Ultrasonic Doppler flow velocity measurements as a co-indicator for the eco-morphological assessment in a residual flow reach

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It is a complex task to evaluate the effects of a river rehabilitation measure on the riverscape's habitat mosaic. This study investigated the medium term effects of a rehabilitation measure in a residual flow reach downstream of a hydroelectric dam. The rehabilitation measure consisted of an artificial flood coupled with a sediment augmentation measure. The evaluation was based on the indicator set of habitat diversity, published by the Swiss Federal Office for the Environment (FOEN) for the outcome evaluation of restoration projects. It is composed of six eco-morphological indicators, among which 1.3 and 1.4 assess the variability of water depth and flow velocity, respectively. In each study reach, the measurements were taken along hydro-morphologically representative cross sections for at least eleven points per cross section. A handheld Acoustic Doppler Velocimeter (ADV) was used to measure flow velocity. Digital, GNSS-supported surveying with a mobile GIS application significantly enhanced the assessment workflow. The study results suggest that neither the single artificial flood nor its coupling with the 2016 sediment augmentation were sufficient to restore a functional habitat mosaic in the medium or long term.

Keywords: Eco-morphological assessment, River rehabilitation, Residual flow reach, Sediment augmentation, Ultrasonic Doppler velocimetry

1. Introduction

Medium and high-head hydropower storage plants produce electricity by conveying water from the reservoir via the pressurized waterway to the powerhouse. The river segment bypassed by the waterway is referred to as residual flow reach. Residual flow reaches are often characterized by a minimum residual flow discharge and little to no upstream bedload supply, due to the trapping of sediments inside the reservoir [1]. These hydro-morphological disturbances reduce morphodynamics in the residual flow reach to a minimum, resulting in eco-morphological degradation [2]. In a natural riverscape, the patchy distribution of eco-morphological characteristics, such as water depth and flow velocity, forms a dynamic mosaic of habitats [3]. To improve the quality of a residual flow reach's habitat mosaic, artificial floods [4], and their coupling with artificial sediment augmentation [5, 6], can be an effective rehabilitation measure.

In the residual flow reach of the Sarine river in Switzerland, downstream of the Rossens dam (Figure 1), an artificial flood was combined with an artificial sediment augmentation in 2016. The bed material (1000 m^3) was excavated from the adjacent alluvial forest and arranged in four alternated deposits along both banks, 9 km downstream of the dam. During the flood, the constant residual discharge (summer 3.5 m^3/s, winter 2.5 m^3/s) was increased to a peak flow of approximately 190 m^3/s. Immediate follow-up studies found the eco-morphological effects to be positive [5], but questioned their persistence in the absence of repetitive rehabilitation measures [6].

This study evaluates the measure's medium-term effects by using and extending the indicator set 1 "habitat diversity" of the guideline for the outcome evaluation of river restoration projects (Monitoring and Evaluation, M&E) [7]. It was published by Switzerland's Federal Office for the Environment (FOEN) in 2019 and includes the assessment of the coefficient of variation (CV) of flow velocity and water depth measurements. Both are important indicators for the eco-morphological assessment of a river reach [7]. In this study, flow velocity was measured with Ultrasonic Doppler velocimetry using a handheld Acoustic Doppler Velocimeter (ADV).

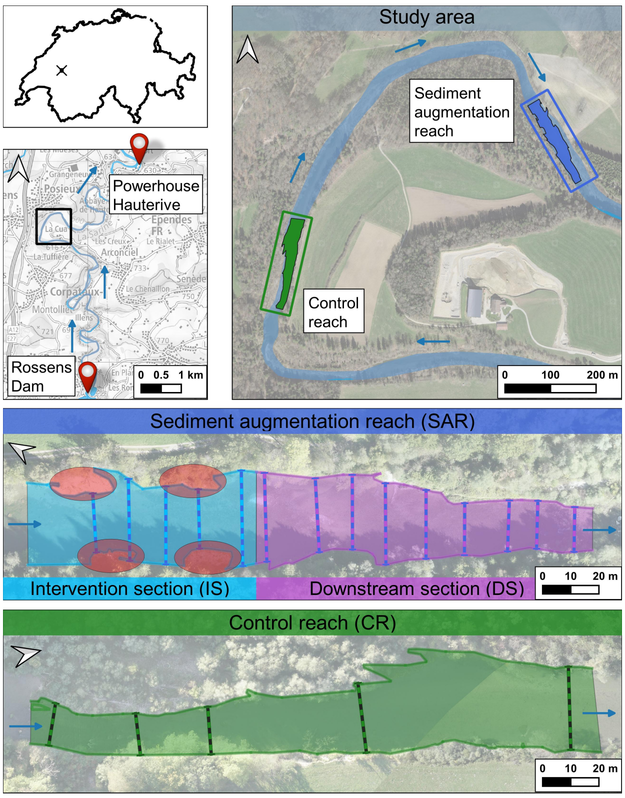

Figure 1: Study reach definition. Positions of the sediment deposits (red ellipses) and of flow velocity measurement cross sections (dashed lines). Maps and study area background © swisstopo; Sediment augmentation reach and control reach background © Research Group for Ecohydrology, ZHAW

2. Materials and Methods

2.1 Study area

The Sarine river is a heavily regulated stream that has its source at Sanetsch (2252 m a.s.l.). In the study area, the Sarine is described as a flat, large watercourse of the colline, carbonatic midlands [8]. At Rossens, it is dammed by a 83 m high arch dam, forming the Lac de la Gruyère, one of Switzerland's five biggest reservoirs (V= 200 million m^3, A=10 km^2). The 13 km long residual flow reach up to the powerhouse Hauterive has an average slope of 0.3 % and is characterized by a channel-riffle-rapids sequence.

The 200 m long study reach around the four sediment augmentation deposits (sediment augmentation reach, SAR) and a suitable upstream control reach (CR) of the same length were defined in accordance with the M&E guideline [9]. As illustrated in Figure 1, the sediment augmentation reach is subdivided into the 80 m long intervention section (IS) and the subsequent, 120 m long downstream section (DS).

2.2 M&E indicator set 1 "habitat diversity"

The indicator set 1 "habitat diversity" consists of six indicators. Each indicator is named after an eco-morphological characteristic and can score a standardized value between 0 (degraded or artificial) and 1 (near-natural). To compensate for the still missing calculation procedure for indicator 1.6 A1 "Substrate composition", the indicator set was extended by the "Indicator of Reproduction suitability based on Substrate degradation" (IRS) [10]. Table 1 provides an overview of the indicators that were applied and their calculation criteria.

Table 1: M&E indicator set 1 "habitat diversity", extended by the "Indicator of Reproduction suitability based on Substrate degradation" (IRS)

Indicator		Indicator calculation with
1.1	River bed structures	Number of bed structures
1.2	River bank structures	Number of structures and non-obstructed length
1.3	Water depth	Coefficient of variation
1.4	Flow velocity	Coefficient of variation
1.5	Presence of cover	Area of cover relative to a reference state
1.6 A1	Substrate composition	*Currently not available*
1.6 A2	Substrate mobilisability	Relative presence of bed load and other mobilisability types
IRS / 1.6 A3	Reproduction suitability based on Substrate degradation	Fraction of suitable, non-consolidated and non-embedded substrate

The calculation of the hydraulic indicators 1.3 and 1.4 is based on measurements along of up to 15 cross sections per study reach. All other indicators require the reach-wide mapping of homogeneous sections and patches. The calculation of indicators 1.1 and 1.2 is based on the number of homogeneous bed and bank structures. The calculation of indicator 1.5 is based on the comparison of the current presence of cover with a natural reference state. For the present study, two independent estimates (P. Vonlanthen, Aquabios Sàrl; C. Weber, Eawag) were averaged. The IRS (indicator 1.6 A3) assesses substrate quality based on brown trout's substrate requirements for reproduction. It makes direct use of and extends the existing mapping procedure for the M&E indicators 1.6 A1 and 1.6 A2.

In the sediment augmentation reach, 14 cross sections (263 points) were sampled. Due to limited capacity, only five cross sections (77 points) were sampled in the control reach. These cross sections were distributed, at the discretion of the authors, to best represent the reach's hydro-morphological characteristics.

From all measurements of a reach, the coefficients of variation (CV) are calculated according to Eq. 1 and Eq. 2 from the sample standard deviation (σ) and the sample mean (μ) for water depth and flow velocity.

$$CV_{max.\ water\ depth} = \frac{\sigma_{max.\ water\ d.}}{\mu_{max.\ water\ d.}} \times 100\ \% \qquad (1)$$

$$CV_{flow\ velocity} = \frac{\sigma_{flow\ velocity}}{\mu_{flow\ velocity}} \times 100\ \% \qquad (2)$$

In the sediment augmentation reach, CV values were additionally calculated separately for the intervention section (5 cross sections, 99 samples) and the downstream section (9 cross sections, 164 samples). To obtain indicator values between 0 and 1, the CV values are linearly standardized as described by the M&E guideline [7].

2.3 Ultrasonic Doppler velocimetry

Flow velocity was measured using the handheld ADV FlowTracker by SonTek. The FlowTracker's acoustic transmitter is located in between two laterally protruding receivers (Figure 2), allowing to perform pointwise 2D velocity measurements.

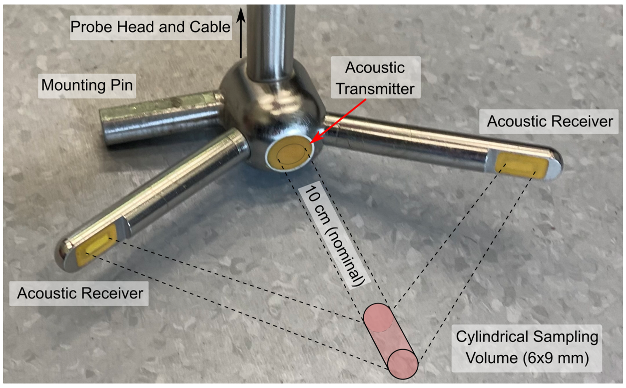

Figure 2: SonTek FlowTracker Probe and Sampling Volume, description according to the FlowTracker Technical Manual

Handheld ADVs offer several advantages. They quickly deliver results of high accuracy, do not require on-site calibration, and do not depend on mechanical parts. Table 2 presents the details of the applied methodology.

Table 2: ADV equipment and sampling methodology

Handheld ADV	FlowTracker by SonTek
Ping rate	10 Hz
Sampling rate	1 Hz
Averaging time	10 s
Measurement error	Typically < 0.01 m/s
Sampling volume distance	10 cm from the probe
Measurement depth	60 % water depth from surface
Distance between samples	1.4 m

2.4 Further equipment and field work

For the field work, a digital mapping environment was set up. It consisted of a field tablet (Trimble T10), a survey-grade GNSS antenna (Trimble R2) and a comprehensive project for the mobile GIS application QField [11]. This set-up allowed for GNSS and orthophoto based mapping and provided decision support for the placement of cross sections. The field equipment is shown in Figure 3. Field work took place in summer 2020 and lasted two weeks. Sunny conditions and moderate turbidity provided for good visibility of the streambed substrate.

Figure 3: Field equipment used for surveying: The handheld Acoustic Doppler Velocimeter FlowTracker by SonTek (left), field tablet Trimble T10 and GNSS antenna Trimble R2 (right)

3. Results

The evaluation of the surveying results was based on the procedure described in the M&E guideline [7]. In the control reach, seven bed structures were identified. The sediment augmentation reach counted 24 structures. Most of its bed structures were concentrated in the intervention section (18 structures). There were eight structures in the downstream section, and two structures extended across the section boundary. The ratio of the areas covered by the dominant bed structures channel, riffle, rapids, and shallow water varied significantly among the study reaches and sections. The highest number of bank structures was identified in the control reach, the highest density in the intervention section.

On average, the sediment augmentation reach had shallower water depths and higher flow velocities than the control reach. In the downstream section, shallow water depths smaller than 0.6 m were dominant. In the intervention section as well as in the control reach, water depths greater than 1.4 m were measured. All CV values of water depth measurements stayed within the range from 0 to 1 and directly translate to indicator scores.

Figure 4 shows the histograms of flow velocity measurements. The flow velocity histogram of the intervention section is dominated by relatively slow flow velocities (v_{max} (IS) = 0,54 m/s). In the rapids zones of the downstream section and the control reach, flow velocities up to v_{max} (DS) = 1.33 m/s and v_{max} (CR) = 1.48 m/s were measured. The smaller number of cross sections and measurement points in the intervention section is the reason for the smaller size of its attributed area in the stacked histogram, compared to the downstream section. The coefficients of variation of water depth and flow velocity in the intervention section and downstream section were significantly lower than the CV values for the entire sediment augmentation reach (Table 3).

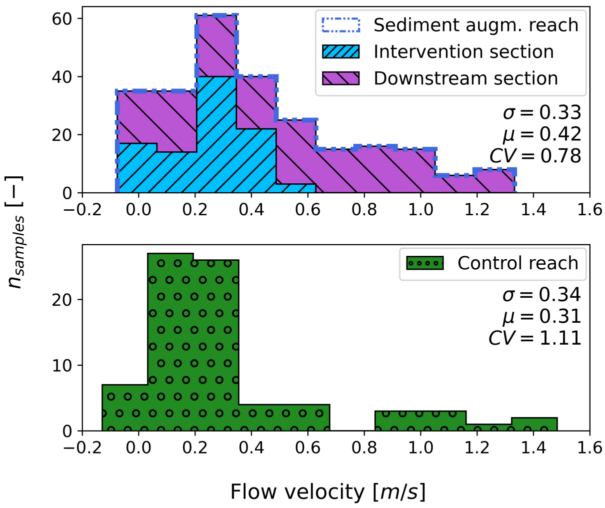

Figure 4: Histograms of flow velocity samples in the sediment augmentation reach (top) and the control reach (bottom). The intervention section and downstream section samples are stacked to form the sediment augmentation reach histogram

The streambed of both study reaches was predominantly stabilized by a coarse-grained top layer (armor layer). Only 3.9 % of streambed area was dominated by bedload. In the sediment augmentation reach, 6 % of the area was dominated by substrate considered as potentially suitable for reproduction in brown trout (gravel and stones) versus 12 % in the control reach. In both study reaches, around 70 % of potentially suitable area for trout reproduction was qualified as non-suitable due to degradation.

Table 3 provides an overview of the final indicator results. Neither the sediment augmentation reach nor the control reach has a global tendency to score higher than the other. All four study reaches and sections obtain higher scores for indicators 1.1 to 1.4 than for indicators 1.5, 1.6 A2 and the IRS. The sediment augmentation reach scores higher than the control reach for two indicators (river bed structures, water depth), obtains equal scores for two other indicators (presence of cover, substrate mobilisability) and a lower score for three indicators (river bank structures, flow velocity, reproduction suitability). Compared to the entire sediment augmentation reach, the intervention section and the downstream section obtain lower scores for both hydraulic indicators (water depth, flow velocity).

Table 3: Indicator results and metrics of water depth and flow velocity for the control reach (CR), the sediment augmentation reach (SAR), the intervention section (IS) and the downstream section (DS). Values are linearly color coded from 1 (green) via 0.5 (yellow) to 0 (red)

Indicator results / Metrics		CR	SAR	IS	DS
1.1	River bed structures	0.75	1.00	1.00	1.00
1.2	River bank structures	0.92	0.90	1.00	0.86
1.3	Water depth	0.53	0.66	0.49	0.54
	σ [m]	0.32	0.23	0.26	0.13
	μ [m]	0.60	0.35	0.53	0.25
	CV	0.53	0.66	0.49	0.54
1.4	Flow velocity	1.00	0.71	0.56	0.63
	σ [m/s]	0.34	0.33	0.15	0.36
	μ [m/s]	0.31	0.42	0.24	0.52
	CV	1.11	0.78	0.61	0.69
1.5	Presence of cover	0.25	0.25	0.25	0.25
1.6 A2	Substrate mobilisability	0.25	0.25	0.25	0.25
IRS / 1.6 A3	Reproduction suitability (Substrate degradation)	0.32	0.27	0.36	0.25

4. Discussion

A control reach based outcome evaluation has the imminent disadvantage that not all key characteristics of the control reach and the rehabilitated reach fully coincide. In particular, the studied reaches and sections turned out to have considerably varying ratios between areas of riffle, channel, rapids, and shallow water, each representing particular hydraulic characteristics. The intervention and downstream sections of the sediment augmentation reach achieved significantly lower CV values for water depth and flow velocity compared to the entire reach. This fact suggests that special care is required for the interpretation of the two indicators in a control reach based outcome evaluation.

The required time to measure a water depth and flow velocity profile of 25 m width at a spacing of 1.4 m was approximately 30 minutes. The digital recording of measurements within the QField application proved to be highly efficient. The signal to noise ratio (SNR), representing the strength of the acoustic reflection from particles in the water, was at any time ideal (> 10 dB) in the natural environment. In turbulent sections, the number of spikes was sometimes higher than the recommended threshold of 10 %. In the context of this study case, the accuracy of the ADV measurements was largely sufficient.

5. Conclusions

Four years after the artificial flood, the Sarine sediment augmentation continued to affect certain components of the residual flow reach's habitat mosaic. The most noticeable difference between the sediment augmentation reach and the control reach is the increased structural diversity in proximity to the partially eroded sediment deposits. Yet, the study's results suggest that the isolated artificial flood with sediment augmentation was not an effective single measure against streambed degradation in the medium term.

To increase bedload and habitat dynamics in a residual flow reach in the long term, the combination of annual flood events, dynamic e-flows, and continuous bedload feeding could be an effective measure. The digital, GNSS-supported surveying with QField was estimated to provide overall time savings of up to 50 % and improve data accuracy. The handheld Acoustic Doppler Velocimeter greatly enhanced data collection for the eco-morphological assessment of the river rehabilitation measure.

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