THE INFLUENCE OF GROUNDWATER CONDITIONS ON NUTRIENT DYNAMICS IN WATERWAYS

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INTRODUCTION

Excess nutrients in waterways contribute to eutrophication and poorer aquatic ecosystem health, a problem affecting rural and urban catchments. Key nutrients such as nitrogen and phosphorus can move between the stream bed sediment and water column due the influence of physical, chemical and microbiological factors in the stream environment, which affect their availability and resulting ecological impact. 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 these urban in-channel systems under the influence of different groundwater conditions.

Therefore, this research aims to understand the dynamics of nutrients (nitrogen and phosphorus) in waterways systems under the influence of different groundwater conditions (seepage, neutral, and drainage). It was hypothesized that groundwater and bed material characteristics affect the concentration and form of pollutants, as well as their mobility. This understanding could help guide stream management decisions.

METHODS

A longitudinal study of pollutant transport and transformation under different groundwater conditions (seepage, neutral or drainage) was undertaken to assess the changes in surface water quality from the start to the end of a representative in-channel treatment system, with a focus on nutrients (nitrogen and phosphorus).

A 19 m long flume was made using 6 mm thick PVC to simulate an in-channel treatment system which contains a gravel base (5-8 mm gravel 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 (60% by volume) and contaminated bed sediment sourced from the Wigram Retention Basin (WRB; 40% by volume). Synthetic stormwater (SSW) was used for the surface water and groundwater. SSW was prepared as a stock solution and then diluted in a 1,000-L IBC tank with tap water to have a target concentration of nitrate nitrogen (NOx-N; 0.4 mg/L), ammoniacal nitrogen (NH_4-N; 0.2 mg/L) and Dissolved Reactive Phosphorus (DRP; 0.2 mg/L), to simulate the in-channel water quality measured in Haytons Stream, which discharges into WRB from an urban industrial catchment.

The flume system was run 12 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 and it was measured using a flow sensor. Under neutral groundwater conditions, there was no groundwater interaction. Under drainage conditions, the groundwater channel was lowered to drain 4.36 L/min of the incoming surface water (2.18 L/min for each length of the flume). Under seepage conditions, the groundwater channel was lifted to seep a total of 4.36 L/min into the flume (2.18 L/min for each length of the flume; Figure 2).

Each flume experiment was run for 30 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 have much variation after this 15 min period). This was characterised by collecting samples at 5 minute intervals over a 40 minute period under each groundwater condition during preliminary experiments. Therefore, samples at the middle and outlet locations were collected at 15, 20, 25 and 30 minutes for the set of experiments presented in this paper. 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.

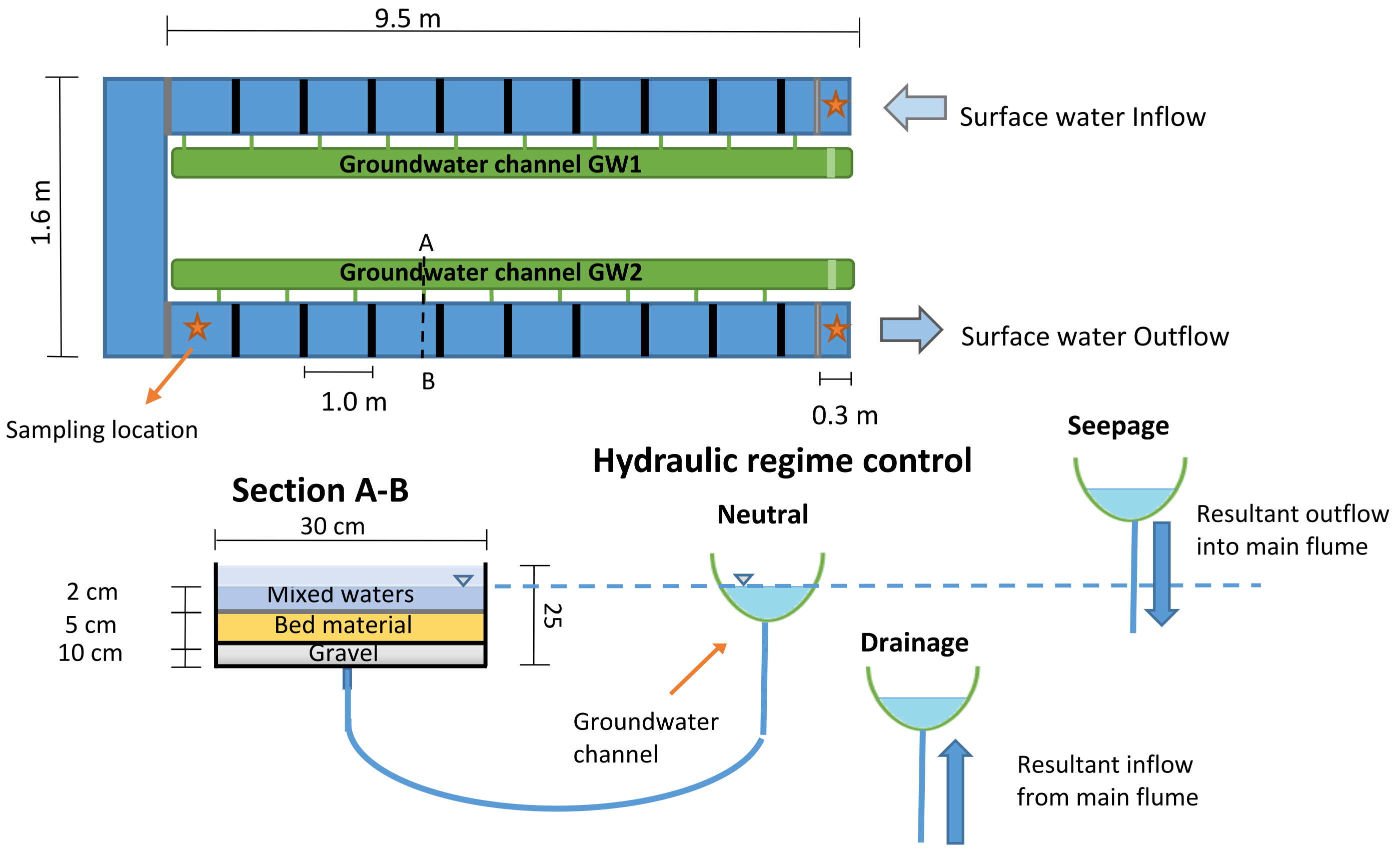

Figure 1: Schematic plan and cross-sectional views of the experimental system with groundwater regimes and groundwater channel relative heights.

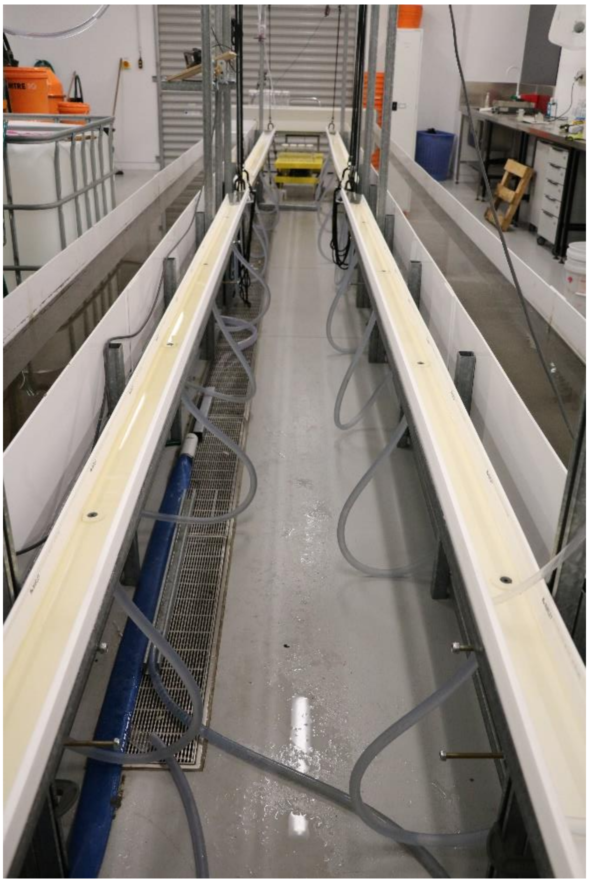

Figure 2: Experiment setup under drainage groundwater conditions.

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 because inlet concentrations were different 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 GW condition influences the range and variation of nutrient concentrations in the surface water for both NOx-N and DRP (Figures 3 and 4). Under seepage conditions, NOx-N concentrations decreased at the middle and outlet locations (7 and 12%, respectively), and DRP concentrations increased at both locations by around 11% (compared to the inlet concentrations). Under neutral and drainage conditions, there was variation in the range of changes, but a statistically significant difference in percentage change was not observed (Table 1).

Changes in concentration were also observed in the samples collected from the groundwater channel under drainage conditions, where NOx-N concentrations decreased drastically and DRP concentrations more than doubled (Figure 5). The reduction in NOX-N suggest it is becoming bound within the sediment as the surface water passes through the bed material into the groundwater channel under drainage conditions, while the opposite is occurring for DRP (i.e. the bed sediment is releasing or flushing out DRP).

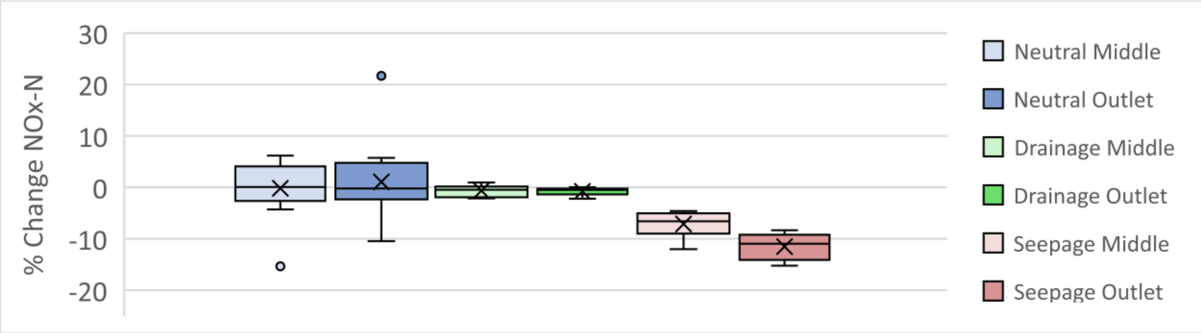

Figure 3: Percentage change in NOx-N concentrations at the middle and outlet of the flume under neutral, drainage and seepage groundwater conditions; x refers to the mean values and circles represent outliers.

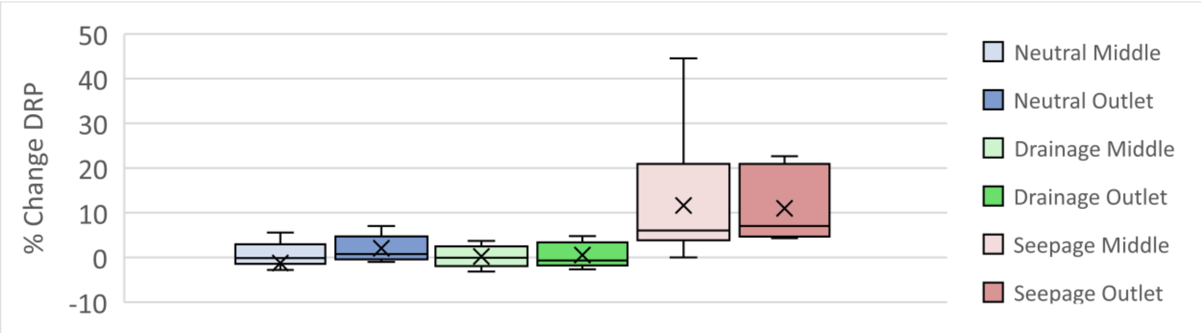

Figure 4: Percentage change in DRP concentrations at the middle and outlet of the flume under neutral, drainage, and seepage groundwater conditions; x refers to the mean values and circles represent outliers.

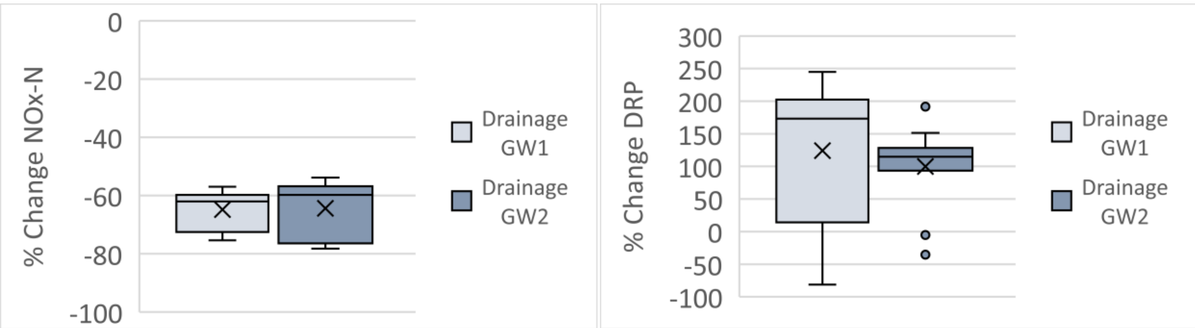

Figure 5: Percentage change in NOx-N and DRP groundwater concentrations under drainage condition; GW1 refers to the groundwater from the first half of the flume (by the inlet) and GW2 refers to the second half (by the outlet); x refers to the mean values and circles represent outliers.

Variation of pH was only significant under seepage conditions, where mean inlet pH changed from 7.81 to 7.41 at the middle and 7.27 at the outlet. There was no specific trend observed for conductivity and temperature; conductivity values remained between 106 to 132 uS/cm at 25°C, with mean values ranging between 120.8 and 112 uS/cm, while temperature values ranged between 16 and 19°C, with mean values between 18 and 17°C.

ORP values did not change significantly under neutral and drainage groundwater conditions, but the difference was significant for seepage groundwater conditions. Under seepage conditions, mean ORP value at the inlet was 373 mV, while at the middle and outlet 98 and 99 mV. The decrease of 270 mV in mean ORP values under seepage condition with only 20% groundwater contribution suggest anoxic, potentially anaerobic, bed sediment condition.

Table 1: T-test results of percentage change in NOx-N and DRP concentrations in the middle and outlet of the flume under different groundwater conditions.

Compound	Sampling Location	Groundwater Condition	Mean change from mean inlet concentration (%)	Variance	Observations	P-value of difference in percentage change between neutral and drainage or seepage
NOx-N	Middle	Neutral	0	34.1	12	
		Drainage	-1	1.2	12	0.787
		Seepage	-7	5.3	11	0.002*
	Outlet	Neutral	1	68.2	12	
		Drainage	-1	0.5	12	0.458
		Seepage	-12	6.4	12	0.000*
DRP	Middle	Neutral	-1	54.5	12	
		Drainage	0	5.4	12	0.516
		Seepage	12	183.9	12	0.010*
	Outlet	Neutral	2	7.7	12	
		Drainage	1	7.4	12	0.195
		Seepage	11	63.6	12	0.003*

* P-value less than alpha of 0.05 showing significant statistical difference between neutral condition and seepage.

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 (Reddy et al. 1999) with Aluminium (Al) and Iron (Fe) the major phosphorus sorbent in acidic soils (Reddy & DeLaune 2008). However, the phosphorus bond with iron oxides in the sediments may be released under anaerobic conditions (Forsmann & Kjaergaard 2014; House & Denison 2002). Large increases in iron, in its dissolved and total forms, were verified at the middle and outlet under seepage conditions and in the groundwater channel under drainage conditions. In addition, gradients in sediments or groundwater may results in movement of dissolved phosphorus and porewater (Withers & Jarvie 2008). Therefore, groundwater seepage through the bed sediment transports dissolved phosphorus, which is released within the sediment to the surface water.

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, thus water exchange through these sediments creates favourable biogeochemical environment for denitrification (Anderson et al. 2005; Boano et al. 2014). In addition, maintaining the flume bed sediment saturated with SSW might have created an ideal anoxic environment and the ORP values observed under seepage conditions support this hypothesis.

Given that each run of the flume lasted a maximum of 2 hours (including preparation such as replacing saturated bed sediment water and the 30-min application of flow through the flume), 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 (MahmoodPoor Dehkordy et al. 2019) contributing to not replace all its saturated water before starting each run. Therefore, the dilution of SSW seeping from the flume's sediment would help explain this decrease in NOx-N concentration. The generation of ammoniacal nitrogen concentration data and analysis of its influence with on NOx-N concentrations due to nitrification process is still being processed and will further clarify the nitrogen transformation processes occurring.

CONCLUSION

This experiment found strong evidence to show that groundwater interaction does influence changes in concentration of nutrients in surface water. This can guide modelling and monitoring of in-channel treatment systems, through better understanding of the relationship between pollutant concentrations and form and groundwater conditions.

Under seepage conditions, an increase in DRP was very evident. The decrease in NOx-N concentrations were also evident, although the denitrification process does not fully explain its decrease and potentially preferred groundwater flow might have contribute to low NOx-N level in the surface water. Ammoniacal nitrogen data, currently being generated, will further deepen the understanding of NOx-N dynamics in the flume.

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