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RESEARCH ARTICLE

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Increasing Streambed Permeability Around Vertical Steps to Enhance Hyporheic Exchange

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Key Points:

- Increases of streambed permeability enhances hyporheic exchange flow due to steps
- Increasing the length of the high-permeability region primarily increases the longer residence times
- The inclusion of low-permeability blocks has a negligible influence on hyporheic exchange

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract In-stream structures can be used to promote hyporheic exchange, that is, the exchange of water and solutes between the stream and the underlying streambed. The modification of streambed permeability around these structures has been proposed to enhance their effectiveness in promoting hyporheic exchange. However, the topic has not been thoroughly studied yet. In this work, the effect of the increase of permeability around in-stream structures has been assessed via numerical models. Different combinations of variations in permeability and geometry of sediments around in-stream structures (steps) were tested to evaluate their potential for river management for improving hyporheic exchange. Structure performance is evaluated on the basis of hyporheic flow, vertical exchange velocity, and residence time distributions. Results showed that even when step-induced exchange velocity values in homogeneous sediments are small, the increase of permeability around the step can effectively enhance hyporheic flow. The numerical simulations showed that a longer high-permeability region resulted in smaller values of exchange velocity. The overall hyporheic flow was slightly larger for lengths of 0.3–0.7 m compared to 0.1 m, and the median residence time was slightly longer for lengths of 0.3–0.7 m compared to 0.1 m. The results also indicated that including low-permeability blocks upstream and downstream of high-permeability regions have no effect on hyporheic exchange. Additionally, the results indicate a moderate influence of the length of high-permeability region on hyporheic exchange and point out the importance of considering the trade-off between increased hyporheic flow and higher costs for replacing a larger volume of sediments.

Plain Language Summary Nowadays, one of the most vital environmental issues is the pollution of waters in streams and rivers and of their sediments, so it is crucial to find out solutions to attenuate this contamination. Many contaminants are removed when stream water interacts with the stream sediments in the hyporheic zone, that is the portion of sediments immediately beneath the stream. The present study investigates how to enhance this interaction using in-stream structures (i.e., vertical steps) and modifying the permeability of the stream sediments around the structures. This study examined a combination of surface structures (steps) and subsurface structures (high-permeability regions and low-permeability blocks) to alter the sediment permeability around the step. The results indicated that placing blocks in the subsurface upstream and downstream of the step had no effect on the magnitude of hyporheic flow or residence time distribution. However, when sediments are modified through the inclusion of a region with high permeability, remarkable changes in hyporheic exchange, including an increase in hyporheic flow magnitude and a decrease in residence time. The results show that sediment modification can effectively increase the interactions between stream water and sediments, and thus it may favor the attenuation of contamination.

1. Introduction

The subsurface volume directly below the river, where downwelling surface water mixes with upwelling subsurface water, is called the hyporheic zone (Triska et al., 1989). In this zone, biogeochemical reactions can affect nutrient availability for stream ecosystems (Brunke & Gonser, 1997; Dahm et al., 1998; Duff & Triska, 2000; Jones & Mulholland, 2000; Lautz & Fanelli, 2008). Hyporheic exchange is often defined as flow that begins in surface water, is driven into the streambed for a variable time, and then returns to surface water (Riedel et al., 2022). This exchange causes the attenuation of certain pollutants such as nutrients or organic contaminants (Zarnetske et al., 2011). Hyporheic flows may be driven by several factors, including variations in hydraulic head over the streambed, in permeability of the porous medium, and in sediment layer thickness (Tonina & Buffington, 2009a, 2009b; Vaux, 1968). The combination of these factors control the characteristics of hyporheic

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flow and of the Residence Time Distributions (RTDs). Natural river morphologies such as meanders and bed-forms (e.g., riffles, pool-riffle sequences, dunes, and alternating bars) result in hyporheic flow, but river restoration can also be a chance to recover or enhance hyporheic flow (Bakke et al., 2020). The comparison between an in-stream structure (cross-vane) and a natural feature (riffle) showed that hyporheic flow paths networks are different in two cases. Also, flow paths induced by cross-vane are spatially larger and temporally longer than riffle (Smidt et al., 2015). Therefore, restoration structures may be able to high hyporheic flow and sufficient residence time to reach to ecological functions as natural features.

Artificial structures that can cause hyporheic flow include those that create a hydraulic gradient between surface water and groundwater and those that increase substrate heterogeneity. Structures that create a hydraulic gradient by inducing a backwater behind a channel obstruction or by altering the profile of the water surface include cross vanes, constructed riffles, steps, and weirs (Gordon et al., 2013; Hester & Gooseff, 2011; Zimmer & Lautz, 2015). Stream restoration projects are undertaken for a variety of reasons, including bank stabilization, fish passage, habitat improvement, riparian management, to control slope, to reduce streambank erosion, and to reduce stream energy; however, water quality improvement is one of the most commonly cited goals (Bernhardt et al., 2005; Rosgen, 2001a, 2001b; Wohl et al., 2015). Stream restoration structures such as debris dams, logs, and steps that enhance hyporheic flow can lead to improved water quality because pollutants are transformed or retained in the hyporheic zone (Daniluk et al., 2012; Endreny et al., 2011a, Endreny et al., 2011b; Hester et al., 2016; Kaushal et al., 2008; Zhou & Endreny, 2013).

Restoration structures that have been used so far to create hyporheic flow include surface or in-stream structures, and subsurface (or buried) structures that modify the permeability of the streambed. In-stream structures are more effective in enhancing hyporheic flow when sediment permeability is high (Hassan et al., 2015; Kasahara & Hill, 2006; Menichino & Hester, 2014). Subsurface structures are blocks of porous medium with altered permeability that promote hyporheic flow and reactions, and their application has been proposed in modeling studies (Herzog et al., 2016, 2018; Hester et al., 2018; Vaux, 1968; Ward et al., 2011). These structures may in some cases be easier to deploy than in-stream structures because they are less likely to affect the morphology of the river. In addition, these structures have a lower impact on the thermal conditions of the river because they avoid the formation of pools that can have higher temperatures (Hester et al., 2009; Ward et al., 2011). Few studies have considered changes in riverbed permeability as the sole driver of exchange between surface water and the substrate (Herzog et al., 2016, 2018; Hester et al., 2018; Vaux, 1968; Ward et al., 2011). The characteristics of subsurface structures that affect hyporheic flow include the dimensions of the structure and the contrast in permeability between the structure and surrounding streambed sediments (Herzog et al., 2016; Ward et al., 2011). The concept of permeability modification was expressed for the first time by Vaux (1968) who investigated the exchange induced by creating adjacent regions of high and low permeability. The effectiveness of subsurface structures relies on modifications of streambed permeability, which is a primary controlling factor for hyporheic exchange (Ward et al., 2011).

The modification of permeability, or streambed engineering, around in-stream structures to improve water quality can be considered a field in its infancy (Bakke et al., 2020; Hester et al., 2018). Even though it is not difficult to qualitatively predict the effects of these modifications (e.g., higher permeability resulting in more intense hyporheic exchange, faster seepage velocities and shorter residence times), it is not trivial to prove a quantitative assessment of these effects. Moreover, there is a lack of knowledge about how to implement these permeability modifications in practice (e.g., how much streambed volume can be altered and in which locations), and this type of information would be helpful to foster the application of this technique. This study investigated the effect of modifications of permeability around steps as an in-stream structures. To achieve this purpose, the study carried out several numerical simulations of hyporheic exchange with modifications of streambed permeability around a step. The presence of blocks with different permeability was considered, and the effects of their size, location, and contrast in permeability were explored. Flow-3D and COMSOL were used to simulate surface flow and hyporheic flow exchange, respectively. The results provide new insights on a novel approach to improve hyporheic exchange in river ecosystems.

2. Material and Methods

2.1. Surface Flow Modeling

For surface flow modeling, a 2D model was built using the Flow 3D software to simulate the flow surface profile in a small stream. Numerical simulations were performed for surface flow in a 2D vertical plane. Each simulation included a computational domain with a 2 m length, except for two simulations in which the domain sizes were 4 times and 8 times larger (as explained below). The simulations were performed using a uniform mesh with a cell size of 5 mm. In the considered setting, hyporheic exchange was expected to be mainly controlled by step height and by spatial variations in permeability, while the specific value of stream depth is less relevant. Hence, a constant stream depth of 2 cm above the streambed was used for the upstream and downstream boundary conditions (see also Tajari et al., 2023). The average velocity of surface flow was set to 0.18 m/s, leading to a Froude number equal to 0.40. The reader is referred to Text S1 in Supporting Information S1 for further simulations on the negligible role of stream depth on the results.

The bottom of the surface water domain (i.e., the streambed surface) was specified as a no-flow boundary. The slope of the substrate was set to zero to limit the overall number of domain configurations. This choice is acceptable because the shape of the surface water profile is mainly controlled by the step height for mild slopes of the streambed. The depth of the substrate was consequently different upstream (42 cm) and downstream (37 cm) of the steps. For simulating surface flow, the software applies the continuity equation:

$$V_F \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u A_x) + \frac{\partial}{\partial y}(\rho v A_y) = 0 \quad (1)$$

where V_F is the fractional volume open to flow, ρ is the fluid density, and (u, v) are the velocity components in the longitudinal (x) and vertical (y) directions, respectively. A_x and A_y are the fractional area open to flow in the x and y directions, respectively (Flow 3D manual). For the momentum equations:

$$\frac{\partial u}{\partial t} + \frac{1}{V_F} \left\{ u A_x \frac{\partial u}{\partial x} + v A_y \frac{\partial u}{\partial y} \right\} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + G_x + f_x \quad (2)$$

$$\frac{\partial v}{\partial t} + \frac{1}{V_F} \left\{ u A_x \frac{\partial v}{\partial x} + v A_y \frac{\partial v}{\partial y} \right\} = -\frac{1}{\rho} \left(\frac{\partial p}{\partial y} \right) + G_y + f_y \quad (3)$$

In these equations (G_x, G_y) are body accelerations (f_x, f_y) are viscous accelerations in the x and y directions, respectively (FLOW-3D Documentation, (2012)). The body accelerations G_x and G_y represent the components of the gravitational acceleration. In this study, the slope was considered negligible for the sake of simplicity and consequently G_x was set to zero and G_y was assigned the gravitational acceleration value (-9.81 m/s^2) in the downward vertical direction. The viscous accelerations f_x and f_y include the contributions of both viscous stresses and Reynolds stresses, and the latter were computed using the Renormalized Group (RNG) $k-\epsilon$ model (Yakhot & Orszag, 1986; Yakhot & Smith, 1992) that improves the estimate of Reynolds stresses in flow fields with high shear rates, as in the case of nappe falling from the step.

2.2. Subsurface Flow Modeling

For subsurface flow modeling, a 2D model was built using COMSOL Multi-physics. A total of 19 simulations were performed on a domain with a length of 2 m (see Section 2.1). The simulated domain is shown in Figure 1, and the sediment properties are summarized in Table 1. The domain represents a vertical step surrounded by an artificial high-permeability (Hk) region—typically composed of a mixture of coarse gravel and cobbles—within an undisturbed alluvial streambed. The Forchheimer equation was adopted because the expected values of pore Reynolds number can be higher than unity for high values of permeability (see Text S2 in Supporting Information S1 for further discussion on the differences between Darcy's and Forchheimer's approaches on the simulated hyporheic exchange). For all simulations, boundaries were defined as no-flow boundaries, except for the streambed surface. For this boundary, values of hydraulic head were derived from the surface flow model.

To investigate the effect of the modifications of permeability of streambed around steps on hyporheic flow, four sets of simulations were run to test the effect of:

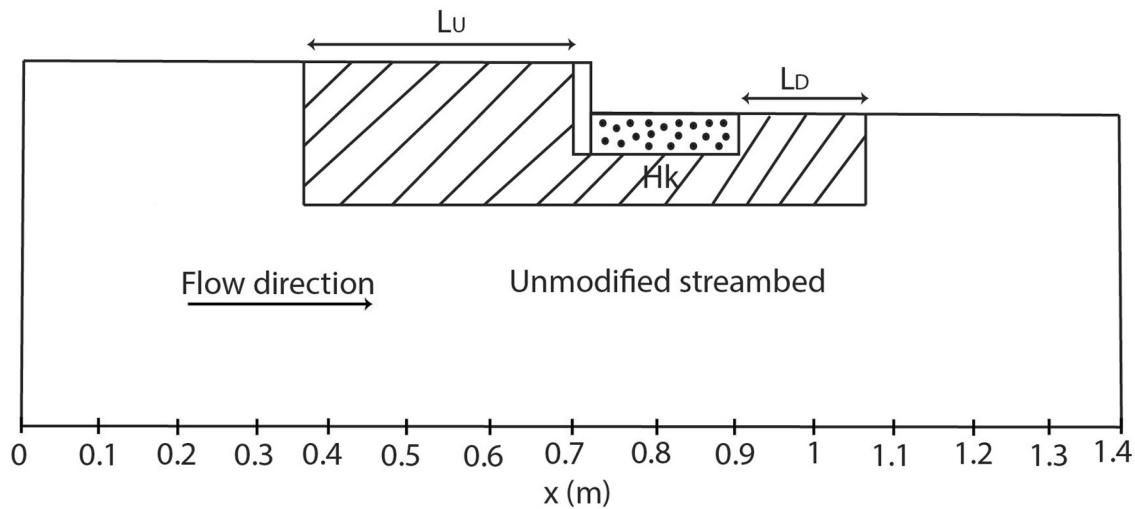


Figure 1. Size of the high-permeability region (Hk) that are modified in the simulations in Table 2. The striped and the dotted patterns denote the high-permeability region and the low-permeability blocks (Lk), respectively.

1. changing the lengths (L_U and L_D) of the high-permeability (Hk) region (Table 2, Figure 1), with the aim of quantifying the incremental benefits of creating wider high-permeability regions compared to more compact ones;
2. changing the location and number of low-permeability (Lk) blocks (Table 3, Figure 2). The deployment of low-permeability blocks was tested to verify the possibility of enhancing hyporheic exchange through the presence of spatial variations in permeability (Tonina & Buffington, 2009b). We considered four possible locations for the low-permeability blocks. Specifically, two blocks (1 and 4, see Figure 2) were considered at the upstream and downstream end of the high-permeability region, respectively, and two other blocks (2 and 3, Figure 2) were placed directly upstream and downstream of the step;
3. dividing the high-permeability region in different parts (Table 4, Figure 3) with high but slightly different permeabilities (H_k and H_k' ; values in Table 1). These simulations were performed to test the effect of more complex geometries of the high-permeability region and to understand the impact of possible loss of permeability (e.g., due to filtration of fine particles; Fox et al., 2018) in the modified streambed material. First, we considered two end-member cases with different permeabilities for the high-permeability region (U3D1 and U3D1-Hk4; Table 4). Then we divided the high-permeability region in five blocks (5–9; Figure 3) which were assigned two high but different values of permeability (H_k and H_k' ; values in Table 1) (Table 4; Figure 3);
4. changing the size of the system, with two simulations (U3D1x4, U3D1x8) in which all sizes were increased by 4 and 8 times compared to a reference case (U3D1 in Table 2).

In addition, a simulation (case S) that considered the case of a step with undisturbed sediments was performed to allow for a comparison of the effectiveness of the modifications of sediment permeability. Values of porosity (n), permeability (k), Forchheimer coefficients (β) and D_{50} (mm) for the different parts of the streambed domain are listed in Table 1.

Table 1
Sediment Characteristics

	n	k (m^2)	β (kg/m^4)	D_{50} (mm)
Hk region	0.45	10^{-8}	10^7	2.4
Lk blocks	0.1	10^{-14}	9×10^{10}	0.04
Undisturbed sediments	0.4	10^{-10}	10^8	0.3
Hk' blocks	0.42	10^{-9}	2×10^7	2

After the simulated flow in the surface domain had stabilized, the results of the total hydraulic head along the streambed were converted to dynamic pressure and then imported into the COMSOL model of subsurface flow. We modeled flow in the porous substrate with the Forchheimer equation. This equation is needed when flow in the substrate can be non-Darcian, which corresponds to values of pore Reynolds number ($\frac{V_{pore} D_{50}}{\nu}$) close to or higher than unity (e.g., >0.7–2.3; Kececioglu & Jiang, 1994), where V_{pore} is the magnitude of pore water velocity (m/s), D_{50} is the average equivalent spherical diameter of the particles of the porous medium (m), and ν is the kinematic viscosity of water (m^2/s):

Table 2

List of Simulations With Changes in the Length of the High Permeability Region (Hk); U and D Denote the Length of High-Permeability Region Upstream and Downstream of the Step, Respectively (LU and LD, See Figure 1)

Simulation	Downstream length of the Hk region (m)	Upstream length of the Hk region (m)
U1D1	0.1	0.1
U3D1	0.1	0.3
U5D1	0.1	0.5
U7D1	0.1	0.7
U1D3	0.3	0.1
U1D5	0.5	0.1
U1D7	0.7	0.1

$$-\nabla p = A|u_{\text{bulk}}|\mu \frac{(1-n)^2}{n^3} + B|u_{\text{bulk}}|^2 \rho \frac{(1-n)}{n^3} \quad (4)$$

where u_{bulk} is the apparent bulk velocity (i.e., the volume flux of fluid through the unit area of the material, m/s), ∇p is the pressure gradient in real space within the porous material, n is porosity, and

$$A = \frac{\alpha}{D_{50}^2} \quad B = \frac{\beta}{D_{50}} \quad (5)$$

where α is a constant, typically around 180, β is a roughness factor typically ranging between 1.8 and 4.0 (representing smooth particles through rough fibers) (COMSOL, Inc. (2008)). The pore Reynolds number was later calculated and found to reach values higher than one, confirming the need to apply the Forchheimer approach for a more accurate representation of the flow field. More details are reported by Tajari et al. (2023).

After the flow field was obtained, the Residence Time Distributions (RTDs) were also simulated for each considered case, as in Tajari et al. (2023). First, a unit concentration of a conservative tracer was imposed on the downwelling area and its subsequent transport into the streambed was modeled with an advection-dispersion equation. Then, the total upwelling flux of solute through the streambed boundary at a given instant was calculated by spatially integrating over the streambed length the local upwelling flux of solute at the same instant. RTDs were then obtained by normalizing this total upwelling flux with the value of total downwelling solute flux into the streambed. This approach allows the consideration of the contributions of advective and dispersive transport processes in the hyporheic zone. Finally, hyporheic flow per unit stream width was calculated by integrating the values of downwelling velocity into the streambed along the streambed boundary.

3. Results

This section will first present results about the flow field (Section 3.1) and the vertical exchange velocity (Section 3.2), followed by those about hyporheic flow (Section 3.3) and RTDs (Section 3.4).

Table 3

List of Simulations With Changes in the Location and Number of Low-Permeability Blocks (Lk) for Case U3D1

	Location of Lk blocks	Number of Lk blocks
U3D1	3	1
U3D1-Lk1	1,3,4	3
U3D1-Lk2	2,3	2

Note. Numbers of block locations are displayed in Figure 2. When a Lk block is not present, the location is treated as high-permeability region and sediment bed respective for block 2 and blocks 1 and 4.

3.1. Flow Field

Some examples of flow fields are presented in Figure 4 to visualize the patterns of streamlines around a step without (case U3D1) and with the presence of low-permeability blocks (U3D1-Lk1 and U3D1-Lk2) upstream and downstream of the step. For case U3D1, streamlines tend to concentrate within the high-permeability region and form a hyporheic flow cell that surrounds the step. In case U3D1-Lk1, two low-permeability blocks were added at locations 1 and 4 (see Figure 2), and even if streamlines near the low-permeability blocks are slightly deflected the shape of the flow cell does not change significantly. For U3D1-Lk2, the hyporheic flow cell

Table 4
List of Simulations With Different Values of Permeability Within the High-Permeability Region for Case U3D1

	Location of Hk region	Location of Hk' block
U3D1	5,6,7,8,9	–
U3D1-Hk1	5,6,8,9	7
U3D1-Hk2	5,9	6,7,8
U3D1-Hk3	5,7,9	6,8
U3D1-Hk4	–	5,6,7,8,9

Note. Values of high (Hk) and moderately high (Hk') permeability are listed in Table 1. Numbers of block locations are displayed in Figure 3.

becomes longer as the presence of the low-permeability block 2 (see Figure 2) causes streamlines to migrate upstream from the step.

3.2. Vertical Velocity Profiles

Vertical velocities at the streambed surface, which denote the local intensity of water exchange, are presented for the cases described in Section 2.

3.2.1. Effect of the Increase in Permeability

The results of the cases S (no permeability modification) and U1D1 are compared in Figure 5a to understand the general characteristics for the vertical velocity distribution over a step with and without improvement of permeability around the step. For case S, in the region upstream of the step, velocities are negative and almost zero. The vertical velocity profile downstream of the step

is divided in two parts (Figure 5a): first, a small area with a sequence of downwelling and upwelling flow (negative and positive velocities, respectively) under the waterfall immediately after the step; then, vertical velocities are positive and lower in magnitude. By modifying the permeability around the step (case U1D1), the values of vertical velocities become larger compared to case S. Velocities are highest in location of the high-permeability regions, while in other points velocities are negligible. These values and patterns are almost symmetrical because of the same symmetry of the high-permeability region (see Figure 2).

3.2.2. Effect of the Length of the High-Permeability Region Upstream of the Step

In the region upstream of the step, the extent of the downwelling area, characterized by negative values of vertical exchange velocity, is enhanced by the increment of the length of the high-permeability region (Figure 5b) which also decreases the values of vertical velocity as hyporheic exchange is distributed over a longer span. Downstream of the step, the spatial patterns of vertical velocity are almost the same because the length of the high-permeability region is constant for all cases, even though the magnitude changes due to variations in the total exchange flux (see also Section 3.3.2). The comparison of the simulations shown in Figure 5b illustrates the interactions between the lengths of influence of the flow fields that are separately induced by the high-permeability region and the step (Herzog et al., 2023): when the length of the Hk region is higher it exerts a minor influence on the downwelling velocities near the step that is similar for cases U7D1 and U5D1. On the other hand, in case U1D1 the downwelling velocities driven by the high-permeability region overlap with the one induced by the step, enhancing the downwelling close to the step and leading to a bimodal pattern in the exchange velocity between $x = 0.6$ and 0.7 m.

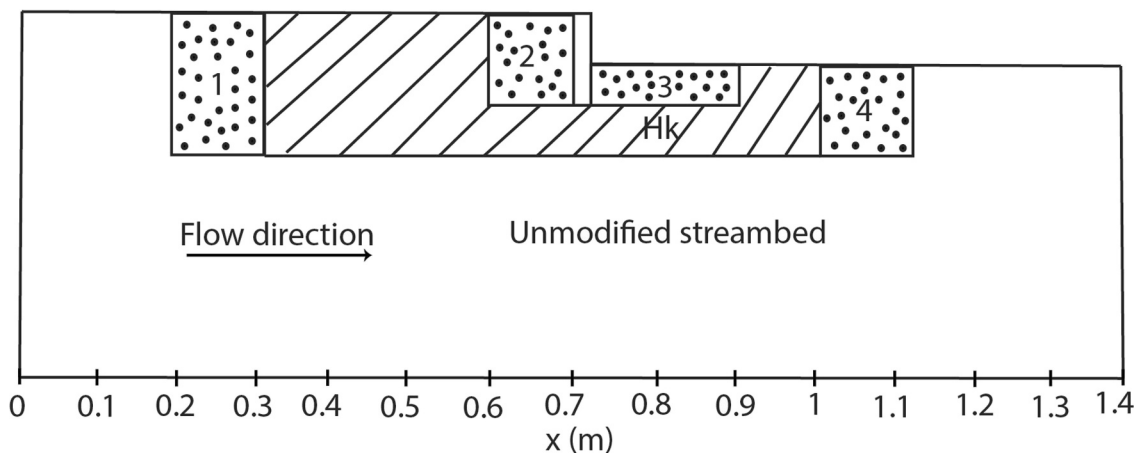


Figure 2. Locations of the low-permeability blocks (Lk) that are modified in the simulations in Table 3. The striped and the dotted patterns denote the high-permeability region (Hk) and the low-permeability blocks, respectively.

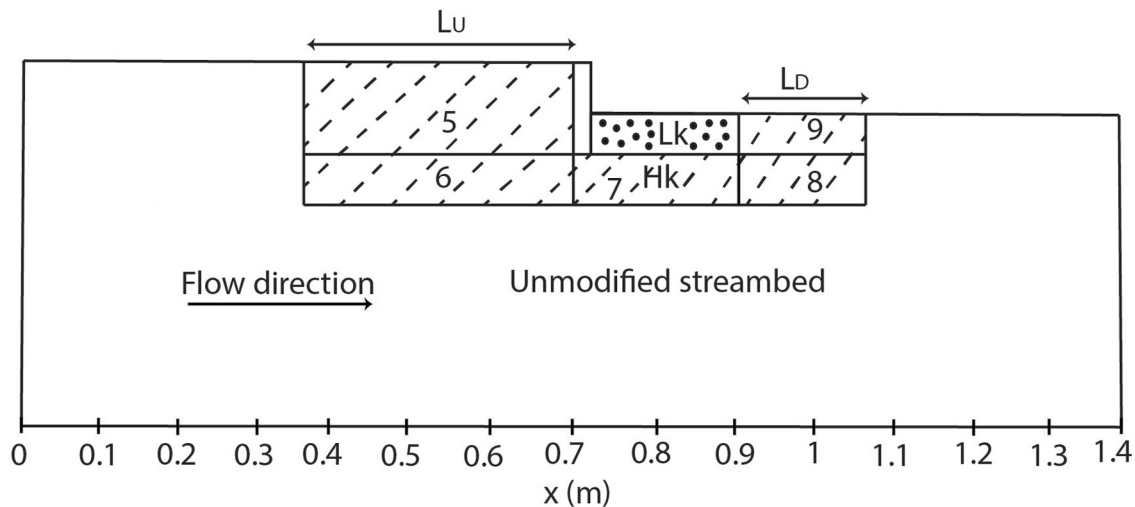


Figure 3. Locations of the parts of the high-permeability region (Hk) that are assigned a moderately high-permeability (Hk', Table 1) in the simulations in Table 4. The striped and the dotted patterns denote the high-permeability region and the low-permeability block (Lk), respectively.

3.2.3. Effect of the Length of the High-Permeability Region Downstream of the Step

Upstream of the step, the values of vertical velocity are almost the same for cases U1D1 to U1D7 because the length of the high-permeability region is constant for all cases. In the region downstream of the step, the extent of the positive velocity area is enhanced by the longer high-permeability region (Figure 5c) which also decreases the values of vertical velocity, as hyporheic exchange occurs over a longer region similarly to the behavior discussed in Section 3.2.2. The comparison between Figures 5c and 5b indicates that a change in the downstream length of the high-permeability region has a lower effect on the extension of the upwelling area compared to the impact of the upstream length of the high-permeability region on the downwelling area.

3.2.4. Effect of the Position of the Low-Permeability Blocks

Cases U3D1 and U3D1-Lk1 were compared in Figure 5d to investigate the effect on the flow field of the presence of low-permeability blocks 1 and 4 at the sides of the high-permeability region (see Figure 2). The comparison indicates a very similar behavior for both cases: downwelling flow occurs at the streambed boundary near the beginning of the high-permeability area. This downwelling pattern continues up to the location of the step ($x = 0.7$ m). In the range $0.72 \text{ m} < x < 0.92 \text{ m}$, where the permeability is lower, the values of vertical velocity are close to zero because hyporheic flow is mostly concentrated in the high-permeability region. Between 0.92 and 1.02 m, the presence of the high-permeability area causes vertical velocity to become positive (Figure 5d) and forces upwelling flow.

In case U3D1-Lk2 (which is similar to U3D1 except for the presence of low-permeability block 2 at the upstream side of the step; Figure 2) the high-permeability area extends from $x = 0.3 \text{ m}$ to $x = 0.6 \text{ m}$, and so downwelling flow occurs in this zone (Figure 5d). The values of vertical velocity are negligible from 0.6 to 0.92 m, which indicates horizontal flow in sediments within this region. Between $x = 0.92 \text{ m}$ to $x = 1.02 \text{ m}$ the flow field is again upward, and the vertical velocity is positive but with lower values compared to cases U3D1 and U3D1-Lk1. Therefore, for case U3D1-Lk2 the presence of the low-permeability block close to the step (location 2 in see Figure 2) decreases the overall exchange flow (see Section 3.3.3 below) due to the longer travel distance that the streamlines have to follow between the downwelling and the upwelling zone.

3.2.5. Effect of the Permeability Structure of the High-Permeability Region

Vertical velocities for case U3D1-Hk1, in which the high-permeability region is characterized by the presence of a slightly less permeable Hk' block below the step (Table 4, Figure 3), are shown in Figure 5e. For this case, values of vertical velocities are negative between $x = 0.4 \text{ m}$ and $x = 0.65 \text{ m}$ but they become positive from $x = 0.65 \text{ m}$ to $x = 0.7 \text{ m}$, denoting the presence of an area of upwelling flow before the step. In the area downstream of the step,

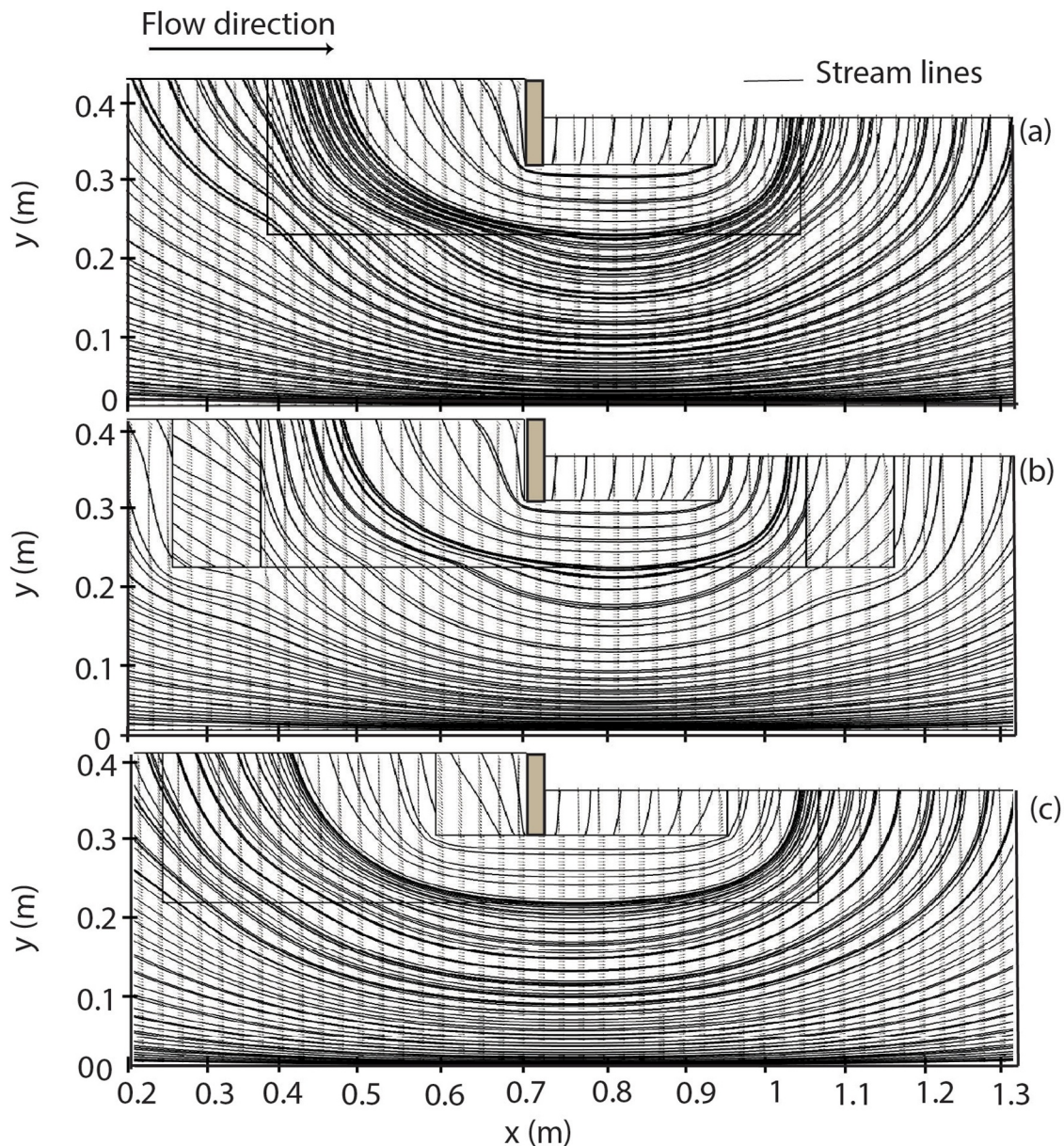


Figure 4. Flow fields for different positions of the low-permeability blocks (Lk) around the high-permeability region (Hk): (a) U3D1, (b) U3D1-Lk1, (c) U3D1-Lk2.

the positive values of vertical velocities are smaller than for case U3D1. Therefore, the slightly lower permeability of the Hk' region below the step (position 3 in Figure 3) decreases the overall exchange flow and favors upwelling upstream of the step.

The values of vertical velocity of case U3D1-Hk2 are almost the same as those of case U3D1-Hk1, although slightly smaller due to the slight reduction in average permeability over the whole length of the high-permeability region (Table 4, Figure 3). For case U3D1-Hk3, the values of vertical velocities are closer to those of U3D1 compared to the other simulations (Figure 5e). Also, all values of vertical velocities upstream of the step are negative, that is, no upwelling is found upstream of the step. Case U3D1-Hk4, in which the high-permeability region has the lowest permeability (Table 4, Figure 3), has the lowest velocities among the considered simulations, and the values of the velocity upstream of the step are always negative as for case U3D1. The comparison among the simulations in Figure 5e hence suggests that the presence of a Hk' region with lower permeability

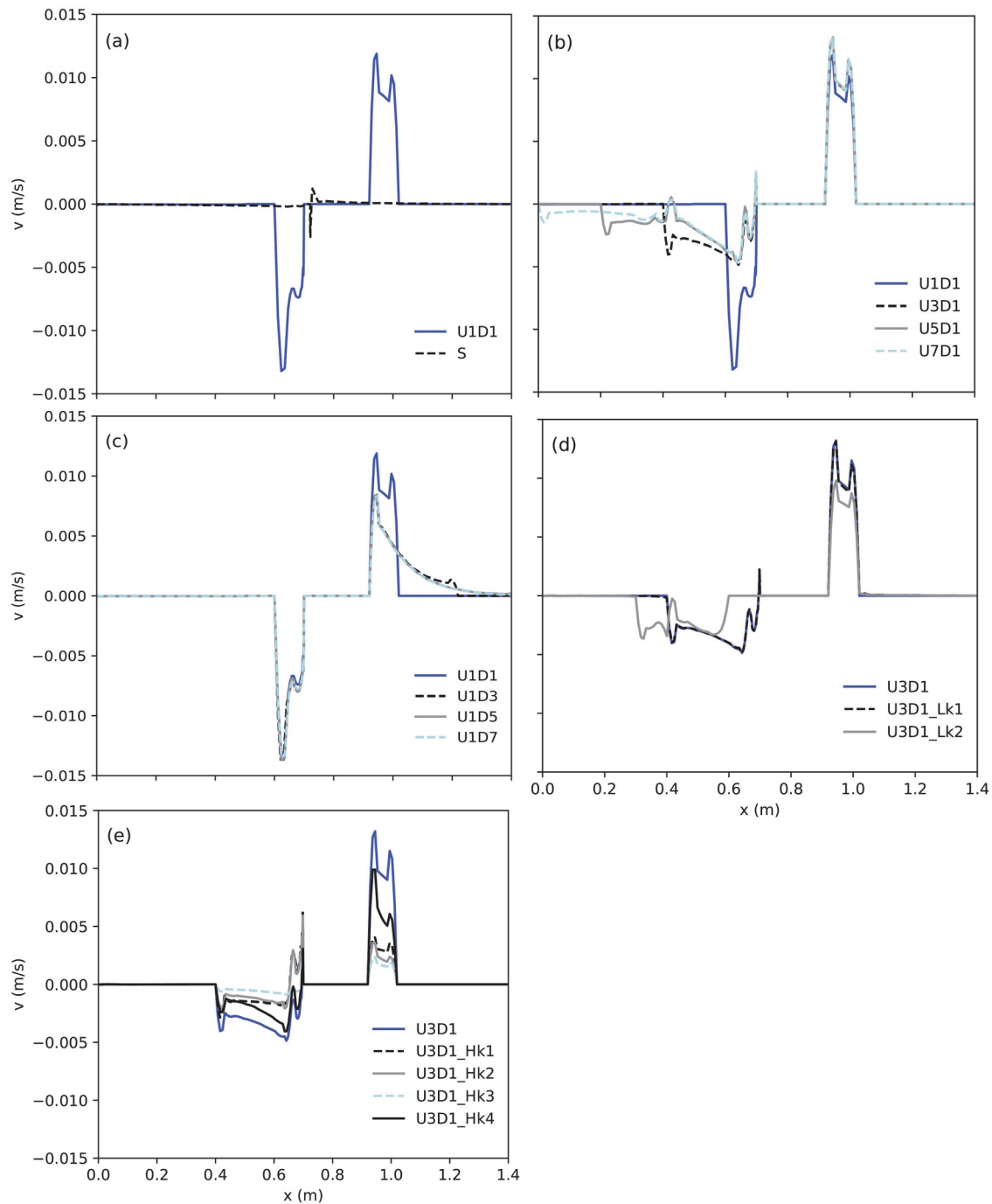


Figure 5. Vertical velocity profiles, negative velocities are downwelling flows and positive velocities are upwelling flows: (a) of cases S and U1D1, (b) for different lengths of the upstream high-permeability region (U1D1 to U7D1), (c) for different lengths of the downstream high-permeability region (U1D1 to U1D7), (d) for different positions of the low-permeability blocks, (e) for different permeabilities of the high-permeability region.

below the step can limit the connectivity among the downwelling and upwelling regions (cases U3D1-Hk1 and U3D1-Hk2; Hk' block 3 in Figure 3) and results in lower values of vertical exchange velocities.

Finally, it is interesting to note that the downwelling velocities in U3D1-Hk3 are greater than those in U3D1-Hk1. This difference arises because in U3D1-Hk3 numerous flow paths intersect only the corners of blocks 6 and 8 (see

Figure 3), focusing the flow outside of the Hk' blocks. Conversely, in U3D1-Hk1 many flow paths traverse the entire Hk' block 7 (see Figure 3), resulting in prolonged interaction with the Hk' regions.

3.3. Hyporheic Flow

3.3.1. Effect of the Increase in Permeability

Without modifications of permeability due to high-permeability structures (case *S*) the value of hyporheic flow per unit stream width induced by the step is $0.2 \text{ m}^2/\text{hr}$, while it is $3.07 \text{ m}^2/\text{hr}$ for case U1D1 (i.e., 15 times larger). Thus, the modification of permeability around the step is very effective in increasing hyporheic flow (Figure 6a).

3.3.2. Effect of the Length of the High-Permeability Region

Increasing the length of the upstream high-permeability region does not affect hyporheic flow, except for the change from 0.1 m (case U1D1) to 0.3 m (case U3D1) which slightly increases hyporheic flow from $3.07 \text{ m}^2/\text{hr}$ to $3.43 \text{ m}^2/\text{hr}$ (Figure 6a). For further increases from 0.3 to 0.7 m (cases U3D1, U5D1, U7D1) the value of the hyporheic flow is almost constant (Figure 6a). A similar pattern is found when the length of the high-permeability region downstream of the step is changed, with a constant value of hyporheic flow ($3.21 \text{ m}^2/\text{hr}$) when this length is equal or higher than 0.3 m (cases U1D3, U1D5, U1D7; Figure 6b).

3.3.3. Effect of the Positions of the Low-Permeability Blocks

Figure 6c shows that the values of hyporheic flow of cases U3D1 and U3D1-Lk1 are the same ($3.43 \text{ m}^2/\text{hr}$). Therefore, the presence of low-permeability blocks 1 and 4 has no effect on hyporheic flow. This is consistent with the results on the RTDs in Section 3.4.3, which demonstrated that the residence times of these cases are the same. Instead, a lower value ($2.68 \text{ m}^2/\text{hr}$) is found for case U3D1-Lk2. This finding reflects the behavior presented in Section 3.2.3, where the presence of the low-permeability block upstream of the step (location 2 in Figure 2) reduced the magnitude of vertical velocity.

3.3.4. Effect of the Permeability Structure of the High-Permeability Region

As displayed in Figure 6d, values of hyporheic flow for cases U3D1-Hk1 and U3D1-Hk2 (1.07 and $0.84 \text{ m}^2/\text{hr}$, respectively) are lower than for case U3D1 ($3.43 \text{ m}^2/\text{hr}$). This is coherent with the results about the velocity profile (Section 3.2.4), because the lower vertical velocities imply less water exchange into the substrate, and so the value of hyporheic flow decreases. Case U3D1 has the highest hyporheic flow ($3.43 \text{ m}^2/\text{hr}$) because it has the highest permeability in the high-permeability region. On the other hand, case U3D1-Hk4 has the lowest hyporheic flow ($0.63 \text{ m}^2/\text{hr}$) because of its slightly lower permeability (see Table 1). Finally, case U3D1-Hk3 has the second highest value of hyporheic flow, in agreement with the findings of vertical velocities and RTDs discussed in the previous sections.

3.3.5. Effect of System Size

When the size of case U3D1 is increased by 4 and 8 times, the hyporheic flow becomes 4.3 (case U3D1x4; $15 \text{ m}^2/\text{hr}$) and 8.6 times larger (case U3D1x8; $30 \text{ m}^2/\text{hr}$), respectively (Figure 6e). These results indicate that hyporheic flow scales almost linearly with system size. The absence of a perfect linear proportion is likely due by the nonlinearities in the Forchheimer equation whose importance becomes more significant at increasingly high values of the Reynolds number.

3.4. Residence Time Distributions

3.4.1. Effect of the Increase in Permeability

Figure 7a compares the RTDs for the cases of homogeneous (*S*) and heterogeneous sediments (U1D1). It is clear from the figure that the increase in permeability around the step with the presence of high-permeability region sharply decreases the residence times: the median residence time (RT_{50}) of the homogeneous case *S* ($1,200 \text{ s}$) is higher by two orders of magnitudes that RT_{50} of case U1D1 (26 s ; Figure 7a). This decrease of residence times reflects the increase in vertical velocities discussed in Section 3.2.1.

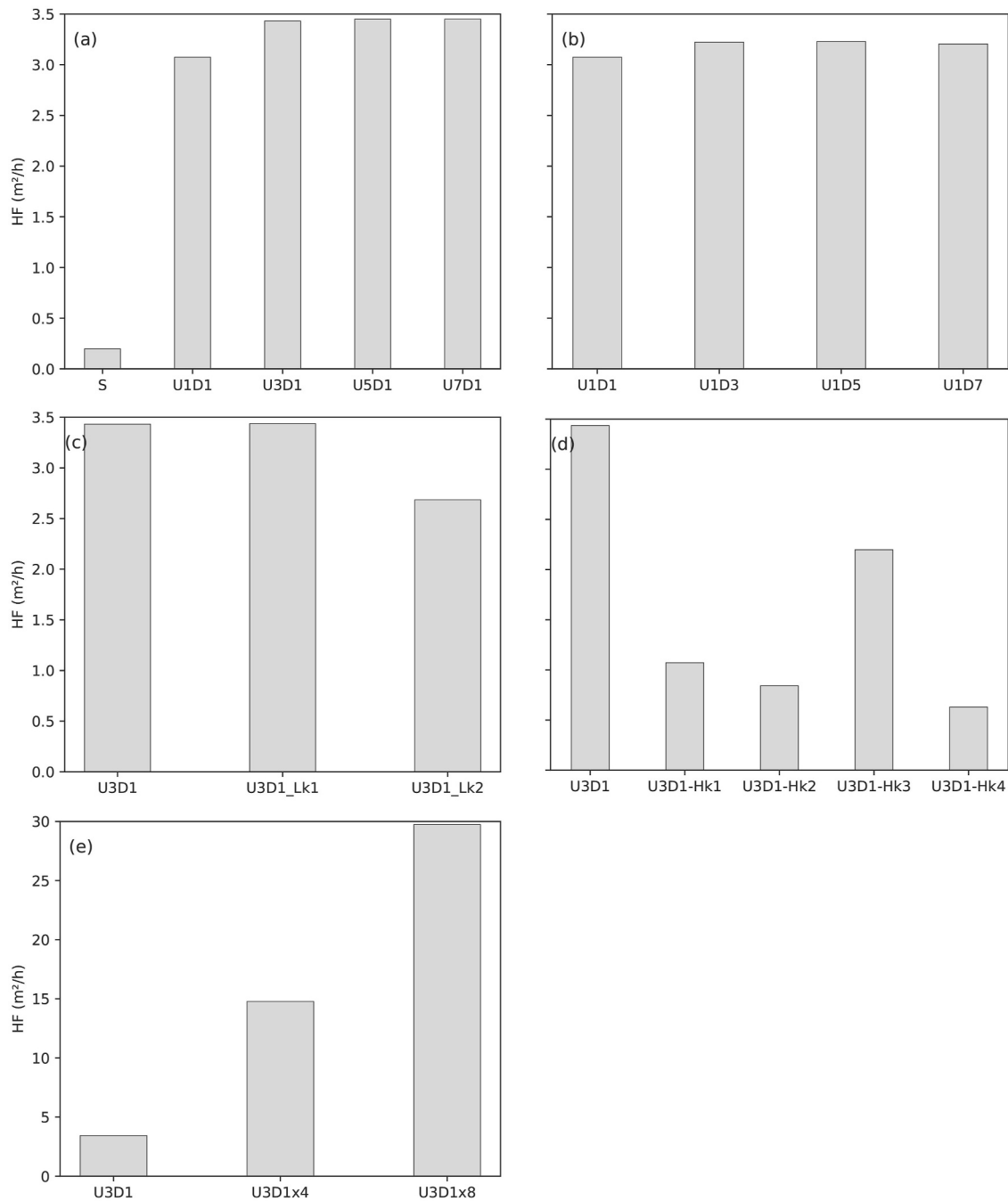


Figure 6. Values of hyporheic flow per unit stream width (a) for the undisturbed homogeneous sediments (case S) and the modified heterogeneous sediments with different upstream lengths of the high-permeability region (cases U1D1 to U7D1), (b) for different downstream lengths of the high-permeability region (cases U1D1 to U1D7), (c) for low-permeability blocks (cases U3D1, U3D1-Lk1 and U3D1-Lk2), (d) for different structures of the high-permeability region (cases U3D1, U3D1-Hk1 to U3D1-Hk4), (e) for different system sizes (cases U3D1, U3D1x4 and U3D1x8).

3.4.2. Effect of the Length of the High-Permeability Region

The RTDs for varying lengths of the high-permeability region upstream of the step are shown in Figure 7b (cases U1D1 to U7D1; Table 2). Increasing the length of this part of the Hk region enhances RT_{80} , which varies from 40 s for case U1D1 to 100 s for case U7D1. Instead, the RT_{50} increases when the length is increased from 0.1 m (U1D1) to 0.3 m (U3D1), but it is almost the same for the other cases. These results indicate that the longer

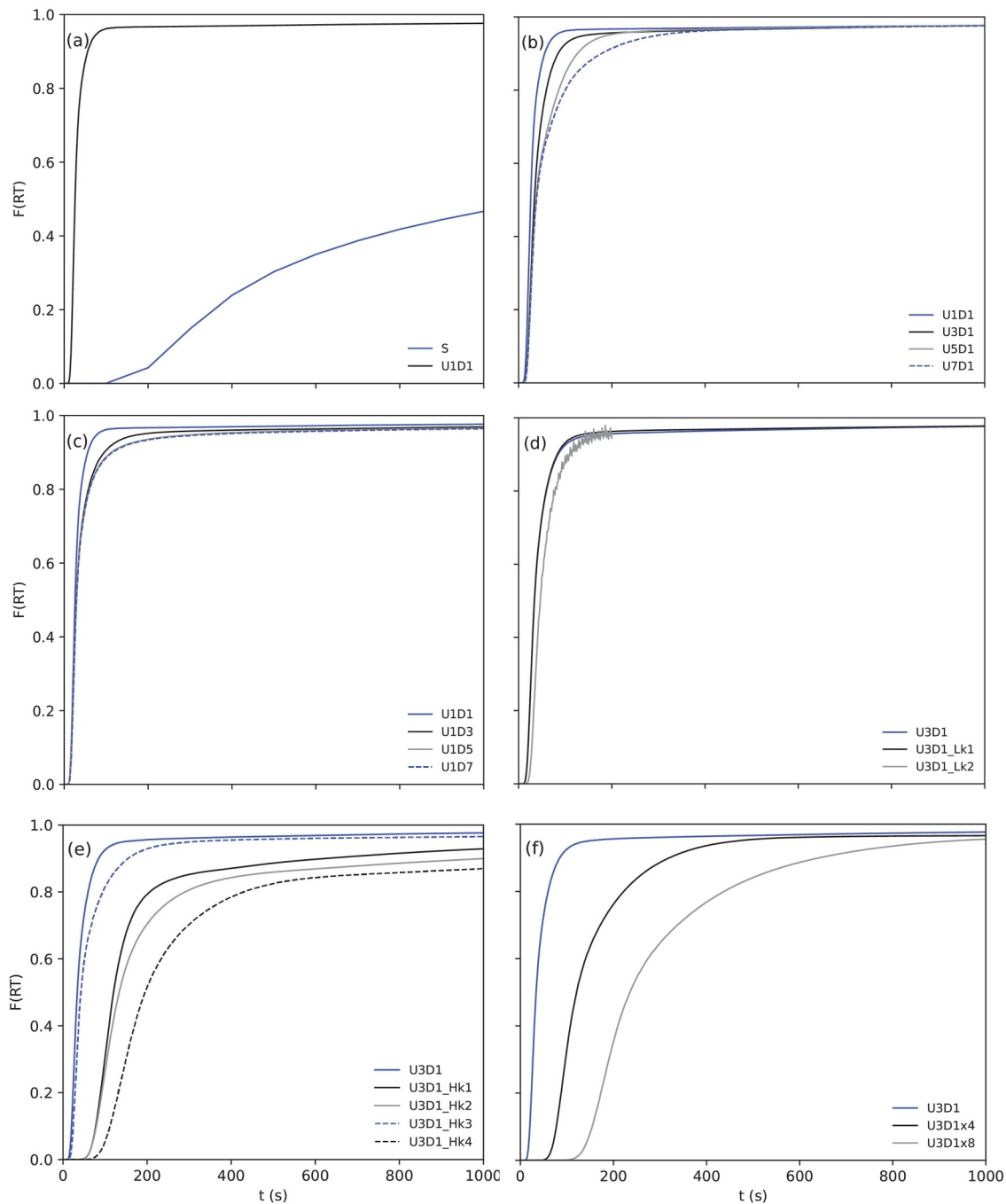


Figure 7. (a) RTDs for the undisturbed homogeneous sediments (case S) and the modified heterogeneous sediment (case U1D1), (b) RTDs for different upstream lengths of the high-permeability region (cases U1D1 to U7D1), (c) RTDs for different downstream lengths of the high-permeability region (cases U1D1 to U1D7), (d) RTDs for low-permeability blocks (cases U3D1, U3D1-Lk1, U3D1-Lk2), (e) RTDs for different structures of the high-permeability region (cases U3D1, U3D1-Hk1 to U3D1-Hk4), (f) RTDs for different system sizes (cases U3D1, U3D1x4 and U3D1x8).

residence times are much more sensitive to the length of the high-permeability region compared to the rest of the RTD.

The RTDs for cases U1D1 to U1D7, where the length of the high-permeability region downstream of the step is progressively increased, are presented in Figure 7c. The results show that increasing the downstream length of the high-permeability region has a very small influence on the RTDs, except for an increase of the longer residence

times from the case of U1D1 to case U1D3. Further increases of the downstream length of the high-permeability region result in marginal increments of the residence times.

3.4.3. Effect of the Positions of the Low-Permeability Blocks

The RTDs for cases U3D1, U3D1-Lk1 and U3D1-Lk2 are presented in Figure 7d to investigate the impact of the positions of the low-permeability blocks. Case U3D1 and U3D1-Lk1 are characterized by the same RTDs, so the removal of low-permeability blocks 1 and 4 (see Figure 2) does not influence the RTDs. For U3D1-Lk2, the addition of the low-permeability block in position 2 (upstream side of the step; see Figure 2) leads to an increase of the residence times. This increase is caused by the upstream shift of the downwelling region (Section 3.2.3, Figure 2d) that increases the length of streamlines. However, it is worth mentioning that the increase in residence times is also associated with a decrease in hyporheic flow (Figure 6c), which reflects a well-known tradeoff between hyporheic flow and residence times (e.g., Herzog et al., 2023).

3.4.4. Effect of the Permeability Structure of the High-Permeability Region

Comparing simulations U3D1 and U3D1-Hk4, for which the high-permeability region has a varying permeability, it is found that the RT_{50} of case U3D1 is 34 s while for case U3D1-Hk4 this value is 195 s (Figure 7e). Thus, by changing the permeability of the Hk region from 10^{-8} to 10^{-9} m², RT_{50} becomes almost 6 times larger. On the other hand, values of RT_{50} for cases U3D1-Hk1 and U3D1-Hk2 are almost the same (121 and 134 s, respectively). As mentioned in Section 3.2.4, these two cases also have similar values of vertical exchange velocity, and they are both characterized by the presence of a less permeable Hk' block below the step (position 3 in Figure 3). Instead, this Hk' block is absent in case U3D1-Hk3, and in this case the value of RT_{50} (43 s) is close to the value for case U3D1 (34 s). The differences between the RTDs of these cases are also small and mostly limited to the longest residence times, confirming the similarities between these cases discussed in Section 3.2.4.

3.4.5. Effect of System Size

The RTDs of case U3D1, U3D1x4, and U3D1x8 are compared in Figure 7f to assess the impact of the size of the system. As expected, the figure shows that the residence times increase for larger systems. Specifically, when the size of the system increases by 4 and 8 times the length of streamlines also increases and RT_{50} becomes 3.5 and 7 times larger, respectively. These values and the RTDs in Figure 3f indicate an approximately linear increase in residence time with system size.

4. Discussion and Conclusions

The first studies on hyporheic exchange induced by step structures considered uniform sediment permeability beneath steps (e.g., Endreny et al., 2011a, Endreny et al., 2011b; Hester & Doyle, 2008), and showed that higher values of permeability increased hyporheic flow while reducing residence times. Later, other studies tested the idea of creating a high-permeability region below these structures to increase hyporheic flow. For instance, Bakke et al. (2020) considered hyporheic exchange driven by a log, which behaves similarly to a step, and confirmed that introducing a region with higher permeability around the log enhances hyporheic flow. However, their study did not analyze the effect of this streambed modification on residence times. A recent study on homogeneous streambeds showed that steps drive longer residence times than subsurface structures (Tajari et al., 2023). Other studies have demonstrated that the modification of streambed hydraulic conductivity increases hyporheic flows and reduces mean residence times (Hester et al., 2018). The present study investigated the influence of the modification of hydraulic conductivity around the step on hyporheic exchange to quantify the benefits of coupling these structures with subsurface modifications. The comparison of the present results with those of Tajari et al. (2023) shows that the inclusion of a region with high hydraulic conductivity leads to a 17-fold increase in the value of hyporheic flow and an 85-fold decrease in RT_{50} . This comparison is in line with the differences observed in the current study between case S (uniform permeability) and case U3D1 (inclusion of a high-permeability region) and it exemplifies the impact that the increment of hydraulic conductivity can have on hyporheic exchange induced by the step as well as the tradeoff between increasing hyporheic flow and decreasing residence times. An increase in water exchange flux was also witnessed in the study by Bakke et al. (2020), who considered a similarly engineered streambed in restored urban stream. However, their study focused on a uniform high-permeability region, excluding spatial variations of permeability. On the other hand, a limitation of the

current study is that we considered neutral conditions, that is, no net upwelling of groundwater or downwelling of stream water except for the exchange caused by the step. Moreover, the present findings are valid for low-slope streams because of the assumption of a negligible slope, and results for steep streams may hence deviate from those of this study. Finally, because the kinetic energy of nappe falling from a step is not only influenced by step height but also by critical flow depth (Chanson, 1994), it should be noted that the results would be quantitatively influenced by variations in the hydraulic properties of the stream affecting the critical depth even though the overall framework would still qualitatively hold.

In terms of geometry of the areas with modified hydraulic conductivity, the main results of the present study can be grouped in three main parts: (a) effect of the length of the high-permeability region, (b) effect of the position of the low-permeability blocks and (c) effect of the permeability structure of the high-permeability region. These results are summarized below:

1. A longer high-permeability region results in smaller values of exchange velocity. Specifically, values of vertical velocity were higher when the length of the high-permeability region upstream of the step was 0.1 m compared to the cases of lengths of 0.3–0.7 m; however, the overall increase in hyporheic flow was marginal. Also, RT_{50} was slightly larger for lengths of 0.3–0.7 m compared to 0.1 m (+30–46%). Similar results were found when the length of the high-permeability region downstream of the step was modified, but the increase in hyporheic flow and residence times were even lower. The results indicated a moderate influence of the length of high-permeability region on hyporheic exchange and point out the importance of considering the trade-off between increased hyporheic flow and higher costs for replacing a larger volume of sediments.
2. The comparison of the cases U3D1 and U3D1-Lk1 allowed to understand the effect of the inclusion of low-permeability blocks around the high-permeability region on the velocity field, hyporheic flow, and RTDs. As the results of the two cases are very similar, the inclusion of low-permeability blocks would imply higher costs without relevant benefits and should thus be avoided. Despite an increase in residence times, the inclusion of a low-permeability block before the step is also not recommended because it was found to decrease the hyporheic flow. Our results on the increase in residence times agree with those of Herzog et al. (2023) who considered the presence of two vertical subsurface plates that affect subsurface flow in a similar manner to the low-permeability blocks. However, their simulations considered a submerged weir instead of a step and hence cannot fully be compared to those of the current study. Finally, it should be stressed that Ward et al. (2011) showed that the penetration depth of low-permeability elements should be a high fraction of total hyporheic depth to exert a significant influence on hyporheic exchange. In contrast, our findings indicated that high-permeability regions of moderate depth can strongly affect hyporheic exchange.
3. As expected, the increase in permeability due to the inclusion of the increase in residence times region enhances hyporheic flow but reduces residence times. Hence, to increase residence times, the reference case U3D1 is compared to different degrees of permeability modifications (cases U3D1-Hk1 to U3D1-Hk4). Case U3D1-Hk4 had the highest residence times among these cases but also the lowest hyporheic flow, while cases U3D1-Hk1 to U3D1-Hk3 fall between these two extremes. These results exemplify how much hyporheic flow and residence time change by modifying the spatial pattern of permeability around the step. Interestingly, a slight reduction in permeability below the step (location 7 in Figure 3; case U3D1-Hk1, Table 4) has a much stronger impact on hyporheic exchange compared to the same permeability reduction upstream and downstream of the step (locations 6,8 in Figure 3; case U3D1-Hk3, Table 4). This suggests that the possible accumulation of fine particles upstream of the step may not impair the enhancement of hyporheic exchange, and it also stresses the need to pay attention to the region below the step during the deployment of the permeability modification.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data generated in this study is available on Zenodo (<https://doi.org/10.5281/zenodo.17418030>).

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