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Impacts of Channel Morphodynamics on Fish Habitat Utilization

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Abstract

It is reasonable to expect that hydro-morphodynamic processes in fluvial systems can affect fish habitat availability, but the impacts of morphological changes in fluvial systems on fish habitat are not well studied. Herein we investigate the impact of morphological development of a cohesive meandering stream on the quality of fish habitat available for juvenile yellow perch (*Perca flavescens*) and white sucker (*Catostomus commersonii*). A three-dimensional (3D) morphodynamic model was first developed to simulate the hydro-morphodynamics of the study creek. The results of the morphodynamic model were then incorporated into a fish habitat availability assessment. The 3D hydro-morphodynamic model was successfully calibrated using an intensive acoustic Doppler current profiler (ADCP) spatial survey of the entire 3D velocity field and total station surveys of topographic changes in a meander bend in the study creek. Two fish sampling surveys were carried out at the beginning and the end of the study period to determine presence–absence of fish as an indicator of the habitat utilization of each fish species in the study reach. It was shown that morphological development of the stream was a significant factor for the observed changes in the habitat utilization of juvenile yellow perch. It is shown that juvenile yellow perch mostly utilized habitat where deposition occurred whereas they avoided areas of erosion. The results of this study and the proposed methodology could provide some insights into the potential impact of sediment transport processes on the fish occurrence, and distribution and has implications for management of small fluvial systems.

Keywords 3D morphodynamic modeling · Morphological changes · Fish habitat modeling · Fish habitat utilization · Yellow perch · White sucker

Introduction

Morphodynamic Modelling

Studies of the morphological behavior of fluvial systems are crucial for understanding the associated quality and availability of aquatic habitat. However, morphodynamic processes have been recognized as some of the least understood phenomena in natural fluvial systems (Wu 2007). Several morphodynamic models have been developed over the past decades in attempt to improve the understanding of fluvial system morphodynamics. Appropriate choice of the morphodynamic model depends on the condition and complexity of the study area (Papanicolaou et al. 2008). Until recently, the state-of-the-art for morphodynamic modeling involved one-dimensional (1D) or two-dimensional (2D) models (Pinto et al. 2012). However, direction and magnitude of bed shear stress, which has a significant influence on sediment transport, may not be accurately estimated from a 1D or a 2D model (Lesser et al. 2001). This could be the case in particular for meandering streams with dominant secondary flow structures, wherein secondary flow occurrence can increase the sidewall shear stress exerted on stream banks (Papanicolaou et al. 2007). Furthermore, due to the complex nature of cohesive sediments, prediction of the erosion and sedimentation patterns of a cohesive bed stream is even more challenging. Three-dimensional (3D) models are more capable of reproducing complex 3D stream hydro-morphodynamics processes compared to 1D and 2D models, and due to the advancement of computer technology, development of 3D hydro-morphodynamic models has

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become more common recently (e.g., Rüther and Olsen 2005; Khosronejad et al. 2007, 2015).

One of the widely used hydro-morphodynamic open source codes is Delft3D, which is developed by Deltares and has a broad range of applications in fluvial systems studies (e.g. Spruyt et al. 2011; Williams et al. 2013, 2016; Kasvi et al. 2015a, b). The morphological module of Delft3D has been validated by Lesser et al. (2004). This code can be further divided to hydrostatic and non-hydrostatic 3D modules. Parsapour-Moghaddam and Rennie (2017) showed that the hydrostatic module is able to predict the secondary flow in a sharply meandering creek. Despite the growing need for 3D morphodynamic modeling, only a few studies have employed Delft3D for 3D morphodynamic modeling in meandering streams. Students in Kleinhans's lab (Kleinhans et al. 2008; Schuurman et al. 2013; Schuurman and Kleinhans 2015) have employed Delft3D to create 3D models to predict morphodynamics of meandering and braided rivers. Their studies have mostly focused on bifurcation dynamics with non-cohesive sediments. Kasvi et al. (2015a) studied the sensitivity and functionality of 2D and 3D hydro-morphodynamic Delft3D models. Their results focused on a sandy bed river bend and were limited to short-term (one flood event) morphodynamic processes.

Fluvial System Morphodynamics and Fish Habitat

Dynamic interaction of the hydro-morphodynamic processes and the aquatic environment define a fluvial system's ecological characteristics (Poff and Zimmerman 2010). In order to improve the conditions of an aquatic ecosystem, it is essential to know how fish populations respond to ecological changes and how different fish species are linked to their habitats (Portt et al. 2006). Fluvial system hydro-morphodynamics influence the quality of habitat for fish and other aquatic species (Baranya et al. 2018; Tamminga and Eaton 2018). Suspended sediment transport can influence the water temperature and dissolved oxygen levels, and can lead to biological impacts on aquatic organisms (Kjelland et al. 2015). It is important to study the morphological changes in fluvial systems and the corresponding sediment loads to manage and preserve fish populations (Sullivan and Watzin 2010).

Numerical simulation of fish habitat has been employed since the 1980s as a useful means for fluvial system management and environmental impact assessment (Mouton et al. 2007). Fish habitat models can quantify a fluvial system's ecological condition. They can also be used to investigate the impact of different restoration plans and fluvial system management measurements (De Kerckhove et al. 2008). Several fish habitat models have been developed to predict the impact of ecological changes in fluvial systems on fish abundance and diversity. Such models can be employed to preserve an aquatic habitat or declining species (Tash and Litvaitis 2007).

There have been few previous attempts to couple morphodynamic model predictions with fish habitat modeling. Kerle et al. (2002) and Baptist et al. (2002) indicated that long-term morphodynamic changes in man-made secondary channels in the Rhine River could significantly affect the quality and availability of fish habitat. Baptist et al. (2002) used a 2D version of Delft3D to model the hydro-morphodynamics and the outputs were then fed into a fuzzy habitat model, CASiMiR. However, no fish sampling survey was conducted during their study so the fish habitat model could not be validated. Accordingly, the relationship between the morphodynamic changes and the availability of the fish habitat was not studied. Hauer et al. (2007) showed that riffle instability would negatively affect the reproduction of nase (*Chondrostoma nasus*), the main fish species in the Austrian lowland Sulm River. They suggested that morphological studies should be considered in river restoration projects. Hauer et al. (2008) subsequently studied how juvenile nase could be impacted by morphodynamic processes in the river. They combined the results of 1D and 2D hydrodynamic models with a fish habitat model. They obtained the sedimentation and erosion of the study river by terrestrial surveys within 3 years. They then conducted an electrofishing survey to study how the juvenile nase respond to the morphological changes. The results of this study confirmed the reduction in habitat suitability due to channel morphological changes; however, no morphodynamic simulation was employed. Moreover, the correlation of the sedimentation and erosion with the available fish habitat was not studied. Escobar-Arias and Pasternack (2010) assessed the functional flow based on the shear stress dynamics to improve ecological functionality of a stream. The ecological functions they considered included spawning, embryo incubation, emergence, and the river bed changing period. This study did not include the linkage between the intricate sediment transport processes and the fish habitat. Noack (2012) used the CASiMiR habitat model to simulate the suitability of a river bed for reproduction of gravel-spawning fish. This study used a 3D morphodynamic model to account for the morphodynamic processes and considered the impact of bed level changes on the hydraulics. However, the habitat model used in this study was mainly based on the water depth, flow velocity, and dominant substrate; the dynamic sedimentation and erosion processes were not included in this model. Despite all the effort to characterize the physical habitat and its requirements, additional research is still required to understand relations between the aquatic ecosystem and physical habitat (Hardy 1998; Escobar-Arias and Pasternack 2010). In particular, based on this review of the literature there appear to have been no previous direct examinations of relations between sedimentation/erosion processes and fish occurrence, which is an important research gap to be filled.

Objectives

Ecological condition of a fluvial system, to a great extent, depends on its physical habitat (Maddock 1999). Previous morphodynamic-fish habitat studies have mostly focused on the sediment grain size and distribution rather than the pattern and location of erosion and sedimentation. The long-term impacts of sediment transport on aquatic species are still not well understood and more study is needed to alleviate the negative effects of sediment transport on fish communities (Kjelland et al. 2015). It is of practical and essential importance to identify and protect fish that are sensitive to channel sedimentation and the associated sediment loads (Sullivan and Watzin 2010).

The present study, to the best of our knowledge, for the first time, studies the relations between morphological development and the fish occurrence in the same fluvial system. In this study, we focused on the fish presence–absence to examine the habitat utilization. We developed a 3D Delft3D model of a natural cohesive meandering stream using unsteady flow with the aim that this methodology and parameters employed therein could be useful in similar case studies. Total station topographic surveys were conducted in 2014 and 2016 to provide bathymetric change data for the morphodynamic module calibration. We also conducted spatially intensive acoustic Doppler current profiler (ADCP) surveys in the study area to obtain data for the hydrodynamic module calibration. The calibrated 3D morphodynamic model was then run for a one-year period to attain the morphological development of the study fluvial system. The data were employed to assess how the fish presence changed over this period. We performed two fish sampling surveys in the study area in 2014 and 2015 to find a relationship between the erosion-sedimentation process and the fish habitat utilization. The results of the 3D morphodynamic model were then incorporated in the fish habitat development. The main objectives of this study can be summarized as:

a. Develop a 3D morphodynamic model of a cohesive meandering channel;
b. Conduct a comprehensive field-measurement campaign including total station, ADCP and fish sampling surveys;
c. Compare the morphodynamic model results to actual measured bed elevation changes;
d. Evaluate relations between selected fish species occurrence and modeled morphological channel characteristics;
e. Develop a fish habitat model incorporating the channel morphological development.

Study Area

The study site was a meandering reach of Watts Creek, which flows into the Ottawa River at Shirley's Bay in the Kanata region of the Municipality of Ottawa, Canada. Watts Creek flows east and north over National Capital Commission (NCC) greenbelt forest property (Fig. 1). The catchment drainage area to the study reach is ~20 km^2 and is characterized by urban development in the headwaters (68%) with the middle catchment area surrounding the reach of interest composed of active agricultural (20%) with some island forests and a forest/meadow buffer around the creek (12%). Catchment elevations range from ~115 masl in

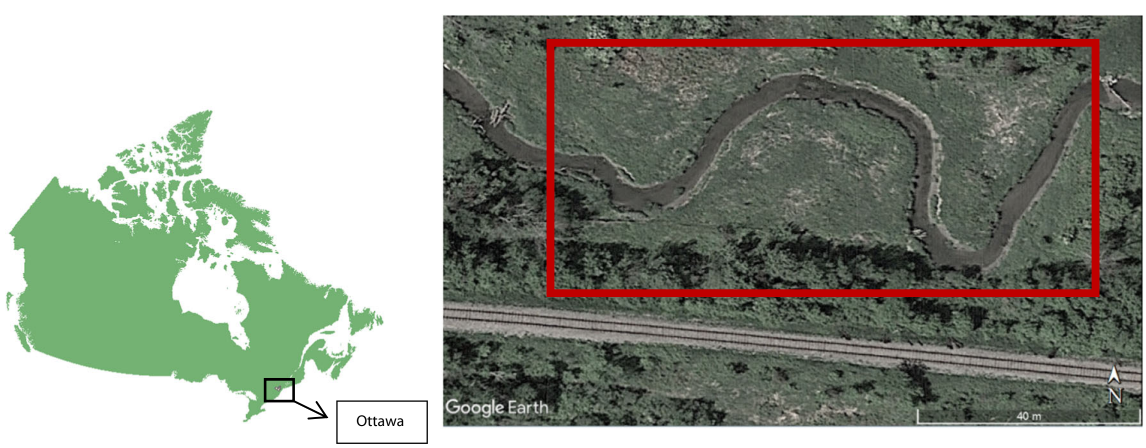

Fig. 1 **a** Location of the City of Ottawa in Canada (adapted from https://www12.statcan.gc.ca). **b** Study creek shown with the square (adopted from Google earth), flow from west (left) to east (right). The center point of the reach is situated at ~431,086.6 m E 5,021,107.4 m N. Note the City of Ottawa rail line immediately adjacent to the south of the creek

the Watt's Creek headwater to 68 masl at the study site to 56 masl downstream of the study reach at the confluence with the Ottawa River. The channel slope is moderate along the Watt's Creek upstream branch, decreasing from 1% for the first 3400 m to 0.5% for the next 2200 m, and is low through the main channel and through the study reach (~0.02%). Core samples of bed sediment collected from the reach were identified as cohesive soils (Salem and Rennie 2017). Watts Creek provides crucial cool water fish habitat and has a high fish abundance (Maarschalk-Bliss 2014). The channel bed is characterised by periodic patches of dense vegetation and alternating open areas, the overbanks are typically well vegetated by grasses, trees, and shrubs providing a range of shade cover from full sun to full shade. However, this creek has undergone erosion and degradation (driven by rapid flow response to urban runoff and an increase in wet–dry cycles for bank material), which can negatively impact the available aquatic habitat. The present study attempts to understand the hydro-morphodynamics to gain a better understanding of fish habitat quality in Watts Creek.

The study reach is adjacent to a rail line. The meander confinement by the rail line has caused excessive erosion and irregular meandering pattern in the reach (Parsapour-Moghaddam and Rennie 2018b). Field reconnaissance of the creek revealed instabilities in the inner banks of meanders, as well as the downstream limb of the outer bends. It was also observed that a concave-bank bench has been generated on the upstream portion of the outer bank at the last sharp bend (Parsapour-Moghaddam and Rennie 2018b). These observations confirmed that the study reach is an active and unstable channel.

Methodology

The methodology employed in this study includes three main components: (1) field studies, which involved terrestrial surveying, ADCP measurements of stream depths and velocities, and fish sampling; (2) 3D morphodynamic modeling in which, using the field measurements, we developed a 3D morphodynamic model to simulate the hydro-morphodynamic processes of the study creek; and, (3) fish habitat studies in which we evaluated the impact of channel morphodynamics on the fish habitat utilization. The results of the presence/absence data obtained from the fish sampling surveys were linked to the results of the developed morphodynamic numerical model. We also developed a fish habitat model to examine how incorporating the river morphodynamics can impact the predicted results of a fish habitat model. Each of the three mentioned methodological components are discussed in the following sections.

Field Studies

Initial bathymetric data needed for the morphodynamic modeling was first collected during summer 2014 using a total station survey with an average spacing of 1.2 and 0.3 m in streamwise and transverse directions, respectively (Fig. 2a). We also conducted a Total station bathymetric survey in the second meander bend of the creek during summer 2016 to assess the morphological changes of the stream within the 2-year period (Fig. 2b). Bathymetric points were collected with an average spacing of 2.7 and 0.6 m in streamwise and transverse directions, respectively. Triangular interpolation method (TIN) was then employed in ArcGIS10.2 to attain the digital elevation model (DEM) for both bathymetric surveyed data points.

We also employed a spatially intensive ADCP method to obtain the spatial distribution of 3D velocities all over the reach. An ADCP is a hydroacoustic tool which, based on the principles of Doppler shift, measures the 3D flow velocities. More detailed information on ADCP theory is available in Simpson (2001), Simpson and Oltmann (1993), and Rennie and Church (2010). We mounted a Sontek M9 River Surveyor ADCP on an Ocean Sciences trimaran riverboat, which was operated and moved in a zigzag pattern

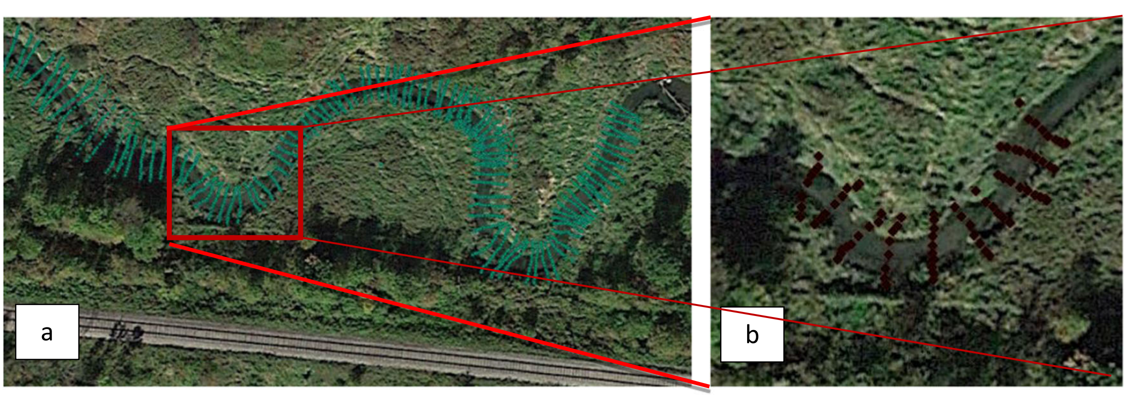

Fig. 2 Total station bathymetric points collected during summer: (**a**) 2014 (**b**) 2016. Flow from left to right. Background pictures taken from Google Earth

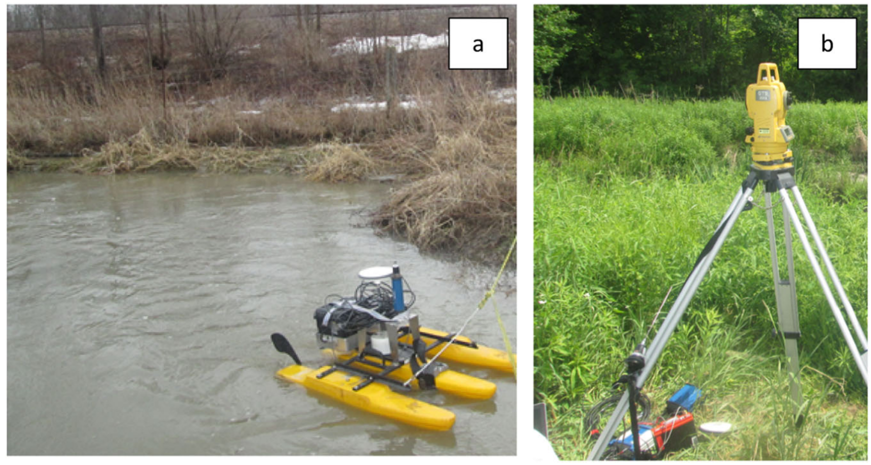

Fig. 3 Field studies in Watts Creek. **a** ADCP mounted on an Ocean Sciences trimaran riverboat employed for spatially intensive ADCP survey. **b** Total Station used for the terrestrial survey

via ropes by two operators at each side of the stream. The sampling frequency of the moving boat was 1 Hz. The compass was calibrated in situ through ADCP rotation with varying pitch and roll. The spatial distribution of 3D velocities, obtained from the ADCP survey, was then employed to calibrate the 3D hydrodynamic model. Calibration of the 3D hydrodynamic model with this method ensures better prediction of the 3D flow field (Parsapour-Moghaddam and Rennie 2018a). Figure 3 shows field studies equipment employed in the present study.

3D Morphodynamic Modeling

For 3D hydro-morphodynamic modeling of the study meandering creek, we employed the Delft3D modeling package (Delft-Flow version 4.01.01). Delft3D is a freely-available, open-source code developed by Deltares. This code includes different components interacting individually or in combination with other modules over a mutual interface (Deltares 2014). It is capable of modeling 2D or 3D hydro-morphodynamics over a rectilinear or a curvilinear grid.

The horizontal grid was generated using orthogonal curvilinear grid cells covering the model domain (Fig. 1b). The initial bathymetry was obtained using the interpolated surveyed bathymetric data from the 2014 Total station survey. To test the sensitivity of the model to the mesh, several grids were developed and examined. A proper grid cell resolution (average grid size of 80 cm) was attained considering the balance between the computational cost and grid cell resolution with a 6 s time step to meet the stability condition. Grid cell properties were examined to ensure the quality of the generated grid, i.e., aspect ratio <2 and orthogonality <0.05 (Fig. 4).

Time series of discharge and water level were used for the upstream and downstream boundary conditions, respectively. SWMHYMO hydrologic modeling software was employed to simulate the continuous upstream boundary discharge and downstream water level (Brennan et al. 2018).

The hydrodynamic module was calibrated using the procedure described by Parsapour-Moghaddam and Rennie (2018a). Manning roughness and horizontal eddy viscosity were the calibration parameters, and the hydrodynamic module output was calibrated using spatially intensive surveyed ADCP data. That is, 3D simulated velocities were compared with the 3D measured ADCP throughout the entire reach obtained on October 2015 (~0.5 m^3/s).

Morphodynamic model calibration was achieved using the data from the two topographic surveys in one channel bend (Fig. 2). For calibration purpose, it was assumed that the input hydrograph in the second year (2015–2016) was the same as the first year (2014–2015) with a similar cycle. Several morphodynamic parameters, such as the erosion parameter, settling velocity, initial sediment layer thickness, critical bed shear stress for erosion and deposition, and horizontal eddy diffusivity were tested to find the sensitivity of the model to each. The model was most sensitive to the horizontal eddy diffusivity and the critical shear stresses for erosion and deposition, thus these parameters were used for morphodynamic model calibration.

Fish Habitat Studies

In order to link the fish habitat quality with the erosion and sedimentation rate, fish sampling surveys were conducted in the creek using backpack electrofishing. Electrofishing is among the widely used methods for fish sampling surveys (e.g. Sharber and Sharber Black 1999; Rosenberger and Dunham 2005; Temple and Pearsons 2007). To be able to assess how the fish occurrence was changed by the morphological changes of the stream, two different fish sampling surveys were conducted during summer 2014 and summer 2015, which were, respectively, at the beginning

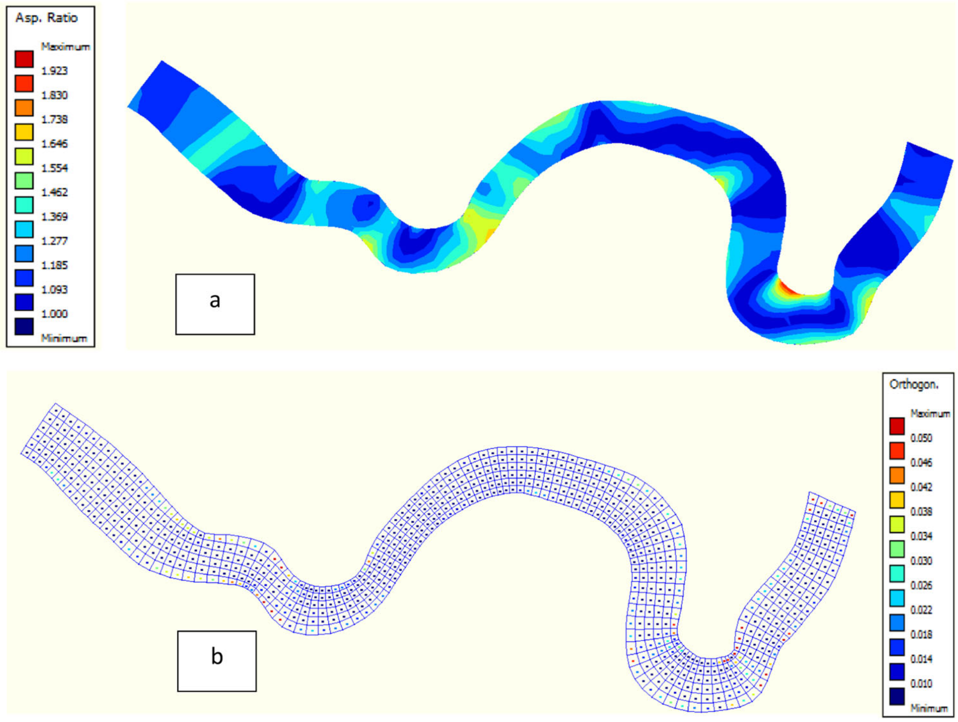

Fig. 4 Generated mesh properties: (**a**) aspect ratio and (**b**) grid orthogonality

and end of the study period. Based on ADCP measurements collected immediately following sampling in both 2014 and 2015, the flow discharge was, respectively, ~0.06 and ~0.08 m^3/s and the temperature was ~18 °C during both surveys. The results of the ADCP field measurements confirmed that the fish sampling surveys were conducted during similar low-flow conditions. Equivalent sampling procedure and effort were employed during both sampling events. The creek was divided into 5 m long subreaches (21 subreaches) covering all the study reach except for the very upstream end of the reach.

Fish sampling was started from downstream of the reach toward the upstream. All fish caught within discrete subreaches were measured to the nearest mm and identified separately. All species were collected to ascertain the species with the most abundant number of juvenile individuals for further analyses. The two species found to be most abundant during sampling were yellow perch (*Perca flavescens*) [$N = 121$, total length 80.38 mm ± 7.34 mm, mean ± SD] and white sucker (*Catostomus commersonii*) [$N = 39$, 77.97 mm ± 35.49 mm]. Yellow perch are a cool-water fish common throughout Eastern North America, and are usually found in shoals near vegetation and other submerged structures in lakes and pools in slow-moving streams (Suthers and Gee 1986; Paukert et al. 2002; Froese and Pauly 2018). They are more common in clear water and abundance generally decrease with increasing turbidity (Krieger et al. 1983). White sucker are an indiscriminate bottom-feeding species with broad environmental tolerances (Froese and Pauly 2018) that is relatively abundant in the Midwest and Northeast regions of North America (Saint-Jacques et al. 2000), and are found near all types of substrates in lakes, streams, and rivers (Minnesota DNR 2018).

To study the linkage between the fish habitat utilization and the stream morphodynamics, we employed the results of the developed 3D hydro-morphodynamic model. The simulated results of cumulative erosion and sedimentation within a one-year monitoring plan (August 2014–August 2015) were spatially analyzed to calculate their statistics in each 5-m subreach. These results were compared to observed changes in the presence–absence of both yellow perch and white sucker during the study period. Specifically, analysis of variance (ANOVA) tests and multiple comparison Tukey test (Tukey 1953; Kramer 1956) were used to test if the predicted morphological changes had a significant influence on habitat utilization of the fish. We also analyzed the significance of other variables, such as mean predicted values of sediment concentration, flow depth, and depth-averaged velocity, on the habitat utilization of yellow perch and white sucker in 2015. The results of the fish sampling surveys were statistically analyzed against different category of the hydro-morphodynamic variables to study which group of the variables could have a significant impact on the habitat utilization.

The results of the developed 3D hydro-morphodynamic model were then incorporated in development of a habitat model for fish species whose presence–absence was impacted by the river's morphology. For fish habitat modeling, we used habitat suitability index (HSI) modeling, which is the most common way to study the fish response to their habitat (Noack 2012). An HSI provides a measure of the quality of a given habitat variable to support particular fish at different life stages, with values ranging from 0 (the most unsuitable condition) to 1 (optimal condition) (Bovee 1986). In other words, the HSI indicates degree of habitat *p* by fish and is shown by a univariate function (habitat suitability curve) (Boavida et al. 2013). The standard hydraulic habitat variables employed in the literature are commonly flow depth, velocity, and substrate (Leclerc et al. 1995).

In the present study, results of the developed 3D morphodynamic model were employed as inputs for these fish habitat models. That means for the simulated result of each grid cell of the numerical model, we assigned an HSI value of 0–1 for each hydro-morphodynamic variable in accordance with the available habitat suitability curves. We employed two different scenarios based on the: (I) hydraulic variables such as flow depth, velocity, and substrate. (II) Hydraulic variables in addition to the morphological changes (i.e. erosion/sedimentation). For both scenarios, to combine the results of HSI modeling based on different hydro-morphodynamic variables, we used the arithmetic mean to obtain a composite habitat suitability index (CSI):

$$\mathrm{CSI} = \frac{\sum_{i=1}^{n} \mathrm{HSI}_i}{n} \tag{1}$$

Results

The hydrodynamic module of the developed 3D model was first calibrated for the Manning roughness and horizontal eddy viscosity using fully 3D ADCP velocities. The morphodynamic module was then calibrated for horizontal eddy diffusivity, critical bed shear stress for both erosion and sedimentation to which the 3D model was more sensitive. The calibrated parameter values are shown in Table 1. Figure 5 shows the results of observed stream morphological changes and the calibrated 3D morphodynamic model from August 2014 to August 2016. As mentioned in Section 3.1, the observed stream bend morphological development was calculated by differencing two total station surveys. As is shown, the calibrated model is in good agreement with the terrestrial measurements. Some discrepancies could still be seen close to the outer bank, which can be attributed to the simple bank algorithm used in Delft3D. Deposition occurred on the outer bank which is consistent with what was reported by Parsapour-Moghaddam and Rennie (2018b). The results of their field study showed the generation of reverse flow eddies, which were interpreted to have caused the development of the concave bank bench in the study reach. Blanckaert et al. (2013) reported an occurrence of a dead water zone in the outer-bank widening of an open channel bend with an immobile gravel bed. It was shown that channel widening could promote a weak horizontal recirculation eddy. Similarly, the modeled outer bank deposition in the study creek can be attributed to the widening meander bend which reduces the flow velocities and consequently causes an outer bank deposition. The calculated mean absolute error of the bathymetric change is 0.11 *m*. It can be seen that the erosion is underestimated and deposition is overestimated, but the locations of erosion and deposition are modeled reasonably accurately. Considering all the uncertainties inherent to sediment transport modeling, these results are promising. Accordingly, the developed 3D model could be further employed to predict the hydro-morphodynamics of the study creek.

Table 1 Calibration results of the developed 3D hydro-morphodynamic model

Calibration parameters	Values
Manning roughness	0.015
Background horizontal eddy viscosity	1 m^2/s
Background horizontal eddy diffusivity	4 m^2/s
Critical bed shear stress for erosion	0.35 N/m^2
Critical bed shear stress for sedimentation	0.35 N/m^2

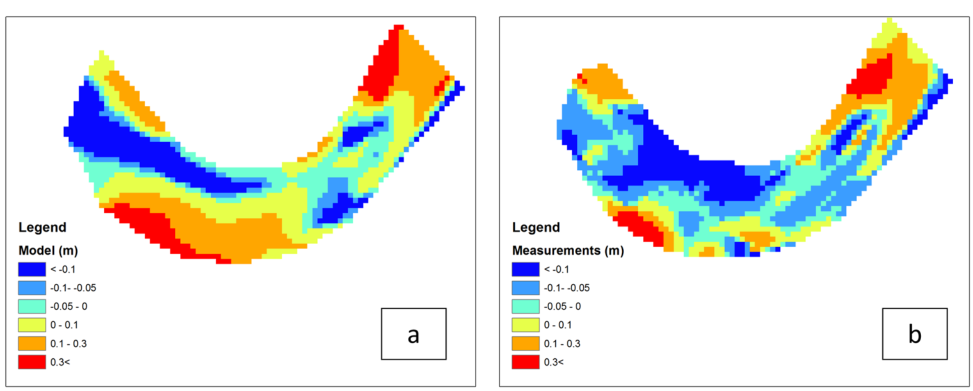

Fig. 5 Morphological changes over the study period (2014–2016) in one bend within the study reach. **a** Results of the 3D morphodynamic model. **b** Observed changes based on total station surveys. Positive values indicate deposition and negative values indicate erosion. Flow from left to right

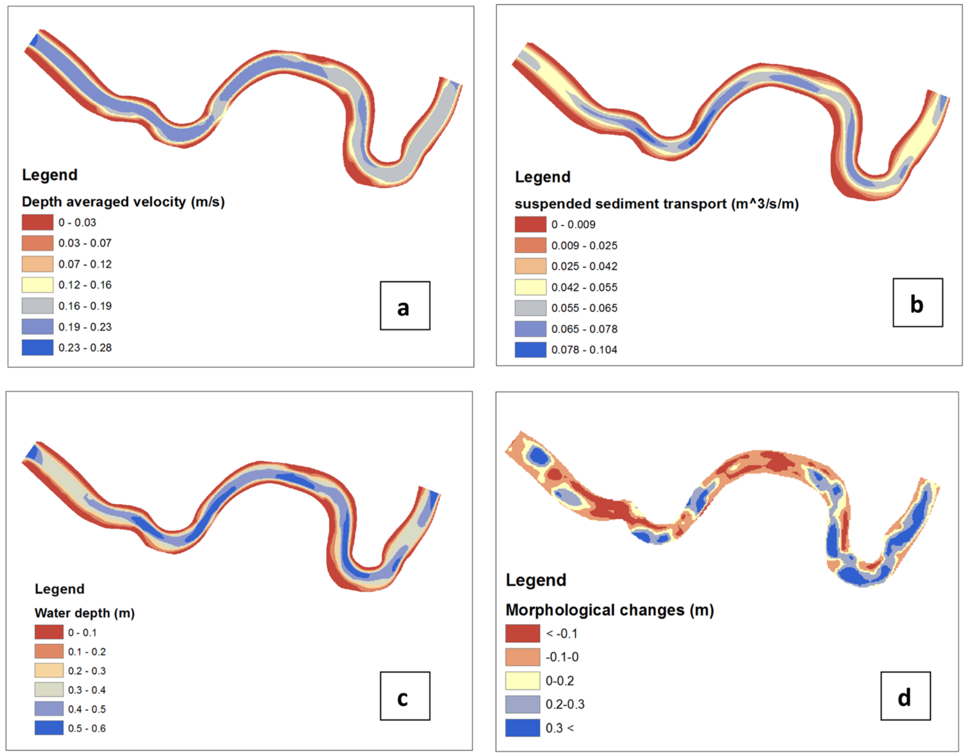

Fig. 6 3D morphodynamic model results at the end of the 1-year study period: (**a**) depth-averaged velocity, (**b**) suspended sediment transport, (**c**) flow depth, and (**d**) cumulative morphological development of the study creek. Flow from left to right

The calibrated 3D model was then run from August 2014 to August 2015. Figure 6 shows the results of the developed 3D model during the one-year study period. Figure 6d shows morphological development of the study area. These results were also qualitatively consistent with the actual morphological changes based on the field reconnaissance in terms of the pattern and location of the sedimentation and erosion (Parsapour-Moghaddam and Rennie 2018b).

Figures 7 and 8 show presence–absence of white sucker and yellow perch during the two fish sampling surveys, respectively. Figure 9 illustrates the changes in the presence of these two fish species with respect to the morphological changes during the study period. Since both fish sampling surveys were conducted at the same time of year under very similar flow conditions and temperature, it may be reasonable to attribute the fish presence changes to the stream morphological changes.

As shown in Fig. 9, presence of yellow perch mainly was gained in zone 3, where sediment deposition was mostly predicted. On the other hand, no consistent trend could be observed for white sucker in this zone, since presence was gained in four sampling subreaches, lost in one subreach, and had no change in the other five sampling subreaches. In zone 2 where erosion was mostly dominant, the presence of yellow perch was lost or had no change. However, white sucker presence mostly increased in this zone. In zone 1, which had a mix of erosion and deposition, presence by yellow perch was increased in two subreaches while in the other three subreaches no change was observed. The white sucker presence did not change in this zone during the study period. ANOVA tests were carried out to identify any significant relations between the model morphodynamic results and changes in the fish presence. Simulated changes in bed elevation during the 1-year study period in each 5-m sampling were compared to observed changes in habitat utilization of fish within each sub-reach. ANOVA test results yielded P values of 0.035 and 0.239 for yellow perch and white sucker, respectively. The results of ANOVA test confirmed that the morphological changes during the study period were a significant factor for change in presence of yellow perch at the 5% significant level, whereas white sucker presence was not significantly affected by the erosion and sedimentation.

We also evaluated the influence of different habitat variables on fish presence–absence within the reach. This was achieved using ANOVA multiple comparison tests (Table 2) to study if the flow depth, depth-averaged velocity, and suspended sediment transport had any impact on the presence–absence of yellow perch and white sucker at the end of the 1-year study period. Each variable was classified into three different categories (low, medium, high) as shown in Table 2.

As is shown in Table 2, yellow perch utilization was significantly affected by low suspended sediment transport and low depth-averaged velocity within each sampling subreach. However, white sucker showed significant influence of only medium depth-averaged velocity. Since the ANOVA test suggested juvenile yellow perch

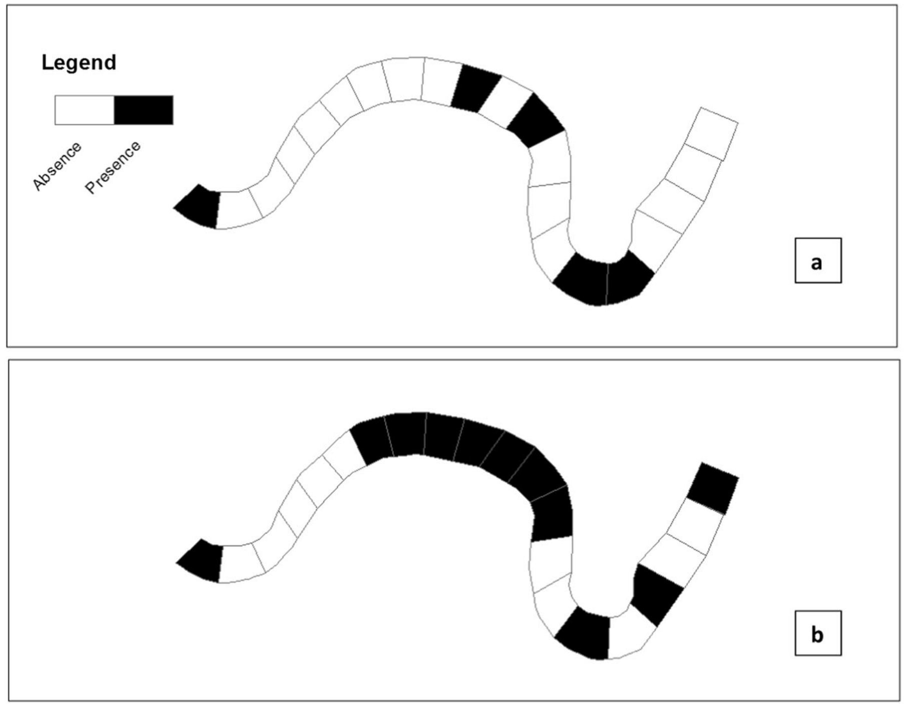

Fig. 7 Presence–absence of white sucker in: (**a**) 2014 and (**b**) 2015

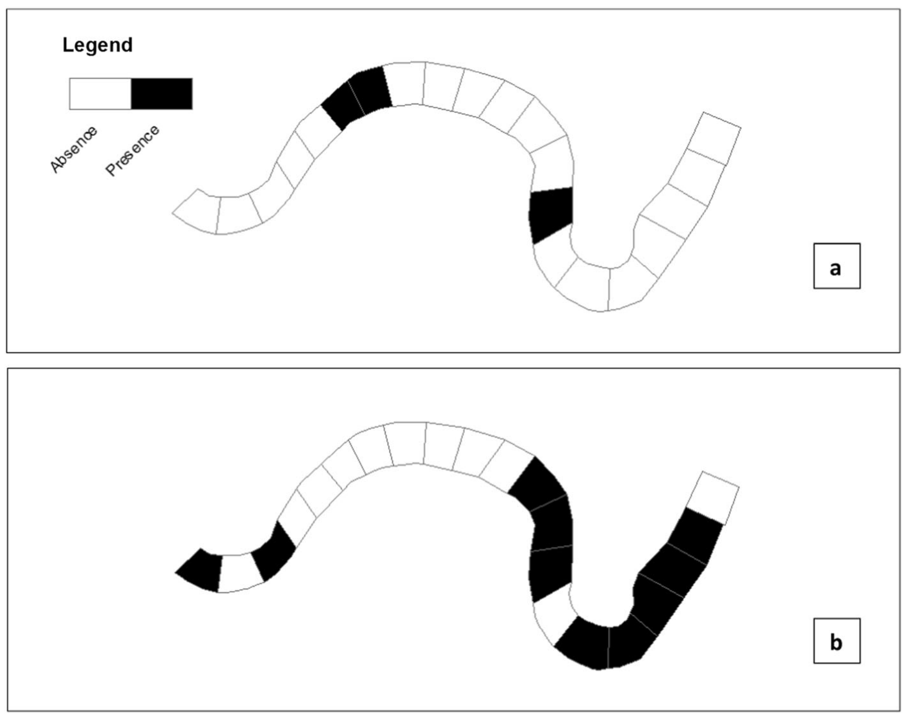

Fig. 8 Presence–absence of yellow perch in: (**a**) 2014 and (**b**) 2015

presence–absence was significantly impacted by morphological changes, HSI models were subsequently developed for juvenile yellow perch to simulate its potential habitat preference in the study creek. In order to develop an HSI fish habitat model, we used habitat suitability curves available for yellow perch based on flow depth, velocity, and substrate according to Krieger et al. (1983). The creek bed substrate is mostly preferred particle size for the juvenile yellow perch, which according to Krieger et al. (1983) is <0.062 mm. The outputs of the developed 3D morphodynamic model were inputted into the fish habitat model. After finding the HSI value of each hydro-morphodynamic variable (i.e., flow depth, velocity, substrate, and erosion/deposition), we calculated a composite habitat suitability index based on the arithmetic mean of the HSI values within each numerical grid cell. These results

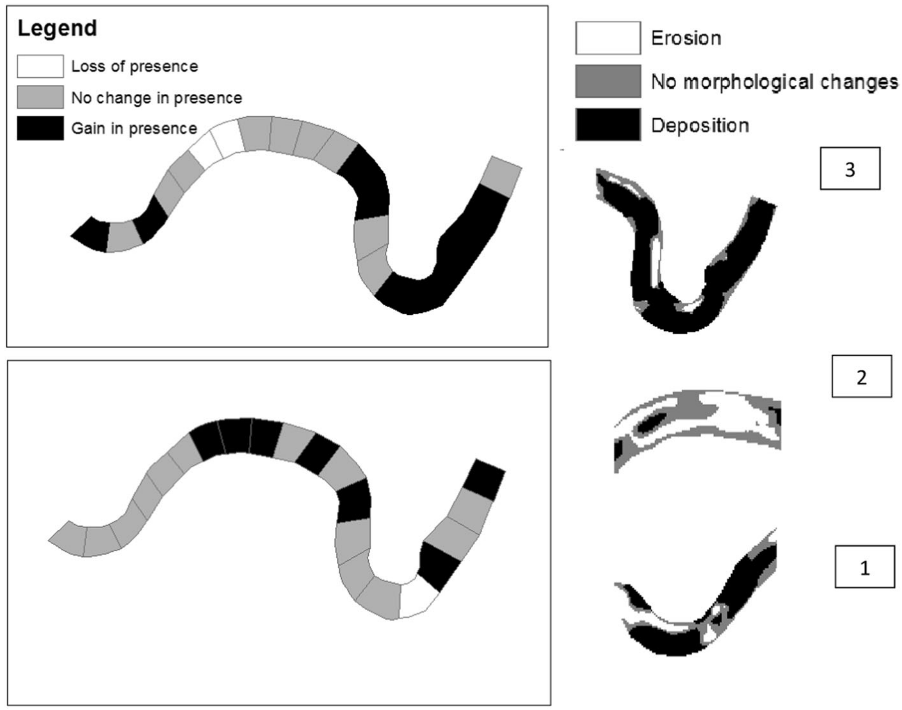

Fig. 9 Changes of presence during the 1-year study period: (**a**) yellow perch and (**b**) white sucker. Morphological changes of each zone (1, 2, 3) in the study reach

Table 2 Statistical analysis based on the multiple comparison ANOVA test. Significantly different variables are highlighted. Range of each variable category is specified in the table

Hydro-morphodynamic variables	Range		
	Low	Medium	High
Fish species			
Yellow perch			
Depth averaged velocity (m/s)	0.1–0.15	0.15–0.2	0.2–0.28
Suspended sediment ($m^3/s/m$)	0.04–0.06	0.06–0.08	0.08–0.1
Depth (m)	0.1–0.2	0.2–0.4	0.4–0.6
White sucker			
Depth averaged velocity (m/s)	0.1–0.15	0.15–0.2	0.2–0.28
Suspended sediment ($m^3/s/m$)	0.04–0.06	0.06–0.08	0.08–0.1
Depth (m)	0.1–0.2	0.2–0.4	0.4–0.6

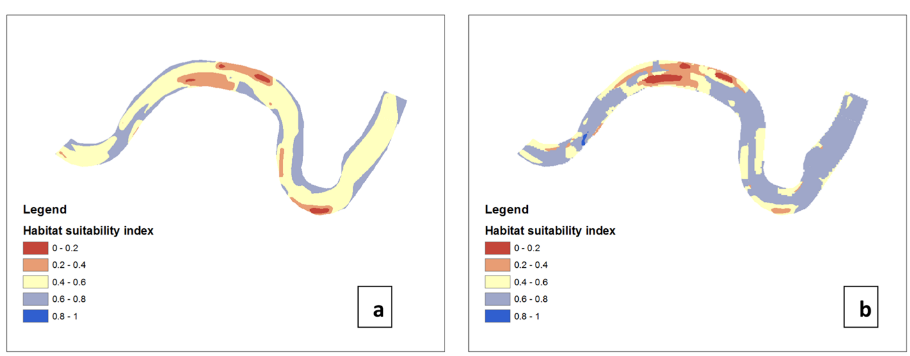

Fig. 10 Predicted habitat suitability map for juvenile yellow perch based one: (**a**) scenario I and (**b**) scenario II (with consideration of the morphological changes)

are shown in Fig. 10. It should be noted that to incorporate the morphological changes in calculation of the HSI model in scenario II (Fig. 10b), in the areas of erosion and deposition we applied HSI of 0 and 1, respectively, since fish habitat studies confirmed that yellow perch were mostly observed in zones where deposition occurred.

The suitability of each fish habitat model can be assessed by comparing Fig. 10 to the observed juvenile yellow perch utilization of habitat (Fig. 8b). It can be concluded that scenario II could better predict the habitat quality in zone 3 (refer to Fig. 9 for locations of each zone) where the fish sampling survey showed the presence of fish. This higher degree of habitat preference by fish is better predicted when the morphological impacts was taken into account. In zone 2, both scenarios estimated less likelihood of the fish presence, which is consistent with the fish absence during the fish sampling surveys (Fig. 8b). As for zone 1, scenario I predicted very similar habitat preference all over the zone. However, based on the fish sampling surveys, yellow perch was present in two sampling subreaches and absent in the other subreaches. This higher habitat preference of fish in zone 1 was better predicted in scenario II. In general, it can be concluded that the habitat preference and variability was better predicted in scenario II in which the morphological changes were taken into account. Consideration of the morphological changes to the fish habitat model leads to a habitat model specifically parameterized in accordance with the fluvial system's eco-morphological conditions.

Discussion

It can be reasonably expected that the hydro-morphodynamic processes of a fluvial system can affect the quality and availability of fish habitat given the strong and inherent connections between streams and their biota (Lapointe et al. 2014). Nevertheless, the impact of fluvial system morphological changes on fish habitat is yet poorly studied. The study herein considered channel morphodynamics in fish habitat modeling. This could be of practical importance river restoration strategies where fish habitat quality for a certain time period is understood, but change in the habitat quality over time is required. The morphological changes of a cohesive meandering creek, obtained from a 3D morphodynamic model, were correlated to changes in the habitat utilization of juvenile yellow perch and white sucker within a 1-year period. The results of the calibrated morphodynamic model reasonably agree observed morphological change obtained by terrestrial surveying. The ability of the model to simulate this process confirms that the developed model could reasonably be employed to predict the morphological changes in this creek.

We carried out two fish sampling surveys, both of which occurred during the same season of summer low flow with very similar low-flow conditions. Based on our last collected data and the antecedent precipitation and temperature from the weather station, we are not aware of any substantial difference in the previous flow condition in two sampling years. Accordingly, it is reasonable to assume that hydrodynamic and other habitat variables, such as temperature and dissolved oxygen were not significant factors in the observed changes in fish utilization of habitat between surveys. Based on the results of this study, it can be concluded that yellow perch was more susceptible to the suspended sediment compared to white sucker. It was demonstrated that juvenile yellow perch utilization of habitat was significantly impacted by the morphological changes and the lower suspended sediment transport. In particular, yellow perch habitat utilization increased in areas of deposition, possibly suggesting that yellow perch were seeking habitat with lower suspended sediment concentration. In general, yellow perch and white sucker have distinctive characteristics and habitat preferences. White sucker range over a larger domain within a river, while yellow perch tend to have more specific physical microhabitat requirements and occupy slower flow zones where deposition is more likely. Furthermore, white sucker are associated with the river-bed whereas yellow perch prefer water column habitat. If yellow perch feed in the water column, suspended sediment could hinder their feeding success. Accordingly, this can be the reason that they were more impacted by the suspended sediment compared to white sucker. Kjelland et al. (2015) reported that yellow perch death was increased with elevated sediment concentration. The results of the present study support this argument that yellow perch could be sensitive to the stream's morphological behavior. On the other hand, the present study illustrated that white sucker was not significantly impacted by the morphological changes and suspended sediment concentration. This is consistent with previous studies which reported that white sucker is tolerant to varying environmental circumstances (Saint-Jacques et al. 2000) and does not show health impairments when exposed to increased levels of fine sand (Merten et al. 2010). It should be noted that this study mainly focused on juvenile yellow perch and white sucker, while the results may be different for other life stages of these fish species.

As the results showed significance of the sediment transport on the yellow perch habitat selection, we developed an HSI habitat model to demonstrate the degree of habitat preference represented by this fish species. It was shown that the HSI model that included the channel morphological changes could better predict the yellow perch habitat preference. Previous studies showed that fish habitat quality depends on the river type (Jungwirth et al. 2000). Accordingly, site-specific HSI is often recommended (Boavida et al. 2014). Consideration of the morphological changes to the fish habitat model can provide a habitat model specifically parameterized in accordance with the study site's eco-morphological conditions.

Similar to other fish habitat studies, there still may be some uncertainties in these results related to the field measurements and the numerical model predictions (Gard 2009). Previous studies have shown that 2D numerical models can be reasonably employed for fish habitat studies (e.g., Boavida et al. 2014, Zingraff-Hamed et al. 2018). However, application of a 2D model for a fish habitat study is inevitably accompanied with errors in estimation of flow velocity and depth (Boavida et al. 2013). To minimize these errors, in the present paper, we employed a 3D numerical model to better simulate the 3D flow field and the impact of secondary flow on the river hydromorphodynamics. Successful calibration and validation efforts by comparison with the field measurements and the field reconnaissance confirmed that the model was able to produce adequately accurate representation of the key habitat variables. Moreover, using the averaged data set in each subreach for the fish habitat studies minimizes the uncertainties associated with the numerical model outputs in each numerical grid cell while still considering the full 3D flow field.

Mathematical combination of hydromorphodynamic variables (i.e., flow depth, velocity, substrate, and sedimentation) in the habitat modeling may be also associated with some uncertainties, since there are different methods to integrate the variables (Muñoz-Mas et al. 2012). In the present study, we applied the arithmetic mean in which it is assumed that poor habitat quality of one variable can be compensated by the rich habitat condition of another variable (Noack 2012). This can be a reasonable assumption since the quality of fish habitat depends on the combination of all variables rather than separate impact of each variable (Lambert and Hanson 1989). Moreover, the results of a sensitivity analysis on different integration methods confirmed that the arithmetic mean can provide sufficiently reasonable results (Parsapour-Moghaddam et al. 2017).

On the other hand, the velocity measurements can be associated with some errors (Gard 2009; Boavida et al. 2013). In this study, we minimized possible velocity measurement errors by conducting a spatially intensive ADCP survey all through the reach (average velocity errors <10%). This helps for more accurate and realistic comparison of the model results with the measurements both vertically and spatially through the reach. This can subsequently increase the model prediction capability. Nevertheless, still, there may be some errors due to the ADCP measurements (Parsapour-moghaddam and Rennie 2018a).

Another source of uncertainty can be due to the fish sampling measurements. We attempted to minimize these errors by standardizing electrofishing effort and sweep techniques in both sampling years. Moreover, due to the narrow width of the channel, it is reasonable to assume that no emigration and immigration occurred between different sampling transects. Moreover, we focused on the occurrence of the selected species, i.e., presence–absence. That is, we examined what would be the preferred habitat for the target fish to occupy, despite the availability of all areas. This reduces the sensitivity of the results to the number of surveyed fish and inter-operator variability in sampling efficiency. Nonetheless, successful calibration and validation results of the numerical model suggests that most of the uncertainties that may exist in the present study arose from the biological measurement. Validation of the developed fish habitat-morphodynamic model with multi-year data could help to alleviate these uncertainties. Regardless, similar to any other fish habitat study, the present study employed some simplified assumptions to simulate the biological response of fish in the real world. Although we attempted to minimize the errors associated with the results, these uncertainties are inevitable and cannot be completely eliminated (Gard 2009; Boavida et al. 2013).

Nonetheless, to the best of our knowledge this study represents the first attempt to validate a stream morphodynamic-habitat model using fish sampling results. The results of this research suggest that much further study of the influence of channel morphodynamics on fish habitat is warranted. For example, habitat suitability curves could be developed based on the impact of morphological changes and suspended sediment concentrations on yellow perch.

Conclusion

Morphological development of a cohesive meandering creek was studied to discover if morphodynamic processes could impact fish habitat utilization for juvenile yellow perch and white sucker. Two fish sampling surveys were carried out at the beginning and end of the study period. Successful validation efforts indicated that the developed model could be reasonably employed to predict the hydromorphodynamics of the study creek. ANOVA tests showed that morphological development was a significant factor in the habitat utilized by juvenile yellow perch, while juvenile white sucker utilization of habitat was not significantly impacted by the morphological changes in this creek. It was shown that habitat utilization of juvenile yellow perch mostly increased in the areas where sediment deposition occurred. Results of multiple comparison ANOVA tests illustrated that low depth-averaged velocity and low suspended sediment transport were significant factors in habitat utilization of juvenile yellow perch. On the other hand, habitat utilization of juvenile white sucker was significantly impacted only by the medium range of depth-averaged velocity. Since juvenile yellow perch was sensitive to the morphological changes, an HSI habitat model was developed to predict the habitat preference of juvenile yellow perch. Accordingly, the results of the developed hydromorphodynamic model were fed into the fish habitat model of juvenile yellow perch. The results demonstrated that the fish habitat model for juvenile yellow perch yielded better predictions of fish habitat utilization when the effect of morphological changes was taken into account. The present study suggested that a stream's morphological changes may have an influence on fish habitat utilization. This could be a step toward better understanding and prediction of fish habitat quality with respect to stream morphological changes, providing some insights into the impact of sediment transport on fish communities. This may enhance the aquatic habitat and have practical importance in the river management. More study is needed to understand the effect of morphological changes on various fish species in a range of fluvial environments. Preferably, future studies will include more comprehensive fish population assessments that consider inter-annual and intra-annual variability in both target and control reaches.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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Appendix

The Delft3D hydrodynamic model solves 3D Navier–Stokes equations for incompressible flow under Boussinesq assumptions. The partial differential equations include the following flow and momentum continuity equations:

$$\frac{\partial \eta}{\partial t}+\frac{\partial (hU)}{\partial x}+\frac{\partial (hV)}{\partial y}=0 \tag{2}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-g\frac{\partial \eta}{\partial x}+\nu_{\mathrm{h}}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(\nu_{\mathrm{v}}\frac{\partial u}{\partial z}\right) \tag{3}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-g\frac{\partial \eta}{\partial y}+\nu_{\mathrm{h}}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(\nu_{\mathrm{v}}\frac{\partial v}{\partial z}\right) \tag{4}$$

In shallow water applications, the vertical momentum equation is reduced to the hydrostatic pressure assumption:

$$\frac{\partial p}{\partial z}=-\rho g \tag{5}$$

where h is the water depth, η is the water surface elevation, U and V are the depth-averaged velocities in x and y directions, respectively, and u, v, and w denote velocity components; g is the gravitational acceleration; ρt is the time; υ_{h} and υ_{v} are, respectively, horizontal and vertical kinematic eddy viscosity coefficients.

After applying the approach of Reynold's averaging, turbulence closure models are employed to solve the Reynolds-averaged Navier–Stokes (RANS) equations. Delft3D-Flow code is numerically solved based on the finite difference method. We employed σ coordinate system in which the vertical layers are bounded by the planes which follow the free surface and the bottom topography. The k–ε turbulence closure model, based on eddy viscosity theory of Kolmogorov and Prandtl (Deltares 2014), was used to calculate the 3D turbulence. The morphodynamic module of Delft3D is capable of simulating the sediment transport of suspended load and bedload for non-cohesive sediments and suspended load for cohesive sediments. As mentioned in Section 2, the study creek has cohesive bed and bank materials. For suspended sediments, Delft3D solves the 3D advection–diffusion equation:

$$\frac{\partial c}{\partial t}+\frac{\partial uc}{\partial x}+\frac{\partial vc}{\partial y}+\frac{\partial (w-w_{\mathrm{s}})c}{\partial z}=\frac{\partial}{\partial x}\left(D_x\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial c}{\partial z}\right) \tag{6}$$

where c is mass concentration of the sediment (kg/m^3), D_x, D_y, and D_z are sediment eddy diffisivities (m^2/s), and w_{s} is sediment settling velocity (m/s). Eddy diffisivities and local flow velocities are calculated according to hydrodynamic model results. Delft3D calculates the sedimentation and erosion of the cohesive sediment employing the Partheniades–Krone formulations (Partheniades 1965):

$$E=MS(\tau_{\mathrm{cw}},\tau_{\mathrm{cr,e}}) \tag{7}$$

$$D=w_{\mathrm{s}}c_{\mathrm{b}}S(\tau_{\mathrm{cw}},\tau_{\mathrm{cr,d}}) \tag{8}$$

$$c_{\mathrm{b}}=c\left(z=\frac{\Delta z_{\mathrm{b}}}{2},t\right) \tag{9}$$

where E is erosion flux, M is a user-defined erosion parameter, D is deposition flux, c_{b} is the average sediment concentration in the near bottom computational layer, $S(\tau_{\mathrm{cw}},\tau_{\mathrm{cr,e}})$ is an erosion step function:

$$S(\tau_{\mathrm{cw}},\tau_{\mathrm{cr,e}})=\begin{cases}\left(\frac{\tau_{\mathrm{cw}}}{\tau_{\mathrm{cr,e}}}-1\right), & \text{when } \tau_{\mathrm{cw}}>\tau_{\mathrm{cr,e}}\\ 0, & \text{when } \tau_{\mathrm{cw}}\le\tau_{\mathrm{cr,e}}\end{cases} \tag{10}$$

$S(\tau_{\mathrm{cw}},\tau_{\mathrm{cr,d}})$ is a deposition step function:

$$S(\tau_{\mathrm{cw}},\tau_{\mathrm{cr,d}})=\begin{cases}\left(1-\frac{\tau_{\mathrm{cw}}}{\tau_{\mathrm{cr,d}}}\right), & \text{when } \tau_{\mathrm{cw}}<\tau_{\mathrm{cr,d}}\\ 0, & \text{when } \tau_{\mathrm{cw}}\ge\tau_{\mathrm{cr,d}}\end{cases} \tag{11}$$

τ_{cw} is maximum bed shear stress due to waves and current calculated through the wave–current interaction, $\tau_{cr,e}$ is the user-defined critical shear stress for erosion, and $\tau_{cr,d}$ is the user-defined critical shear stress for deposition.

The Delft3D morphodynamic module also includes bed level update as well as the bank erosion. Bank erosion is a function of erosion flux in the adjacent dry cell. In the developed model, 50% of the erosion in the wet cell was redistributed to the neighboring dry cells. Wet cells were defined to have at least 10 cm of water depth.

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