Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

Final report dated 14.03.2022

HBR-BS hydraulics of downstream fish migration facility at the case study hydropower plant Schiffmühle

HBR-BS Hydraulik der Fischabstiegsanlage am Fallstudien-Wasserkraftwerk Schiffmühle

Source: ©VAW, 2018

Location: Bern

Publisher:
Swiss Federal Office of Energy SFOE
Hydropower Research Programme
CH-3003 Bern
www.bfe.admin.ch
energieforschung@bfe.admin.ch

Subsidy recipients:
ETH Zürich
Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW)
Hönggerbergring 26
CH-8093 Zürich
www.vaw.ethz.ch

Authors:
Dr. Ismail Albayrak, ETH Zürich, albayrak@vaw.baug.ethz.ch
Mohammadreza Maddahi, ETH Zürich, maddahim@vaw.baug.ethz.ch
Andreas Doessegger, LKW AG, andreas.doessegger@regionalwerke.ch
Chidu Narayanan, AFRY (ÅF Pöyry, formerly AF-Consult), chidu.narayanan@afry.com
Andrew Carlson, AFRY (ÅF Pöyry, formerly AF-Consult), andrew.carlson@afry.com
Dr. Armin Peter, FishConsulting GmbH, apeter@fishconsulting.ch
Prof. Dr. Robert Boes, ETH Zürich, boes@vaw.baug.ethz.ch

SFOE project coordinators:
Dr. Michael Moser, michael.moser@bfe.admin.ch
Dr. Klaus Jorde, klaus.jorde@kjconsult.ch

SFOE contract number: SI/501759-01

The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.

Zusammenfassung

Wasserkraftwerke (WKW) mit Turbinen und Wehrüberfällen können zu erheblichen Verletzungen oder zum Tod von Fischen führen, was sich wiederum in einem Rückgang der Fischbestände auswirken kann. Horizontale Feinrechen mit einem Bypass-System (HBR-BS) sind eine wirksame Fischschutz- und -leittechnik, um solche Auswirkungen zu mindern. Das vorliegende Projekt zielt darauf ab, die Effizienz und Hydraulik der Fischleitung des HBR-BS am Dotierkraftwerk Schiffmühle an der Limmat durch Feldversuche und hydro-numerische 3D-Modellierung zu untersuchen und Lehren für die Verbesserung solcher Fischschutz- und –leitsysteme zu ziehen.

Die erste Feldmesskampagne wurde im Oktober / November 2018 durchgeführt. Es wurden 3D-Strömungsgeschwindigkeiten aufgenommen sowie Bathymetriemessungen mit dem Ultraschall-Doppler-Profil-Strömungsmessgerät (ADCP) durchgeführt, die entlang von 69 eng verteilten Querprofilen, stromaufwärts des Dotierkraftwerks, am Fischbypass und Turbineneinlauf sowie entlang der Restwasserstrecke und des Oberwasserkanals zum Hauptkraftwerk stattfanden. Die Bathymetrie- und Geschwindigkeitsdaten wurden eingehend analysiert und zum Aufsetzen sowie zur Kalibration und Validation der 3D-Numerik des Dotierkraftwerks verwendet. Am HBR-BS und sowohl bei der technischen als auch der naturnahen Fischaufstiegsanlage wurde ein Fischmonitoring durchgeführt, indem mehr als 3000 Fische aus 13 verschiedenen Fischarten mit einer PIT-Markierung versehen wurden.

Die Resultate zeigen, dass Fische sowohl der Hauptströmung in den Oberwasserkanal folgen als auch zum Restwasserkraftwerk schwimmen. Die Lockströmung für den Fischabstieg via Bypass ist zu schwach, und eine Rezirkulationszone beeinträchtigt das Auffinden des Eingangs in den Bypass, oder in den Bypass bereits eingestiegene Fische sind nicht motiviert abzusteigen. Zwei Individuen von 445 abgestiegenen Fischen stiegen über das Bypassrohr ab, was die Probleme mit dem Strömungsfeld rund um den Bypass veranschaulicht. 178 (40 %) von 445 Fischen stiegen über die Fischaufstiegshilfe ab. Dies zeigt, dass die hydraulischen Bedingungen beim Einstieg in die Fischaufstiegshilfe und beim Absteigen durch diese das Abwandern zulassen. Somit besteht für die Abwanderung ein weiterer Migrationskorridor. Ausserdem benutzten 265 (60 %) der 445 abgewanderten Fische die Turbinen oder den Wehrüberfall beim Restwasserkraftwerk oder das Hauptkraftwerk als Abwanderungskorridor.

Vier Varianten eines neuern Bypass-Systems wurden als Alternative zum bestehenden entworfen und mittels 3D-Numerik modelliert. Die Variante 4 mit einer vertikalachsigen Klappe (Stemmtor) mit boden- und wasserspiegelnahen Öffnungen und einer 15° geneigten Rampe zwischen der Klappe und einem Überfallwehr zeigt dabei die besten Strömungseigenschaften im Vergleich zu den drei anderen Varianten sowie dem bestehenden System (Nullvariante). Damit würde die Fischleiteffizienz des HBR-BS vermutlich deutlich verbessert. Dennoch sind weitere und detailliertere numerische Simulationen erforderlich, um den Entwurf weiter zu verbessern. Alternativ wird empfohlen, ein HBR-BS oder ein neuartiges Vertikalrechen Bypass-System mit gekrümmten Rechenstäben (CBR-BS), welches an der VAW entwickelt wurde, am Hauptkraftwerk in Schiffmühle zu installieren, statt mit viel Aufwand das bestehende HBR-BS am Dotierkraftwerk zu verbessern. Dies deshalb, weil die meisten Fische mit der Hauptströmung in den Oberwasserkanal und zum Hauptkraftwerk schwimmen.

Die Ergebnisse zeigen auch, dass sowohl die vertikalen Schlitze als auch die naturnahen Fischpässe am WKW Schiffmühle für stromaufwärts wandernde Fische gut funktionieren und eine hohe Anziehungs-, Einstiegs- und Passiereffizienz aufweisen.

Die vorliegenden Ergebnisse aus der Fallstudie des Dotierkraftwerks Schiffmühle unterstreichen, dass Design, Lage und Betrieb eines Bypass-Systems für eine erfolgreiche Implementierung und eine hohe Effizienz der Fischleitwirkung von HBR-BS von zentraler Bedeutung sind. Darüber hinaus bieten diese Erkenntnisse ein breites Anwendungsspektrum für andere Kraftwerke mit ähnlicher Größe und dienen als Grundlage für ein optimales Design von HBR-BS.

Résumé

La dévalaison des poissons par des turbines ou des déversoirs des centrales hydroélectriques (HPP) peut causer des blessures ou la mortalité des poissons, ce qui entraîne un déclin des populations de poissons. Les grilles orientées avec barreaux horizontaux avec un système de dérivation (Horizontal Bar Rack – Bypass System (HBR-BS)) sont une technologie efficace de guidage des poissons qui atténue ces impacts. Ce projet vise à étudier l'efficacité du guidage des poissons et l'hydraulique du HBR-BS à la HPP Schiffmühle sur la rivière Limmat par une surveillance sur le terrain et une modélisation numérique 3D afin de tirer des conclusions pour l'amélioration de tels systèmes de protection et de guidage des poissons.

Une campagne de mesure de la vitesse a été menée en octobre 2018. Les vitesses d'écoulement 3D ont été mesurées et la bathymétrie a été cartographiée à l'aide d'un profileur de courant Doppler acoustique (ADCP) sur 69 sections transversales densément espacées en amont de la HPP autour de la dérivation des poissons et de la prise d'eau de la turbine, ainsi que le long de la portée d'écoulement résiduel et du canal d'amenée de la HPP principale. Les données de bathymétrie et de vitesse d'écoulement ont été analysées en profondeur et utilisées pour mettre en place, calibrer et valider un modèle d'écoulement hydro-numérique 3D. Un suivi des poissons a été effectué à la HBR-BS, à la passe à poissons à fentes verticales et à la passe à poissons de type naturel en posant des étiquettes PIT sur plus de 3000 poissons appartenant à 13 espèces différentes.

Les résultats montrent que les poissons se déplaçant vers l'aval s'approchent à la fois du canal d'amenée et de la HPP à débit résiduel. Le débit d'attraction vers la dérivation pour le passage vers l'aval est inefficace et une zone de recirculation affecte peut-être les poissons qui cherchent l'entrée de la dérivation, ou les poissons qui entrent ne sont finalement pas motivés pour utiliser la dérivation. Deux poissons sur les 445 poissons marqués qui se sont déplacés vers l'aval ont été détectés dans le tuyau de dérivation, confirmant le mauvais champ de vitesse autour de la dérivation. 178 poissons sur 445 (40%) ont été détectés dans les passes à poissons amont, indiquant que les conditions hydrauliques à la sortie et le long de la passe à poissons amont sont suffisamment attractives et favorables pour guider les poissons vers l'aval, présentant ainsi une voie de passage alternative pour les poissons. De plus, 265 poissons sur 445 (60 %) ont utilisé soit le déversoir soit les turbines de la HPP à débit résiduel, soit les turbines de la HPP principale de Schiffmühle comme voies de passage alternatives et ont survécu grâce à ces passages.

Quatre variantes d'un nouveau système de dérivation comme alternative au système actuel ont été développées et modélisées numériquement en 3D. La variante 4, avec une porte à axe vertical avec des ouvertures supérieures et inférieures et une rampe inclinée à 15° entre la porte et le déversoir, présente les meilleures conditions d'écoulement par rapport aux trois autres variantes et à la dérivation actuelle (variante zéro), améliorant probablement de manière significative l'efficacité du guidage des poissons de la HBR. Cependant, des simulations numériques plus détaillées sont nécessaires pour améliorer encore la conception. Comme alternative, un système efficace de protection et de guidage des poissons tel qu'un HBR-BS ou le gril avec barres courbes et un système de dérivation (Curved-Bar Rack – Bypass System) développé à VAW est recommandé pour la HPP principale de Schiffmühle au lieu de faire un effort pour améliorer le HBR-BS actuel à la HPP résiduelle, car la plupart des poissons dans la rivière sont censés suivre le flux principal vers le canal d'amenée. Les résultats montrent également que la passe à poissons à fentes verticales et la passe à poissons de type naturel de la HPP Schiffmühle fonctionnent bien pour les poissons se déplaçant vers l'amont avec des efficacités d'attraction, d'entrée et de passage élevées.

Les résultats actuels de l'étude de cas de la HPP Schiffmühle indiquent que la conception, l'emplacement et le fonctionnement d'un système de dérivation sont d'une importance primordiale pour une mise en œuvre réussie et une efficacité élevée de guidage des poissons de la HBR-BS. En outre, ces résultats ont un large champ d'application pour d'autres HPP de taille similaire et serviront de base pour une conception optimale de HBR-BS.

Summary

Downstream fish passage through turbines or over spillways of hydropower plants (HPPs) may cause fish injury or mortality resulting in a decline in fish populations. Horizontal Bar Racks with a Bypass System (HBR-BS) are an effective fish guidance technology to mitigate such impacts. This project aims at investigating fish guidance efficiencies and hydraulics of the HBR-BS at the residual flow HPP Schiffmühle on the Limmat River by field monitoring and 3D numerical modelling to draw conclusions for the improvement of such fish protection and guidance systems.

A velocity measurement campaign was conducted in October/November 2018. 3D flow velocities were measured, and the bathymetry was mapped using Acoustic Doppler Current Profiler (ADCP) at 69 densely spaced cross-sections upstream of the HPP around the fish bypass and turbine intake as well as along the residual flow reach and headrace channel of the main HPP. The bathymetry and velocity data were analyzed in-depth and used to set-up, calibrate and validate a 3D hydro-numerical flow model. Fish monitoring was conducted at the HBR-BS and both the vertical slot and nature-like fish passes by PIT-tagging more than 3000 fish belonging to 13 different fish species.

The results show that downstream moving fish approach both the headrace channel and the residual flow HPP. The attraction flow to the bypass for downstream passage is inefficient and a re-circulation zone possibly affects fish searching the bypass entrance, or fish entering are finally not motivated to use the bypass. Two fish out of 445 tagged fish that moved downstream were detected in the bypass pipe, confirming the poor velocity field around the bypass. 178 fish out of 445 (40%) were detected in the upstream fish pass, indicating that the hydraulic conditions at the exit and along the upstream fish pass are attractive and favorable enough to guide fish downstream, presenting an alternative downstream passage route for fish. Furthermore, 265 fish out of 445 (60%) used either the weir or turbines of the residual flow or the main HPP powerhouse as alternative passage routes and survived from these passages.

Four variants of a new bypass system as an alternative to the present one were developed and 3D numerically modelled. Variant 4 with a vertical-axis gate with top and bottom openings and a 15° inclined ramp between the gate and weir show the best flow conditions compared to the other three variants and the current bypass (Zero Variant), likely significantly improving the fish guidance efficiency of the HBR. However, more detailed numerical simulations are needed to further improve the design. As an alternative, an effective fish protection and guidance system such as an HBR-BS or a novel Curved-Bar Rack-Bypass System developed at VAW is recommended for the main HPP of Schiffmühle instead of making an effort to improve the current HBR-BS at the residual HPP, because most fish in the river are expected to follow the main flow towards the headrace channel.

The results also show that both vertical slot and nature-like fish passes at HPP Schiffmühle function well for upstream moving fish with high attraction, entrance and passage efficiencies.

The present findings from the case study HPP Schiffmühle indicate that the design, location and operation of a bypass system are of prime importance for a successful implementation and high fish guidance efficiency of HBR-BS. Furthermore, these findings have a wide range of application for other similarly sized HPPs and will serve as a basis for an optimal design of HBR-BS.

Main findings

- ADCP velocity measurements indicate that most fish in the river are expected to follow the main current towards the headrace channel, while a small portion is likely to move towards the residual flow HPP.
- The attraction flow to the bypass for downstream movement seems inefficient and a re-circulation zone possibly affects fish searching and finding the bypass entrance.

- A new bypass design with a vertical-axis gate with top and bottom openings and a 15° inclined ramp between the gate and the existing weir show the best flow conditions compared to the other three variants and would likely improve the fish guidance efficiency of the HBR.
- Both vertical slot and nature-like fish passes at HPP Schiffmühle function well for upstream moving fish with high attraction, entrance and passage efficiencies.

Contents

Abbreviations

AFC	AF-Consult Switzerland AG
AFRY	AF-Pöyry Switzerland AG
ADCP	Acoustic Doppler Current Profiler
BFE	Bundesamt für Energie
BG	Bypass Gate
CBR-BS	Curved-Bar Rack with a Bypass System
DGPS	Differential *Global Positioning System*
FCO	Fish Consulting GmbH
FGE	Fish Guidance Efficiency
FGS	Fish Guidance Structures
FIThydro	Fishfriendly Innovative Technologies for Hydropower
FOEN	Federal Office for the Environment
HBR-BS	Horizontal Bar Racks with a Bypass System
HPP	Hydro Power Plant
LKW	Limmatkraftwerke AG
NLFP	Nature Like Fish Pass
PIT	Passive Integrated Transponder
SFOE	Swiss Federal Office of Energy
SVG	Spatial Velocity Gradient
UTM	Universal Transverse Mercator
VAW	Laboratory of Hydraulics, Hydrology and Glaciology
VR	Bypass Velocity Ratio
VSFP	Vertical Slot Fish Pass
WPA	Swiss Waters Protection Act
WPO	Water Protection Ordinance

1 Introduction

1.1 Background information and current situation

The installation of hydropower plants (HPPs) and dams may cause a number of problems for the fish fauna. These include: blocking or delaying up- and downstream fish migrations, damage or mortality of fish when passing turbines or spillways, and mortality due to predation by fish or birds. As a result, species population can decline. The revised Swiss Waters Protection Act (WPA) and Waters Protection Ordinance (WPO) introduced in 2011 aim at restoring water bodies and eliminating negative impacts of HPPs as to fish migration until 2030. Similarly, the European Water Framework Directive effective from 2000 demands undisturbed fish migration. For hydropower installations, new fish passages and connections to adjoining waterbodies must be established, and existing structures must be reviewed and may have to be adapted if they do not function properly. As to downstream fish protection technologies, these pose particular challenges to HPP operators and local authorities due to the current lack of design standards. Horizontal Bar Racks with a Bypass System (HBR-BS) are effective Fish Guidance Systems (FGS) to mitigate negative impacts of HPPs by protecting and guiding the fish to the tailwater of the HPP without turbine contact (Figure 1; Meister, 2020). To fill these research gaps, the laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich conducted an interdisciplinary research project on HBR-BS for run-of-river hydropower applications in the scope of the EU-Horizon 2020 Project "Fishfriendly Innovative Technologies for Hydropower (FIThydro)". The research involves laboratory and case-study investigations. VAW partners with AFRY Switzerland AG (former AF-Consult Switzerland AG, AFC), Limmatkraftwerke AG (LKW) and Peter Fish Consulting (FCO), amongst others.

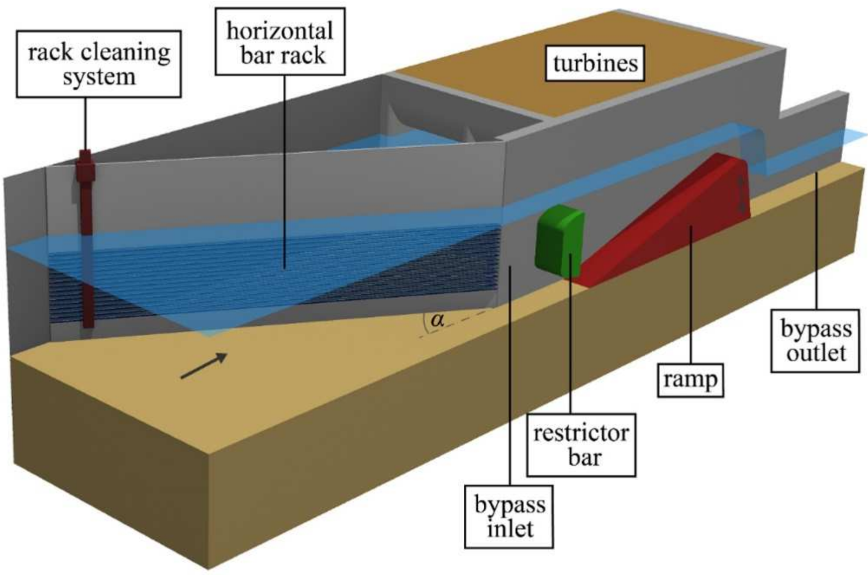

Figure 1: Principle sketch of a HBR-BS, adapted from Ebel (2016).

HBR-BSs are widely used and approved by authorities (Boes et al., 2016; Meister et al., 2020a). They function as physical protection and guidance barriers with a small bar spacing b = 10 ÷ 30 mm. The target fish size determines the bar spacing through which most fish should not physically pass. The use of HBR is limited to relatively small HPPs of design discharges (subscript d) Q_d < 120 m^3/s (Boes et al., 2016; Meister et al., 2020a). If at larger discharges, the time-averaged flow velocity normal to the rack axis, V_n exceeds the target fish species' sustained swimming speed, V_{sus}, fish may be impinged against the rack and would eventually be injured by the rack cleaning machine (Ebel, 2016). The fish swimming capacity at the rack should therefore be superior to the rack normal velcoity, i.e. $V_{sus} \geq V_n = U_r \times \sin(\alpha)$, where U_r is the time-averaged resulting flow velocity. A general value of V_n = 0.50 m/s is recommended for smolts and silver eels (Raynal et al., 2013). For an effective fish guidance, $V_p / V_n > 1$ in front of the rack must be maintained, where V_p is the rack parallel velocity (Courret & Larinier, 2008). The bars of HBRs can be built with different bar shapes, such as rectangular bars, rectangular bars with a circular tip, rectangular bars with an ellipsoidal tip & tail, and foil-shaped bars. Most modern HBRs are equipped with foil-shaped bars or rectangular bars with an ellipsoidal tip & tail to reduce head losses. Additionally, these bars can be cleaned easier than rectangular bars due to the thickness reduction from tip to tail (Meister et al., 2020a, b).

In general, HBRs are placed across an intake canal or forebay at an angle to the flow direction of typically α = 30°÷ 65° with mean approach flow velocities ranging from 0.20 to 0.80 m/s (Ebel, 2016). For high fish guidance efficiency, the ratio of the bypass inlet velocity to the approach flow velocity (bypass velocity ratio =*VR*) is recommended to be between *VR* = 1÷2 by Ebel (2016), 1.1÷1.5 by USBR (2006) and 1.2÷1.4 by Beck (2020) and Beck et al. (2020c).

The bypass system of a HBR is important for a successful fish guidance (Figure 1). Its main function is to attract, safely collect and transport the fish and to return them unharmed to the river downstream of the obstacle. An optimal bypass layout can significantly increase FGE (Albayrak et al., 2020; Beck, 2020, Beck et al., 2020c). The bypass must be easily found by all fish species, accepted quickly while reducing energy expenditure, escape and exhaustion. The optimal position of a bypass is at the downstream end of the HBR (USBR, 2006; Ebel, 2016). The weir in the bypass should provide a uniform Spatial Velocity Gradient (SVG) increase of 1 m/s/m with negligible hydraulic separation and turbulence and be designed to attract fish into the elevated velocity bypass flow (up to 3 m/s) at the top of the weir (Haro et al.,1998; Enders et al.,2012).

HBR can be configured with either bottom or both top and bottom overlays to improve the FGE and diversion of driftwood and/or bedload to the bypass. Small HPPs such as Halle-Planena on the Saale River, Raguhn on the Mulde River and Rappenberghalde on the Neckar River in Germany, and Rüchlig on the Aare River in Switzerland are examples of HBR applications demonstrating a large fish passage potential for other HPPs without any FGS. Design, head loss, velocity field and fish monitoring results of many HBRs are documented in Ebel (2016), Meister et al., (2020a, b) and Meister (2020).

In the scope of FIThydro, VAW conducted a laboratory investigation to improve the geometric design of HBR and its bypass system in order to minimize the head loss and maximize the FGE. To this end, hydraulic and live-fish tests were conducted (Meister et al., 2020a, b; Meister, 2020). Fish behaviours and FGE were determined using a 3D fish tracking system developed based upon a successfully applied 2D fish tracking system (supported by BFE SI/500957-1 and SI/501585-01). The findings of the laboratory investigation served as a basis for the present field investigation, in particular for numerical modelling. Similarly, the findings of the present study will serve as an exemplary benchmark to interpret the results from the laboratory study with regard to upscaling of the results.

Overall, the field studies highlight that fish monitoring is of prime importance to evaluate the efficiency of the HBR-BS. Not only the HBR layout, but also the bypass design are the key elements of a successful design of a downstream fish passage facility. More field and laboratory studies including fish monitoring and also investigation of flow fields are needed to better assess the performance of different HBR-BS configurations for various fish species from different geographical regions and for various hydraulic conditions. Both laboratory and field data will allow to establish robust design criteria for HBR-BS.

1.2 Purpose and objectives of the project

The main goal of the present study is to fill a portion of the research gaps described above by conducting fish and hydraulic monitoring and numerical modelling studies at the residual flow HPP Schiffmühle on River Limmat (Figure 2). The objectives of the study are to evaluate the guidance efficiency of HBR-BS installed at the study HPP, to recommend improvements and additionally to evaluate the efficiency of upstream fish passes based on the fish monitoring data. The findings of this project as well as laboratory investigation will have a wide range of applications for other similarly sized HPPs, answer the fundamental questions on the fish behaviour at HBR-BS and serve as a basis for an optimal design of HBR-BS.

Figure 2: HPP Schiffmühle (Dotierkraftwerk – residual flow HPP) with HBR-BS.

2 Procedures and methodology

To reach the goal of the proposed research project, we (i) quantified FGE of HBR-BS as well as the upstream fish passes at the HPP using PIT-tagging monitoring technique, (ii) measured flow velocities and bathymetry around the HPP using Acoustic Doppler Current Profiler (ADCP), and (iii) simulated the hydraulics of the HBR-BS and four alternative different bypass layouts using a 3D numerical model.

2.1 HPP Schiffmühle

The field investigations were conducted at the residual flow run-of-river HPP Schiffmühle. In addition to this HPP, there is also the main diversion-type run-of-river HPP Schiffmühle. Both HPPs are located on the 35 km long river Limmat in Untersiggenthal and Turgi near Baden, some 27 km downstream of Lake Zurich. The characteristics of both HPPs are listed in Table 1. Figures 3 and 4 show the locations and close-up photos of the HPPs, respectively.

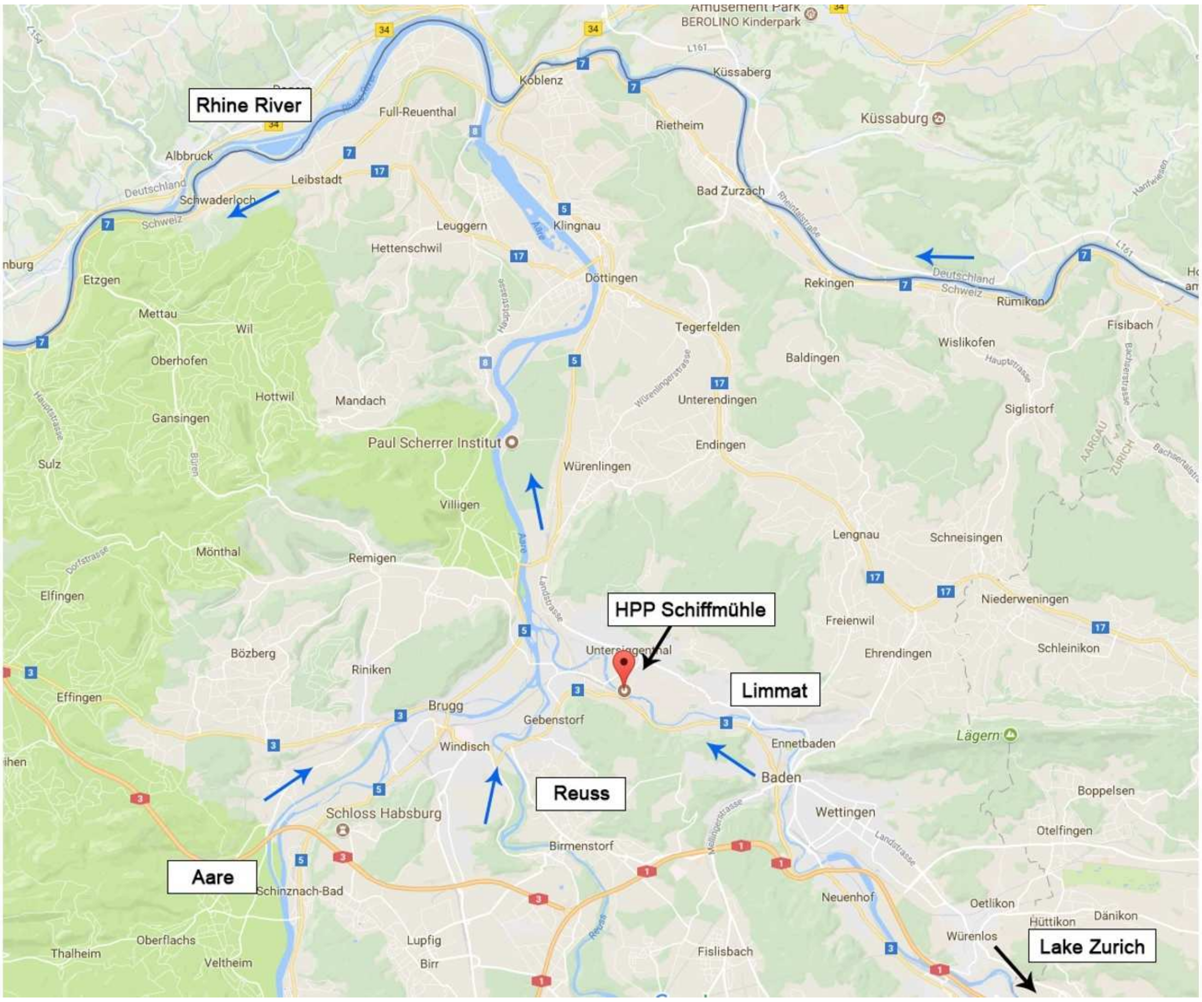

Figure 3: Location of HPP Schiffmühle (Dotierkraftwerk – residual flow HPP) with HBR-BS.

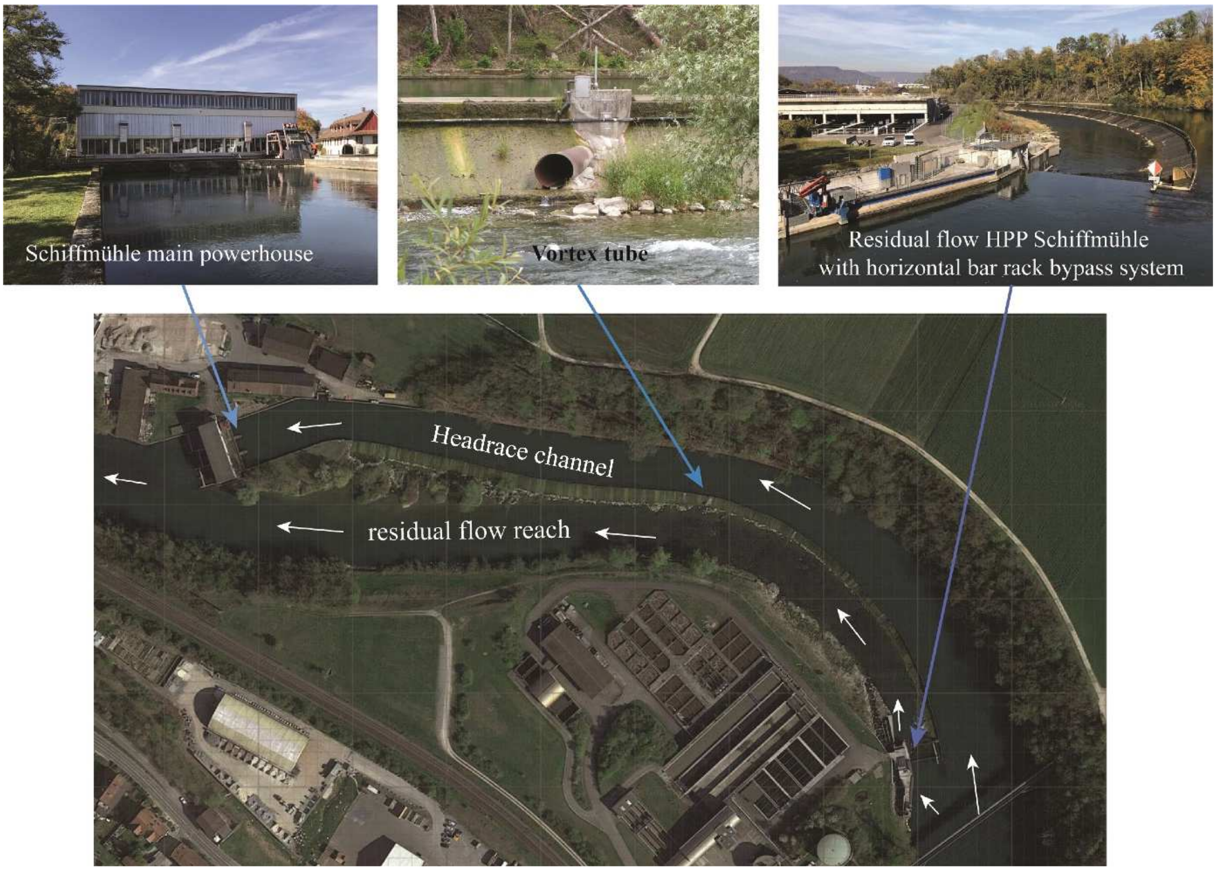

Figure 4: Schiffmühle main powerhouse and residual flow HPP.

Table 1: Main characteristics of the HPPs Schiffmühle.

Watercourse	Limmat
Location:	Untersiggenthal and Turgi near Baden
Mean annual discharge (1951-2018)	101 m^3/s
Design discharge (Schiffmühle main powerhouse)	108 m^3/s
Head (Schiffmühle main powerhouse)	3.2 m
Capacity (Schiffmühle main powerhouse)	3.46 MW (three vertical Kaplan turbines)
Design discharge (Schiffmühle residual flow HPP)	14 m^3/s
Head (Schiffmühle residual flow HPP)	2.97 m
Capacity (Schiffmühle residual flow HPP)	0.50 MW (bevel gear bulb turbine)
Fish species concerned:	26 species; target species: barbel, spirlin, trout, grayling; salmon expected in the next 10 - 20 years

At HPP Schiffmühle (Dotierkraftwerk - residual flow HPP), an angled fish guidance structure with horizontal bars, termed Horizontal Bar Rack (HBR) with a Bypass System (BS), has been implemented in 2013 to protect and guide fish to the tailwater of the HPP (Figure 5). The rack is positioned parallel to the main flow to have a lateral intake. The specifications of the HBR-BS are:

- Length of HBR: 14.60 m,
- Height of HBR:1.82 m,
- Total height of turbine intake: 2.32 m,
- Vertical angle of HBR: 90°,
- Clearance between the bars: 20 mm,
- The bars have rectangular profiles,
- The approach flow velocity at design discharge is 0.5 m/s,
- At the end of the rack there is a bypass with two openings in a vertical chamber at different water depths (close to the bottom, central and close to the surface),
- A 25 cm diameter pipe is supposed to bypass fish from the chamber to the tailwater reach,
- Design discharge in the bypass pipe: 170 l/s,
- Bypass pipe outlet is about 0.2 m above the tailwater surface at mean flow,
- 1 PIT-tag antenna was installed at the bypass to monitor downstream migrating fish.

For upstream migration, there are a technical Vertical Slot Fish Pass (VSFP) and a Nature-Like Fish Pass (NLFP) going around the powerhouse on the left bank (Figure 5). To monitor upstream migration and fish behaviour in these passes, PIT-tag antennas were installed (Figure 5).

The specifications of the fishways are:

- NLFP is located approx. 36 m downstream of the turbine flow outlet
- The bottom slope of NLFP is on average approx. 4 %.
- VSFP's entrance is located 2 m downstream of the turbine flow outlet
- The bottom slope of VSFP is approx. 6.28%
- The outlet of VSFP is merged to NLFP at an elevation of 336.83 m a.s.l.
- Total discharge in both fishways (NLFP+ VSFP): 0.5 m^3/s
- 5 PIT-tag antennas have been installed in the technical vertical slot fish pass and in the nature-like bypass to monitor upstream migration and fish behaviour in the migration facilities.

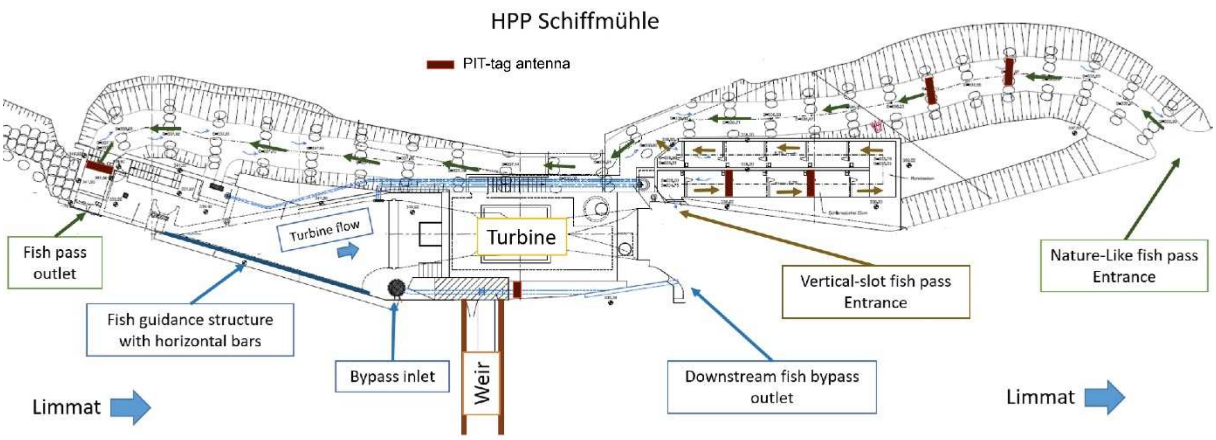

Figure 5: Plan view illustration of HPP Schiffmühle.

2.2 Methodology overview

Regarding fish guiding efficiency (FGE), due to the re-licensing, the HPP owner, Limmatkraftwerke AG (LKW), regularly monitors the effectiveness of the fish passes, i.e., the HBR-BS and the upstream fish passes, not only at HPP Schiffmühle but also at the upstream HPPs operated by LKW, providing a good data basis to assess fish migration in that reach of the Limmat river. Peter Fish Consulting conducted fish monitoring at the Aue and Schiffmühle HPPs by tagging more than 3000 fish.

VAW conducted high-resolution 3D velocity and bathymetry measurements using ADCP mounted on a remote controlled boat (Figure 6) and provided data to set-up, calibrate and validate a 3D numerical model developed by the FIThydro partner company AFRY. The flow fields around the HBR-BS and the downstream flow reach and head losses at HPP Schiffmühle were simulated using the 3D numerical model. The measured and simulated flow field data and fish data were evaluated to assess the FGE of the HBR-BS, and a further numerical investigation was conducted to show changes of the current HBR-BS geometry for an improved FGE.

Figure 6: Flow velocity measurements at HPP Schiffmühle using Acoustic Doppler Velocity Profiler (ADCP) with remote controlled boat (ADCP photo: courtesy of Teledyne Marine, USA).

2.3 Fish monitoring by FishConsulting GmbH

The up- and downstream fish movements were monitored at the HBR-BS and both technical slot (VSFP) and nature-like fish passes (NLFP) using the PIT-tagging technique over three years at Schiffmühle HPP (Figure 5).

Two antennas in the NLFP and another two antennas in the VSFP detected the entrance behavior of fishes. One additional antenna at the exit of the fish pass registered the fish leaving the fish pass (Figure 5). One antenna was installed in the bypass system of the HBR to detect downstream migrating fish. All six antennas were connected to readers recording detections at a rate of about 14 scans per second. Data from the readers were remotely downloaded and the function of the readers was controlled from the office and by field inspections.

Fish tagging started in September 2017. In the first year (2017), we tagged 549 fishes belonging to 10 different species. In 2018, 1’782 fishes belonging to 17 species were tagged. A total of 2’331 individuals tagged in 2017 and 2018 were released downstream of HPP Schiffmühle. Additional tagging occurred in 2019 so that finally 3’087 individuals were tagged at the Schiffmühle HPP. Most of the fish were caught in the counting facilities (N=2’890), except 73 individuals that were electrofished on 26 September 2018 upstream of the HPP and translocated to downstream areas and additional 124 individuals were caught in 2019 by electrofishing in the tailwater. These 124 individuals were translocated upstream of the HPP to track the downstream migration behaviour. Smaller fishes (< 160 mm) were tagged with 12 mm PIT tags, larger fishes (≥ 160 mm) with 32 mm tags. We used HDX PIT-

Tags from OREGON RFID (Manufacturer Texas Instruments, ISO 11784/11785). With a small incision the tags were placed in the fish body cavity. For the handling fishes were anesthetized with clove oil (30 mg/l). Before releasing fish back to the water, they could fully recover from anesthesia. Fishes caught in the counting facilities and from the HPP forebay were released after the recovery about 160 m downstream of HPP Schiffmühle.

2.4 Velocity and bathymetry measurements using Acoustic Doppler Velocity Profiler

High resolution 3D velocity as well as bathymetry measurements were conducted using an Acoustic Doppler Current Profiler (ADCP) mounted on a remote control boat in October 2018. The models of the ADCP and the boat are River Pro 1200 kHz including piston style four-beam transducer with a 5th, independent 600 kHz vertical beam and Q-Boat supplied by Teledyne Marine, USA, respectively (Figure 6).

The first campaign took place during an average river discharge of Q = 70 m^3/s from 13-15 March 2018, while the second campaign was done on 31st October and 1st November 2018 (herein we call it October 2018 field campaign) with an average river discharge of Q = 45 m^3/s. The main goals of both campaigns were to map river bathymetry and measure flow velocities in the upstream and downstream river reaches of the HPP. The data are used to construct, calibrate and validate the 3D numerical model, study the hydraulics of the HBR at the HPP and quantify sediment erosion and deposition in the river. The post-processing was done according to the workflow sketched in Figure 7 using the software WinRiver II[1] and VMT[2]. In addition to the ADCP measurements, we measured flow velocities inside the downstream bypass inlet using a propeller type handheld probe.

ADCP measurement cross-sections at the first (46 cross-sections) and second field campaigns (69 cross-sections) are shown in Figure 9 for the boundary conditions of numerical model and Figure 18 for comparison of velocity filed from ADCP with the numerical model, respectively. Due to a low accuracy of altitude measurement with the DGPS system of the ADCP, we used a TS02 Leica total station and a target on the boat to determine the water surface elevation at each transect during the second field campaign in October 2018.

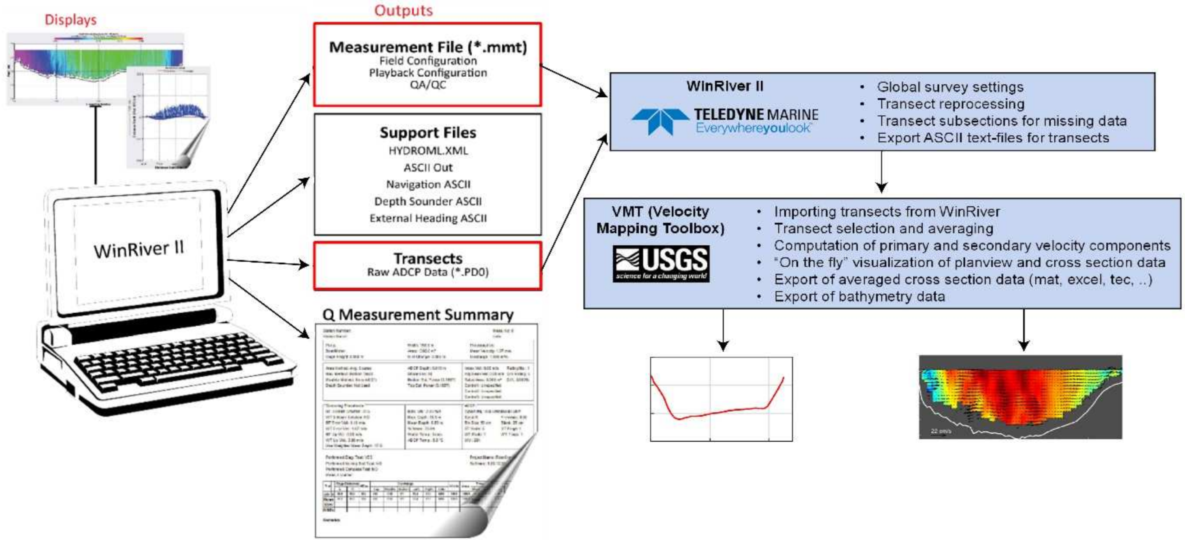

Figure 7: ADCP data analysis workflow.

1 Data collection and post processing software provided by U.S. Geological Survey

2 Matlab based software for processing and visualizing ADCP data provided by U.S. Geological Survey

2.5 3D numerical modelling

Flow conditions upstream and downstream of residual flow HPP Schiffmühle were simulated with the software FLOW-3D (Flow Science, 2016). The goal is to simulate flow conditions at the in- and outlets of the fish passage structures at variable Limmat discharges and, accordingly, with variable operating conditions of the HPPs at Schiffmühle. The following modelling concepts were applied.

2.5.1 Topographical and geometrical input data

For the generation of the model geometry, three types of data were combined:

- Topography
- As-built drawings of the structures of the residual flow HPP and of both the near-natural and technical fish passes.
- Bathymetry data measured in the present project and additional cross sections further upstream and downstream recorded by FOEN in 2013.

The topographical data were used to model the river reach including floodplain (Figure 8). The bathymetric cross sections were used to establish the geometry of the Limmat river, the headrace channel and the residual flow section as displayed in Figure 9. From the as-built drawings a 3D geometry of the residual HPP was established within AutoCAD/ Revit. The decisive geometry was then transferred as input to FLOW-3D (Figure 10).

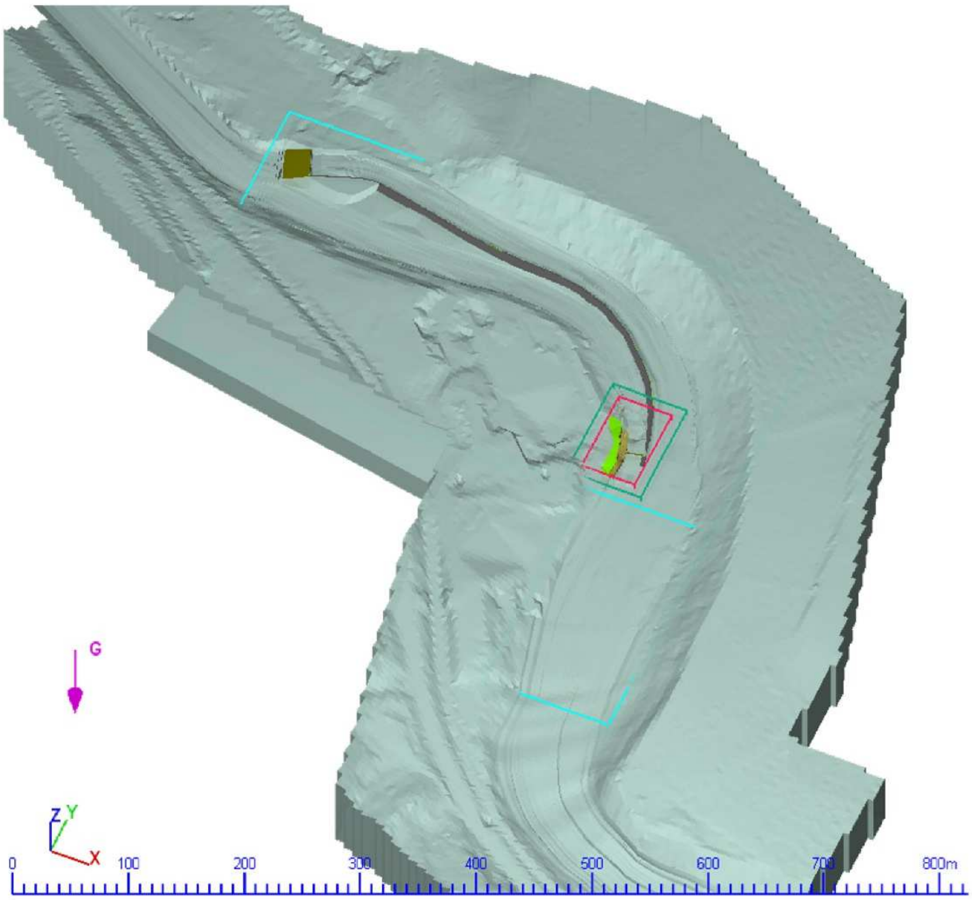

Figure 8: 3D geometry of the river reach, headrace channel, main and residual flow HPPs in terms of topographical data.

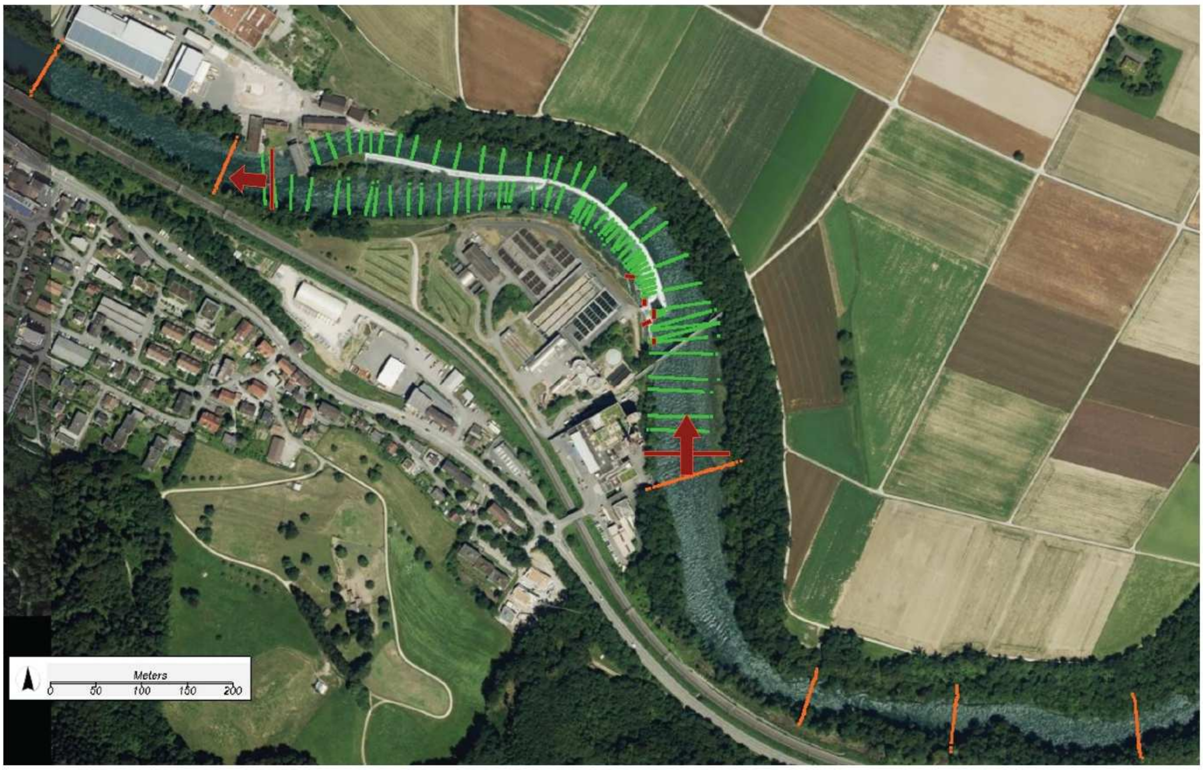

Figure 9: Available bathymetric cross sections, green (this project, residual flow bathymetry from March 2018 measurements and headrace channel bathymetry from October 2018), orange (FOEN, 2013) and red lines and arrow for boundary conditions of the numerical model.

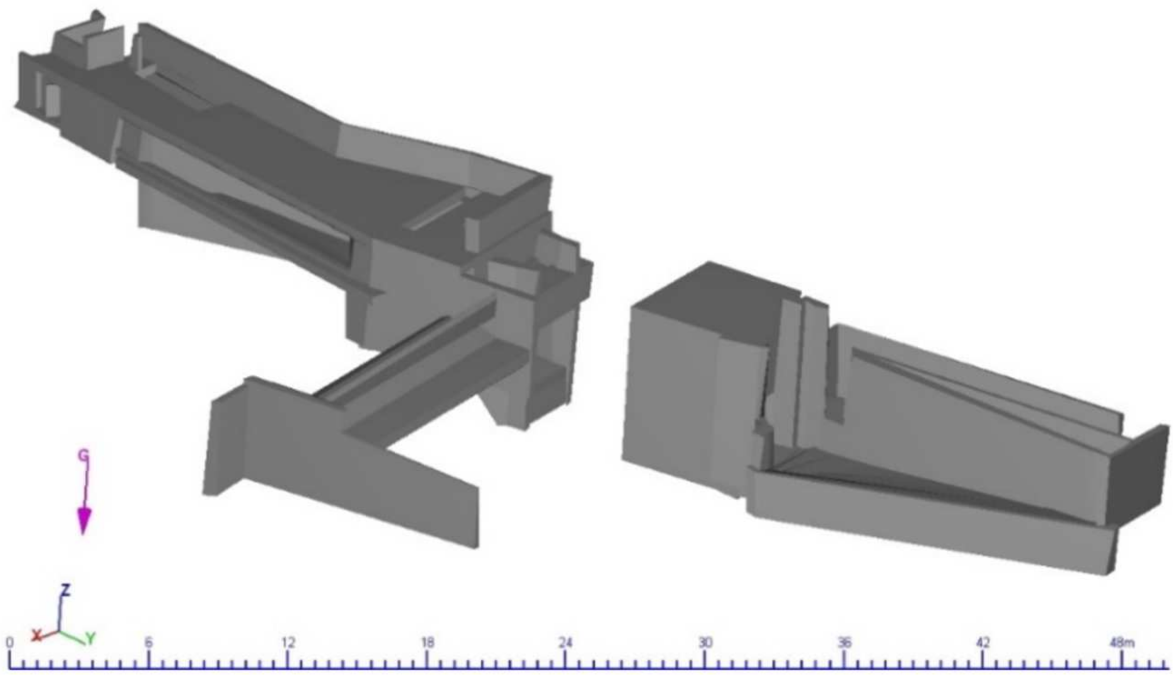

Figure 10: 3D geometry of the residual HPP with upstream (left) and downstream (right) parts.

2.5.2 Boundary conditions

The outer model boundary conditions were defined as inflow boundary condition at the upstream (approximately 200 m upstream of the residual HPP) and a water level-discharge relation at the downstream model end (Figure 9).

The inner model boundary conditions for individual elements such as the turbine, the fish upstream and downstream migration devices are explained in the following sections.

2.5.3 Modelling concepts of structures

Horizontal Bar Rack-Bypass System (HRB-BS)

Bar racks in front of intakes of HPPs represent a particular problem for numerical simulations. The reason for this is the especially fragmented geometry of the rack bars in comparison to other structural elements. Therefore, a baffle was used as an alternative approach to include the head losses of HBR into a 3D-numerical simulation with FLOW-3D. This allowed to account for the hydraulic effects of the rack without having to simulate each individual bar by direct numerical simulation with a resolution fine enough to properly resolve its hydraulic effects – an almost impossible endeavour given the trash rack size and bar spacing (Feigenwinter et al., 2019). It has been shown by specific research (Krzyzagorski et al., 2016), that the representation of a trash rack by a baffle leads to correct hydraulic effects. The input parameters were the rack porosity and the quadratic head loss. The quadratic loss coefficient was calculated based on the formula developed by Meusburger (2002, pages 170/171), including the loss coefficient due to the obstructed area as

$$\zeta_{obstruction} = K\left(\frac{P}{1-P}\right)^{\frac{3}{2}}$$

where P is the ratio between area obstructed by rack bars, spacers and support structure elements and gross flow area of the rack projected to the vertical and K = bar shape coefficient. Assuming an obstruction grade of 0.38, a shift grade of 0.05 and perpendicular flow the coefficient equals 1.185. Oblique flow direction is directly accounted for by the FLOW-3D simulation.

As the rack was not aligned with the orthogonal model cells, FLOW-3D fitted the rack in a stepped shape on the grid. This artificially increased the rack surface. By reducing the porosity of the rack, the increase was compensated. With this correction, the open surface of the rack and therewith the flow velocities within the rack were properly represented.

The horizontal direction of the approach flow was not influenced by the rack since the bars were horizontally arranged. The impact on the vertical flow direction was not considered here because of the small vertical velocity component. Figure 11 shows a photo of the HPP and its 3D numerical model including the velocity field.

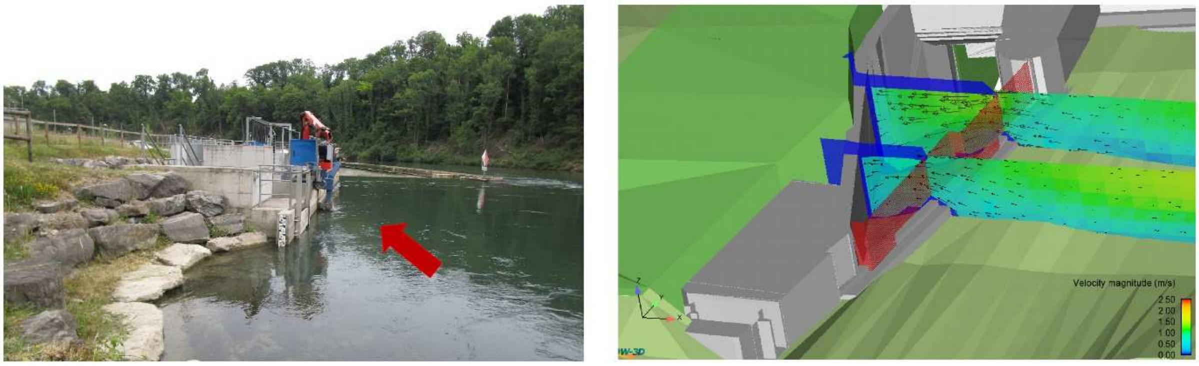

Figure 11: Horizontal Bar Rack - Bypass System-at Schiffmühle HPP: Reality (left) vs. model (right).

Fish downstream passage

The bypass system of the HBR is designed for a bypass flow of Q_b = 0.170 m^3/s when the weir flap is fully raised. The inlet of the device consists of two rectangular openings at different depth in the side wall of the HPP structure approximately 4 m upstream of the weir. The openings lead to a chamber from where a DN250 bypass pipe leads to the residual flow river section. In the model, this flow was specified by an outflow boundary condition at the downstream end and an inflow boundary condition at the upstream end of the pipe. Figure 12 shows the bypass entrance and the outlet pipe and the inflow conditions at the bypass from the numerical simulation.

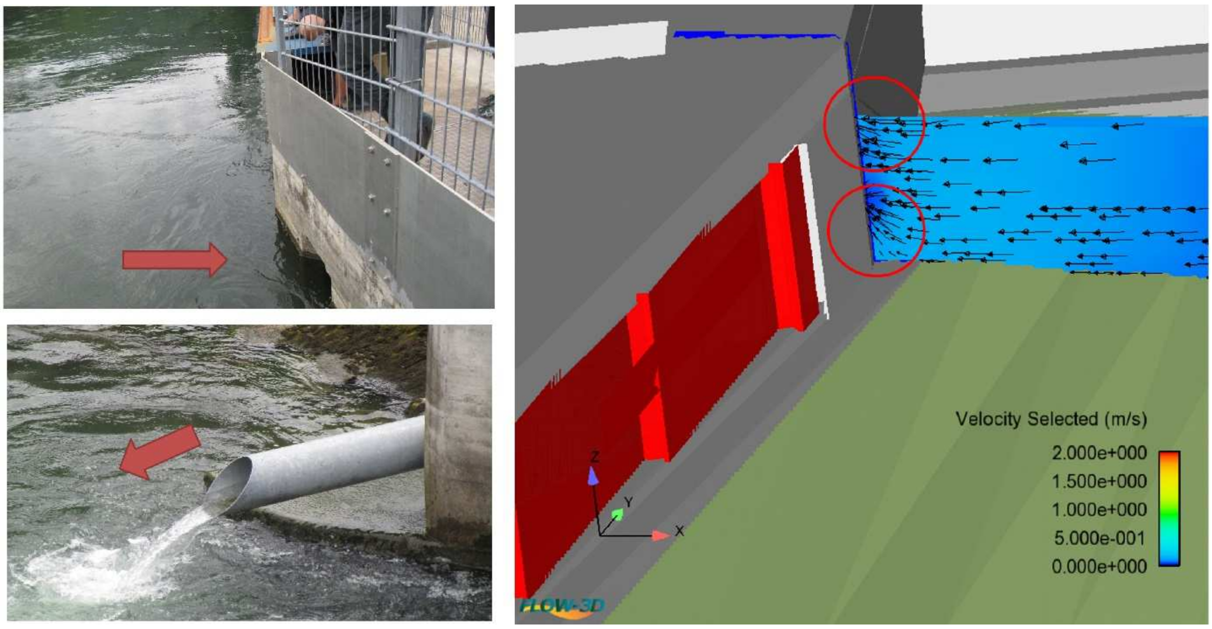

Figure 12: Fish downstream passage - Reality with bypass entrance (upper left) and bypass outlet (lower left) vs. model bypass entrance (right).

Fish upstream passage, Vortex Tube, Turbine

Fish passes, a vortex tube system for bedload diversion in the headrace channel and the turbines at the main HPP were also modelled. Since the present project focuses on the downstream fish passage facility, i.e., the HBR-BS at the residual flow HPP, they are not detailed herein.

2.5.4 Meshing

The meshing of the numerical 3D model consisted of different mesh resolutions. Decisive parts and structures were refined, whereas river stretches were coarser meshed (Figure 13). The variable grid size was as follows:

- X-Y direction: 2 m to 0.25 m
- Z-direction: 1 m to 0.125 m

In this context it is important to mention that the smallest cell size largely influences the computational time required, which is around two to four days per simulation.

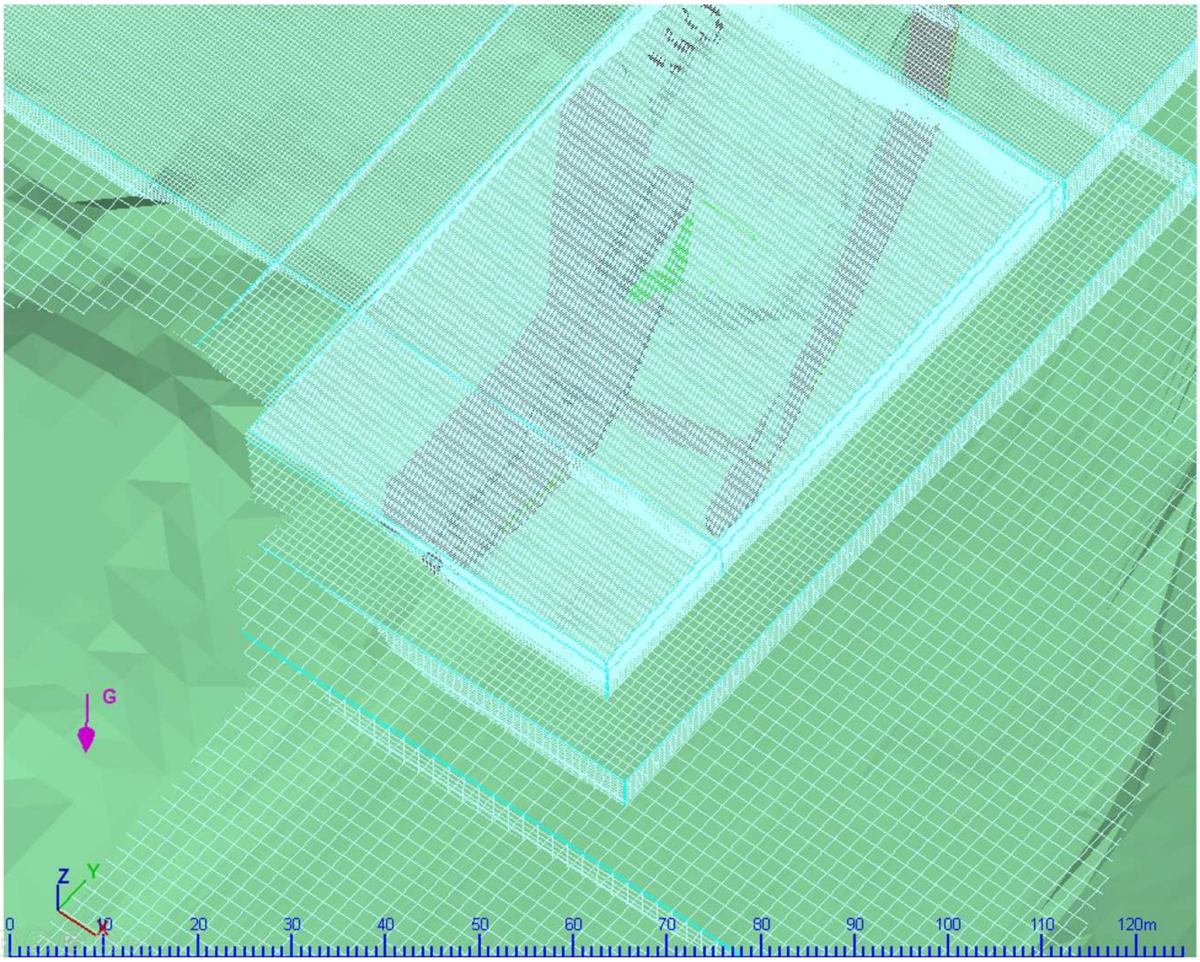

Figure 13: 3D model meshing.

2.5.5 Flow condition scenarios

3D numerical simulations were conducted for various discharge conditions to represent significant states for hydraulic assessments and further analyses. Simulation cases were used for different analyses such as sediment studies and fish passage. Since the main focus lies in the fish downstream passage, the goal is to simulate flow conditions at the in- and outlets of the fish passage structures at variable Limmat discharges and accordingly, with variable operating conditions of the HPPs.

The Limmat discharge conditions and operating conditions were selected according to the following approach: First, only periods in which fish migration occurs are considered. These are mid-May to mid-June and September till beginning of October. In these periods the three prescribed residual flow allocations turbined at the residual flow HPP are 8, 10 or 14 m^3/s. As seen in Figure 14, four sub-periods with different prescribed residual flows must be considered. For these four sub-periods, the Limmat hydrograph was analysed and Limmat flows of 5%, 50 %, 80% and 95 % (347 day) exceedance probability were evaluated (Figure 14). In total a set of ten flow conditions were thus considered to be studied as representative scenarios. It can be noted that weir overflow, starting at 123 m^3/s, takes places for seven out of the ten scenarios.

Flow structures around the bypass inlet, in front of the HBR and weir are of prime importance to evaluate the efficiency of the HBR-BS. Simulations in these areas were run for the river discharge of 100 m^3/s (~ mean discharge with 50% exceedance probability in migration months) with all possible discharges through the residual flow HPP (8,10,14 m^3/s).

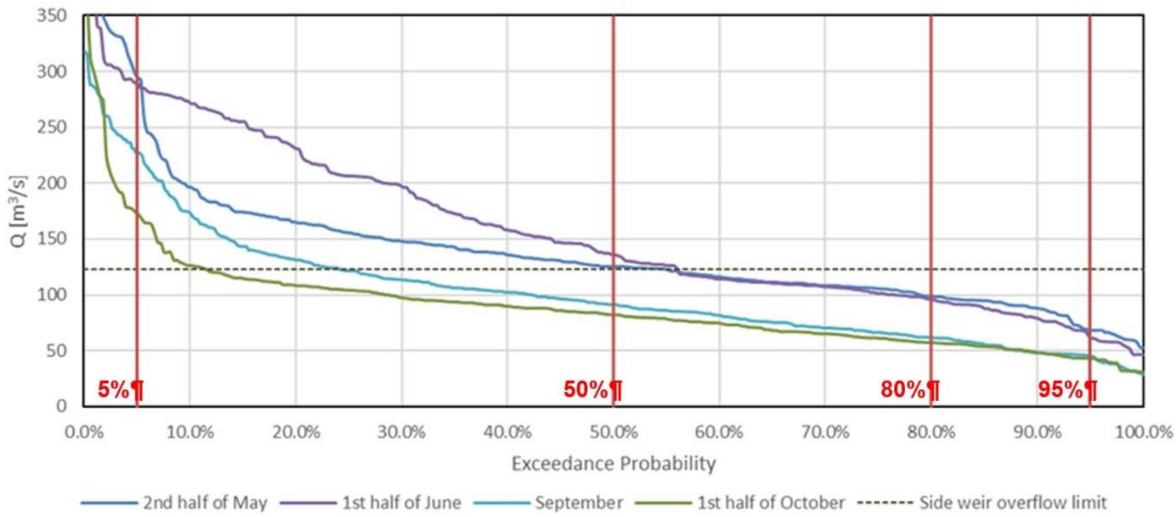

Figure 14: Flow duration curves established based on 1997-2018 Limmat flow data for the four sub-periods of fish migration.

3 Results

3.1 Fish monitoring results

Upstream fish passage monitoring results presented in the following are not the focus of the present project but give an overview of the number, size and species of the tagged fish and furthermore of the efficiency of two different types of upstream fish passes, which is separately treated here from the downstream fish passage. The monitoring study was conducted as a part of FIThydro project and partly funded by BFE to evaluate the FGE of the downstream fish passage facility at the HPP Schiffmühle.

Upstream fish passage

The lengths of 2890 tagged fish caught in the counting facilities at the fish pass ranged from 82 to 900 mm (median 130 mm). Between 28 September 2017 and February 2020 hundreds of thousands of detections were registered at the installed antennas. Figure 15 shows the length distribution of each fish species detected at different locations, i.e., the Vertical Slot Fish Pass (VSFP), and the Nature-Like Fish Pass (NLFP). An overview of the detected fishes in VSFP, NLFP and unknown paths of fish accent is presented in Table 2. Overall, 1’946 of all tagged fishes (67.3 % of total number of tagged fish) were detected. This is considered as a high detection rate. 1’858 tagged fish (95.5 % of all detected fishes) entered the fish passes (defined as entrance efficiency) and 81.4 % of them successfully ascended to the headwater reach (defined as passage efficiency). Barbel preferred the entrance of the VSFP, while chub, roach and especially dace preferred to enter the NLFP (see Table 2).

The attraction efficiency is defined as the ratio between the number of fish registered at the first antenna at the fish pass entrance and the number of the tagged and released fish. It differs between the species but is always in the range between 60 – 90 % (except for species with only a few individuals). Bleak did not have a specific preference for one of the two entrances into the pass, whereas dace showed a high preference for the NLFP (79.3 % of the individuals). Roach showed also a preference for the NLFP (69.1 % of the individuals). Chub and perch had a lower, but still a clear preference for the same entrance. Mainly the barbel preferred the entrance into the VSFP with 42.3 %

of the individuals compared to only 24.3 % of the individuals in the NLFP. Spirlin seem to have the same preference for the VSFP. The total passage efficiency for all tagged fish in the counting facility is high (81.4 %). The total (whole fish pass) attraction efficiency is 67.3 %, which is considered to be good to high. The total attraction efficiency for fishes caught in the forebay is 78 % and therefore even higher (Table 2).

Passage duration: The values of the median passage duration in the VSFP (Table 3) are very meaningful. For most of the fish species at least 50 % of the individuals had a passage duration of less than 60 minutes.

The passage duration in the NLFP is a little bit longer than in the VSFP (Tables 3 and 4). The values of the median increased by 24.8 minutes (species without spirlin). The passage duration of spirlin was 502.8 minutes. The spirlin remained for a long time in the NLFP. However, the fastest spirlin passed within 36.4 minutes which can be interpreted that spirlin were not restricted in a quick passage.

In conclusion, the detection rate of 67.3 % (also attraction rate) and the entrance efficiency of 95.5 % of the fish passes at Schiffmühle are quite high. In other studies lower attraction efficiencies were found. Benitez et al. (2018) found a value of 32.9 % in a Belgian study. Peter et al. (2016) reported values up to 30 % at HPP Rheinfelden on the Rhine river. Bunt et al. (2012) found average attraction efficiencies of 66 % for different species and different types of fish passes. Both entrances at Schiffmühle were equally used and entrance efficiencies were high for both types. But there was a difference between species in the preference of the fish pass type. The entrance efficiency was higher in the VSFP. The passage efficiencies for the whole fish pass is very high (81.4 %). Bunt et al. (2012) reported a passage efficiency of 45 % for VSFPs and 70 % for NLFPs. The duration of passage is less than 60 minutes for most of the species, so that the passage can be classified as fast. No length selectivity was observed. In summary, both fish passes (VSFP & NLFP) at Schiffmühle are assessed to be functional. All the parameters can be characterized as good or very good. The two entrances complement each other, both are preferred by different species. However, the attraction efficiency could not be tested for salmonids.

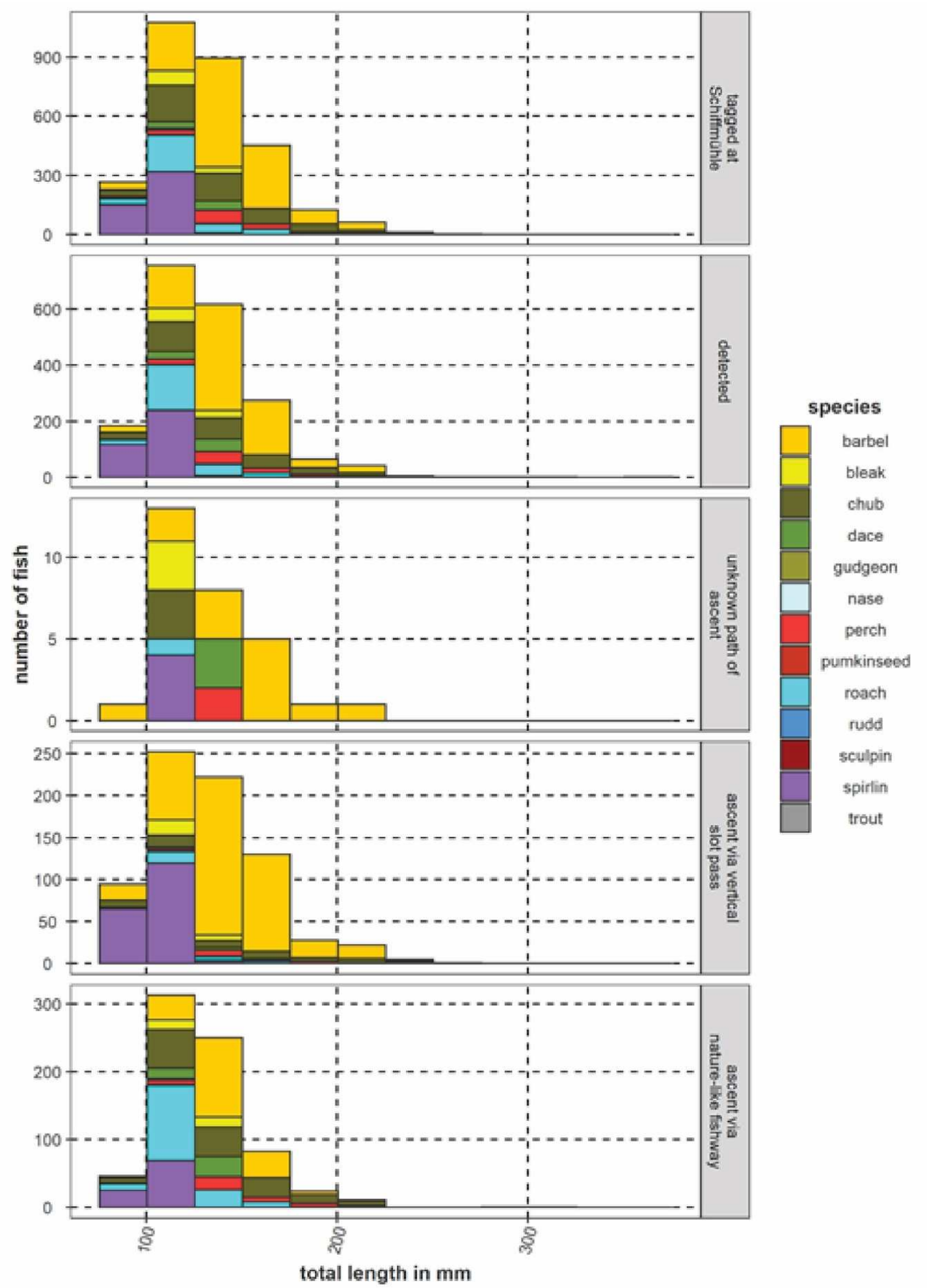

Figure 15: Overview of length distribution of all tagged fish caught in the counting facilities.

Table 2: Monitoring results of fishes caught in the counting facilities. VSFP= vertical slot fish pass, NLFP=nature-like fish pass.

species	N tagged	N detected	N entered	Unknown path of ascent	Acscended in VSFP	Ascended in NLFP	Attraction efficiency of VSFP in %	Entrance efficiency of VSFP in %	Passage efficiency of VSFP	Attraction efficiency of NLFP in %	Entrance efficiency of NLFP	Passage efficiency of NLFP	Attraction efficiency of whole fishpass in %	Entrance efficiency of whole fishpass in %	Passage efficiency of whole fishpass in %
chub	496	292	281	3	50	158	14.3	100	70.4	50.8	90.9	69	58.9	96.2	75.1
Brown trout	2	2	1	0	1	0	50	100	100	50	0	-	100	50	100
barbel	1278	806	777	13	442	202	42.3	97.8	83.6	24.3	84.2	77.4	63.1	96.4	84.6
perch	134	90	88	2	17	41	23.1	100	54.8	50.7	95.6	63.1	67.2	97.8	68.2
bullhead	3	0	0	0	0	0	0	-	-	0	-	-	0	-	0
gudgeon	16	1	0	0	0	0	0	-	-	6.2	0	-	6.2	0	0
dace	82	73	64	3	6	46	9.8	100	75	79.3	84.6	83.6	89	87.7	85.9
bleak	105	76	74	3	25	29	35.2	100	67.6	40	90.5	76.3	72.4	97.4	77
nase	5	3	2	0	0	2	0	-	-	60	66.7	100	60	66.7	100
roach	291	237	213	1	23	156	16.2	100	48.9	69.1	87.6	88.6	81.4	89.9	84.5
rudd	3	2	1	0	1	0	33.3	100	100	33.3	0	-	66.7	50	100
spirlin	472	361	354	4	187	94	49.8	99.1	80.3	38.3	90.1	57.7	76.5	98.1	80.5
pumpkinseed	3	3	3	0	2	1	100	66.7	100	33.3	100	100	100	100	100
Total	2890	1946	1858	29	754	729	33.7	98.5	78.5	39	87.9	73.6	67.3	95.5	81.4

Table 3: Duration of passage (in minutes) from the last registration at the lowest antenna until the first registration at the upper antenna at the exit of the VSFP.

species	average	median	minimum	maximum	N
eel	76.1	76.1	76.1	76.1	1
chub	77.5	38.0	15.0	927.4	53
Brown trout	29.4	29.4	29.4	29.4	1
barbel	217.9	62.6	12.2	28809.0	434
perch	71.4	59.8	19.6	217.9	17
dace	33.2	29.0	14.2	67.0	6
bleak	70.4	42.3	18.0	580.8	24
roach	61.5	42.4	16.0	429.5	23
rudd	52.8	52.8	52.8	52.8	1
spirlin	1549.6	136.7	15.0	53952.9	179
pumpkinseed	759.9	759.9	106.4	1413.4	2

Table 4: Duration of passage (in minutes) from the last registration at the lowest antenna until the first registration at the upper antenna at the exit of the NLFP.

species	average	median	minimum	maximum	N
chub	191.1	56.8	6.4	7844.3	182
barbel	252.5	97.4	24.5	8406.1	196
perch	225.9	88.7	31.0	926.6	33
dace	56.0	47.8	22.4	211.3	47
bleak	109.1	62.9	22.2	764.0	27
nase	290.0	290.0	96.3	483.6	2
roach	117.6	69.2	27.6	1408.3	148
spirlin	1225.8	639.5	36.4	21518.8	77
pumpkinseed	88.4	88.4	88.4	88.4	1

Downstream fish passage

During the whole study period (29 months) only 2 individuals used the Bypass System (BS) of the Horizontal Bar Rack (HBR) installed at the residual flow HPP Schiffmühle: one barbel with a total length of 151 mm and one spirlin with 96 mm. However, other downstream corridors were used more often.

A total of 445 downstream fish movements were observed. 178 fish (40%) used the fish passes for downstream movement. The VSFP had a double downstream migration frequency compared to the NLFP. 265 unknown fish descents were detected corresponding to 60% of the total number of the downstream moving fish (Table 5). These fish were using either the side weir along the headrace channel, the movable weir next to the residual flow HPP or the turbines of the main or residual flow HPP as a downstream migration corridor. They were later again detected on the antennas in the fish passes, indicating that they have survived from the unknown decent paths.

Overall, the BS of the HBR for the downstream migration is not functional. Fish should be guided to enter the bypass by the 20 mm HBR. On the one hand, the pipe of the BS is often clogged with woody debris. On the other hand, the flow field between the HBR and the BS entrance and from there to the entrance of the bypass pipe is not favourable. In addition, the velocity increase in the bypass pipe is very high. Therefore, the bypass can be regarded to have no function for downstream moving fish. From the ecological point of view, it is questionable if there has to be a functional bypass into the residual flow section. However, building a downstream fish protection and guidance system at the main HPP is important and should be considered (see the discussion and conclusion sections below).

Table 5: Origin of downstream moving fishes. Some individuals were counted several times if they used different corridors or the same corridor more than once.

	HPP Aue upstream of Schiffmühle	Schiffmühle forebay	Schiffmühle tailrace	Schiffmühle counting facility	Total
Descent in the bypass system (BS)	0	0	0	2	**2**
Descent in nature-like fishway	0	1	0	55	**56**
Descent vertical slot pass	0	1	1	120	**122**
Unknown descent	4	6	10	245	**265**
Total	**4**	**8**	**11**	**422**	**445**

3.2 Results of ADCP measurements

During the field measurements, the discharge in the river Limmat slightly fluctuated around Q_r = 49 m^3/s in October 2018. The discharge of the residual flow HPP was around 8 m^3/s and the total discharge in the residual flow reach was approx. 10 m^3/s including the discharges from the HPP, fish passes, downstream bypass flow and the side weir along the headwater canal. As a result, the discharge in the headrace channel was approx. 39 m^3/s.

Figures 16 to 18 show the flow depths, river reach bathymetries and upstream and downstream depth average flow velocities, respectively. The bathymetry data were used to construct the 3D numerical model (Figure 17). At the upstream right bank of the river, the water depth is shallow and continuously deepens towards the left bank and the residual flow HPP Schiffmühle (Figure 16). The water depth deepens along the power canal and reaches its maximum of 5 m in front of the main power house. In the residual flow reach, the water depth is approx. 2 m at the turbine exit and becomes shallower along the river up to the location of the vortex tube. Downstream of the vortex tube, the water depth deepens until downstream of the main powerhouse.

Figure 18 shows the depth-averaged flow velocity distribution in the upstream and downstream flow reaches of the HPP Schiffmühle. At the furthest upstream of the HPP, the flow velocity is around 60 cm/s and slightly increases towards the HPP and the headrace channel. It slightly decreases along the power canal as the water depth deepens (Figures 16 and 18). The flow velocity increases from downstream of the residual flow HPP up to the entrance of the fish pass and reaches its maximum of 250 cm/s. Downstream of that location, it gradually decreases along the river reach until downstream of the main power house.

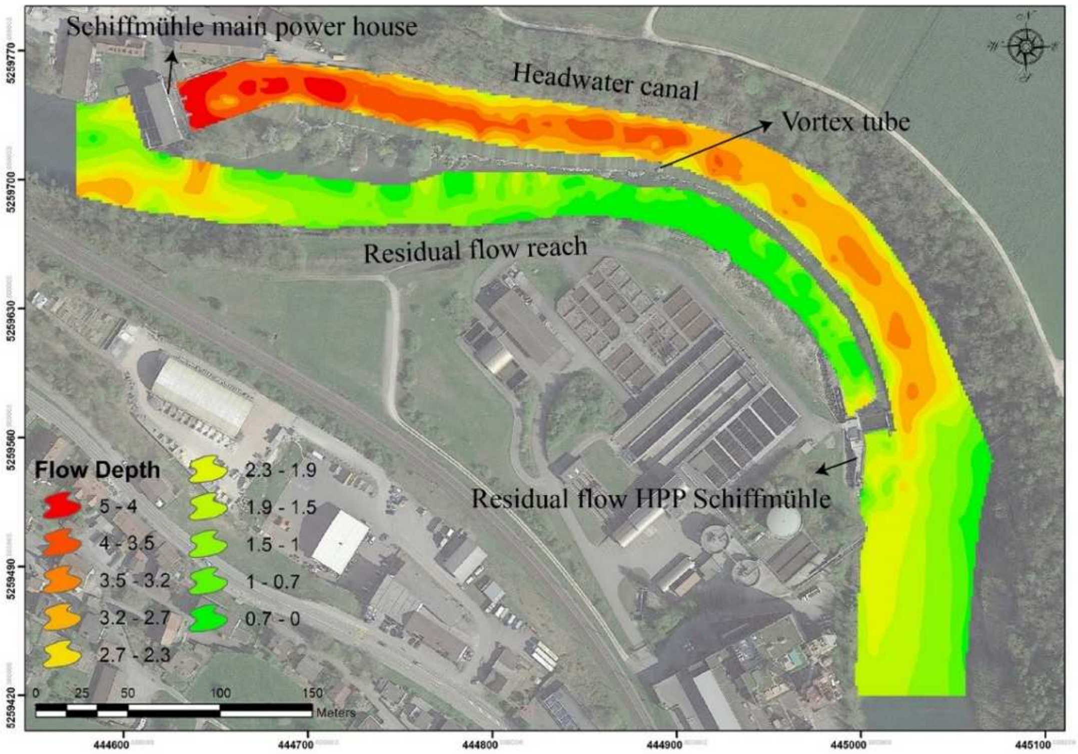

Figure 16: Flow depths upstream and downstream of the HPPs Schiffmühle.

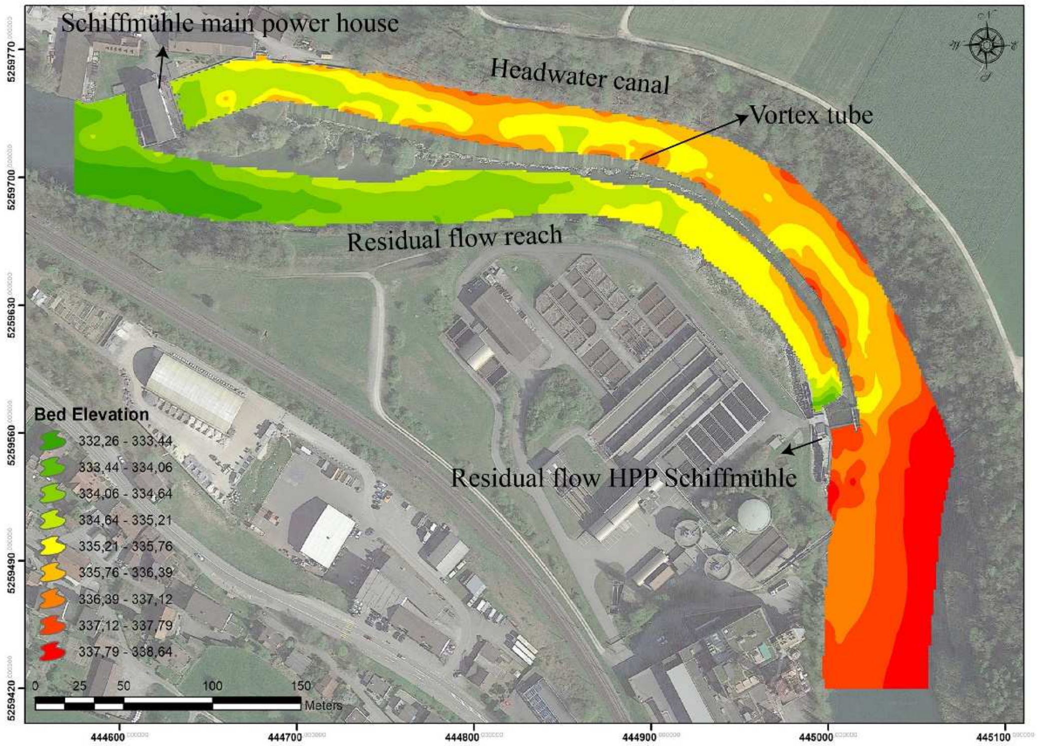

Figure 17: Bed elevations (bathymetry) upstream and downstream of the HPPs Schiffmühle.

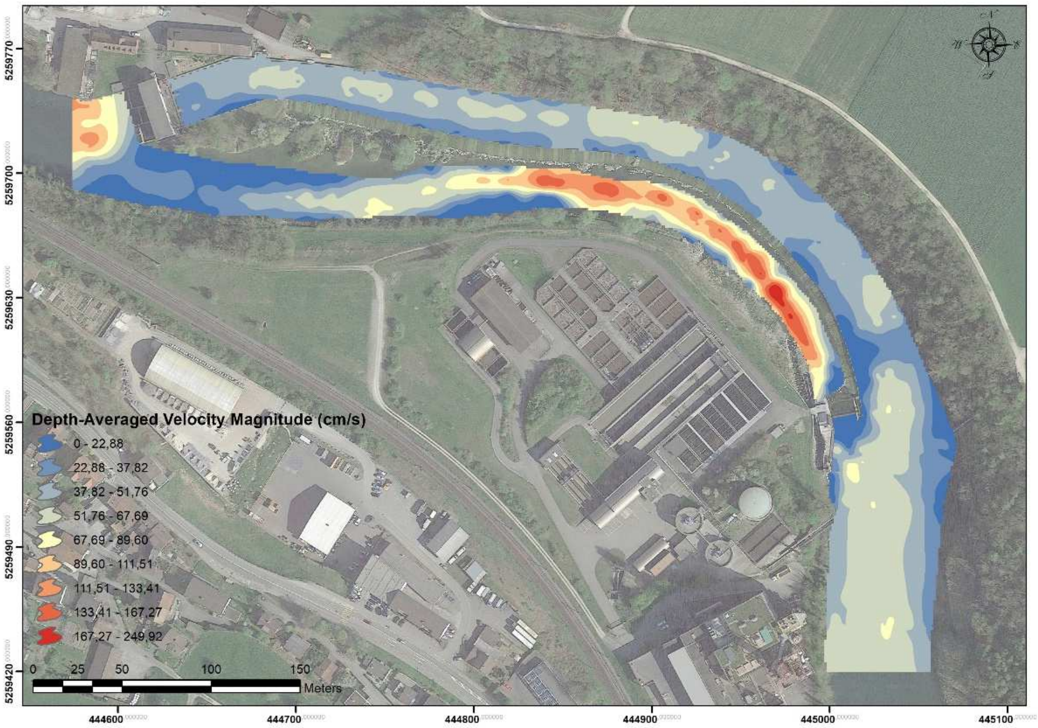

Figure 18: Depth-averaged flow velocities of upstream and downstream flow reaches of the HPPs Schiffmühle.

Figure 19 shows the depth-averaged velocity distribution and streamlines around the residual flow HPP measured in October 2018. The flow velocities are high just upstream of the HPP close to the left bank of the river. Velocities slightly decrease towards the turbine intake. A discharge of 8 m^3/s goes into the turbine intake and a little flow goes towards the weir and the bypass inlet. The rest of the flow, i.e., about 41 m^3/s, goes into the headrace channel corresponding to about 80% of the river discharge. As indicated with red arrows in Figure 19, fish moving in most part of the river are expected to follow the mainstream towards the headrace channel, while a portion moving close to the left shore swims towards the residual flow HPP. When fish arrive at that HPP, it is likely that they do not find the bypass entrance because of the re-circulation zone and low velocities between the weir and the bypass inlet compared to high flow velocities at the turbine intake (Figures 19 and 20). The design discharge of the bypass is 0.170 m^3/s and the computed corresponding average velocities in front of the bypass, at two rectangular bypass openings and in the pipe are approx. 0.35 m/s, 2 m/s and 3.46 m/s, respectively. However, the ADCP field data show that the velocity in front of the bypass is around 0.10 m/s instead of 0.35 m/s (Figure 20). To confirm this result, we measured velocities inside the bypass. The average flow velocity at the two rectangular bypass openings was 0.66 m/s and the total bypass discharge amounted to 0.055 m^3/s. For this bypass discharge, the computed average flow velocity in front of the bypass is 0.11 m/s, which is in agreement with the ADCP measurement. The measured bypass discharge is less than 1/3 of the bypass design discharge, which is likely due to clogging of the bypass pipe. Although the bypass pipe entrance is regularly cleaned according to the operator, the regular clogging seems to be unavoidable. Overall, due to mainly the re-circulation zone, low flow velocities in front of the bypass as well as almost zero tangential velocity between the turbine and bypass intakes, the fish guidance efficiency of the bypass system is expected to be low. We discuss this result together with the fish monitoring result in the next subsection and present alternative solutions studied with 3D numerical modeling.

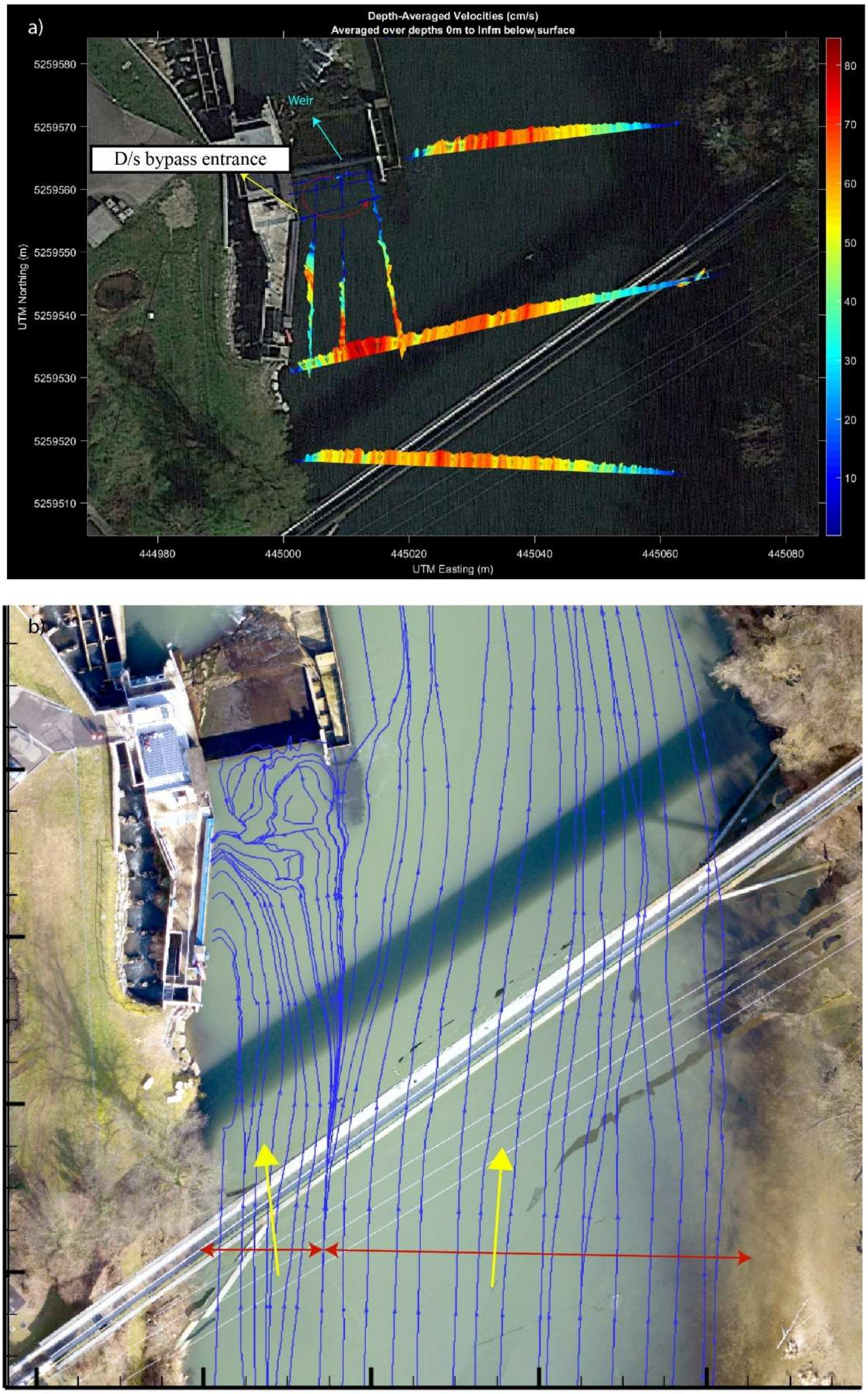

Figure 19: Depth-averaged velocity profiles (a) and streamlines (b) from ADCP measurements at HPP Schiffmühle in October 2018.

Figure 20: Velocity distribution along the HBR-BS in October 2018.

3.3 Numerical model results

3.3.1 Validation of 3D model

The validation of the 3D model was made by comparing the ADCP data of VAW from velocity field measurements during March and October 2018. For the residual flow reach, the data from March 2018 were used, since the bathymetry was similar to the numerical model. For the headrace channel and the river discharge, the data from October 2018 were used, since the gravel depositions in the power channel were already removed by excavation and the bathymetry in the numerical model is the same.

For the numerical validation the following discharges were used, corresponding to the discharges measured with ADCP in October 2018:

- River Limmat discharge: Q_r = 45 m^3/s
- Residual flow HPP turbine discharge: Q_t = 8 m^3/s and discharges at fish passes and the bypass system: $Q_{f=}$ 0.50 m^3/s and Q_b = 0.17 m^3/s, respectively
- Discharge of the main HPP: Q_m = 36.66 m^3/s

General Comparison

First some general comparisons between the measured and the modelled data are executed. The measurements were conducted in October 2018. The flow pattern and magnitude of the compared data sets match fairly well as shown in Figure 21. Figure 22 indicates the streamlines in front of the intake of the residual flow HPP and the bypass system. The main current flows through the rack into the power plant. In front of the weir streamlines build turbulent structures and backwater patterns. The graphical representations of the streamlines from measured and modelled data are in a good agreement. The measured water level in the Limmat river at the gauging station just upstream of the fish vertical slot pass inlet matches the water level value from the model (2 cm difference, compared to Figure 23).

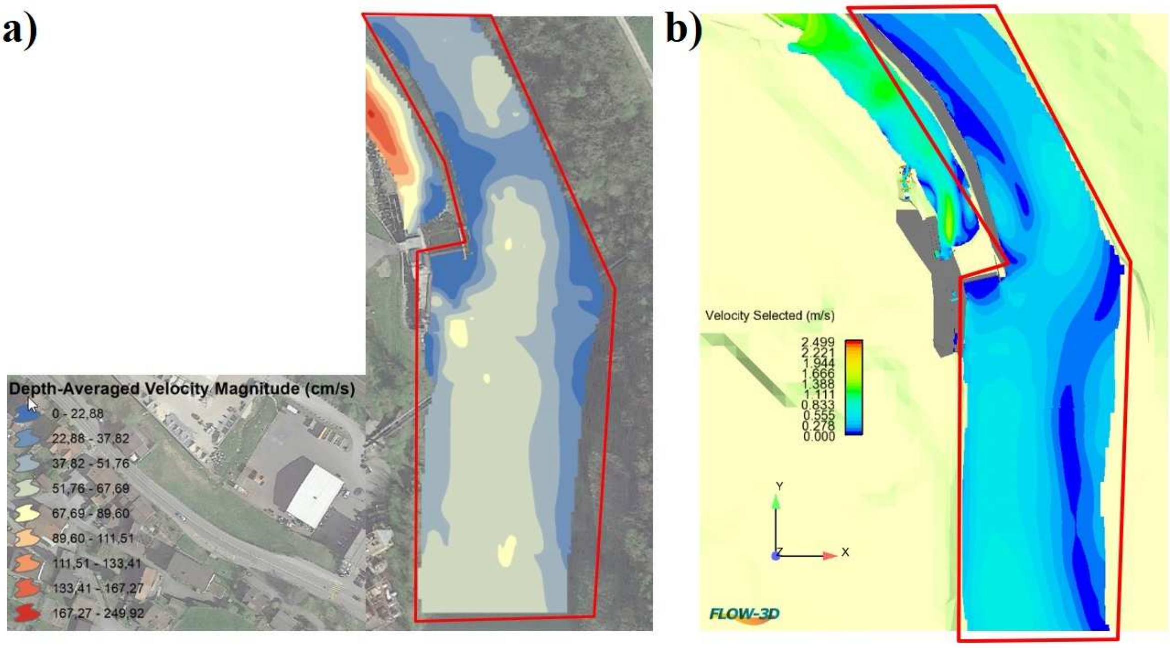

Figure 21: Velocity distributions in front of HBR-BS from ADVP data (a) and numerical model (b).

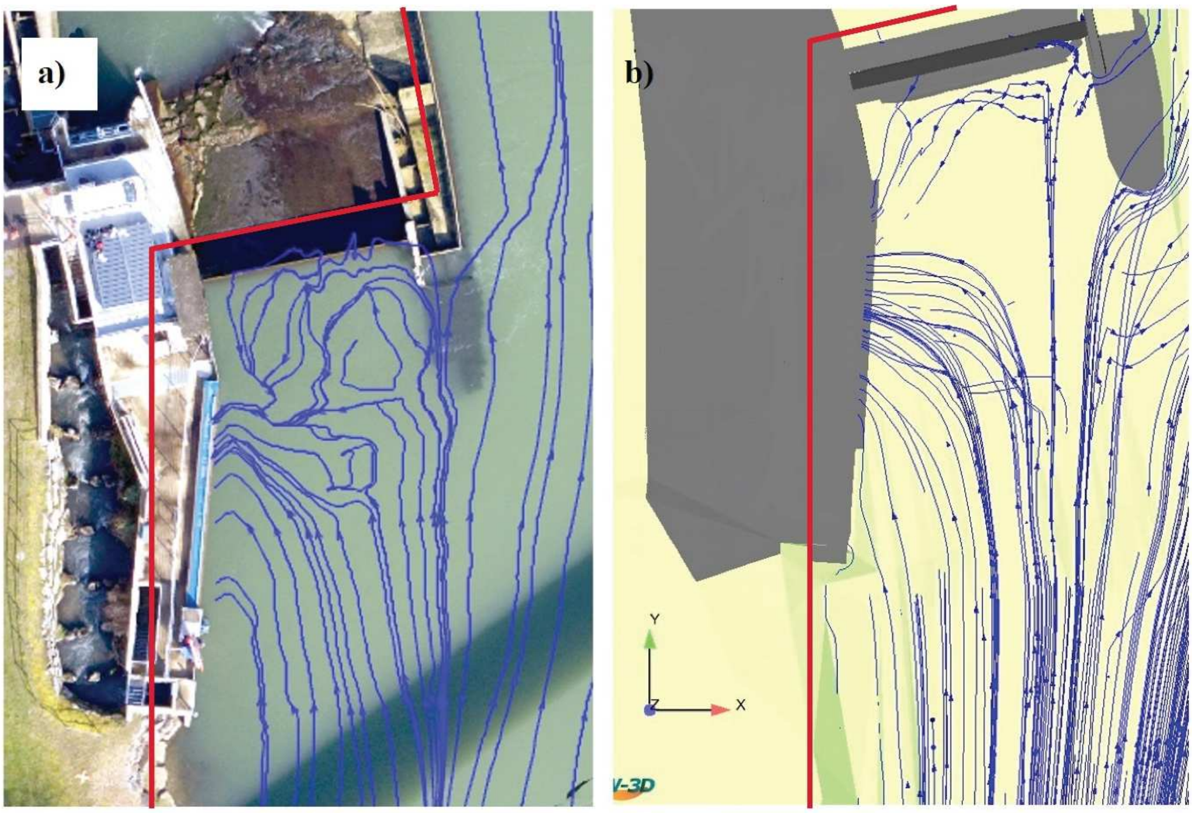

Figure 22: Streamlines in front of HBR-BS from ADVP data (a) and numerical model (b).

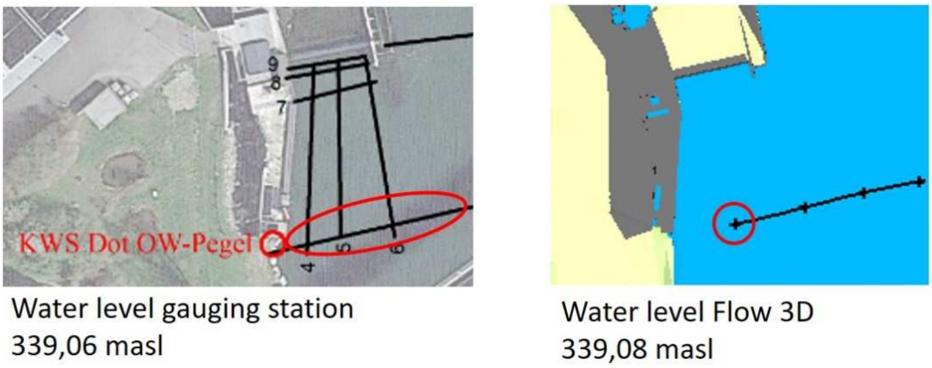

Figure 23: Streamlines in front of HBR-BS from ADVP data (a) and numerical model (b).

Velocity in Cross Sections

An optical validation of flow velocities on significant cross sections is highlighted in Figure 24. The cross-sectional velocity distributions at cross section 3 and 7 are shown in Figures 25 and 26, respectively.

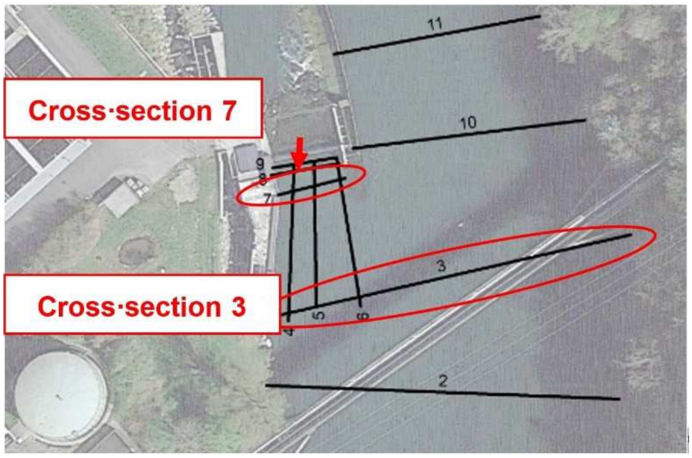

Figure 24: Cross sections for comparison between ADCP and numerical model data.

Figure 25 shows the streamwise velocity distribution from the ADCP measurements and numerical model (in case of the 3D model in y-direction) at cross section 3. The highest flow velocities (~0.6 m/s) are located right in front of the residual flow HPP, whereas the flow velocities decline towards the right boundary (~0.4- 0.1 m/s). The numerical model velocity data match fairly well with the ADCP data at this location.

Figure 26 shows the streamwise velocity distribution from the ADCP measurements and numerical model (in case of the 3D model in y-direction) at cross section 7 in front of the weir of the residual flow HPP. The flow velocities are quite low and even a reverse flow at the left part around the inlet of the bypass occurs. The highest flow velocities (~0.2 m/s) are located on the right side, close to the central pillar between the residual flow channel and the headrace channel. Right in the middle of the channel the river water is accumulated and the flow velocity declines towards 0 m/s. Once again, the numerical model velocity data match fairly well with the ADCP data at this cross section.

It is clearly seen from Figures 25 and 26 that typical flow patterns, like maxima, minima of the velocities and flow distribution over the cross section, are similar between the ADCP and numerical data. Water flow is only tangible for a constant point of time since flow velocity pulsates in the system. The ADCP measurements deliver a representation of a current situation, which equals the flow velocity at a particular time serving as an auxiliary value. Therefore, the modelled and measured data can differ slightly. It is concluded that the flow velocity pattern matches the measured data in general and the validation process was successful.

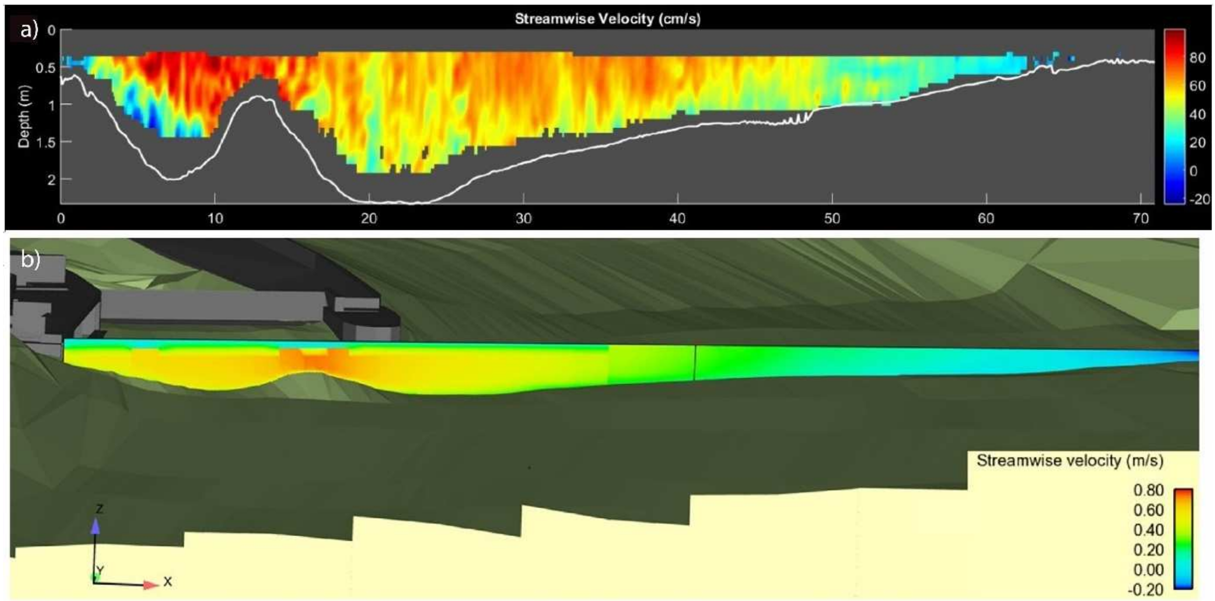

Figure 25: Streamwise velocity distribution from ADCP measurements (a) and numerical model (b) at cross section 3 (see Figure 24).

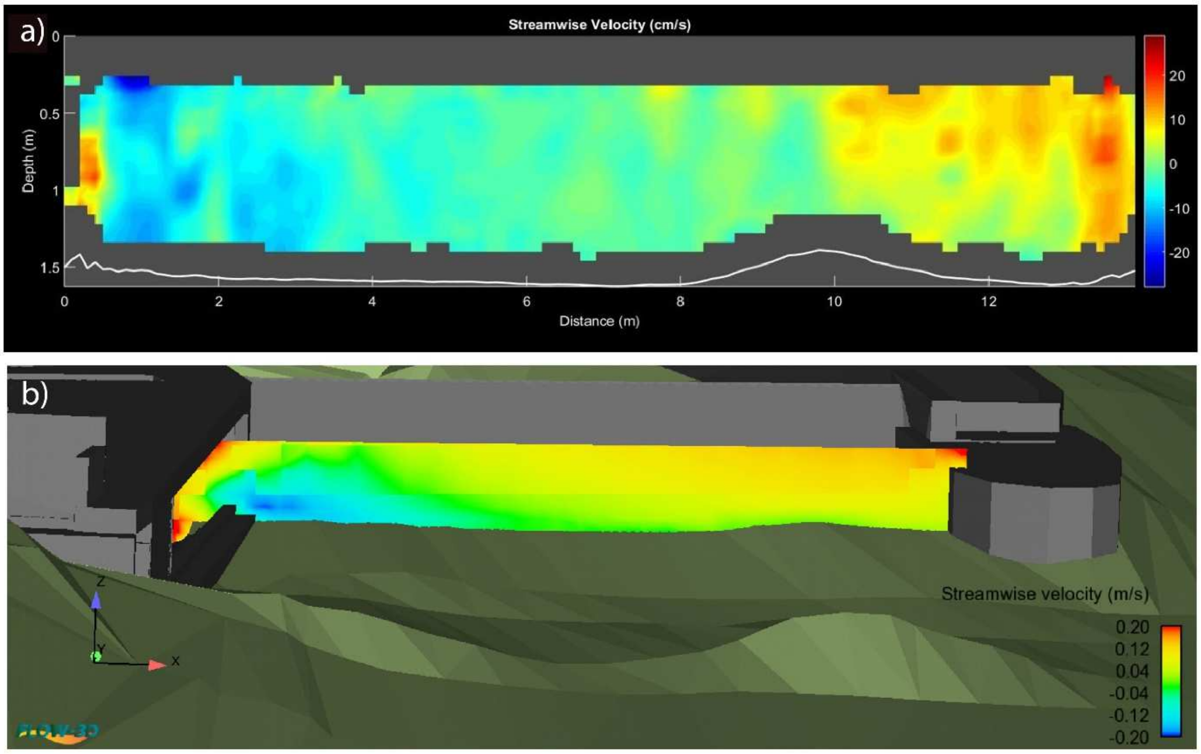

Figure 26: Streamwise velocity distribution from ADCP measurements (a) and numerical model (b) at cross section 3 (see Figure 24).

3.3.2 Simulations for improvement of HBR-BS

To improve the fish downstream passage through the HBR-BS at HPP Schiffmühle, four different alternative bypass systems were designed and numerically modelled.

These four variants were developed based on the bypass design of the residual HPP Rüchlig on the Aare river in Switzerland. Note that the dimensions differ since the design discharge at HPP Schiffmühle is much lower than at HPP Rüchlig. All variants of the bypass include a separation wall at the left-hand side of the weir, which generates a bypass channel with an approximate width of 0.5 m.

The first variant includes a vertical-axis bypass flap gate with top and bottom openings placed 2 m downstream of the new bypass channel inlet (Figure 27a). The gate can be fully opened to flush driftwood and floating debris when the cleaning machine works. Moreover, the exiting movable weir is modified with a 0.20 m deep and 0.50 m wide top opening to bypass fish across the weir. The second variant does not include a vertical-axis flap gate and hence makes the design even simpler. In this case, the existing end weir includes a top and a bottom opening to bypass fish to the tailwater (Figure 27b). The third variant has no gate but a 15° inclined ramp in the bypass channel reaching to the weir, which has a 0.50 m wide and 0.33 m high top opening to guide fish to the residual flow reach (Figure 28a). The fourth variant is similar to the third one with a vertical-axis bypass flap gate placed 1 m downstream of the new bypass channel inlet. The gate has two openings of 0.30 m by 0.30 m at the top and bottom near the right side wall (Figure 28b).

The flow fields of all modelled variants were numerically simulated for a river discharge of Q_r = 125 m³/s, a turbine discharge of Q_t = 14 m³/s of the residual flow HPP, a fish pass discharge of Q_f = 0.50 m³/s and a bypass discharge of Q_b ≈ 0.170 m³/s.

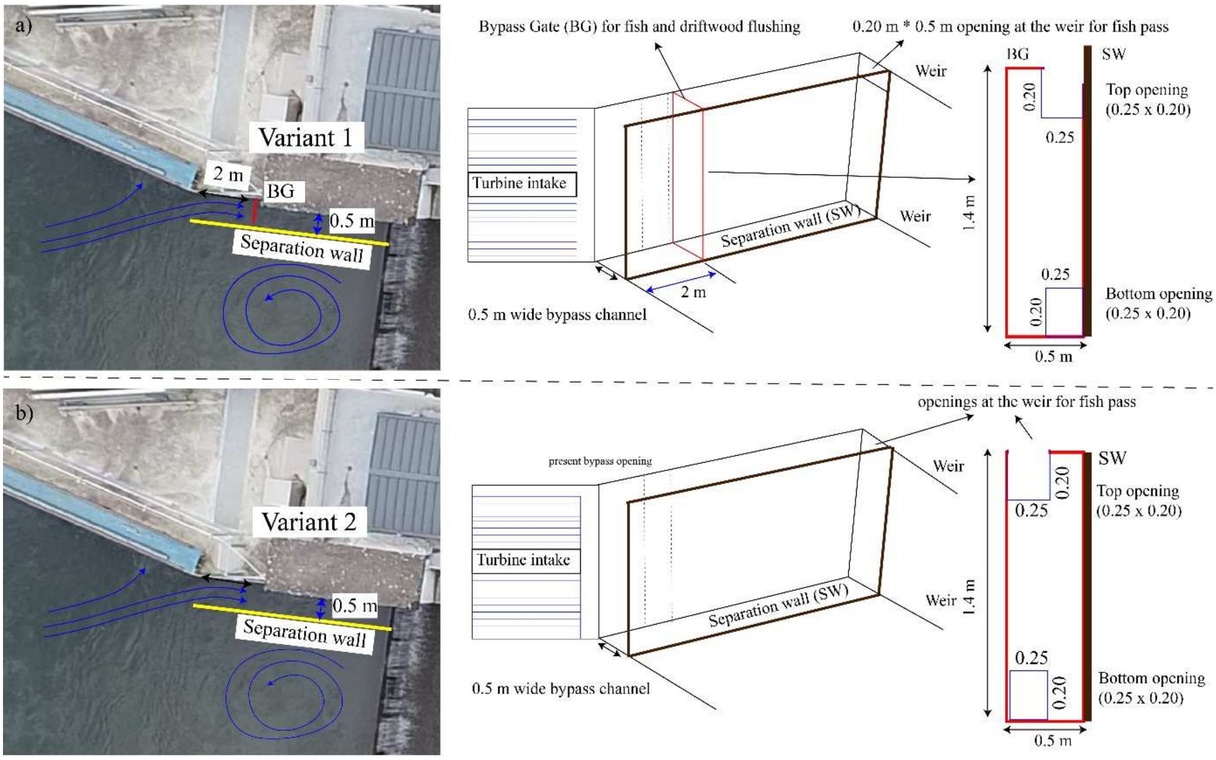

Figure 27:New bypass designs to improve the function of the HBR-BS at Schiffmühle HPP: variant 1 (a) and variant 2 (b).

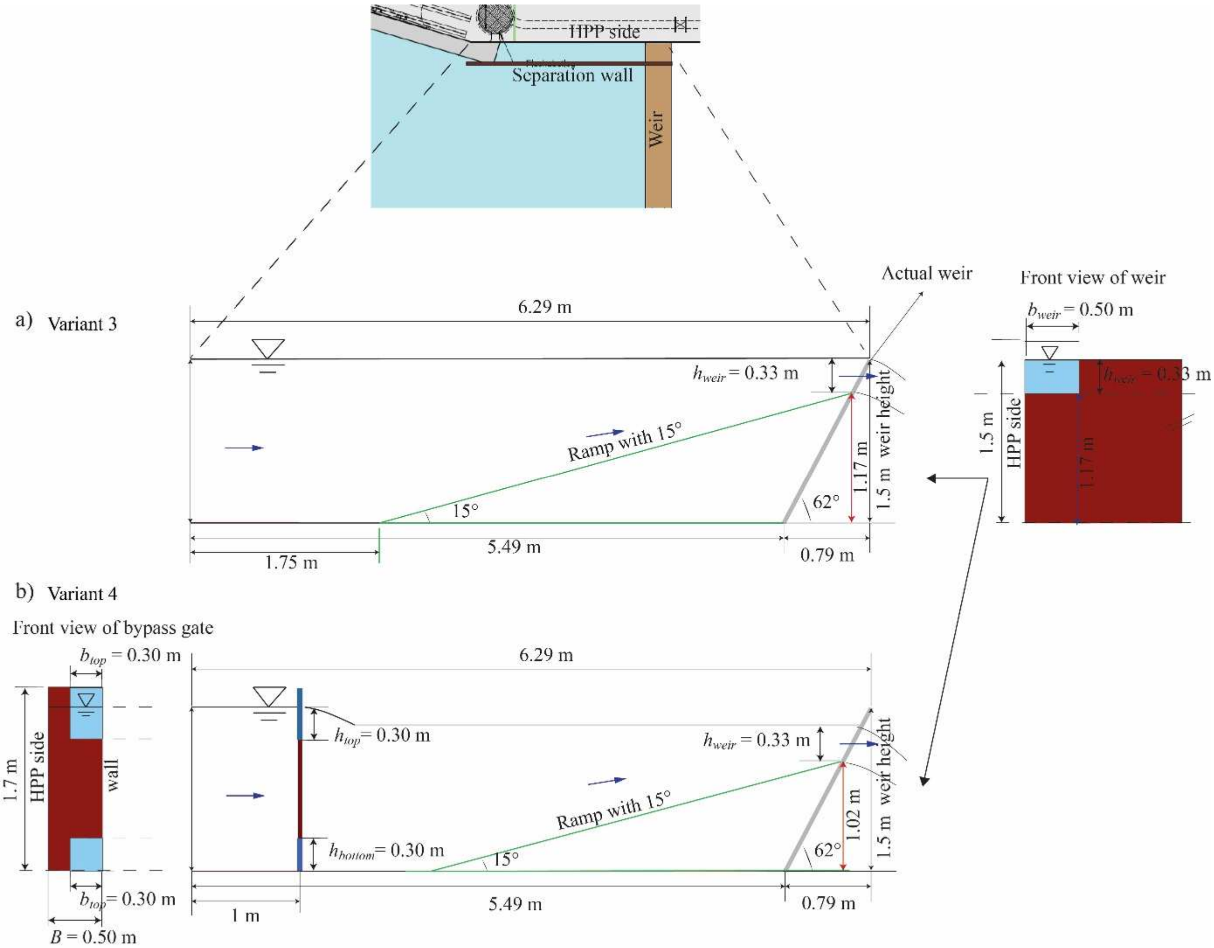

Figure 28:New bypass designs to improve the function of the HBR-BS at Schiffmühle HPP: variant 3 (a) and variant 4 (b)

Variant 1

Figure 29a shows the resulting velocity distribution with the streamlines in front of the residual flow HPP for variant 1. Similar flow structures occur for variant 2 but with different flow structures within the bypass channel (see below for the variant 2 section). With the new bypass design, the large return flow shown in Figure 22 is broken into two smaller counter-rotating vortices. Furthermore, a part of the flow going through the turbine is diverted to the entrance of the new bypass channel. Figure 29b shows the strong flow divergence towards to the entrance of the bypass channel.

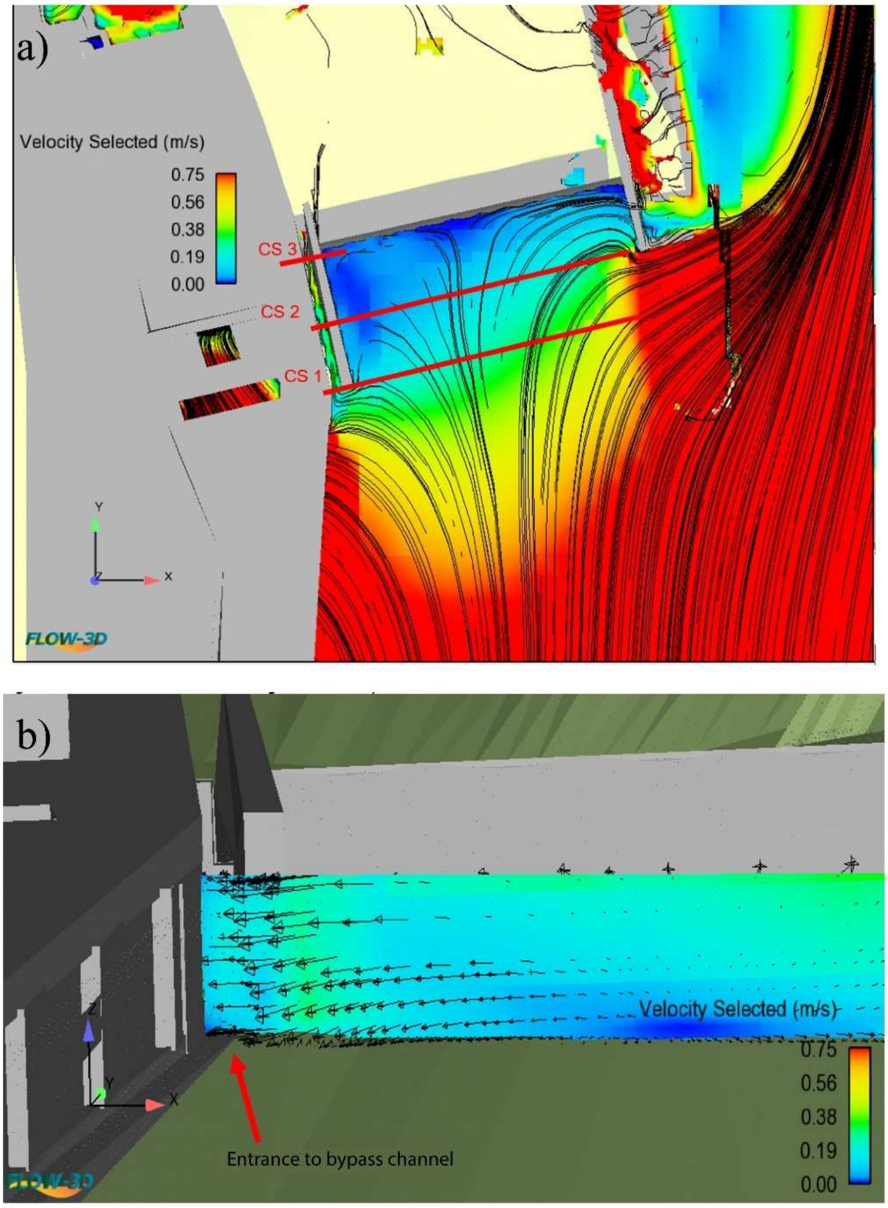

Figure 29: Resulting flow velocity distribution with streamlines for (a) variant 1 (new bypass design) and with 2D velocity vectors at (b) cross-section 1 (CS1).

The velocity normal to the rack, V_n, increases along the HBR and reaches 0.8 m/s near the bypass entrance before decreasing to around zero (Figure 30a and b). On the contrary, the velocity component parallel to the rack, V_p, decreases from the beginning of the turbine intake towards the bypass entrance (Figure 30c). V_p / V_n >1 at the left-hand side half of the turbine intake, indicating a good fish guidance (Courret and Larinier, 2008). However, along the right-hand side half of the turbine intake, this ratio reduces below 1, indicating a poor fish guidance (Figure 30c and d). Between the turbine intake and the bypass inlet this ratio becomes negative indicating fish guidance towards the intake (Figure 30d). From the turbine inlet along the bypass channel, V_p increases up to 0.60 m/s at the top opening of the bypass gate and then reduces towards the top opening at the weir (Figure 30d and e). Such flow conditions at the inlet and inside of the bypass channel are more favourable for fish than for the current bypass flow conditions with low flow velocities at the inlet of the bypass and a large circulation zone between the bypass and weir.

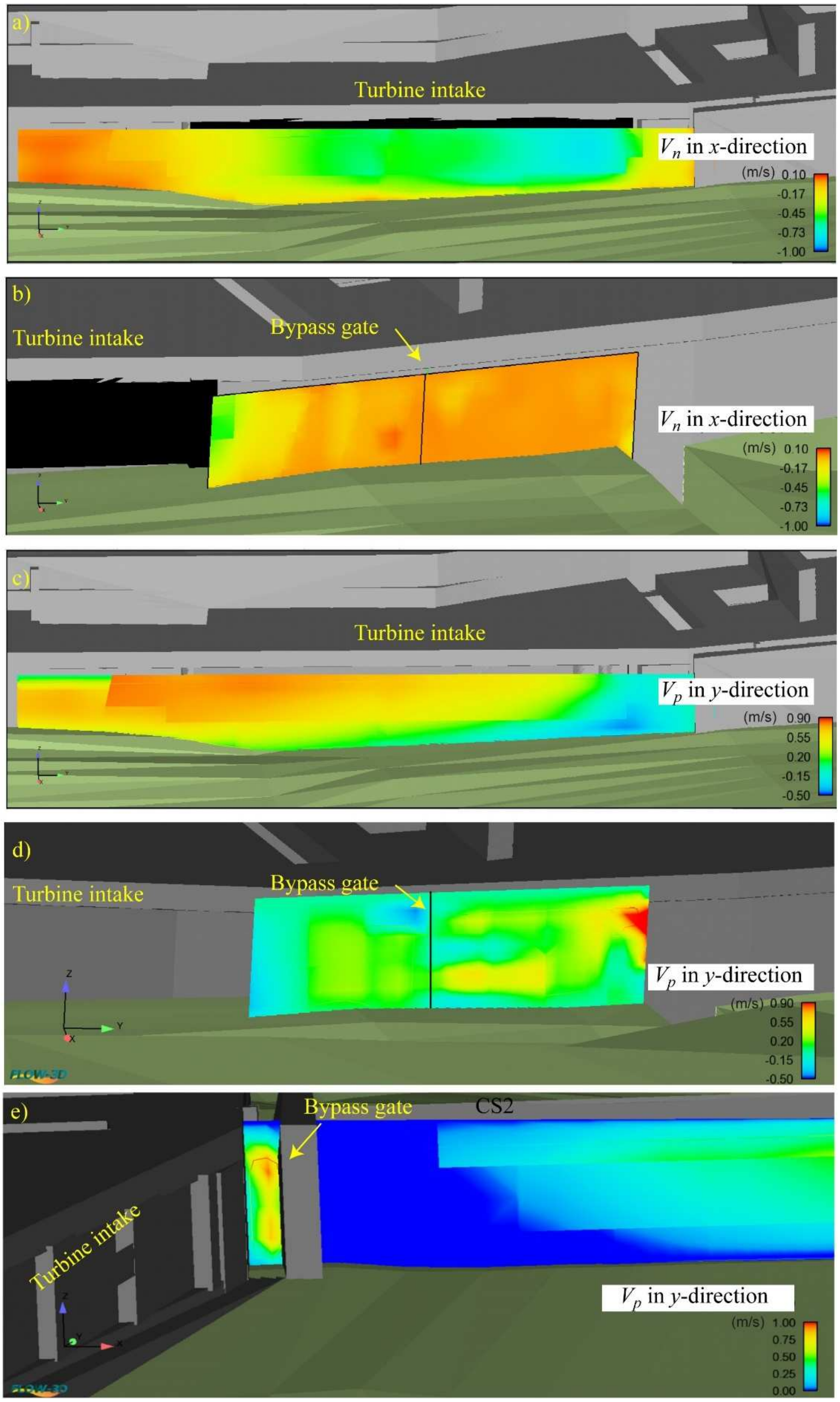

Figure 30: Distribution of normal velocities V_n, along the turbine intake (a) and the bypass channel (b), parallel velocities V_p along the turbine intake (c) and the bypass channel (d) and V_p at the bypass inlet (e) for variant 1.

Variant 2

Figure 31 shows the velocity fields for variant 2. Both normal and parallel velocity distributions in front of the turbine intake are similar to variant 1 (Figure 31a and c), while both velocity distributions deviate from variant 1 inside the bypass due to the lack of the bypass gate at the inlet of the bypass (Figure 31b and d). Only between the turbine intake and the bypass channel inlet, the flow conditions are not favourable to attract the fish towards the bypass. Despite this, V_p / V_n > 1, increasing towards the bypass openings at the weir, indicating a good fish guidance (Figure 31b, d and e). Overall, variant 1 and 2 show better results than the current bypass conditions.

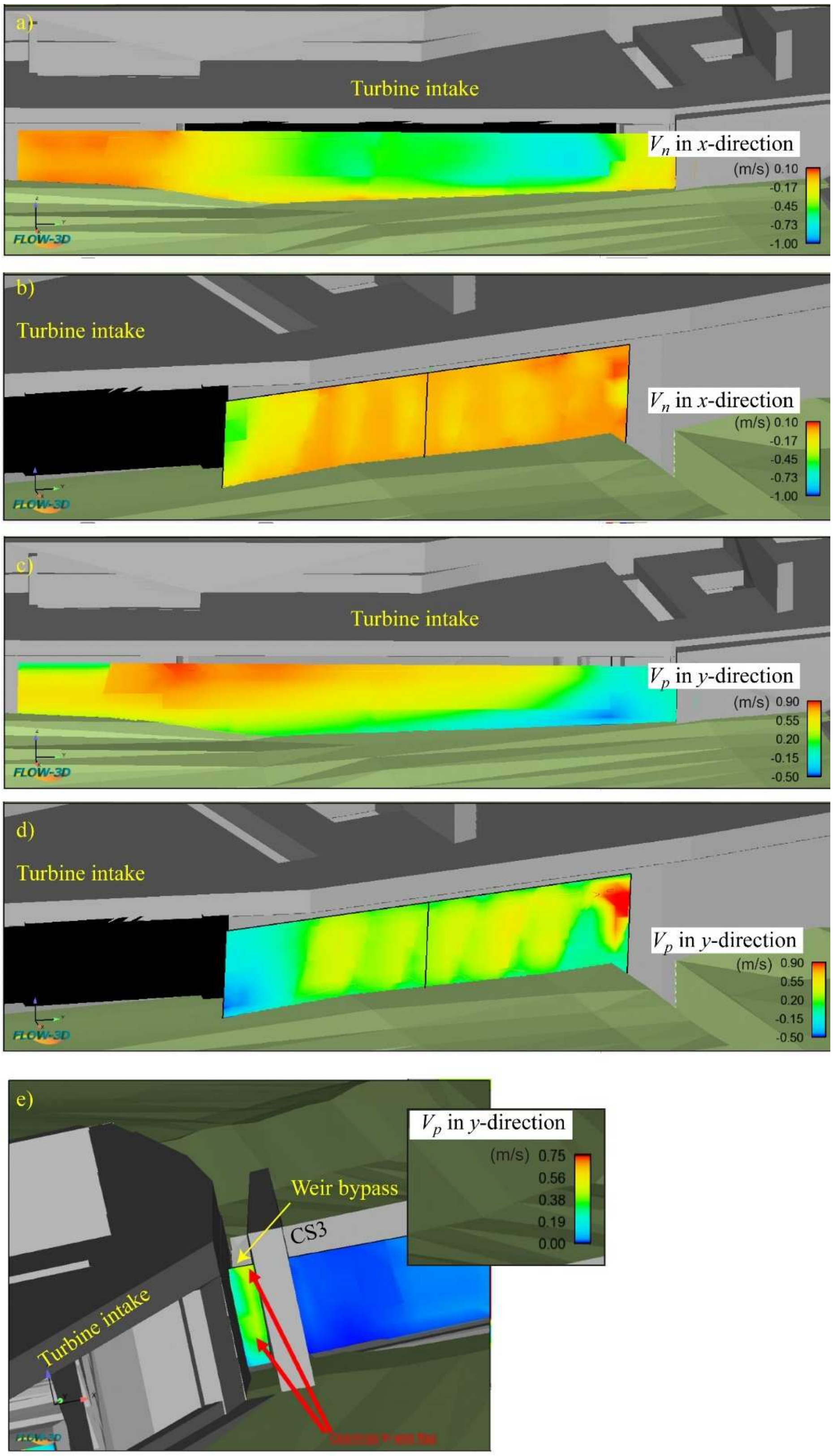

Figure 31: Distribution of normal velocities V_n, along the turbine intake (a) and the bypass channel (b), parallel velocities V_p along the turbine intake (c) and the bypass channel (d) and V_p at the bypass inlet (e) for variant 2.

Variant 3

Figure 32a shows the resulting velocity distribution with the 2D velocity vectors in front of the residual flow HPP for variant 3. With the new bypass design, the large return flow shown in Figure 22 is broken into two smaller counter-rotating vortices and a strong flow divergence occurs towards the entrance of the bypass channel. Overall, the flow field is similar to those of variants 1 and 2. Figure 32b shows the spatial velocity gradient (SVG) distribution. SVGs are higher than 1 s^{-1} near the end of the HBR where the flow is strongly diverted to the turbine and it is also higher than 1 s^{-1} at the end of the bypass channel near and above the weir opening. At those locations, it is expected that fish may show avoidance behaviour because of high local flow accelerations (Beck, 2020).

The velocity component parallel to the rack, V_p, decreases from the beginning of the turbine intake towards the bypass entrance (Figure 33a). On the contrary, the velocity normal to the rack, V_n, increases along the HBR and reaches 0.75 m/s with a circulating flow pattern near the end of the HBR before decreasing to around 0.08 m/s (Figure 33a and b). Since $V_n > V_{\text{sustained}}$ = 0.50 m/s (Ebel, 2016), fish are expected to be at risk to be entrained into the turbine or impinge on the rack in the high normal velocity zone.

Figure 33c shows that V_p / V_n >1 at the left-hand side half of the turbine intake, indicating a good fish guidance (Courret and Larinier, 2008). However, along the right-hand side half of the turbine intake, this ratio reduces to below 1 and even becomes negative near the river bed between the HBR and the bypass inlet, indicating a poor fish guidance capacity (Figure 33c). The spatial velocity gradient distribution (Figure 33d) shows strong velocity gradients near the bed between *SVG* = 1 and 0.75 s^{-1} whereas the velocity gradient is mild near the water surface. SVG is also mild being around 0.25 s^{-1} between the HBR and the bypass inlet showing an unattractive flow pattern for fish to find the bypass (Figure 33d).

The distribution of different flow quantities along the bypass channel at the centre line (Figure 34a) is shown in Figure 34. From the turbine inlet along the bypass channel, V_p increases from 0.15 m/s up to 0.90 m/s at the top opening at the weir (Figure 34b). The mean flow velocity at the bypass entrance is 0.429 m/s for a bypass discharge of Q_r = 0.232 m^3/s. The inflow velocity at the turbine intake is around 0.75 m/s (Figure 32a). The ratio between the bypass to the approach flow velocities (bypass Velocity Ratio = *VR*) is *VR* = 0.429/0.75= 0.57, which is well below the recommended values of 1.2-1.4 by Beck (2020) and Beck et al. (2020c), 1-0-2.0 by Ebel (2016) and 1.1-1.5 by USBR (2006). The normal velocity V_n, is near zero as expected but with some velocity patches smaller than 0.25 m/s (Figure 34c). Such patches likely stem from the low resolution of the numerical model. The SVG distribution in the flow direction ranges from 0 to around 1.25 s^{-1} with higher values up to 5 s^{-1} at the top of the weir opening where hesitation of fish passing the weir is expected (Figure 34d). Compared to the current flow condition, variant 3 creates a better flow field but does not satisfy the recommended values of SVG and *VR* (Beck, 2020).

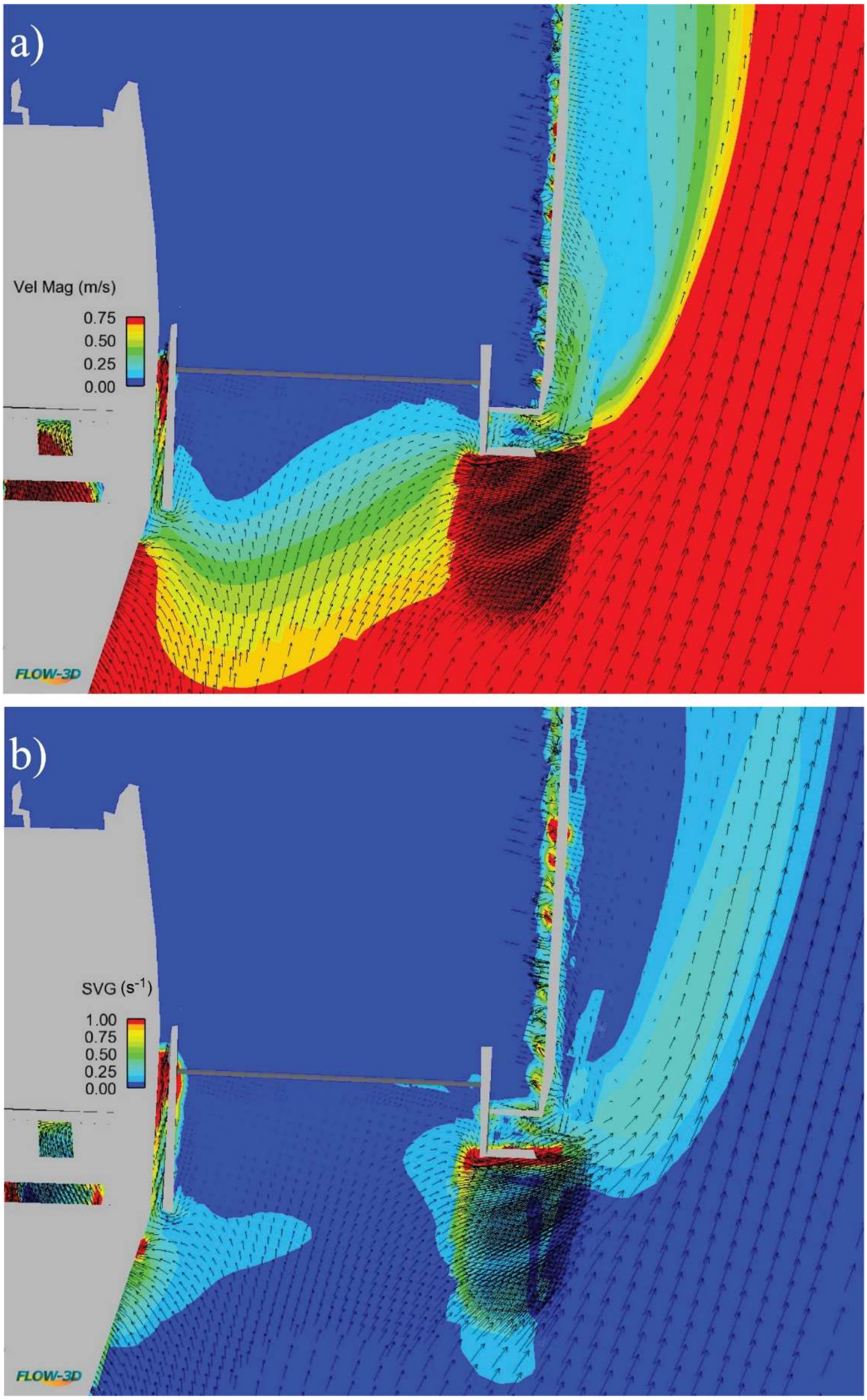

Figure 32: Resulting flow velocity distribution (a), spatial velocity gradient (*SVG*) (b) with 2D velcoity vectors at the horizontal level 0.285 m below the water surface for variant 3.

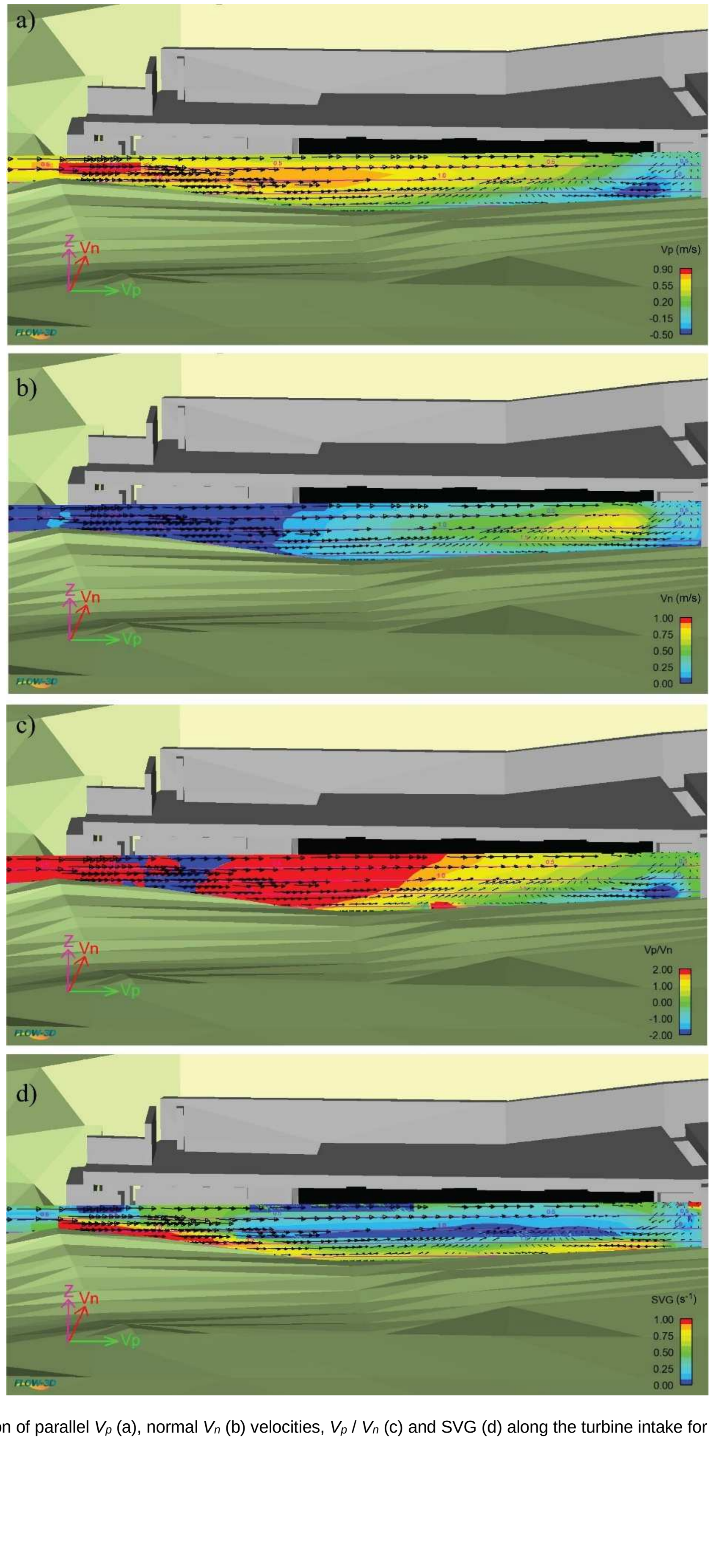

Figure 33: Distribution of parallel V_p (a), normal V_n (b) velocities, V_p / V_n (c) and SVG (d) along the turbine intake for variant 3.

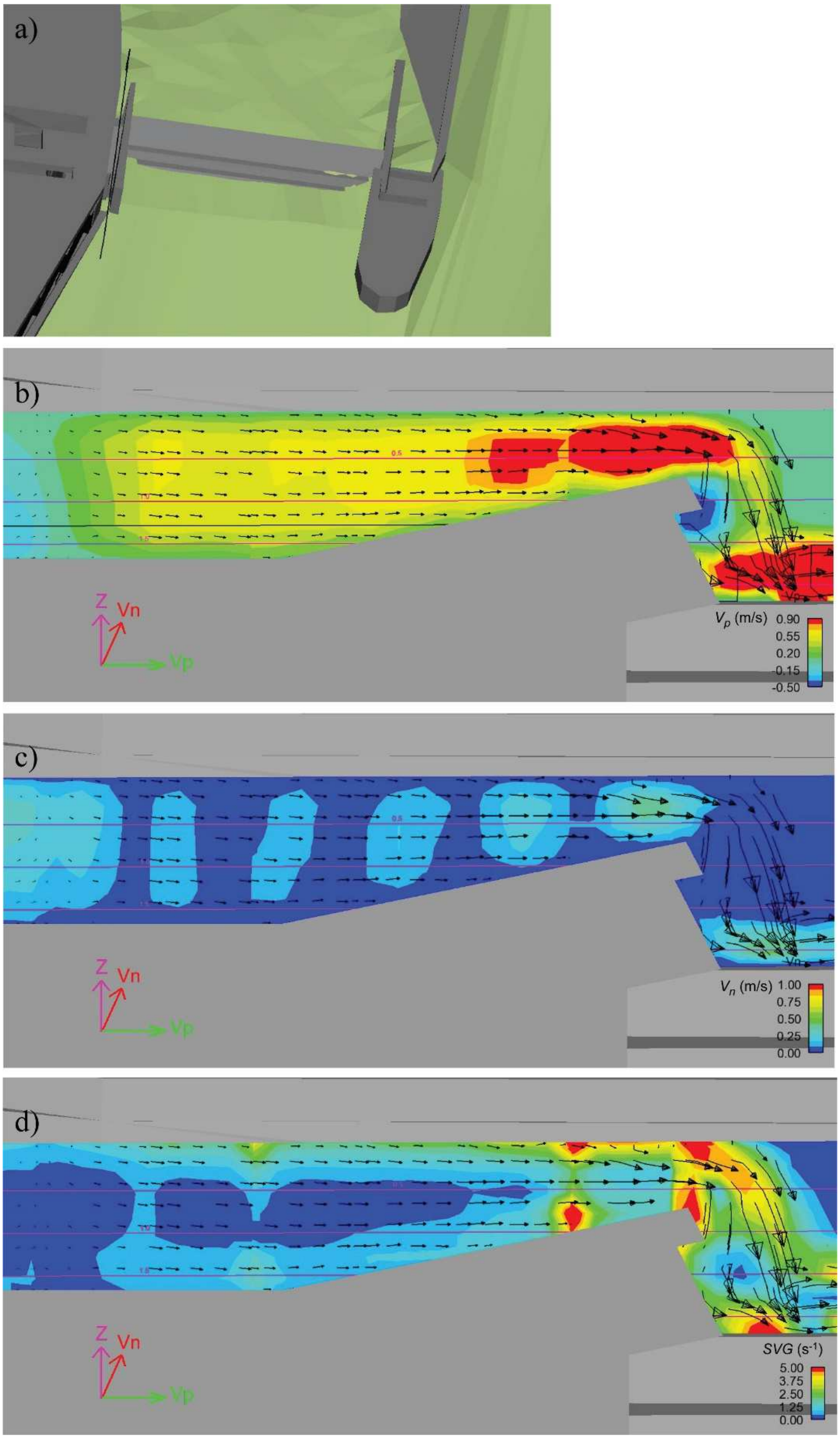

Figure 34: Plane location (a), distribution of parallel V_p (b), normal V_n velocities (c) and SVG (d) along the bypass channel for variant 3.

Variant 4

Figure 35a shows the resulting velocity distribution with the 2D velocity vectors in front of the residual flow HPP for variant 4. Overall, the flow field is similar to those of variants 1, 2 and 3 except near the bypass inlet. At the bypass inlet, the vertical-axis gate causes high flow velocities and acceleration, i.e., large SVG values (Figure 35a and b). After the gate towards the weir top opening, flow velocity and as well as SVG reduce (Figure 35b).

The distribution of parallel V_p, and normal V_n, velocities, their ratio = V_p/V_n and SVG for variant 4 is quasi-similar to variant 3 in the front of the turbine intake (compare Figure 33 with 36). There is only a slight difference between variant 3 and 4 on the flow field between the turbine intake and bypass inlet, which is not visible in Figure 33.

The distribution of flow quantities along the bypass channel at the centre line is shown in Figure 37 for variant 4. They strongly and positively deviate from those for variant 3 (Figure 34) due to effect of the vertical-axis gate. Between the turbine intake and the gate, V_p gradually increases from -0.15 m/s up to 0.90 m/s (Figure 37a). A small part of the flow goes through the bottom opening of the gate, while a large part of the flow is conveyed through the top opening. The reason for this unequal discharge distribution between the top and bottom openings results from the recirculation zone occurring between near the end of the HBR, i.e., the turbine intake, and the gate (Figure 36). The velocity at the top and bottom openings are around 0.90 m/s and 0.30 m/s, respectively (note that these velocities are along the centre axis of the bypass channel). The average flow velocity at the bypass openings are around 1 m/s for a bypass discharge of 0.177 m^3/s. The inflow velocity at the turbine intake is around 0.75 m/s (Figure 35a). The ratio between the bypass to the approach flow velocities is VR = 1/0.75= 1.33, which is in the range of the recommended values of 1.2-1.4 by Beck (2020), 1-0-2.0 by Ebel (2016) and 1.1-1.5 by USBR (2006). The normal velocity V_n, along the bypass channel is near zero as expected but with some velocity patches smaller than 0.25 m/s (Figure 37b). The SVG distribution in the flow direction increases from 0 to around 1.25 s^{-1} at the top opening and reaches 5 s^{-1} after the top opening (Figure 37c). The location of the highest SVG is downstream of the gate and covers half of the water depth. At this location, fishes passing the top opening of the gate have no chance to return but continue moving over the ramp towards the weir opening. Along the ramp, SVG changes between 0 and 1.25 s^{-1} and attains values roughly between 1.25 and 2.5 s^{-1} over the weir opening (Figure 37c). Compared to the current flow condition and variants 1, 2 and 3, variant 4 creates a much better flow field in terms of fish guidance capacity and quasi satisfies the recommended values of SVG and *VR.* We therefore conclude that variant 4 is the best option out of the four variants examined with favourable flow conditions for fish bypass. This is in agreement with the design recommendations of Ebel (2016) who also favours a vertical-axis flap gate followed by an inclined ramp.

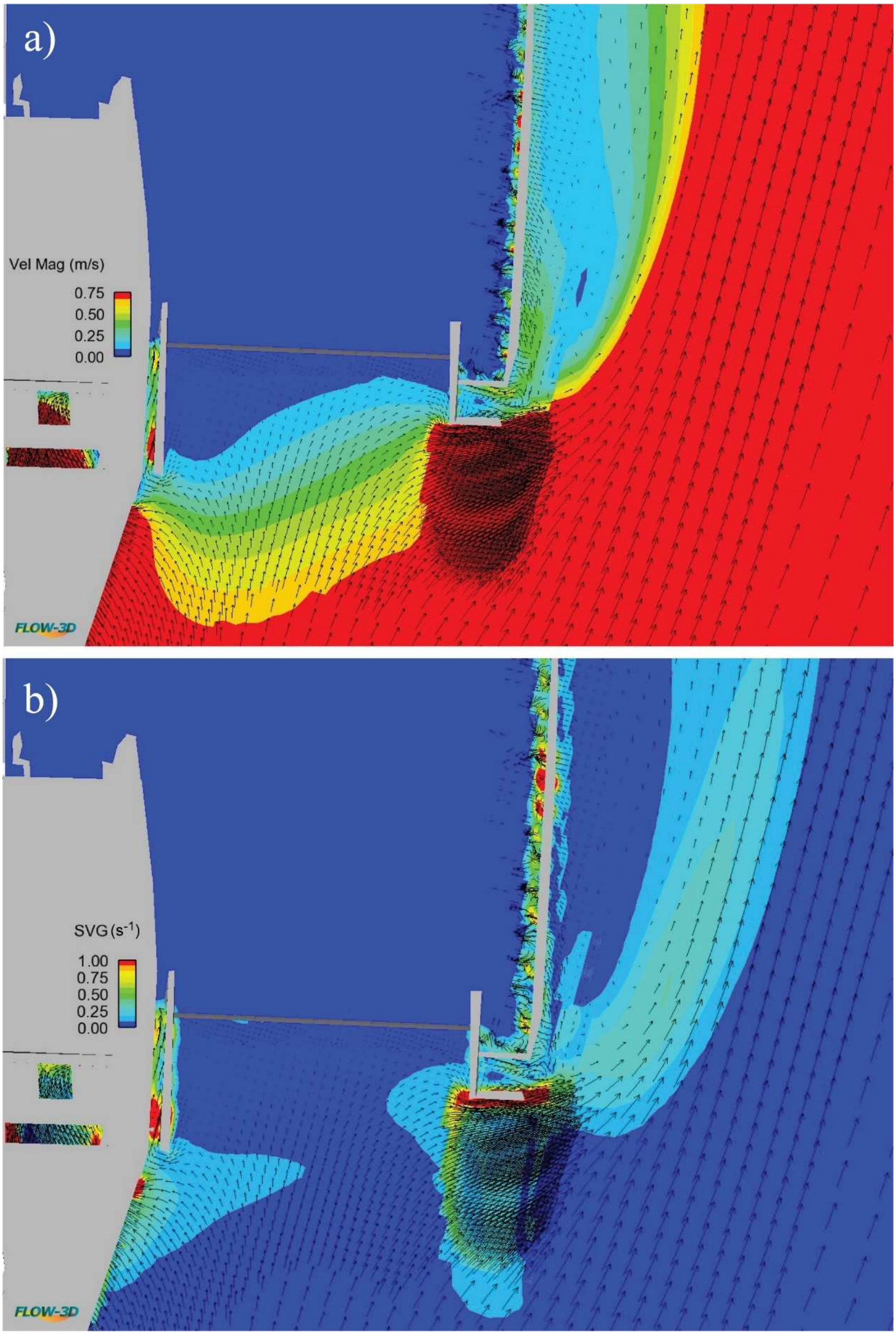

Figure 35: Resulting flow velocity distribution (a), spatial velocity gradient (SVG) (b) with 2D velcoity vectors at the horizontal level 0.285 m below the water surface for variant 4.

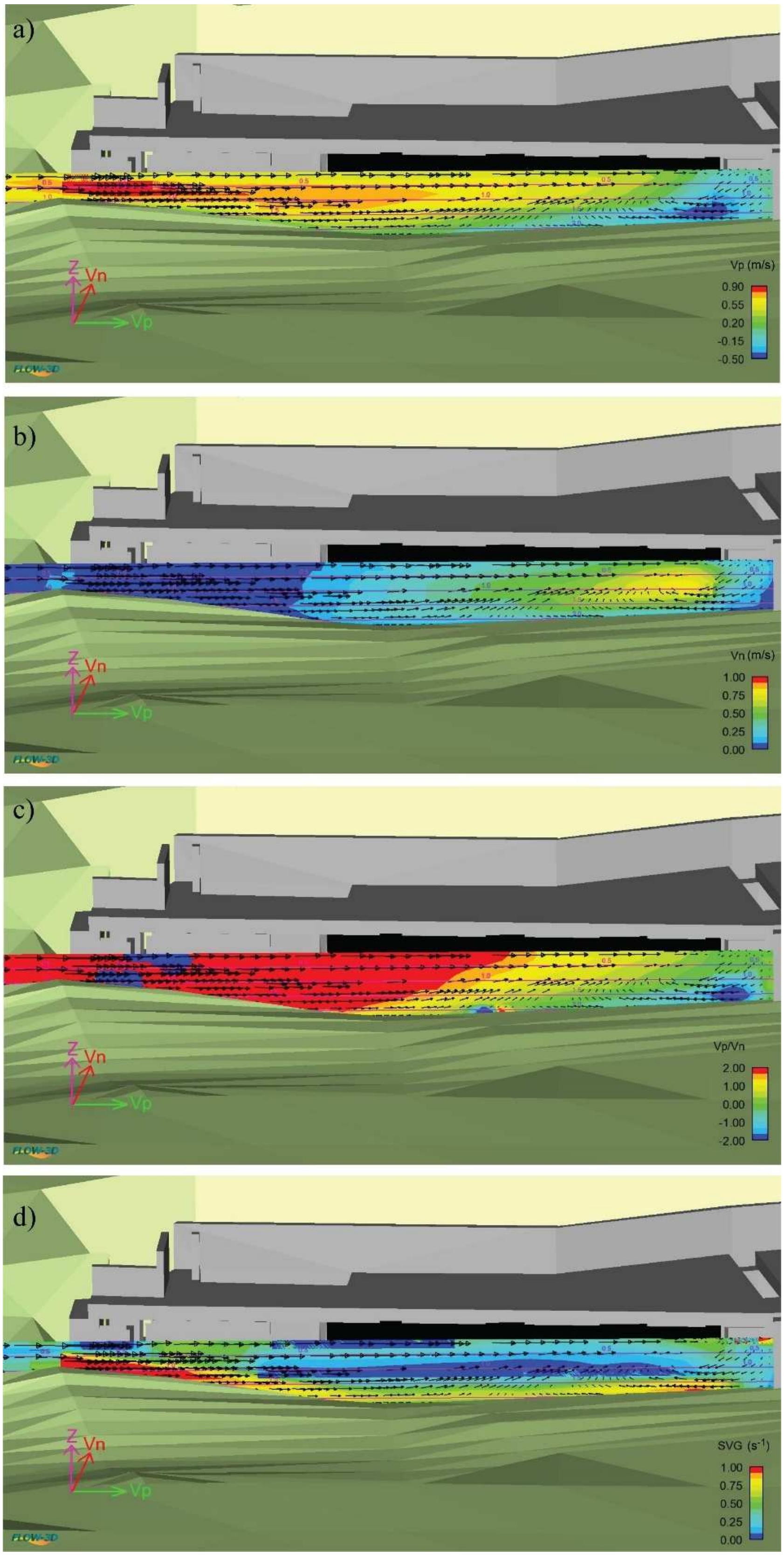

Figure 36: Distribution of parallel V_p (a), normal V_n (b) velocities, V_p / V_n (c) and SVG (d) along the turbine intake for variant 4.

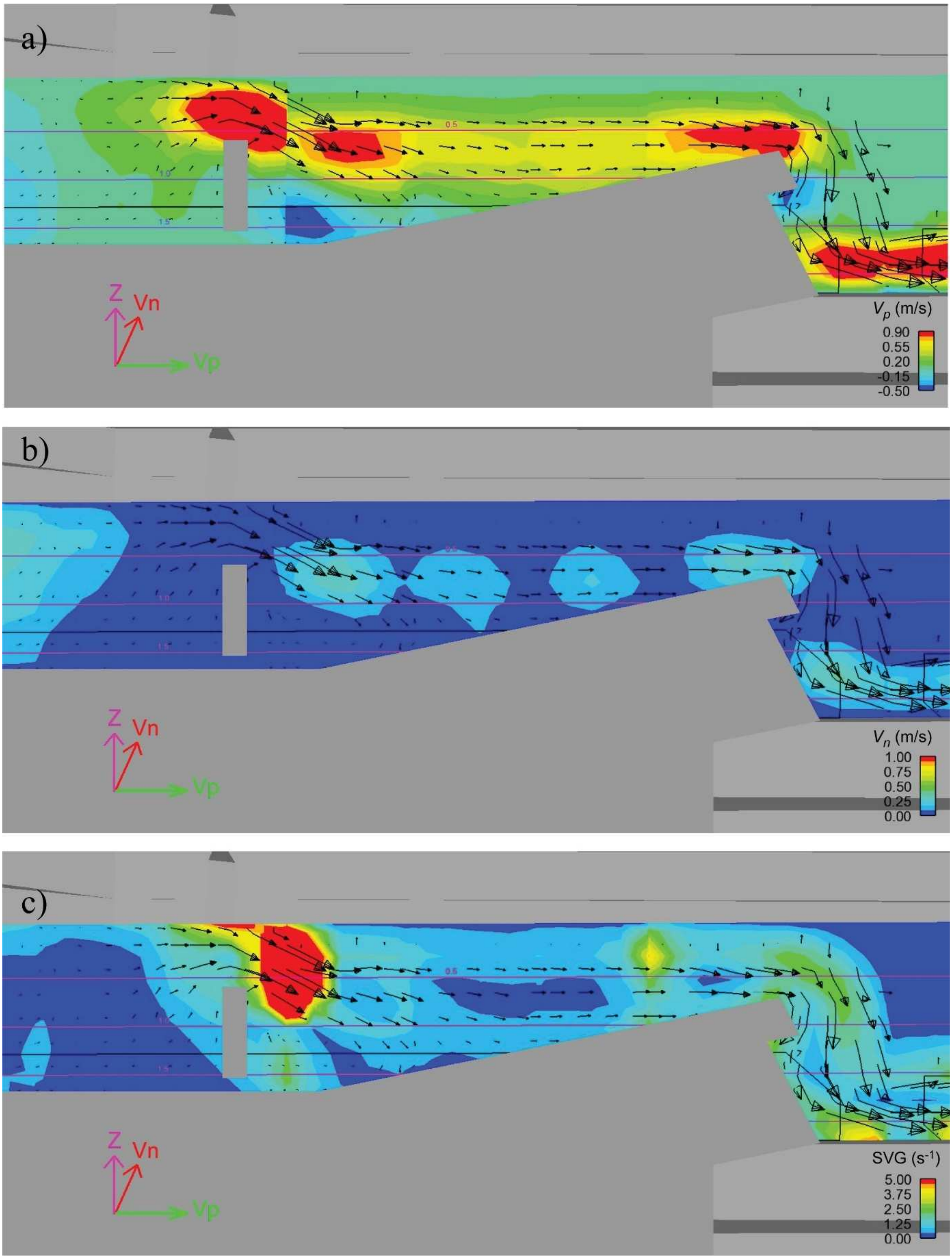

Figure 37: Distribution of parallel V_p (a), normal V_n (b) velocities and SVG (c) along the bypass channel for variant 4.

4 Discussion of results

We documented the current situation and investigated the hydraulics, bathymetry and fish guidance efficiency of an HBR-BS at the residual flow HPP Schiffmühle by means of field monitoring and 3D numerical modelling in the area near the powerhouse, bypass inlet and weir. The monitoring comprised:

- characterization of the flow field and river bathymetry using ADCP
- 3D numerical simulations
- survey of the fish movements using PIT-tagging technique

The obtained hydraulic and fish monitoring results show that most fish in the river are expected to follow the main flow towards the headrace channel, while a small portion likely swims towards the residual flow HPP. Furthermore, the attraction flow to the bypass for downstream moving fish seems inefficient and a re-circulation zone possibly affects fish searching the bypass entrance. Fish monitoring results show a very low fish guidance efficiency (< 1 %) with 2 fish using the bypass out of 445 fish, confirming the fact that the bypass hydraulic conditions are not favorable to guide fish. In order to improve this situation, four alternative bypass geometries were numerically modelled using the software FLOW 3D. The results from the numerical simulations show that the hydraulic conditions are improved with increased flow velocities at the bypass inlet compared to the current bypass conditions. All four variants have a separation wall at the left-hand side of the weir, which generates a bypass channel with an approximate width of 0.5 m between the turbine intake and the weir. The numerical simulation results show that in all variants, the separation wall breaks the large circulation zone between the weir and the HPP, which helps fish find the bypass channel entrance near the turbine intake.

Variant 1 includes a vertical-axis bypass flap gate with top and bottom openings located 2 m downstream of the bypass inlet and featuring a top opening of 0.5 m by 0.2 m at the weir. For variant 1, the flow velocities vary along the channel when passing the gate openings, between the gate and the weir and at the weir’s top opening, creating accelerations and decelerations. Such varying flow condition are unfavorable for a successful fish bypass design, for which a rather gradual velocity increase along the bypass channel is aimed at (Albayrak et al., 2020; Beck, 2020; Beck et al., 2020). For Variant 2 without a vertical-axis flap gate and two openings at the existing weir, the flow field is improved with a gradual velocity increase along the bypass channel until the weir openings where flow velocities reach their maximum values. Despite such an improvement, the bypass velocity at the inlet is smaller for variant 2 compared to variant 1, which affects bypass acceptance by fish. Therefore, the advantages of both variants have been combined in variants 3 and 4. The latter variants have a 15° inclined ramp in the bypass channel to control the flow at the openings of the gate (variant 4) and to gradually increase the flow in the bypass channel until the weir. Variant 3 does not have a vertical-axis flap gate, while variant 4 does. This results in a better inflow field for variant 4 with a higher bypass velocity ratio (*VR*) and acceleration (SVG) compared to variant 3. Overall, compared to the current flow conditions and variants 1, 2 and 3, variant 4 creates a significantly improved flow field, satisfying the recommended values of SVG and *VR*, and hence is the best option of the four variants examined with favourable flow conditions for fish bypass. A more detailed numerical study is needed to further improve the design of variant 4 and to better assess the hydraulics. Furthermore, floating debris handling has to be also considered during the design phase.

At HPP Schiffmühle, downstream moving fish have five potential passage routes, namely via: (I) HBR-BS, (II) turbine of the residual flow HPP, (III) weir, (IV) turbines of the main HPP and (V) upstream fish passes. Fish monitoring data show that only 2 of 445 tagged fish used the bypass system (I), while 40% of the tagged fish used the fish passes, which have an exit (inlet for downstream moving fish) a few meters upstream of the turbine intake. This result indicates that the flow conditions at the exit and inside the fish pass are sufficiently attractive and favorable, respectively, for fish to move downstream. Most tagged fish were relatively small barbel, spirlin and chub so that they could physically pass between the horizontal bars of the HBR with a bar spacing of 2 cm. Also, they could pass through the turbines of the main HPP as it does not have a fish protection facility. The monitoring data show that 60 % of the fish used either the weir or turbines of the residual flow or main HPP powerhouse. Since there were no antenna installed at the inlets of the HPPs and at the weir, we do not know which route the fish actually used. However, it is known that the fish survived from either weir or turbine passages as they returned and passed the HPPs using the fish passes, where they were detected by the antennas. Overall, the fish monitoring data suggest a high fish survival rate at the Schiffmühle HPPs, independent of the route the tagged fish used during their downstream passage. However, since the fish monitoring data is limited to only 445 tagged fish out of a total of 2890 fish tagged to study upstream movement, we cannot generalize this conclusion for other fish species. Therefore, we recommend a further fish monitoring campaign to study all possible migration corridors, including different antennas close to the turbine intake and outlet as well as at the weir and the main HPP.

5 Conclusions and Outlook

In this project, we evaluated the hydraulics and fish guidance efficiency of a Horizontal Bar Rack-Bypass System (HBR-BS) installed at the residual flow HPP Schiffmühle by conducting in-situ velocity measurements, fish monitoring and numerical modelling.

A successful two-day field measurement campaign was conducted in October 2018. 3D flow velocities were measured and bathymetry was mapped using Acoustic Doppler Current Profiler (ADCP) at 69 densely spaced cross-sections upstream of the HPP, around the fish bypass and at the inlet of the turbine as well as along the residual flow reach and headrace channel. The bathymetry and velocity data were analyzed in-depth and provided to our partner AFRY for numerical modelling of the HPP. Based on these, AFRY set-up, calibrated and validated a 3D numerical model. Since the hydraulic conditions at the bypass were not favorable, four variants of new bypass systems were modelled, and their hydraulic conditions were simulated. Fish Consulting GmbH (FCO) conducted fish monitoring at the HBR-BS and at both technical and nature-like fish passes by PIT-tagging almost 3000 fish belonging to 13 different fish species. The key results of these works include:

1) ADCP velocity measurements indicate that most fish in the river are expected to follow the main current towards the headrace channel, while a small portion is likely to move towards the residual flow HPP.
2) The attraction flow to the bypass for downstream movement seems inefficient and a re-circulation zone possibly affects fish searching and finding the bypass entrance.
3) 2 fish out of 445 were detected in the bypass pipe, confirming the poor fish guidance capacity due to an unfavorable velocity field around the bypass.
4) Clogging of the bypass pipe is a problem affecting the bypass discharge and velocity.
5) 178 fish out of 445 (40%) were detected in the fish passes, indicating that the hydraulic conditions at the exit and along the fish passes are attractive and favorable enough to guide fish downstream, presenting an alternative downstream passage route for fish.
6) 265 fish out of 445 (60%) used either the weir or turbines of the residual flow or main HPP powerhouse, indicating a high survival rate independent of these routes.
7) The present downstream bypass system needs optimization.
8) Four variants of new bypass systems as an alternative to the present one were developed and 3D numerically modelled.
9) Variant 4 with a vertical-axis gate with top and bottom openings and a 15° inclined ramp between the gate and the existing weir show the best flow conditions compared to the other three variants and would likely improve the fish guidance efficiency of the HBR.
10) Alternatively, an effective fish protection and guidance system such as HBR-BS or newly developed Curved-Bar Rack-Bypass System (CBR-BS, Beck et al. 2020a, b, c; Beck, 2020) should be realized at the main HPP of Schiffmühle instead of making an effort to improve the current HBR-BS at the

residual HPP because most fish in the river are expected to follow the main flow towards the headrace channel.

11) As a side study result, both vertical slot and nature-like fish passes at HPP Schiffmühle function well for upstream moving fish with high attraction, entrance and passage efficiencies.

The above-listed findings from the present study at HPP Schiffmühle indicate that a proper hydraulic and fish-behavioral design, location and operation of a bypass system are of prime importance for a successful implementation and high fish guidance capacity of HBR-BS. Furthermore, these findings have a wide range of applications to other similarly sized HPPs and will serve as a basis for an optimal design of HBR-BS.

As an outlook, we recommend to improve the existing downstream migration facility followed by an additional tagging campaign confirming the function of the downstream migration. This could be done by an additional PIT-tagging analysis or using radio telemetry techniques. Furthermore, a high-resolution 3D model of the studied alternative bypass system with improved geometry and more numerical simulations for various discharge scenarios are recommended to obtain a final bypass design. We also recommend to implement an effective fish protection and guidance system such as HBR-BS (Meister, 2020) or newly developed CBR-BS (Beck, 2020) at the main HPP of Schiffmühle, which is considered even a better option than to purely improve the current bypass.

6 National and international cooperation

In this project, VAW conducted field investigation on the hydraulic and fish guidance performance of the HBR-BS at Shiffmühle HPP with its partners. The partners are the operator of Limmatkraftwerke AG (LKW), Fish Consulting GmbH and AFRY AG. LKW supported the project with their staff during the field campaign and provided operational data. Fish Consulting GmbH conducted fish monitoring study and provided the data to VAW. AFRY closely collaborated with VAW for the numerical modelling of the HPP and development of alternative bypass system and provided the results of the numerical simulations. Finally, VAW and all partners evaluated the results and contributed to this final report.

7 References

Albayrak, I., Boes, R.M., Kriewitz-Byun, C.R., Peter, A., Tullis, B.P. (2020). Fish guidance structures: new head loss formula, hydraulics and fish guidance efficiencies. *Journal of Ecohydraulics*, https://doi.org/10.1080/24705357.2019.1677181.

Beck, C. (2020). Fish Protection and Fish Guidance Using Innovative Curved-Bar Rack Bypass Systems. In: Boes R.M., editor. *VAW-Mitteilungen* 257. Zurich (Switzerland): Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich.

Beck, C., Albayrak, I., Meister, J. and Boes R.M. (2020a). Hydraulic performance of fish guidance structures with curved bars: Part 1: Head loss assessment. *Journal of Hydraulic Research*, 58 (5), 807-818, https://doi.org/10.1080/00221686.2019.1671515.

Beck, C., Albayrak, I., Meister, J. and Boes R.M. (2020b). Hydraulic performance of fish guidance structures with curved bars: Part 2: Flow fields. *Journal of Hydraulic Research*, 58 (5): 819-830, https://doi.org/10.1080/00221686.2019.1671516.

Beck, C., Albayrak, I., Meister, J., Peter, A., Selz, O.M., Leuch, C., Vetsch, D.F. and Boes, R.M. (2020c). Swimming behaviour of downstream moving fish at innovative curved-bar rack bypass systems for fish protection at water intakes. *Water* 12 (11), 3244, https://doi.org/10.3390/w12113244.

Benitez, J. P., Dierckx, A., Nzau Matondo, B., Rollin, X., Ovidio, M. (2018). Movement behaviours of potamodromous fish within a large anthropised river after the reestablishment of the longitudinal connectivity. *Fisheries Research*, *207* (June), 140–149.

Boes, R., Albayrak, I., Kriewitz, C. R., Peter, A., (2016). Fischschutz und Fischabstieg mittels vertikaler Leitrechen-Bypass-Systeme: Rechenverluste und Leiteffizienz (Fish protection and downstream fish migration by means of guidance systems with vertical bars: head loss and bypass efficiency). *Wasser Wirtschaft*, 7(8), 29-35.

Bunt, C. M., Castro-Santos, T., Haro, A. (2012). Performance of fish passage structures at upstream barriers to migration. *River Research and Applications*, *28* (4), 457–478.

Courret D, Larinier M. (2008). Guide pour la conception de prises d'eau "ichtyo-compatibles" pour les petites centrales hydroelectriques [Guide for the design of fish-friendly intakes for small hydropower plants]. Report No: RAPPORT GHAAPPE RA.08.04. http://www.onema.fr/IMG/pdf/2008_027.pdf (in French).

Ebel, G. (2016). Fischschutz und Fischabstieg an Wasserkraftanlagen — Handbuch Rechen und Bypasssysteme. Ingenieurbiologische Grundlagen, Modellierung und Prognose, Bemessung und Gestaltung (Fish Protection and Downstream Passage at Hydro Power Stations — Handbook of Bar Rack and Bypass Systems. Bioengineering Principles, Modelling and Prediction, Dimensioning and Design). 2nd edn. *Büro für Gewässerökologie und Fischereibiologie Dr. Ebel*, Halle (Saale), Germany [in German].

Enders, E. C. , Gessel, M. H. , Anderson, J. J. , & Williams, J. G. (2012). Effects of decelerating and accelerating flows on juvenile salmonid behavior. *Transactions of the American Fisheries Society*, 141(2), 357–364.

Feigenwinter, L.; Vetsch, D.F.; Kammerer, S.; Kriewitz, C.R.; Boes, R.M. (2019). Conceptual approach for positioning of fish guidance structures using CFD and expert knowledge. *Sustainability*, 11(6), 1646; https://doi.org/10.3390/su11061646.

Flow Science, Inc. (2016). FLOW-3D User Manual, Release 11.2.3, USA 2016.

Haro, A., Odeh, M., Noreika, J., Castro-Santos, T. (1998). Effect of water acceleration on 564 downstream migratory behavior and passage of Atlantic salmon smolts and juvenile American 565 shad at surface bypasses, *Transactions of the American Fisheries Society*, *127*(1): 118–127.

Kzyzagorski, S., Gabl, R., Seibl, J. et al. (2016) Implementierung eines schräg angeströmten Rechens in die 3D-numerische Berechnung mit FLOW-3D. Österr. Wasser- und Abfallw. 68: 146. doi:10.1007/s00506-016-0299-2.

Meister, J. (2020). Fish protection and guidance at water intakes with horizontal bar rack bypass systems. *VAW-Mitteilung 258* (R.M. Boes, ed.). Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zurich, Switzerland.

Meister, J.; Fuchs, H.; Beck, C.; Albayrak, I.; Boes, R.M. (2020a). Head Losses of Horizontal Bar Racks as Fish Guidance Structures. *Water*, 12(2): 475. http://dx.doi.org/10.3390/w12020475.

Meister, J.; Fuchs, H.; Beck, C.; Albayrak, I.; Boes, R.M. (2020b). Velocity Fields at Horizontal Bar Racks as Fish Guidance Structures. *Water*, 12(1): 280. http://dx.doi.org/10.3390/w12010280.

Meusburger, H. (2002): Energieverluste an Einlaufrechen von Flusskraftwerken. VAW-Mitteilungen 179 (H.-E. Minor, ed.), ETH Zürich. http://people.ee.ethz.ch/~vawweb/vaw_mitteilungen/179/179_g.pdf.

Peter, A., Mettler, R., Schölzel, N. (2016). Kurzbericht zum Vorprojekt „ PIT-Tagging Untersuchungen am Hochrhein – Kraftwerk Rheinfelden ". 45 p.

Raynal, S., Chatellier, L., Courret, D., Larinier, M., & Laurent, D. (2013). An experimental study on fish-friendly trashracks - Part 1. Inclined trashracks. *Journal of Hydraulic Research*, *51*(1), 56-66.

USBR - US Bureau of Reclamation (2006). Fish protection at water diversions - a guide for planning and designing fish exclusion facilities. Denver (CO): US Department of the Interior. p. 480.