The investigation of in-channel aquatic vegetation (IAV) effect on hyporheic exchange (HE) with the solute tracer experiment

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Abstract. To explore and quantify the effect of in-channel aquatic vegetation (IAV) on hyporheic exchange (HE), the research with solute tracer method were launched in a homogenous sand bed flume. The experiments took 3 trials including one control trial and two subsequent trials with only dependent variable of emergent IAV’s canopy area. The hypothesis that that IAV area has the positive correlation with mean hydraulic residence time (HRT) and correspondingly negative correlation with mean rate of HE. Comparation of the experimental support the hypothesis. However, rate of HE shows negative correlation with IAV area increasing at initial period. It is speculated that phenomenon is caused by sediment mobility which changed water pressure diffidence and formed long seepage path under IAV area. The speculation requires further research. The exploration of the complex interaction between IAV and HE requires further is still in its infancy. This research provides the promising evidence to further investigation.

1. Introduction

Water quality of natural water system is the footstone of ecological environment health and plays an important role in ecological stability and species diversity. Hyporheic zone (HZ), where is the connection area of waterway’s surface runoff and subsurface flow, plays an important role of water self-purification since it is capable to provide water-purifying organisms with nutrient from the latter and dissolved oxygen from the former [1].

The main drivers of the biological water-purification processes in HZ include microorganisms, macroinvertebrates, and various aquatic vegetations and animals. These complexed processes involve plenty of different parameters such as biological species and their growing period, oxygen content, subsurface flow velocity, water temperature, pollutants concentrations etc. The investigation of these parameters can provide important reference for sustainable management of water systems. One of the comprehensive parameters is the reaction time or flows’ staying time in HZ defined as the hydraulic residence time (HRT), which can be calculated by hyporheic flux (HZ) entering HZ divided by rate of hyporheic exchange (HE) [2].

In-channel aquatic vegetation (IAV) is a population of water-purifying organisms covering various aquatic plant species growing in surface runoff. IAV can be roughly divided into submerged types and emergent types. Although removal of IAV from waterways is used for flow regulation in river management, there are still a lot of research gaps in the effect of IAV on HE and further water self-purification. The approaches of IAV influencing HE are through complex physical, chemical and
biological reactions which involve plenty of corresponding parameters including the shape, species, density and covering area of IAV with its varying along growing period, surface flow’s flow rate, water pressure, oxygen content and pollutant concentration, as well as subsurface seepage’s flow velocity, nutrient content, infiltration to groundwater and turbulence by bedform variation. The major difficulty to explore and quantify the interaction of IAV and HE is due to temporal and spatial interaction of these parameters, which makes it hard to research the effect by proposed computational modal analysis. Therefore, physical experiment is required to this research, and the solute tracer experiment is used since it is the common method applied in exploration of bedform properties effect on HE. Due to time and financial constraints, this research focus on artificial emergent IAV’s covering area within a channel in a homogenous sand bed flume.

2. Hypothesis
The solute tracer experiment is that a homogeneous sand bed flume simulated a real stream while groundwater’s upwelling is neglected, and complex stream bed geological properties are simplified to that of homogeneous sand. The real IAV is represented by artificial emergent IAV neglecting any biological reactions. The dependent variable is constrained to canopy area and then temperature’s influence on solute concentration can be remove in calculation process. The hypothesis is with the conditions mentioned that IAV area has the positive correlation with mean hydraulic residence time (HRT) and correspondingly negative correlation with mean rate of HE.

3. Methodology

3.1 Experimental method
In solute tracer experiments, solute is a non-reactive dye injected into the surface flow initially, then gradually dispersed into subsurface flow and finally evenly distributed in both flows. With runoff flowing through the channel in the recirculating laboratory flume, stream bed keeps changing and further varies rate of HZ along the channel over the flowing time. The dye concentration decay curve can track the rate of HZ variation and illustrate comprehensive result as mean RTD [3]. The related numerical method is referenced from Stewardson [4].

3.2 Experimental design
According to the principle of controlled trials, the solute tracer experiments take 3 trials including one control trial and two subsequent trials with only dependent variable of emergent IAV’s canopy area. The homogenous sand bed of the flume and stream bed inside are repaved by the same leveling tool to ensure that the geological properties of the sand bed are consistent among the 3 trials.

The Melbourne University provided the experience equipment including the homogenous sand bed flume with recirculating pumping systems and levelling tools, materials of artificial IAV models, dye Rhodamine and Cyclops-7 (C7) fluorometers.

3.2.1 Sand bed flume
The 12-meter flume was filled with homogenous sand bed whose particles properties referred to median particle size with 1.37 mm.

The straight stream was set at the control of the flume with a 1.8-meter and a 1-meter bend at the inlet and outlet sections respectively where coarse stones were laid to reduce sand bed grain loss. The slope of stream banks’ flat and stream bed were both set to be 1:300. The size labeling and cross sections along the flume is shown in Fig. 1. The cross section of the stream (C-C’, Fig. 1) is an inverted trapezoid with 0.4-meter base, 0.32-meter top and the height of 4cm ± 2mm.

The upstream tank (A-A’, Fig. 1) and the downstream tanks (B-B’, Fig. 1) were connected by a recirculating system that could pumping water from downstream to upstream with fixed flow rate of 1.5 L/s. The connection pipes net took 16-meter long with internal diameter of 52.5 mm.

Taking water leaks and evaporation into consideration, a water level controller was installed at downstream tank. Its function of automatic water replenishment ensured that the overall water volume was unchanged in the recirculating flume with pumping systems along each trail.
3.2.2 Solute tracer
Rhodamine is a stable fluorescent pink dry which was took as solute trace in the experiments. The Rhodamine concentration can be detected by fluorometers. Two Cyclops-7 fluorometers were used to record the Rhodamine concentration in upstream and downstream tanks respectively along each trial. The data used for the analysis was collected from the upstream tank, while the downstream tank’s data was for data checking, since watering dropping leaded to much higher turbulence in the latter and fully mixed the water with different Rhodamine concentration. The data collected from the upstream tank could better represent the Rhodamine concentration of surface water in the stream.

In addition, Cyclops-7 fluorometers recorded real-time water temperature which was necessary to modify its effect from raw data to real concentration. The water levels along the channel were measured and recorded as well for hydraulic gradient calculation.

3.2.3 IAV model
The typical size of emergent IAV is with 5-15 mm diameter stem and 2.5cm to 18m long referencing reed. Since the artificial IAV model was half inserted into the sand bed, its required to keep the canopy emerged of water surface (> 4cm water depth) without being swept away by stream flow, the model size was determined to be as Fig. 2 after several flowing attempts. The roots were simplified and simulated by 8 bifurcated thin wires with overall length around 6cm, while heat shrink wrap pipe concentrated them as stem which was approximately 6cm long as well with diameter about 5mm.

3.2.4 Experimental arrangement
The canopy area and the number of IAV models for the 3 trials area displayed in table 1, in which the scale of trial 3 were doubled of that of trial 2. To make the effect of IAV on HE prominent with IAV area as the only dependent variable, the canopy density was proposed to be as high as possible without roots overlapping. Therefore, the IAV models were arranged in interspersed patterns of four-unit rows and five-unit rows, covering the whole channel width and spreading from the center of the channel.
Table 1. Arrangement of 3 experimental trials.

| Trial | IAV type | IAV area (m²) | No. IAV models |
|-------|----------|---------------|----------------|
| #1    | None     | None          | 0              |
| #2    | Emergent | 0.715         | 157            |
| #3    | Emergent | 1.430         | 314            |

3.2.5 Numerical method
Salehin et al. made experiments about HE in heterogeneous streambeds in 2004 which provide the cited equations in this research with the same theoretical basis and similar experiments streambeds [6].

The normalized concentration $C^*(t)$ as Equation (1) determined, is the method to convert the concentration from numerical to proportional and further offset the effect of the initial concentration on the data comparison.

$$C^*(t) = \frac{C(t)}{C_0}$$  \hspace{1cm} (1)

Where:
- $C(t)$ – tracer concentration at time $t$, recorded by fluorometers per 10 minutes;
- $C^*(t)$ – normalized tracer concentration at time $t$;
- $C_0$ – initial tracer concentration of surface water, determined by tracer mass injected and total water volume of surface water.

Darcy’s Law can be applied for rate of HE approximate calculation, as Equation (2) and Equation (3) illustrates.

$$Q = -KA \frac{dh}{dL} = -KAi$$ \hspace{1cm} (2)

$$\frac{1}{q} = -Ki$$ \hspace{1cm} (3)

Where:
- $\theta$ – porosity, mean porosity the sand bed is 0.4;
- $Q$ (m³/s) – discharge through sediments;
- $K$ (m/s) – hydraulic conductivity, mean hydraulic conductivity of the sand bed is $1.1 \times 10^{-3}$ m/s;
- $A$ (m²) – area of sediments;
- $dh$ (m) – hydraulic head;
- $dL$ (m) – distance along hydraulic head dropping;
- $i$ – hydraulic gradient determined as $dh/dL$;
- $q$ (m/s) – mean interfacial flux

Equation (4) shows the process of modify temperature effect of solute concentration of Rhodamine [7].

$$Adjusted \ C^*(t) = C^*(t)e^{0.026(T(t)-20)}$$

Where: $T(t)$ – temperature at time $t$.

4. Results

4.1 Sediments variation

Figure 3. Photographs of steam sediments variation for 3 trials (trial 1, 2, 3 as left, middle and right)
Photographs of the streambed (Fig.3) were took after draining of each experimental trial, displayed the different sediments variation patterns. The comparation shows in following 3 aspects:

i. Sediments deposition increase in stream bed: visible sediments deposition increasing with IAV models placement, which was shown that the stems of IAV units were buried deeper.

ii. Erosion more serious in stream banks: water velocity increase around IAV stems bring more sediment from stream banks that trapezoidal cross sections turned into rectangle. The erosion was more serious with canopy area growing.

iii. Overall sedimentation augment: compared to the amount of erosion, that of sediments deposition was obviously dominant, since IAV units increased the roughness of the stream and leaded to mean water velocity decrease based on Manning’s equation.

4.2 Concentration decay curve

The raw data recorded by Cyclops-7 fluorometers were processing by MATLAB after modifying temperature effect. The results are shown as Figure 4. The tracer concentration decay curve started with the injection of Rhodamine tracer and ended at fully mixing of surface and subsurface water. The normalized concentrations were at maximum initially and finally tended to be roughly constant.

![Figure 4. The normalized tracer concentration decay curve for initial period of each trial (left) and for entire trial (right).](image)

The initial period records illustrates that solute concentration decreasing rate, absolute value of derivative of each curve at time 0, reduced with the growing IAV models’ covering area, which suggests that the solute transfer rate from surface runoff to subsurface flow, rate of HE, is decelerated with the originally same streambed topography. However, when the time stretched to more than 1.3 hours, the opposite happened.

As the first 7 hours of right graph of Fig.4 displays, normalized tracer concentration is in the sequence of trial 1, 2, 3, implying increasing IAV models’ covering area accelerates rate of HZ at this period. There are inflection points of the decay curves that solute concentration converted from decreasing to increasing, especially in trial 2 and 3, suggesting solute mass reappeared in surface water body after entering sediment layer. Integrating the entire period of each trial, trial 3 took longest to solute evenly distributed, while the time difference between trial 1 and trial 2 is hard to be observed directly.

4.3 Hyporheic exchange rate

| Trial | Canopy area (m²) | Total head difference (m) | Hydraulic gradient (i) | Mean HE rate (L/s) | Mean interfacial flux (m/s) |
|-------|-----------------|--------------------------|-----------------------|-------------------|--------------------------|
| #1    | 0               | 0.0366                   | 0.0059                | 0.025             | 6.5*10^-6               |
| #2    | 0.715           | 0.0359                   | 0.0058                | 0.024             | 6.3*10^-6               |
| #3    | 1.430           | 0.0306                   | 0.0049                | 0.021             | 5.4*10^-6               |
As Tab. 2 indicates, the placement of IAV models is obstacles adding to the stream, leading to mean water velocity decelerating, streambed rising with sediment accumulation and mean water table rising. The integrated result of IAV area increasing is the decreasing water head drop and reduced hydraulic gradient. The mean interfacial flux based on Darcy’s Law and corresponding mean rate of HE reduced as IAV area growing. This result is consistent with what tracer concentration decay curve indicated in previous section.

The diffusion of solute is a dynamic process due to sediments mobility, mean rate of HZ of the streambed is with temporal variation. After plenty of parameters offsetting their effect, one factor dominates the integrated rate of HZ. It is speculated that at initial period, the increasing water pressure is the major driver rising HZ rate. As sediment accumulates in the streambed, especially the bed table increasing in IAV area, the depression of effective water pressure gradually formed. It drives solute seepage through long path under IAV area instead of short and shallow path near streambed. However, further research is required to verify this speculation.

5. Conclusion

Comparison of the experimental trials results, it can be concluded that the implantation of IAV clearly affects mean rate of HE in the flume reach. Sediments accumulated at streambed, especially in IAV area, while stream banks were eroded more seriously with IAV area placement. In the entire process starting at solute diffusion from surface runoff to subsurface flow and ending at solute evenly distribution, rate of HE shows negative correlation with IAV area increasing at initial period, while then shows positive correlation. The mean rate of HE and HRT through the whole trail rises with IAV area growing. It is speculated that phenomenon is caused by sediment mobility which changed water pressure diffidence and formed long seepage path under IAV area. The speculation requires further research.

This investigation is aimed to explore and quantify the IAV effect on HE. The hypothesis is supported by experimental results that that IAV area has the positive correlation with mean hydraulic residence time (HRT) and correspondingly negative correlation with mean rate of HE. However, there are many simplifications and uncertainties in the experiments, the mathematical relations are not universal. The exploration of the complex interaction between IAV and HE requires is still in its infancy. This research provides the promising evidence to further investigation.

References

[1] F. Boano, J. W. Harvey, A. Marion, A. I. Packman, R. Revelli, L. Ridolfi, and A. Wörman, Hyporheic flow and transport processes: Mechanisms, models, and biogeochemical implications, Geophysics, 52 (2014), 603-679.
[2] L. Campbell, A. Boulton, and A. Brock, M. Australia Freshwater Ecology, Processes and Management, Vol. 19, (2000).
[3] A. I. Packman and K. E. Bencala, Modeling Surface–Subsurface Hydrological Interactions. In J. B. Jones & P. J. Mulholland (Eds.), Streams and Ground Waters, San Diego, Academic Press, 2000, pp. 45-80.
[4] M. Stewardson, & Arora, M. Understanding streambed sediments as complex systems: A review of interacting environmental processes influencing hydraulic conductivity of streambeds, Unpublished Research Paper, Department of Infrastructure Engineering, The University of Melbourne, 2018
[5] D. J. Tilley, and L. St. John, Plant Guide for common reed (Phragmites australis), Aberdeen: ID Plant Materials Center, 2018, Retrieved from https://plants.usda.gov/plantguide/pdf/pg_phau7.
[6] M. Salehin, A. I. Packman and M. Paradis, Hyporheic exchange with heterogeneous streambeds: Laboratory experiments and modelling, Water Resources Research, 2004, 40(11).
[7] TurnerDesigns. Fluorescence is temperature sensitive – Turner Designs. [EB/OL]. https://www.turnerdesigns.com/general-fluorometer-faq/article/718-flouresence-temperature-sensitive, 2018