a hyporheic zones. Consideration of the possible effects of the land treatment system on the hyporheic zone identify gaps in knowledge, without which land application systems could be resulting unintended environmental effects.

BACKGROUND

Hyporheic zone

The hyporheic zone is defined as the saturated zone beneath the stream bed and above groundwater (Biddulph, 2015; Boulton *et. al.*, 1997; Marmonier *et. al.*, 2012). The extents of the hyporheic zone have been best defined as the boundary where 10% of the pore water originates from surface water (Boano *et. al.*, 2014; Hancock, 2002). It is characterised by the mixing of water originating from both the stream and groundwater (Boano *et. al.*, 2014). Its general location and flow mixing is summarised by Fig. 1 and Fig. 2 below. The scale of this zone can vary from a few centremetres to several metres in size (Biddulph, 2015).

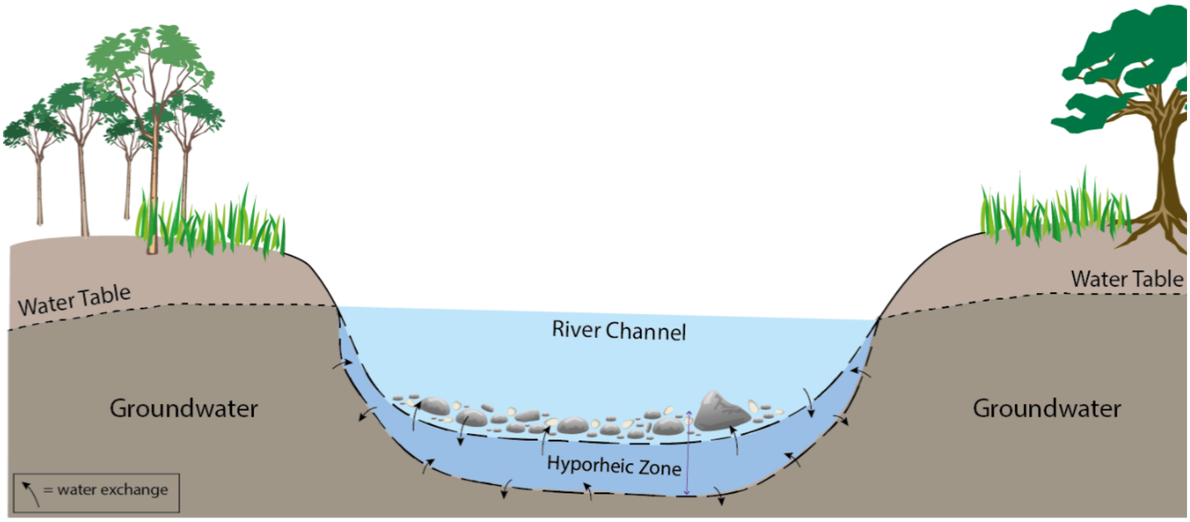

Fig. 1. The approximate position of the hyporheic zone from a cross-sectional view of a stream (adapted from Biddulph, 2015).

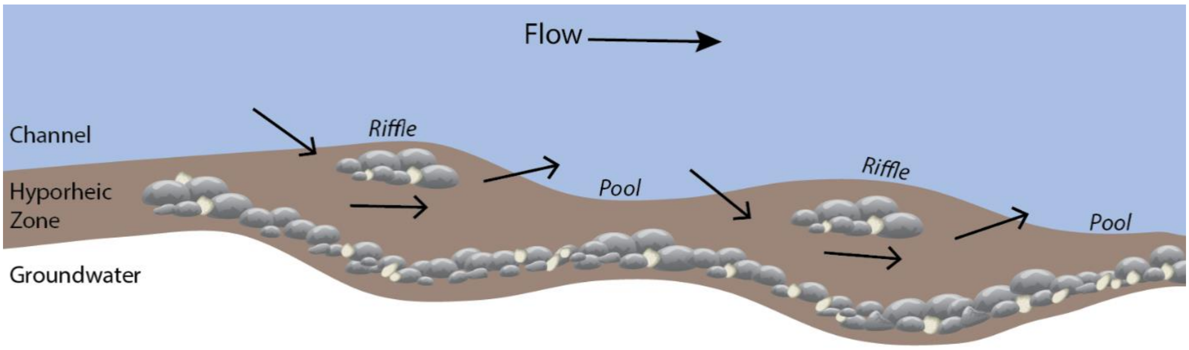

Fig. 2. The approximate position of the hyporheic zone from a long-sectional view of a stream including typical flows through a riffle pool sequence (adapted from Biddulph, 2015).

The movement of groundwater and surface water varies spatially and temporally in response to varying permeability and hydraulic pressure within the hyporheic zone. Groundwater and surface water interactions are driven on a larger scale by the relative hydraulic head, which can change in response to short-term rainfall events (surface water) and long-term dry and wet weather variability (groundwater) (Biddulph, 2015). On a smaller scale pressure changes are documented to occur between riffle and pool sequences (Elliot and Brooks, 1997; Garigilio *et. al.*, 2013; Tonina and Buffington, 2007).

Throughout the hyporheic zone, chemical gradients in temperature, dissolved oxygen (DO), nutrients, carbon, and mineral content occur. The chemical characteristics within the hyporheic zone are highly variable, often with steep chemical gradients, in particular between low DO in groundwater and high DO in surface water (Biddulph, 2015; Boulton *et. al.*, 1998). This gradient means that reduction-oxidation reactions (redox) will occur, influencing the forms of other chemicals present within the zone (Feris, 2003). These conditions within the zone contribute significantly to processing organic matter, and cycling of carbon, nitrogen and phosphorus (Burrows, 2017; Mulholland *et. al.*, 2003; Zhou *et. al.*, 2014).

Areas influenced by groundwater characteristics are likely to promote reduction of other chemicals present. In the case of nitrogen and sulphur, reduced forms (ammoniacal nitrogen and sulphide) can be toxic to many species at high concentrations (Hickey and Vickers, 1994;

Kelley *et. al.*, 2016). Areas influenced by surface water are likely to promote oxidation of other chemicals present. Nitrogen and sulphur's oxidised forms (nitrate-nitrogen and nitrite-nitrogen, and sulphate) tend to be more bioavailable forms of these nutrients, but can be toxic at higher concentrations (Fertilizer and Lime Research Centre *et. al.*, 2018).

Metabolism within the hyporheic zone contributes to the overall metabolism of the stream, and has been shown to exceed the metabolism from the surface water environment alone (Grimm and Fisher, 1984; Pusch, 1996). The ecological community within the hyporheic zone contains species typical of surface water, including microbial communities, macroinvertebrates and fish species during certain lifecycle stages (Biddulph, 2015; Boulton *et. al.*, 1997; Marmonier *et. al.*, 2012). It also includes species typical of groundwater habitats (stygofauna) and peculiar to the hyporheic zone. Surface water species will seek refuge in hyporheic zones during times of drought, flood and contamination (Biddulph, 2015).

Spatial and temporal variability in physical, chemical and biological characteristics allows different micro zones to occur, such that diverse biogeochemical processes can occur within a relatively small volume (Boulton *et. al.*, 1998).

Importance of the hyporheic zone

Surface water and groundwater have long been acknowledged as important resources to be protected (Davis-Colley, 2013; Hancock, 2002). Surface water and groundwater shape the global ecosystem and have critical roles in:

1. Providing a freshwater resource to support terrestrial (including human) life;
2. Supporting aquatic ecosystems;
3. Transportation and processing (cycling) of dissolved chemicals; and
4. Erosion and transportation of mineral (rock) material.

The hyporheic zone has been demonstrated to contribute significantly to stream water quality (Lawrence *et. al.*, 2013), stream ecology (Mulholland *et. al.*, 1997), and biogeochemical reactions (Boano *et. al.*, 2014). The hyporheic zone forms an integral part of the overall stream function, and given the level of interaction, the stream and its hyporheic zone needs to be considered holistically (Hancock *et. al.*, 2002; Mulholland *et. al.*, 1997).

New Zealand's protection of these resources via environmental regulation is based on assessments on how activities may impact these resources. Where groundwater is not required for human or stock consumption, these effects are often measured as surface water quantity, quality and ecosystem health. The function of the hyporheic zone is not often considered. The hyporheic zone has been shown to provide a natural attenuation of chemicals often considered contaminants (Burrows, 2017; Mulholland *et. al.*, 2003; Zhou *et. al.*, 2014), a refuge for species during low flows or stream pollution (Biddulph, 2015; Hancock, 2002). These qualities may provide greater resilience for the whole stream system.

Conversely, the nature of the hyporheic zone as gradient of water chemistry, spatially and temporally variable zone of micro zones; makes it vulnerable to subtle changes in water quality and quality from both groundwater and surface water sources. This health of the hyporheic zone has been shown to be impacted by land use and surface water contamination (Boulton *et. al.*, 1997). In some cases, effects on the hyporheic zone may be more critical than effects on groundwater or surface water.

Land treatment effects on the hyporheic zone

Traditionally the potential effects of land application on the water quality have concentrated on the effects of run-off, with the groundwater contribution a secondary consideration, and the hyporheic zone only considered as it influences environmental monitoring in the stream once the activity has commenced. However, in areas with incised streams that intersect the shallow groundwater and where hyporheic zones can be large, the groundwater contribution can have a significant effect on the water quality and ecology of the hyporheic zone and surface water systems.

Run-off generally occurs during high flow conditions when concentrations of contaminants will be more diluted. Groundwater discharge into streams can occur year-round, but the greatest proportional contribution can occur under low flow conditions if the streams have an unbalanced groundwater base flow contribution. This means that the discharge of groundwater with high concentrations of contaminants can have a disproportionate effect on water quality in the drier months and where hyporheic zones are large relative to the stream.

Investigations into the effects of land treatment on the hyporheic zone are not widely available. However, many land treatment schemes in New Zealand are currently required to monitor and assess effects on both nearby groundwater and surface water. From this data, it is reasonable to approximate changes that may occur within the hyporheic zone. The following are changes can be expected in the hyporheic zone:

1. Increased groundwater to surface water flux; which is particularly significant during dry, base flow conditions.

2. Increased groundwater concentrations of nitrogen (typically nitrate-nitrogen, but also ammoniacal-nitrogen) and other soluble contaminants (Katz *et. al.*, 2009).

3. Increased surface water concentrations of nitrogen, phosphorus, biological oxygen demand (BOD), pathogens and other contaminants; mobilised via runoff (Wang *et. al.*, 2004).

This list is not a comprehensive list of the potential effects on the hyporheic zone; however, it looks at the most critical considerations in the present climate. The cost of land in most regions drives land treatment schemes to operate as intensively as regulation allows. Intensive land treatment systems and poor management practices can exacerbate these effects.

CASE STUDY

In the example under consideration, historically poor land treatment practices have led to leaching of nitrate-nitrogen into the groundwater below the site. The regional groundwater gradient is relatively shallow and the aquifer is layered, meaning that regional groundwater flow is relatively slow. This has allowed the concentration of nitrate-nitrogen to accumulate to more than five times the drinking water value in the shallow groundwater below the site.

The area is crossed by two incised streams, which intersect the shallow water table across the majority of the site. These streams are generally fenced and have vegetated boundaries to minimise the risks of direct run-off. Although there are no obvious springs, the groundwater provides base flow to the streams through the hyporheic zone year-round. Long-term water quality monitoring indicates that nitrate-nitrogen concentrations increase significantly along the streams as they cross the site during low flow conditions, frequently exceeding the national bottom line of the NPSFM (MfE, 2017) during the summer months.

The investigations undertaken indicate that the most likely source of this nitrate-nitrogen is groundwater discharge into the streams. In fact, it appears that the streams are intersecting a significant proportion of the shallow groundwater flow with the nitrate-nitrogen plume remaining in relatively stable condition below the site and not extending significantly down hydraulic gradient. Due to their orientation relative to the plume, the streams are effectively removing nitrate-nitrogen from the shallow groundwater before it leaves the site.

The presence of elevated nitrate-nitrogen within the groundwater represents a significant long-term source, which is likely to impact upon stream quality, at least periodically, for many years. This has meant that, whilst nutrient modelling indicates that the system can support moderate to higher nitrogen loading, it has been necessary to reconsider the actual sustainable rate of nitrogen application. With a reduced load the groundwater source will gradually decrease, but the water quality of the streams will continue to be negatively impacted potentially for several decades.

This case study highlights the importance of considering groundwater/surface water interactions when designing and monitoring land treatment systems and the potential long-term effects of poor practices.

DISCUSSION

The NPSFM (MfE, 2017) suggests that at the in-stream nitrate-nitrogen concentrations reported at this site, observed effects will include growth effects on up to 20% of species. There is little evidence available on the effects that would occur in the hyporheic zone. The following are a series of theoretical impacts that could be occurring in this region:

1. Groundwater attenuation of nitrate-nitrogen prior to the boundary of the hyporheic zone is unknown. It is possible the groundwater entering the hyporheic zones could be at acute toxicity concentrations for some species.

2. Regions of the hyporheic zone with higher groundwater contributions are typified by lower DO and reduction reactions (Boulton *et. al.*, 1998). Assuming that the biogeochemical processes are not interrupted by the elevated nitrate-nitrogen concentrations, nitrogen reducing reactions could occur (Zhou *et. al.*, 2013). By-products include nitrite ion (unstable and likely to occur in low concentrations), nitrogen gas (inert) and ammoniacal-nitrogen (toxic) (Zhou *et. al.*, 2013).

    a. Ammoniacal-nitrogen is considered to be toxic at lower concentrations that nitrate-nitrogen (MfE, 2017). It is possible that in these low DO reducing regions that ammoniacal-nitrogen could result in greater toxicity effects.

    b. Nitrogen could be processed out of the stream system if released to the atmosphere as nitrogen gas.

3. Increased consumption of oxygen (as nitrate-nitrogen is reduced) could couple with oxidation reactions, further modifying the water chemistry in this typically anoxic zone.

4. Regions of the hyporheic zone with higher surface water contributions are typified by higher DO and oxidation reactions (Boulton *et. al.*, 1998). Assuming that the biogeochemical processes are not interrupted by the elevated ammoniacal-nitrogen and nitrate-nitrogen concentrations, it's expected that ammoniacal- nitrogen will be oxidised (Zhou *et. al.*, 2013). By-products include nitrite ion, nitrogen gas, and nitrate-nitrogen (Zhou *et. al.*, 2013).

It's also expected that an effect of this land treatment system is an increased flow of groundwater to these streams from the hydraulic loading to land that mobilises drainage to groundwater (Hancock, 2002). This slight change in hydraulic gradient could be reducing the down flow of surface water into the hyporheic zone and the corresponding high dissolved oxygen, carbon and organic processing zones.

Without specific research into the effects of land treatment on the hyporheic zone, particularly in relation to elevated nitrate-nitrogen concentrations and increased base flow contributions, ad-hoc management of land treatment systems could signal inadequate protection of the whole stream environment. Attenuation within groundwater and the hyporheic zone itself could reduce in-stream nitrate-nitrogen concentrations to below levels of concern in some stream systems. However, disruption within the hyporheic system could result in unintended impacts on the global stream ecology.

Without this knowledge, land treatment schemes could be resulting in negative environmental effects. These effects could continue into the future well after the land treatment activities are progressively tightly controlled due to longer residence time for groundwater flows.

CONCLUSIONS

The importance of the hyporheic zone is widely documented for its contribution to stream water quality and ecological health (Hancock, 2002; Leigh, 2013); and in its own right as a diverse ecosystem and hub for biogeochemical processes (Boulton *et. al.*, 1998). There seems to be a distinct lack relevant literature studies that provide a link to the effects of land treatment on the hyporheic zone. However, the physical, chemical and biological characteristics of the zone have been well studied (Boulton *et. al.*, 1998).

Using this knowledge of the hyporheic zone, it is possible that effects on the zone itself could contribute to unintended degradation of surface water. These effects could be associated with changes in hydraulic gradients that dictate movement of groundwater and surface water, changes in water chemistry (especially relevant s the introduction of nitrate-nitrogen), and toxicity effects of hyporheic ecosystems.

The land treatment systems could be contributing to degradation of conditions that provide for hyporheic zone ecology that may continue well after tighter controls are put on existing land treatment systems because of long-term effects of higher nutrient laden groundwater discharges into surface water.

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