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Influence of Permeable Cells on Hyporheic Flow in Restored Streams

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Abstract

Many important stream ecosystem functions occur in the hyporheic zone, the saturated area beneath and adjacent to a stream where groundwater and surface water interact. Hyporheic processes include water temperature moderation, recycling of carbon, energy, and nutrients, natural attenuation of certain pollutants, and habitat for benthic and interstitial organisms. The role of the hyporheic zone is increasingly recognized for its significance in the context of river management, conservation, and restoration, but stream restoration designs still are not often driven by the effects on hyporheic exchange and hyporheic habitats. This study evaluated hyporheic flow in the shallow subsurface of a recently-restored rural stream. The restoration project included two experimental hyporheic treatment cells, where excavations beneath the stream bed 12-16 feet long by 3 feet deep were filled with a mixture of coarse sand and gravel to improve groundwater-surface water interactions. Permeameter tests of the streambed gravels were conducted to estimate hydraulic conductivity (10.9 – 14.7 m/day) and a transect of monitoring well nests were installed to determine the vertical gradient of flow at various points within the treatment cells. Results revealed a statistically significant upward flow pattern in the treatment cells as compared to the control region between the cells. This suggests that the treatment cells are enhancing groundwater recharge to the restored stream and that the future use of permeable hyporheic treatment cells could be expanded to improve hyporheic exchange.

1. Introduction

The hyporheic zone is the saturated subsurface zone beneath and adjacent to a stream channel where surface water and groundwater interact[1]. This zone is commonly defined as the zone that contains >10% stream water and <90% groundwater[2]. The hyporheic zone creates a unique habitat for many aquatic organisms that play a crucial role in the overall health of a stream's ecosystem. The hyporheic zone is a habitat for stream invertebrates and provides ideal spawning gravels for salmonid species[3]. The hyporheic fauna rely on the dissolved oxygen, chemicals, and nutrients carried by the stream, while the metabolic activity of the hyporheic microbial communities has a strong impact on the in-stream water quality dynamics[4].

Hyporheic exchange enhances the mass transfer of dissolved solutes and particulates between the stream and the underlying sediment, and the transformation and retention of nutrients, organic matter, and trace metal occurring in the hyporheic zone is important for stream ecosystem function[2]. Additionally, hyporheic exchange facilitates water temperature moderation and natural attenuation of certain pollutants[2].

The fundamental hydrodynamic mechanism used to characterize hyporheic fluxes is the presence of pressure gradients on the streambed surface that are able to induce flow within the fluvial sediments. These pressure gradients are generally caused by the interaction between the free-surface stream and geomorphological features like bedforms, point bars, pool-riffle sequences, and changes in the bed slope[4]. These pressure gradients also occur in the form of large-scale regional groundwater flows and local-scale turbulent coherent structures[4].

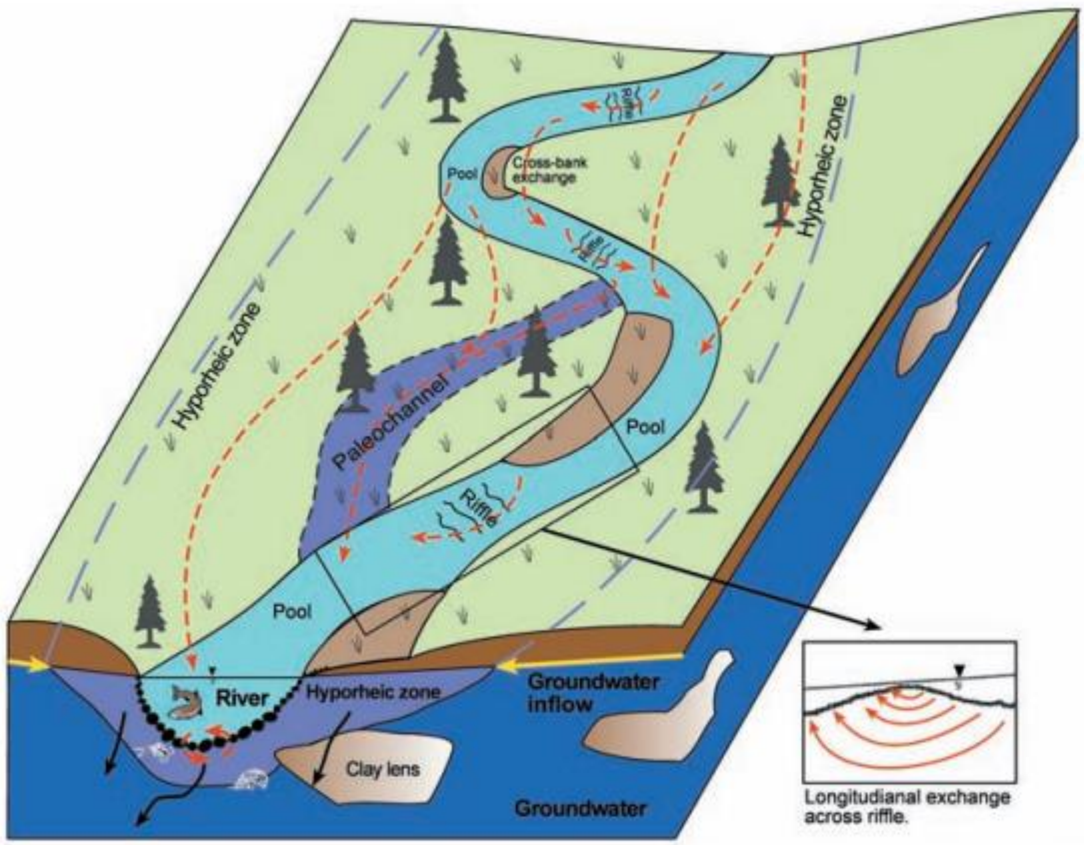

Figure 1. Visual representation of the hyporheic zone at river corridor scale[5].

Hydraulic conductivity (K) is an important sediment property, which affects the flow of water through sediments and thus it is has a large influence on the amount of water flowing into the hyporheic region, the amount of time spent in this region, and the size of the hyporheic zone[6]. Land use practices such as agriculture and urbanization increase the runoff of fine sediments and potentially the deposition of these sediments onto the streambed[7]. Deposition of fine sediment can clog gravel pore spaces and reduce hyporheic zone exchange[8].

Many streams have been extensively altered by channelization, and channel restoration to rehabilitate damaged or degraded reaches of these streams has become an important aspect of stream management in recent decades[2]. Channel restoration projects are typically designed to restore surface heterogeneity of stream channels and improve habitat for fish and invertebrates, but do not often consider the effects on the hyporheic zone[8]. Increasing our understanding of hyporheic flow is important for improved modeling of the biogeochemical processes that occur in this region[9].

This study evaluated hyporheic exchange in the shallow subsurface of a recently-restored rural stream in Fletcher, North Carolina. A series of well nests were used to determine the vertical gradient of flow through highly permeable treatment cells used to induce flow within the hyporheic zone.

2. Methods

2.1. Site Description

The study site was a recently-restored rural stream in Fletcher, NC. The stream is part of the Cane Creek watershed and the French Broad river basin. The stream had been previously channeled for agricultural use but was regraded as part of the restoration project to establish a more natural floodplain (Figure 2). Native shrubs and herbs were planted following the restoration and had become established in the immediate area surrounding the stream by the time of this study. The restoration project included two experimental hyporheic treatment cells, where excavations beneath the stream bed 12-16 feet long by 3 feet deep were filled with a mixture of coarse sand and gravel to improve groundwater-surface water interactions. Permeameter tests of the treatment cell material were conducted in a laboratory setting to estimate hydraulic conductivity (10.9 – 14.7 m/day)[10]. The treatment cells were designed to have a higher hydraulic conductivity than the surrounding streambed material. No hydraulic conductivity measurements were taken for the surrounding streambed.

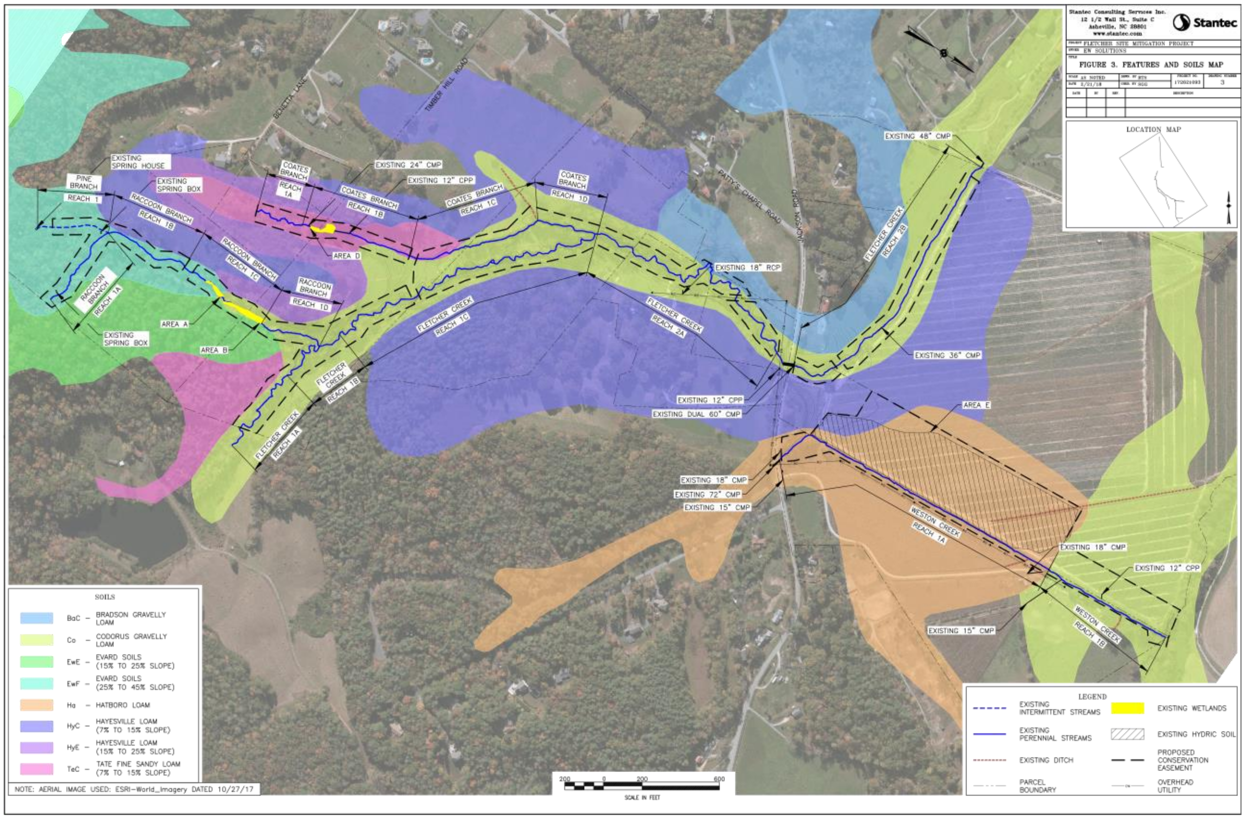

Figure 2. Map of Fletcher, NC stream site with restored floodplain shown in green[11].

2.2. Well Nests

A series of 12 well nests were installed within a 42.25 ft stretch of stream (Figure 3). The wells were constructed of 1-inch solid PVC pipe with a 3-inch slotted well screen at the base. Each well nest consisted of a deep well and a shallow well (5.5ft and 4.5ft, respectively). The first four and last four well nests were located within two separate treatment cells bound by logs on both sides. An additional four well nests were installed between the treatment cells (where the streambed had not been excavated) to serve as a control. The deep wells and shallow wells were driven approximately 2.5ft and 1.5ft into the ground, respectively, leaving the top-of-casing at the same height above the streambed. The top of each well was surveyed, along with the streambed elevation. Water levels were measured in each of the wells after allowing them to equilibrate during several days with no precipitation. Measurements were taken on October 17th, 2020. Vertical gradients were calculated using the difference in head measured at each well nest. Higher water levels in the deep well indicate an upward flow pattern, while higher water levels in the shallow well indicate downward flow beneath the streambed.

2.3. Statistical Analysis

A Wilcoxon rank-sum statistical analysis was used to test for a statistically significant difference in vertical flow gradients of the well pairs within the treatment cells compared to the well pairs between the treatment cells.

Figure 3. Photo of Fletcher, NC stream site taken during well installation.

3. Results

This study revealed a distinct upward flow pattern in seven of eight well pairs in the treatment cells, but only one of four in the region between the treatment cells (Table 1 and Figure 4). A Wilcoxon rank-sum statistical analysis determined that the vertical gradients within the treatment cells were significantly higher than those measured in the area between the treatment cells ($p<0.05$).

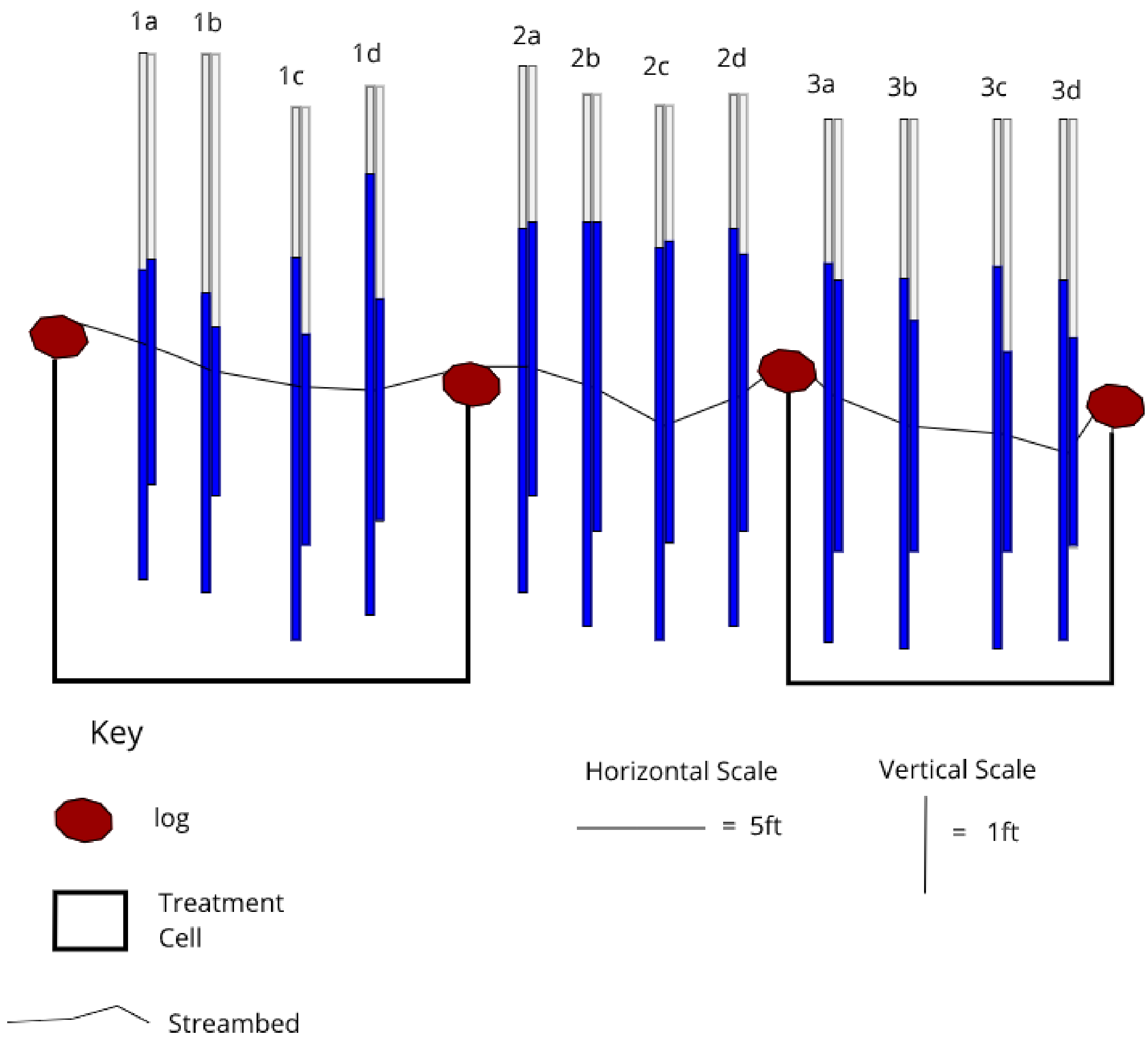

Figure 4. Scale diagram of Fletcher, NC stream site showing 12 wells pairs, consisting of a deep and shallow well.

Well pairs 1a, 1b, 1c, and 1d were installed within a treatment cell. 3a, 3b, 3c, and 3d were installed within a separate treatment cell. 2a, 2b, 2c, and 2d were located between the treatment cells and used as a control. The curved black line represents the streambed. Locations where the deeper well in the well pair has a higher water level (head) indicates an upward flow gradient. Locations where the shallow well in the well pair has a higher head indicates a downward flow gradient. No difference in head indicates no vertical flow in that location. Larger differences in head indicate steeper gradients.

Table 1. Vertical flow gradients of each well pair at Fletcher, NC stream site.

ID	Gradient
1a	-0.1
1b	0.35
1c	0.775
1d	1.25
2a	-0.05
2b	0
2c	-0.125
2d	0.225
3a	0.2
3b	0.425
3c	0.875
3d	0.525

4. Discussion

The hyporheic zone provides ecological benefits that help sustain streambed and aquatic conditions. Among these benefits are water temperature moderation, recycling of carbon, energy, and nutrients, natural attenuation of certain pollutants, a sink/source of sediment for the channel, and habitat for benthic and interstitial organisms[2]. Typical stream restoration projects are implemented to stabilize channels, control bank erosion, and enhance the quality of aquatic habitat by modifying instream structures[2]. Common methods are the placement of boulders, the construction of deflectors and riffles, and channel remeandering[4]. Additionally, the reestablishment of relatively coarse substrates that do not erode during peak discharge events is a common practice[2]. These channel features have been identified as an important driving force of hyporheic exchange in natural streams[4]. Although restoration projects are often designed to improve instream habitat structures, these projects are also likely to enhance hyporheic function in stream ecosystems[2]. Studying these channel features in the context of the hyporheic flow can provide valuable information for the improvement of stream restoration techniques.

This study demonstrates that the permeable treatment cells can be used to improve groundwater-surface water exchange. The data are also consistent with previous studies which have demonstrated that variations in permeability can significantly affect the flow of water though hyporheic systems[7]. In addition to flow patterns, subsurface heterogeneity can have a large impact on fluid fluxes and residence times[7]. The upward flow pattern observed in 7 of 8 well nests within the cells indicates that groundwater is flowing into the stream, while the downward flow pattern indicates that the stream is discharging into groundwater. A stream with ideal conditions has both upward and downward flow patterns. The design used in this stream restoration, which spaced the treatment cells apart, was conducive for establishing upward and downward flow.

5. Conclusion

This research could help inform future stream restoration projects as an effective method for inducing hyporheic flow. Processes occurring in the hyporheic zone should be regarded as key elements for the conservation, management, and restoration of the whole river environment. An inter-disciplinary, multi-scale conceptual framework should be developed which recognizes the importance of vertical and lateral connections of rivers with surrounding floodplains and underlying aquifers[8].

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7. References

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