1D Simulation of Hyporheic Exchange in a Stream Dammed by Beaver

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Abstract: Hyporheic exchange, the exchange of water between streams and adjacent subsurface sediments, is an important interface between groundwater and surface water. Knowing the location and magnitude of hyporheic exchange is useful in evaluating the fish spawning habitats, biogeochemical processes, and capacity for aquifer recharge of a given stream. Vertical hyporheic exchange (VHE) through the streambed is driven by variations in longitudinal energy head gradient. Modifications to bed topography, such salmon nests, boulders, fallen logs, and beaver dams, all promote increased hyporheic exchange. The magnitude of exchange typically increases as more of the stream flow is obstructed. Beaver dams are unique in that they are designed to be channel-spanning obstructions at least as tall as the stream depth, often obstructing flow so effectively that a large pond forms upstream of the dam. Beaver dams further change the upstream topography within their ponds through increased sedimentation rates and excavation of pond-bottom mud by the beavers. It follows that the dominant drivers of hyporheic exchange in beaver-occupied streams will be the beaver dams. To better understand the relationship between beaver damming and vertical hyporheic exchange, we have developed a one-dimensional numeric model.

Background and Motivation

Beaver damming can have many effects on a stream. One impact of beaver dams is their tendency to induce strong downwelling and upwelling around the dam - on the order of 0.1 m/day of water flux. This can mix surface water and groundwater, leading to changes in water temperature and biogeochemistry. The vertical water fluxes are particularly prominent in streams where the lateral water flux into the banks is limited. This is typically the case for beaver dams that are tall and fairly watertight, with an upstream pond constrained by steep, rocky sidewalls such as in a narrow mountain channel (below, left). Less tall and/or leaky beaver dams build on relatively flat terrain where the upstream pond expands into a diffuse wetland will have significant lateral exchange and limited vertical exchange (below, right). This model is designed to capture the vertical water fluxes around a mountain channel dam using the simplest, most numerical approach possible.

Figure 1: Left, an example of a beaver dam that the model we developed would work well for – relatively tall and watertight, pond constrained by steep sidewalls. Right, an example of a beaver dam the model we developed would not work well for – relatively short and leaky, upstream pond is a diffuse wetland..

Mathematical Basis of VHE Flux Model

Conservation of Mass

The model is fundamentally based on conservation of mass within a unit cell of subsurface sediment beneath the streambed as shown in Figure 1. From this representation, we can obtain the mass balance equation for the volume of water within the unit cell,

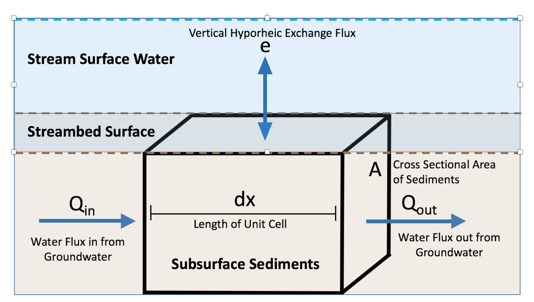


Figure 2: A simplified drawing of mass balance within a unit cell of subsurface sediments beneath a stream.

Equation 1
$$\frac{dV_w}{dt} = Q_{in} - Q_{out} + e \cdot dx$$

Where V_w is the volume of water within the unit cell. We assumed that the total volume of water within the cell does not change, and utilize Darcy's Law to define *Q*. Applying the derivative then yields the general equation for vertical hyporheic exchange per unit length (Tonina and Buffington 2009), where *K* is the hydraulic conductivity, *A* is the cross-sectional area of the unit cell, and *h* is the total streambed pressure, or energy head.

Equation 2
$$e = -KA\left(\frac{d^2h}{dx^2}\right), -K\left(\frac{dA}{dx}\right)\left(\frac{dh}{dx}\right) - A\left(\frac{dK}{dx}\right)\left(\frac{dh}{dx}\right)$$

The three terms on the right hand side of Eq. 3 represent the contributions of spatial changes in energy head gradient, spatial changes in alluvium area, and spatial changes in hydraulic conductivity respectively. This model assumes uniform hydraulic conductivity and alluvium depth, so the second and third right-hand terms go to zero, meaning the vertical hyporheic exchange flux will vary solely due to spatial changes in the energy head gradient.

Energy Head Calculations

We define the energy head *h* as a sum of three components: the elevation head (*z*), the static pressure head (h_p), and the dynamic pressure head $\left(C\frac{U^2}{2g}\right)$ with *C* being a generic loss coefficient, *U* being the mean surface flow velocity, and *g* being the acceleration due to gravity (Tonina and Buffington, 2009), as shown below in Eq. 5.

Equation 3
$$h = z + h_p + C\frac{U^2}{2g}$$

Surface Water Velocity Calculations

The pond was treated as a series of rectangular cross sections with area A_p We assumed a constant volumetric flow rate of water entering the system, *F*, so the mean surface water velocity, *U*, is give by $U = \frac{F}{A_p}$.

Development of Theoretical Beaver Dammed Streambed Profiles

This study examines a series of four theoretical beaver dammed streambed profiles designed beginning with a newly built dam (New Pond), and ending three timesteps later with an actively maintained pond in relative steady-state (Pond Profile 3) such that the rate of sediment excavation by beavers matches the rate of sediment deposition within the pond.

From a one-dimensional perspective, there are three main controls on streambed topography within the pond behind a beaver dam that make it a significantly different system than an undammed stream: decreased water velocity, the dam as a physical barrier, and excavation of sediment by beavers.

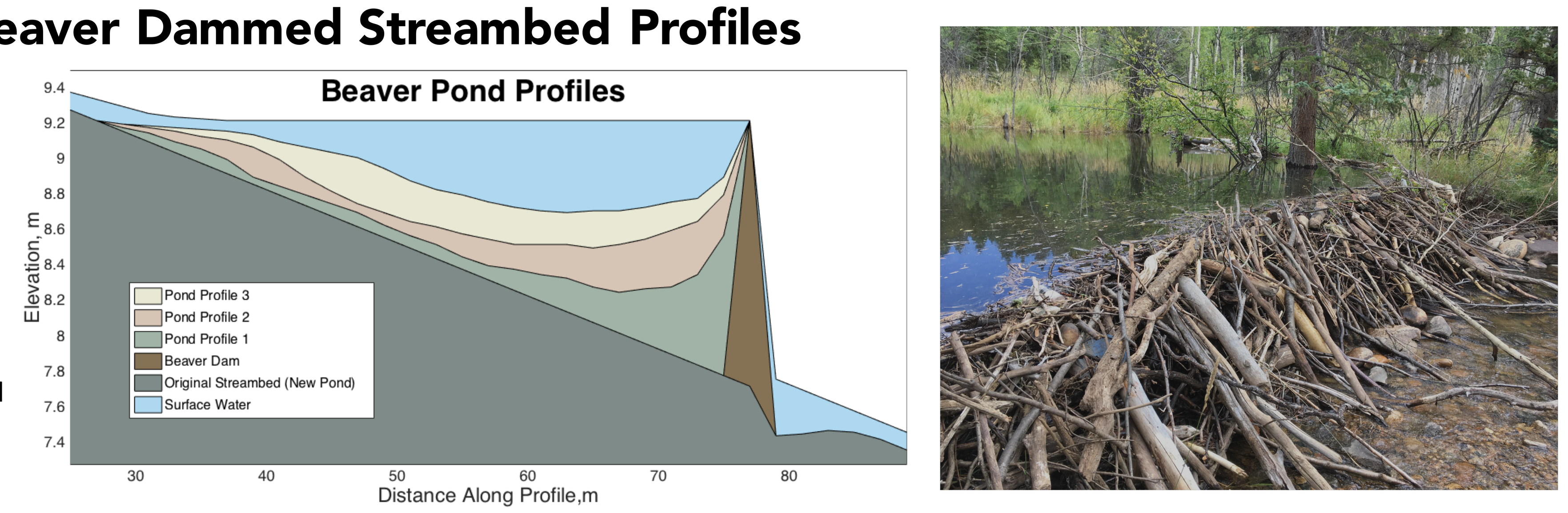


Figure 3: Left, The final beaver pond profiles that were used in the 1D model. New Pond is the pond before any sedimentation occurs, then Pond Profile 1-3 are the evolution through time. The net effect of the various controls on sediment distribution is the characteristic bowl shape of the beaver pond with a significant volume of accumulated sediment in the pond. Right, the actual beaver dam that inspired this model and served as validation for Pond Profile 3.

Decreased Water Velocity

Water velocity, *U*, is related to stream capacity, *c*, by the relation $c \propto U^6$. The water velocity profiles in the 4 simulated timesteps are shown below.

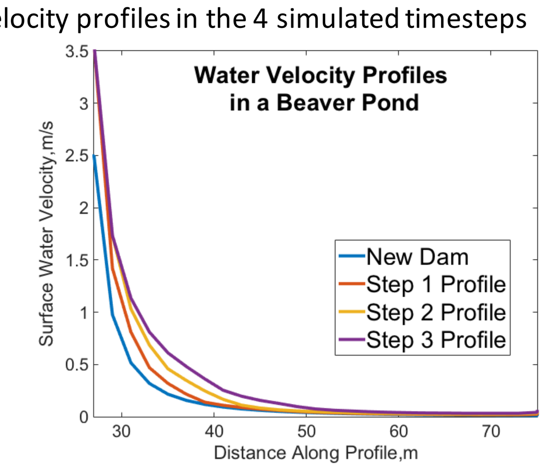


Figure 4: All pond profiles show a sharp velocity drop off, which means an abrupt dumping of sediment in the first ~5m within the pond. Once deposited, that sediment will diffuse and saltate downstream.

Dam as Physical Barrier

The beaver dam acts as a physical barrier to all saltating particles, resulting in a large accumulation of sediment immediately upstream of the dam.

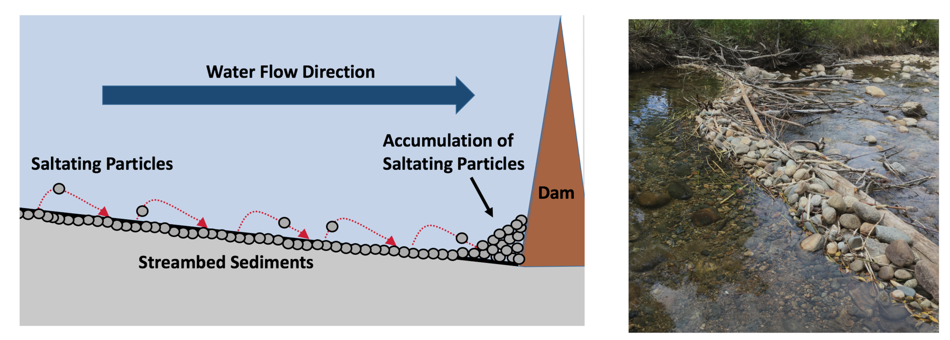


Figure 5: Left, schematic of saltating particle accumulation upstream of dam. Right, an actual dam with pebbles and sand accumulating upstream of it.

Excavation by Beavers

Beavers dig up sediment from the bottom of their ponds for a couple of reasons (Gurnell 1998):

1. to use it as building material in their dams and lodges
2. to maintain a minimum pond depth such that they can both swim away from predators and prevent freeze-through in the winter.

This excavation will continue to occur for as long as there are beavers maintaining the dam.

Model Results

The model simulations consistently showed a large VHE Cell at the dam consisting of strong downwelling flux immediately upstream of the dam and a strong upwelling flux immediately downstream of the dam. Within the pond small VHE cells developed as the streambed topography became more complex due to sedimentation, accumulation of saltating particles, and excavation by beavers.

Evolution of Upwelling and Downwelling Fluxes Through Time

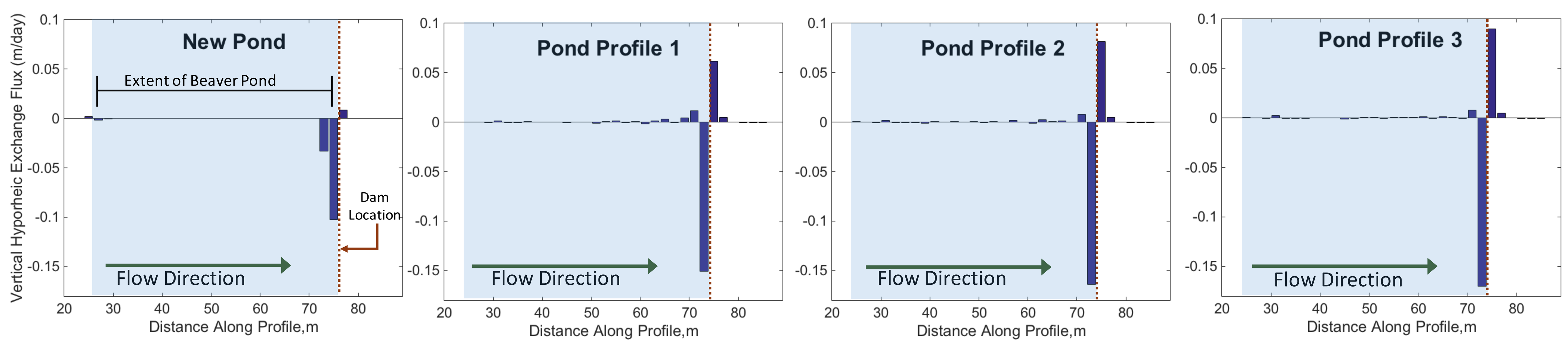


Figure 6: Upwelling and downwelling within the beaver dammed stream. Note the large downwelling flux immediately upstream of the dam and the large upwelling flux immediately downstream of the dam that persists through all four simulations.

Large VHE Cell at Dam

Static Pressure Head + Elevation Head

- There is a large drop in combined elevation of water depth and ground elevation at dam
- This drop is both high in magnitude and occurs very suddenly
- Resulting sharp gradient in this component of energy head drives a large, deep VHE cell at the dam that persists through time.
- 0.1-0.2 m/day in magnitude

Small VHE Cells in Pond

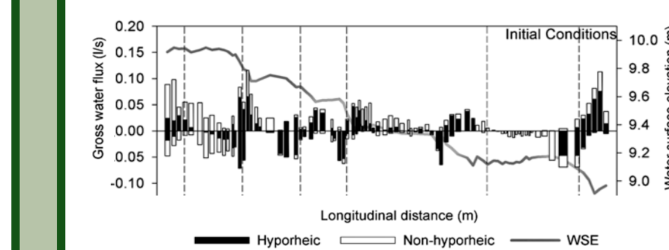
Dynamic Pressure Head

- Sum of Elevation head & Static Pressure head is a constant within the pond
- All VHE in pond is driven by dynamic pressure head, i.e. the changes in water velocity around vertical perturbations in streambed
- Variations in bed topography within pond create many small, shallow VHE cells that are spatially and temporally heterogeneous
- 0.001 – 0.002 m/day in magnitude

Comparison to Literature

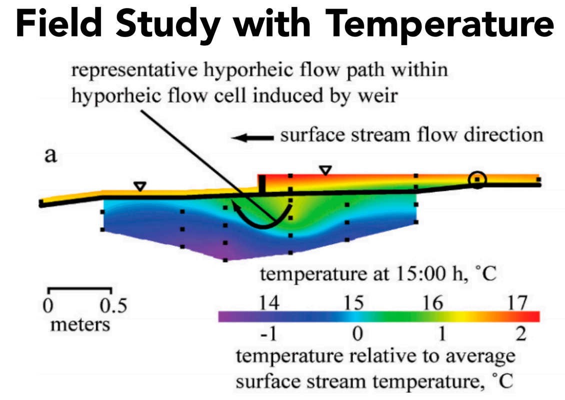
The trend of strong downwelling upstream of the beaver dams, and strong upwelling downstream of the dams shown by our 1D semi-numerical model results are very similar to several studies in the literature that examined similar systems using different techniques.

Modeling Study with Groundwater Modeling Software



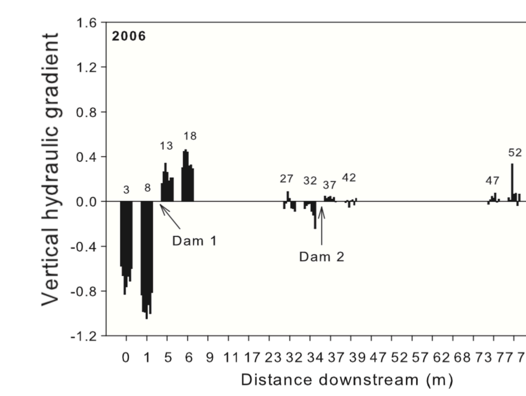
From Wondzell et. al. 2009. Figure shows vertical hyporheic exchange along the longitudinal profile along with the water surface elevation. Results were obtained from model simulations created using MODFLOW and MODPATH. Stream flow direction to the right.

Field Study with Temperature as a Tracer



From Hester et. al. 2009. Figure shows vertical hyporheic exchange along the longitudinal profile along with the water surface elevation in a stream dammed by a weir. Results were obtained from temperature tracer field studies. Stream flow direction to the left.

Field Study with Hydraulic Head Measurements



From Janzen and Westbrook 2011. Figure shows vertical hyporheic exchange along the longitudinal profile of a beaver dammed stream. Results were obtained from field measurements using piezometer nests. Stream flow direction to the right.

Conclusions

- There is a large persistent downwelling flux immediately upstream of the beaver dam, and a similar upwelling flux immediately after the dam that is consistent with the literature.
- The scale of the large VHE cell at the dam dwarfs the small cells within the pond

Whether the small VHE cells would actually be measureable in the field is unclear. They are likely on the same scale or smaller as other bed topography perturbations in beaver ponds not addressed in this model – such as the semi-porous food caches and large woody debris, and impermeable boulders or underlying bedforms that pre-date beaver dam, as shown below.

If this is the case, then the small VHE cells would likely still be very heterogeneous, but in the case of the food caches would change seasonally or in the case of large woody debris or pre-existing boulder deposits would not change significantly over the time which the beaver dam is maintained.

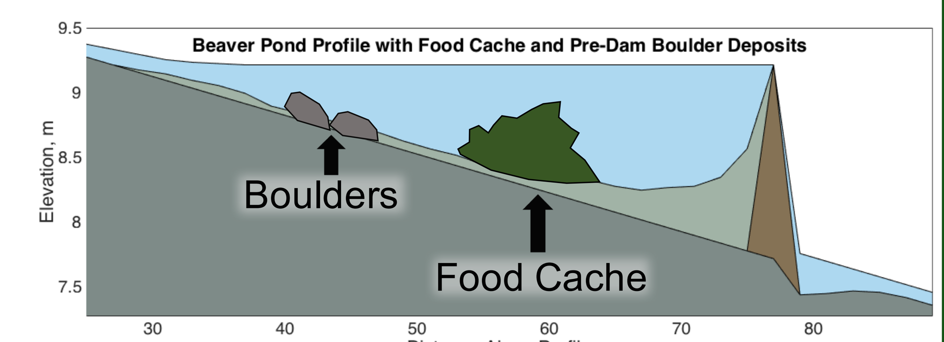


Figure 6: Schematic illustrating how the beaver's food cache and previous deposits of boulders might modify streambed topography and induce VHE more on a larger scale than modifications to streambed topography through sediment aggradation alone.

Acknowledgements and Citations

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