Influence of groundwater condition on nutrient dynamics in urban waterways

F. C. Silveira[1*], T. A. Cochrane[1], R. Bello-Mendoza[1] & F. Charters[1]

[1]Department of Civil and Natural Resources Engineering, University of Canterbury, 20 Kirkwood Avenue, Upper Riccarton, Christchurch, 8041, New Zealand
*Corresponding author email: fabio.cabralsilveira@pg.canterbury.ac.nz

Highlights

- Groundwater seepage condition increased phosphorus and ammonia in the surface water.
- Groundwater seepage condition decreased nitrate concentrations in the surface water.

Introduction

Excess nutrients in waterways contribute to eutrophication and decrease aquatic ecosystem health, a problem affecting both rural and urban catchments. In order to address excess nutrient problems in urban waterways, authorities have been developing strategies to mitigate impacts by using in-channel and land-based stormwater treatment to remove pollutants via settling and other physical, chemical and/or biological processes. However, little is known about how pollutants are transported and transformed in urban in-channel systems under the influence of different groundwater conditions. Therefore, this research aims to understand nutrient dynamics (nitrogen and phosphorus) in waterway channels under the influence of seepage, neutral, and drainage conditions. It was hypothesized that groundwater and bed material characteristics affect the concentration and form of surface pollutants, as well as their mobility. This understanding could help guide stream management decisions.

Methodology

A longitudinal study of pollutant dynamics under seepage, neutral or drainage conditions was undertaken to assess the changes in surface water quality, with a focus on nitrogen and phosphorus. A 19 m long PVCE flume was used to simulate a channel system which contains a 5-8 mm gravel base chip size, a layer of bed material, surface water and a system for controlling groundwater interactions (Figure 1). Bed material was a mix of sand (25% volume) and contaminated bed sediment sourced from the Wigram Basin (WB; 75% volume) in Christchurch. Synthetic stormwater (SSW) was used for the surface water and groundwater to have a target concentration of 0.4 mg/L nitrate nitrogen (NO_X-N), 0.2 mg/L ammoniacal nitrogen (NH4-N) and 0.2 mg/L Dissolved Reactive Phosphorus (DRP). This simulates the in-channel water quality measured in Haytons Stream, which discharges into WB from an urban industrial catchment.

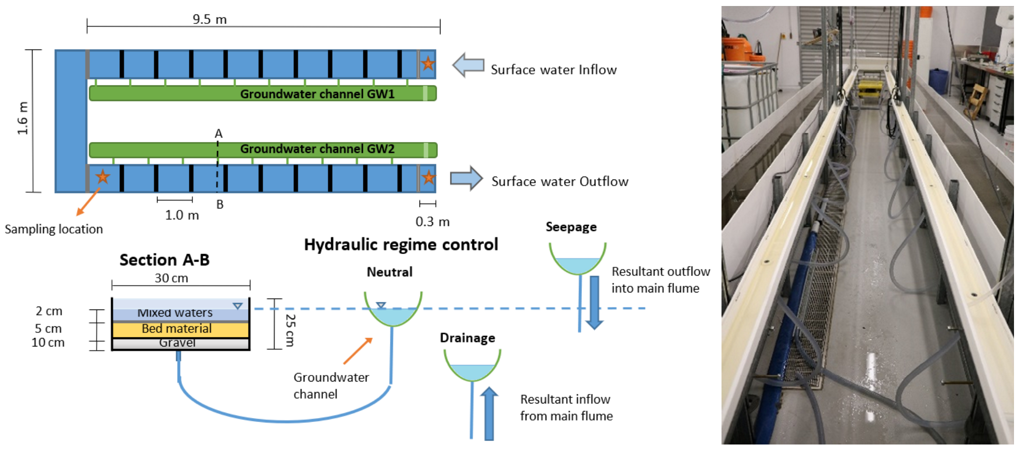

Figure 1. The schematic plan and cross-sectional views of the experimental system with groundwater regimes and groundwater control channel relative heights (left) and image of experiment setup under drainage groundwater conditions (right).

The flume system was run 9 times (3 runs each under seepage, neutral and drainage groundwater conditions). Gravel and bed material remained saturated with SSW between runs and before starting each run, this saturated water was replaced by fresh SSW. Under all groundwater conditions, 21.8 L/min flow of SSW was added into the flume as surface water. Under neutral groundwater conditions, there was no groundwater interaction. Under drainage conditions, 4.36 L/min of the incoming surface water was drained (2.18 L/min for each length of the flume). Under seepage conditions, a total of 4.36 L/min was seeped into the flume (2.18 L/min for each length of the flume). Each flume experiment was run for 35 minutes and water samples were collected at the inlet, middle and outlet of the flume (Figure 1). Inlet samples were collected at 0, 10, 20 and 30 minutes. A stabilisation period of 15 minutes was observed at the middle and outlet sampling locations from the time when surface water was added at the flume inlet (i.e. pollutant concentrations did not vary significantly after this 15 min period). Therefore, samples at the middle and outlet locations were collected at 15, 20, 25, 30 and 35 minutes. In addition to the samples collected, YSI Professional Plus probes were placed at each sampling location to monitor changes in pH, conductivity, temperature and oxidation-reduction potential (ORP) during each run at 1-minute intervals.

The contaminant concentrations of samples collected at the middle and outlet of the flume were compared with the average inlet samples' concentration of each run due to inlet concentrations differing for each run. The resultant percentage changes in each contaminant concentration were then compared across all runs. T-tests were conducted (with alpha = 0.05) to check for statistically significant differences between percentage change of each water quality data set under different groundwater conditions to verify its impact on the surface water quality.

Results and discussion

Results showed that the groundwater condition influences the range and variation of nutrient concentrations in the surface water for NO_X-N, NH_4-N and DRP and (Figure 2). Under seepage conditions, NO_X-N concentrations decreased at the middle and outlet locations (mean values of 8 and 13%, respectively), and NH_4-N concentrations increased at both locations (23 and 51%, respectively), and DRP concentrations increased at both locations from 15 to 200% compared to the inlet concentrations. Under neutral and drainage conditions, there was a small variation in the range of changes, but a statistically significant difference in percentage change was not observed for DRP and NH_4-N (Table 1).

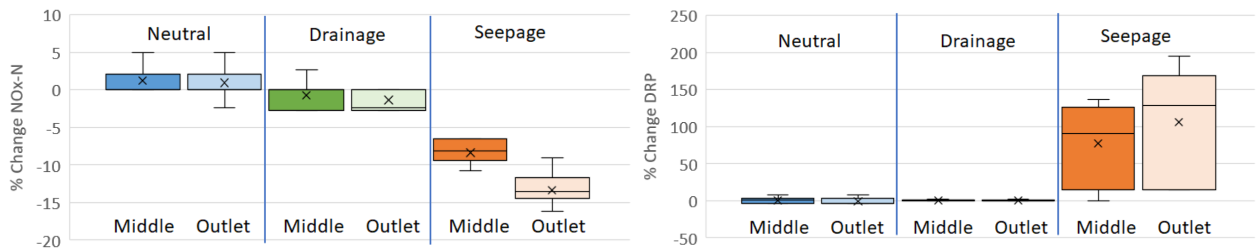

Figure 2: Left image is the percentage change in NO_X-N concentrations at the middle and outlet of the flume under neutral, drainage and seepage groundwater conditions; right image is the percentage change in DRP concentrations at the middle and outlet of the flume under neutral, drainage, and seepage groundwater conditions; x refers to the mean values.

Table 1: T-test results of percentage change in NO_X-N and DRP concentrations in the outlet of the flume under different groundwater conditions; * P-value less than alpha of 0.05 showing significant statistical difference.

Compound	Groundwater Condition	Mean change from mean inlet concentration (%)		Variance		Observations		P-value of difference in percentage change between neutral and drainage or seepage	
		Middle	Outlet	Middle	Outlet	Middle	Outlet	Middle	Outlet
NO_X-N	Neutral	1	1	3.2	4.0	15	15		
	Drainage	-1	-1	2.5	1.8	15	15	0.004*	0.001*
	Seepage	-8	-13	2.4	3.0	15	15	4.0E-15*	2.8E-18*
NH_4-N	Neutral	1	1	1.8	9.4	15	15		
	Drainage	1	0	3.1	5.6	15	15	0.709	0.457
	Seepage	23	51	375.5	2213.9	15	15	0.001*	0.001*
DRP	Neutral	0	-1	11.3	13.7	15	15		
	Drainage	1	0	4.1	2.6	15	15	0.864	0.431
	Seepage	77	106	2573.9	4965.9	15	15	4.0E-5*	4.1E-05*

Changes in concentration were also observed in the samples collected from the groundwater channel under drainage conditions, where NO_X-N concentrations drastically changed (increase of 400% on first run; >95% decrease for the two last runs), NH_4-N concentrations increased from 200 to 500% and DRP concentrations increased 100% increase on the first run and 2000% on the last two runs. The reduction in NO_X-N suggest it is uptaken within the sediment as the surface water passes through the bed material under drainage conditions, while the opposite is occurring for NH_4-N and DRP (i.e. the bed sediment is releasing or flushing out NH_4-N and DRP). Variations in pH and ORP were only significant under seepage conditions, where mean inlet pH changed from 7.8 to 7.3 at the middle and 7.1 at the outlet; mean ORP value at the inlet was 407 mV, while 317 mV at the middle and 194 mV at the outlet. No specific trend was observed for conductivity and temperature.

Oxidised nitrogen removal in streams is mainly due to the denitrification process in the sediment-water interface, which is influenced by carbon content, porosity, residence time and oxygen levels (Hampton et al., 2020). In small streams, the proportion of sediment's contact area to the water flow area is high which creates favourable biogeochemical environment for denitrification (Boano et al., 2014). The decrease of 213 mV in mean ORP values under seepage conditions with only 20% groundwater contribution suggest anoxic, potentially anaerobic, bed sediment conditions. Given that each flume run lasted a maximum of 2 hours, anoxic micro-zones might have remained within the sediment, thus promoting denitrification process to occur. However, due to the very low water resident time, the denitrification process does not fully explain this decrease in concentration. In addition, the stagnant water in the flume would have low oxidised nitrogen concentration; the greater residence time in the flume would promote denitrification process to occur in higher rates (Klocker et al., 2009). Streams with sandy sediment have preference flow (Dehkordy et al., 2019) so the saturated water was not completely replaced before starting each run. Therefore, the dilution of SSW seeping from the flume's sediment would help explain this decrease in NOx-N concentrations.

The observed leaching of DRP into groundwater under drainage conditions supports previous observations (Yoder, 2014). Major retention mechanisms for dissolved phosphorus in waterways include sorption to the soil and plant uptake with Aluminium (Al) and Iron (Fe) the major phosphorus sorbent in acidic soils (Reddy et al., 1999). However, the phosphorus bond with iron oxides in the sediments may be released under anaerobic conditions (Forsmann and Kjaergaard, 2014).

Conclusions and future work

This experiment found strong evidence to show that groundwater interaction does influence changes in concentration of nutrients in surface water, under seepage conditions, increase in DRP and NH_4-N and degrease in NO_X-N concentrations were very evident. This can guide modelling and monitoring of in-channel treatment systems, through better understanding of the relationship between pollutant concentrations, bed material, and groundwater conditions.

References

Boano, F, Harvey, JW, Marion, A, Packman, AI, Revelli, R, Ridolfi, L & Wörman, A 2014, 'Hyporheic flow and transport processes: Mechanisms, models, and biogeochemical implications', Reviews of Geophysics, vol. 52, no. 4, pp. 603-679.

Dehkordy, FM, Briggs, MA, Day-Lewis, FD, Singha, K, Krajnovich, A, Hampton, TB, Zarnetske, JP, Scruggs, C & Bagtzoglou, AC 2019, 'Multi-scale preferential flow processes in an urban streambed under variable hydraulic conditions', Journal of Hydrology, vol. 573, pp. 168-179.

Forsmann, DM and Kjaergaard, C 2014, 'Phosphorus release from anaerobic peat soils during convective discharge—Effect of soil Fe: P molar ratio and preferential flow', Geoderma, vol. 223, pp. 21-32.

Hampton, TB, Zarnetske, JP, Briggs, MA, Dehkordy, FM, Singha, K, Day-Lewis, FD, Harvey, JW, Chowdhury, SR and Lane, JW 2020, 'Experimental shifts of hydrologic residence time in a sandy urban stream sediment–water interface alter nitrate removal and nitrous oxide fluxes', Biogeochemistry, vol. 149, no. 2, pp. 195-219.

Klocker, CA, Kaushal, SS, Groffman, PM, Mayer, PM and Morgan, RP 2009, 'Nitrogen uptake and denitrification in restored and unrestored streams in urban Maryland, USA', Aquatic Sciences, vol. 71, no. 4, pp. 411-424.

Reddy, K, Kadlec, R, Flaig, E and Gale, P 1999, 'Phosphorus retention in streams and wetlands: a review', Critical reviews in environmental science and technology, vol. 29, no. 1, pp. 83-146.

Yoder, CE 2014, Quantifying subsurface hydrology effects on chemical transport in agriculture drainage ditches using a 20 meter flume, M.S. Thesis, Purdue University, https://docs.lib.purdue.edu/open_access_theses/288.