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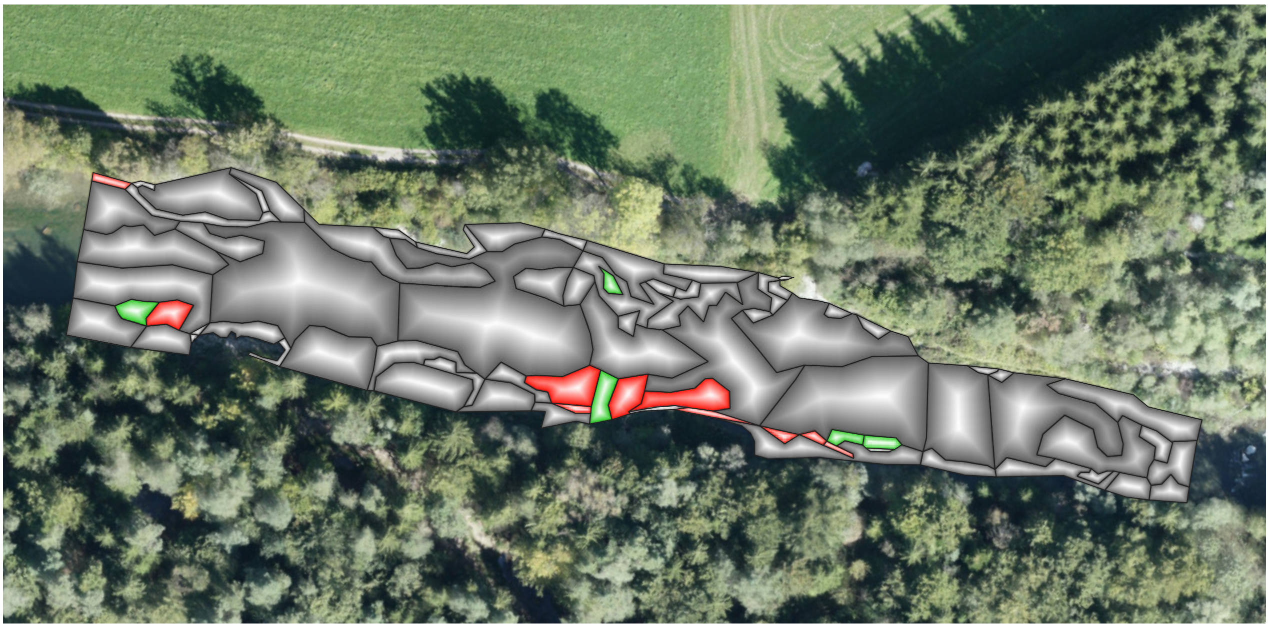

Master Thesis

Eco-Morphological Evaluation of a Residual Flow Reach Restoration Measure

Enhancing habitat assessment with a new substrate degradation indicator and digital surveying

Robin Schroff | October 2020

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> *To restore stability to our planet we must restore its biodiversity.*
> *The very thing we've removed.*
> – David Attenborough

In the past centuries, the majority of European rivers and streams were "corrected" and regulated for control and exploitation. Today, aquatic ecosystems are collapsing in many places and are heavily suffering almost everywhere else. Disappearing species lead to an irreversible loss of biodiversity. Where human interventions cannot be reversed, their adverse effects must be reduced to a minimum by extensive restoration programs. The present study's objective is to contribute to such programs by offering insights from a recent restoration project and by presenting useful tools that were developed in this context.

I would like to thank Christian Mörtl for the excellent overall guidance and the 100 % commitment during field work, Dr. Christine Weber for all the inspirational ideas and her expert advice and Dr. Giovanni de Cesare for making the project possible and paving the way for its publication. I am thankful to Prof. Karl Deindl and Julian Brosda for the thesis' supervision at the Technical University of Munich, to Dr. Pascal Vonlanthen for the provided data and the interesting conversations, to Prof. Michael Döring for providing the aerial photographs, to Cédric Bron for the technical support and drone experiences, to Déborah Bouvresse and Leona Repnik for their invaluable assistance during field works, to Romain Dubuis for sharing his knowledge on streambed colmation, to Dr. Lukas Hunzinger for the constructive feedback, to Séverine Sudre for the administrative support, to Brigitte Germann for lending the underwater periscope and to Francis Terreaux for granting access to his land and infrastructure. A special thank you goes to my good friend Simon Lever for engineering the digital data bridge that was a major game changer for the entire field work. I want to thank Dr. Klaus Lanz for the valuable impulses that inspired this work in various ways. I am deeply grateful to my beautiful partner, my beautiful daughter and my entire family for their love, support, and guidance.

Lausanne, October 2020 Robin Schroff

Abstracts

EN It is a complex and challenging task to evaluate the effects of a river restoration measure on the riverscape's habitat mosaic. This study investigated the medium term effects of a restoration measure in a residual flow reach downstream of a hydroelectric dam. The restoration measure consisted of a sediment replenishment that was coupled with an artificial flood in the Sarine river in 2016. It was evaluated using the indicator set *habitat diversity* of FOEN's recently published guideline for the evaluation of revitalization projects. Although dedicated to a different category of restoration projects, the guideline's indicator set proved to be a transferable and effective assessment tool kit for the studied sediment replenishment. To quantify the observed impairment of streambed habitat by substrate degradation, a proposal for an indicator was developed, which can extend the indicator set. The assessment workflow was significantly enhanced by a digital, GNSS-supported surveying solution, which was estimated to provide time savings of up to 50 % and improve data accuracy. The study's results suggest that neither the single artificial flood nor its coupling with the 2016 sediment replenishment are sufficient to restore a functional habitat mosaic in the medium or long term.

DE Die Bewertung einer Flussrenaturierungsmassnahme hinsichtlich ihrer Auswirkungen auf das Habitatmosaik des Flusses ist ein anspruchsvolles Vorhaben, das die Beantwortung komplexer Fragestellungen erfordert. In der vorliegenden Arbeit wurden die mittelfristigen Auswirkungen einer Wasserkraftsanierungsmassnahme auf das Habitatmosaik einer Restwasserstrecke untersucht. Die Sanierungsmassnahme betraf die Restwasserstrecke der Saane stromabwärts des Greyerzersees und bestand aus einer Sedimentzugabe, die mit einem künstlichen Hochwasser im Jahr 2016 gekoppelt wurde. Die Massnahme wurde anhand des Indikatorsets *Habitatvielfalt* bewertet, welches der kürzlich publizierten BAFU-Praxisdokumentation zur Wirkungskontrolle von Revitalisierungsprojekten entstammt. Obwohl die untersuchte Massnahme kein Revitalisierungsprojekt im eigentlichen Sinne darstellt, erwies sich das Indikatorset der Praxisdokumentation als übertragbares und wirksames Bewertungsverfahren für die untersuchte Sanierungsmassnahme. Um die beobachtete Degradierung der Gewässersohle durch Kolmation zu quantifizieren, wurde ein Vorschlag für einen geeigneten Indikator entwickelt, der sich in das Indikatorset integrieren lässt. Für die Feldarbeiten wurde eine digitale, GNSS-gestützte Kartierlösung entwickelt. Dies ermöglichte eine Reduktion des Zeitaufwands um bis zu 50 % sowie eine hohe Datengenauigkeit. Die Ergebnisse der Arbeit legen nahe, dass weder das künstliche Hochwasser 2016, noch dessen Kopplung mit der Sedimentzugabe ausreichen, um mittel- oder langfristig ein funktionales Habitatmosaik wiederherzustellen.

FR L'évaluation d'une mesure de renaturation en fonction de ses effets sur la mosaïque des habitats de la rivière est une tâche complexe. La présente étude examine les effets à moyen terme d'une mesure d'assainissement de la force hydraulique dans un tronçon à débit résiduel de la Sarine. La mesure consistait en des dépôts de sédiments qui ont été couplés avec une crue artificielle lâchée du lac de la Gruyère en 2016. Cette mesure a été évaluée sur la base du jeu d'indicateurs *diversité des habitats*, élément essentiel de la documentation pratique de l'OFEV pour le contrôle des effets des projets de revitalisation. Bien que la mesure examinée ne représente pas un projet de revitalisation au sens strict, le jeu d'indicateurs de la documentation pratique s'est révélé être une procédure d'évaluation transférable et efficace pour la mesure d'assainissement étudiée. Afin de quantifier la dégradation observée du fond de lit de la rivière, une proposition pour un nouvel indicateur a été développée et intégrée dans le jeu d'indicateurs. Une solution de cartographie numérique, basée sur des systèmes GNSS, a été développée pour le travail sur le terrain. Cette démarche a permis de réduire la charge de travail jusqu'à 50 % et d'obtenir une haute précision des données. Les résultats de l'étude suggèrent que ni la crue artificielle lâchée en 2016, ni sa combinaison avec les dépôts de sédiments ne sont suffisantes pour revitaliser la mosaïque des habitats à moyen ou long terme.

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Nomenclature

A	Area	[m^2]
A_b	Total reach area between bank toes	[m^2]
A_{cov}	Total reach area with presence of cover	[m^2]
A_{long}	Assessment parameter *Longitudinal obstructions*	[-]
$A_{NSS-Deg}$	Area covered by substrate of type *2_NSS-Deg*	[m^2]
A_{RSS}	Current area of suitable substrate for reproduction in brown trout	[m^2]
$A_{RSS,ref}$	Area of suitable substrate for reproduction in brown trout under reference conditions	[m^2]
$A_{Structure}$	Assessment parameter *Structural elements*	[-]
A_{wet}	Total wetted reach area	[m^2]
CF	Concentration fine sediments in terms of weight	[%]
Cov_{curr}	Percentage of wetted area currently occupied by cover	[%]
Cov_{ref}	Percentage of wetted area occupied by cover in a reference state	[%]
CV	Coefficient of variation	[-]
D_{cov}	Deviation of current presence of cover from a reference state	[%]
D_m	Mean grain size	[mm]
h	Water depth	[m]
h_{max}	Maximum water depth	[m]
Ind1.1	Indicator 1.2: River bed structures	[-]
Ind1.2	Indicator 1.2: River bank structures	[-]
Ind1.3	Indicator 1.3: Water depth	[-]
Ind1.4	Indicator 1.4: Flow velocity	[-]
Ind1.5	Indicator 1.5: Presence of cover	[-]
Ind1.6_A2	Indicator 1.6_A2: Substrate mobilisability	[-]
Ind1.6_A3	Indicator 1.6_A3: Substrate degradation	[-]
IO_2	Interstitial oxygen concentration	[mg/L]

L	Length	[km]
L_r	Reach length	[m]
L_u	Reach unit length	[m]
$N_{Structures}$	Number of river bed structures; number of river bank structures	[-]
PFC	Percent Fine Cover; Streambed embeddedness by fine sediment	[%]
Q	Discharge	[m^3/s]
V	Volume	[m^3]
v	Flow velocity	[m/s]
v_{max}	Maximum flow velocity	[m/s]
$W_{b,avg}$	Average river bed width	[m]
z	Water column level	[m]
ϵ	Horizontal position accuracy	[m]
μ	Mean value	
σ	Standard deviation	
1_RSS	**R**eproduction-**S**uitable **S**ubstrate for brown trout without or with an acceptable level of substrate degradation.	
2_NSS-Deg	**N**on-**S**uitable **S**ubstrate due to anthropogenically caused **Deg**radation or due to an artificial cover layer.	
3_NSS-Nat	**N**on-**S**uitable **S**ubstrate due to water depth or due to a **Nat**ural, non-suitable substrate composition type.	
A1-A3	M&E assessment attributes	
C1-C6	Sediment requirement criteria by Pulg (2013)	
CR	Control reach	
DS	Downstream section	
FOEN	Federal Office for the Environment	
GIS	Geographic information system	
GNSS	Global Navigation Satellite System	
GPKG	Geopackage format	
HT	Hypothesis	
IS	Intervention section	
M&E	Monitoring & Evaluation, used as a synonym for FOEN's guideline entitled *Evaluating the outcome of revitalization projects*	

NMEA 0183	Position information standard by the National Marine Electronics Association
PT	Post-treatment design
R1-R5	Assessment method requirements
RQ1-RQ3	Research questions
RR	Replenishment reach
SBAS	Satellite-Based Augmentation Systems
WPA	Waters Protection Act (Federal Act on the Protection of Waters)
WPO	Waters Protection Ordinance
X1-X3	Auxiliary assessment attributes for substrate degradation

Hydropower mitigation	Hydropower mitigation comprises re-establishing the longitudinal connectivity for fish migration, mitigating hydropeaking effects and restoring a functional sediment regime. (DE: Sanierung Wasserkraft; FR: Assainissement de la force hydraulique)
Restoration	The two main types of river restoration in Switzerland are river revitalization and hydropower mitigation. (DE: Renaturierung; FR: Renaturation)
Revitalization	River revitalization aims to restore the functionality of altered, obstructed or covered surface waters by constructive measures. (DE: Revitalisierung; FR: Revitalisation)

1. Introduction

There exists a long tradition of shaping the riverscape to meet human needs. Originally, flood protection and land reclamation constituted the main objectives for human interventions in the aquatic environment (Wirth et al., 2011, Vischer, 2003). In the 20th century, the sudden rise in energy demand gave place to widespread hydroelectric exploitation in Switzerland (SFOE, 2018). Dams were constructed and artificial lakes were created, entailing a whole series of adverse effects. River fragmentation and the transformation from stream to lake habitat increased the ecological pressure on the alpine river network (Wüest, 2010). Downstream of the dams, the rivers' biogeochemical, hydro-morphological and eco-morphological conditions were altered, thus posing a threat for the riverscape's ecosystem (Stanford et al., 1996).

Downstream impacts of dams Hydropower storage plants produce electricity by conveying water from the reservoir via a penstock to the powerhouse. The river segment bypassed by the penstock is commonly referred to as *residual flow reach* (Felix et al., 2016). This reach is characterized by an unnaturally stable, low-discharge regime and a disturbed sediment regime (Hauer et al., 2018). The residual flow reach's bed load supply is usually cut off by the reservoir (Schleiss et al., 2016). In a natural riverscape, the discrete, patchy distribution of eco-morphological characteristics can be described as a dynamic mosaic of habitats (Stanford et al., 1996). By forcing an artificial hydro-morphological regime onto the residual flow reach, morphodynamics and environmental disturbance are reduced to a minimum, resulting in eco-morphological degradation of the habitat mosaic (Peter, 2010; Brown & Pasternack, 2008). Important examples of such degradation are the formation of streambed armor layers and substrate consolidation (Hauer et al., 2018). Undisturbed substrate in a non-dynamic environment can be consolidated by onkoid formation, i.e. lime coagulations from calcifying cyanobacteria (Hägele, 2007, Pulg et al., 2013). A different and more common process responsible for substrate consolidation is colmation.

Streambed colmation Colmation is commonly defined as clogging of interstitial pore space by fine sediment (Wharton et al., 2017). There exist various causes, types and formation processes of colmation (Schälchli et al., 2002; Parzefall et al., 2014). Depending on the research objective, a large variety of quantification and classification methods can be used to describe the degree of colmation, i.e. its physical appearance Duerdoth et al., 2015. A comprehensive overview over different methods is offered by Schälchli et al. (2002). Two common measures used for colmation assessment are the degree of substrate consolidation and the extent of fine sediment cover (e.g. Mürle et al., 2003, LfU, 2018; Schälchli et al., 2002). These two characteristics directly influence habitat quality for many aquatic species (Pulg et al., 2013; Descloux, 2011). The significance of streambed degradation for gravel-spawning fish species is exemplarily outlined for brown trout (*Salmo trutta*) in Box 1.1.

Box 1.1: Reproduction in *Salmo trutta*

Brown trout (*Salmo trutta*) depend on high-quality, functional substrate for reproduction. Brown trout prepare their spawning grounds by digging nests or redds in areas of loose gravel or stones. The incubation time describes the period of egg development in a redd and lasts several months. Fine sediment accumulations in the streambed's interstitial pore space (colmation) can interfere with egg development by disturbing oxygen supply and metabolic waste removal. Human interventions such as damming can favor streambed colmation and threaten the survival of brown trout embryos and fry.

(Pulg et al., 2013; Aarts & Nienhuis, 2003)

River restoration in legislation

The wide-spread destruction of riverscape habitats by obstruction, regulation and morphological alteration of streams called for a substantial revision of the Swiss legislation on waters protection. Since 2011, the *Federal Act on the Protection of Waters* (Waters Protection Act, WPA) and the *Waters Protection Ordinance* (WPO) explicitly demand the restoration (German: "Renaturierung", French: "Renaturation") of surface waters in order to re-establish the river systems' natural functions (Federal Assembly, 24 Jan 1991; Federal Council, 28 Oct 1998). Two main types of river restoration are discriminated. River revitalization (German: "Revitalisierung", French: "Revitalisation") aims to restore the functionality of altered, obstructed or covered surface waters by constructive measures. Hydropower mitigation (German: "Sanierung Wasserkraft", French: "Assainissement de la force hydraulique") comprises re-establishing the longitudinal connectivity for fish migration, mitigating hydropeaking effects and restoring a functional sediment regime.

Along with the planning and realization of river restoration projects, the WPO also obliges cantonal authorities to evaluate them and report on their effects (WPA Art. 38a; WPO Art. 47, 49). In order to standardize the evaluation procedure across revitalization projects, the Federal Office for the Environment (FOEN) published an extensive guideline entitled *Evaluating the outcome of revitalization projects* (Monitoring & Evaluation, M&E) in December 2019. The M&E guideline comprises 22 indicators which are assembled into 10 synergistic indicator sets. Each indicator set can be attributed to and is named after a typical revitalization goal. Indicator-Set 1 is called *Habitat diversity* and evaluates a series of eco-morphological characteristics. Its assessment is mandatory for each restoration project evaluated by the M&E method (Weber et al., 2019). In contrast to revitalization projects, the evaluation procedure for hydropower mitigation measures is not fully standardized. A guideline for the evaluation of sediment regime restoration measures is under development.

Residual flow reach restoration and methods of evaluation To improve the functionality of a residual flow reach's habitat mosaic, artificial floods (Mürle et al., 2003) and their coupling with a sediment replenishment (Stähly et al., 2019; Döring et al., 2018) have been found to be an effective restoration measure. The combination of an artificial flood event with a sediment replenishment was found to improve hydraulic habitat quality when comparing hydro-morphological characteristics before and after the flood (Stähly et al., 2019). Little is known about the effects the sediment replenishment had on other components of the habitat mosaic, such as the streambed's substrate quality. Moreover, concerns were raised about the persistence of the restoration measure's positive effects in the medium and long term (Döring et al., 2018). To evaluate these effects and to support the learning process for future projects, the importance of a defined monitoring and evaluation procedure was emphasized.
FOEN's recently published M&E guideline constitutes a universal and mandatory evaluation method for river revitalization measures in Switzerland Weber et al. (2019). The method has not yet been applied to a restoration measure consisting of a sediment replenishment combined with an artificial flood (Weber, personal communication). Its suitability for such hydropower mitigation projects has thus not yet been assessed. A defined and dedicated evaluation procedure for sediment regime restoration is currently not available in Switzerland. The M&E guideline might constitute a valuable tool to assess such restoration projects. The traditional approach for M&E surveys consists of analogous mapping in the field, followed by data digitization in a desktop environment. In other scientific fields, efficiency and accuracy of environmental field surveys have very recently been successfully increased by using mobile GIS applications (Nowak et al., 2020). Digital mapping solutions can be assumed to hold considerable potential for M&E surveys.

Study objectives and hypotheses This study aims to reply to three principal research questions (RQ). Two hypotheses (HT) were formulated based on observation, experience and previous research.

RQ1: What are the medium-term effects of a sediment replenishment in combination with an artificial flood on the quality of the residual flow reach habitat mosaic compared to an artificial flood without sediment replenishment, four years after the flood event?

RQ2: To what extent are the indicators of M&E Indicator-Set 1 sufficient to answer RQ1? / How could the indicator set be extended to answer RQ1 more comprehensively?

HT: When applying the M&E method in its current version, substrate quality assessment is not detailed enough to comprehensively answer RQ1.
(c.f. Mürle et al., 2003; Döring et al., 2018)

RQ3: How can innovative hardware and software solutions provide efficiency and accuracy gains during data collection and processing of M&E surveys?

HT: Innovative technology can significantly increase workflow efficiency by task automation and by providing decision support in the field. The accuracy of spatial data becomes quantifiable.
(c.f. Nowak et al., 2020)

2. Materials and methods

A multi-step approach was followed to obtain answers to the study's research questions. In a first step, the river reach of principal interest (replenishment reach) and a suitable control reach were defined by examination of aerial imagery combined with a preliminary field inspection. Substrate quality observations and an extensive literature review resulted in a proposal for a new substrate degradation indicator that can extend FOEN's Monitoring & Evaluation (M&E) guideline. In parallel, an advanced technical mapping solution was developed using available equipment and freely accessible open source GIS software. The technology-supported field survey was conducted following the guideline of M&E Indicator-Set 1 and including the new substrate degradation indicator. Mapping results were evaluated, validated and interpreted.

2.1. Study area and restoration measure

Building on previous research of Stähly et al. (2019) and Döring et al. (2018), this study investigates a section of the Sarine river residual flow reach below the Rossens dam. The Sarine river is a heavily regulated stream that has its source at Sanetsch (2252 m a.s.l.). After 125 km and several interruptions by dams and reservoirs it finally drains into the Aare river. In the study area, the Sarine is described as a flat, large watercourse of the colline, carbonatic midlands (FOEN, 2013). Brown trout is the fish species with the highest presence in the residual flow reach (FFSP, 2004). Further details of the study area are provided in Box 2.1 and Figure 2.1.

Box 2.1: Study area description (Stähly et al., 2019)

Rossens arch dam

- Location: Canton Fribourg (Switzerland)
- Completion: 1948
- Height = 83 m

Reservoir: Lac de la Gruyère

- $V = 200 \cdot 10^6\,\mathrm{m}^3$ | $A = 10\,\mathrm{km}^2$ | $L = 13\,\mathrm{km}$
- Among Switzerland's five biggest reservoirs

Residual flow reach

- From Rossens dam to powerhouse Hauterive
- Length = 13.4 km | Average slope = 0.3 %
- Meandering morphology in natural canyon

Damming impacts

- Complete interruption of bed load transport
- Constant residual discharge
  $Q_{Winter} = 2.5\,\mathrm{m}^3/\mathrm{s}$ | $Q_{Summer} = 3.5\,\mathrm{m}^3/\mathrm{s}$
- Channel incision and substrate degradation

In September 2016 an artificial flood was released from the Rossens dam, reaching a peak flow of approximately $200\,\mathrm{m}^3/\mathrm{s}$. This two-year return period flow was combined with a sediment replenishment 9 km downstream of the dam. The replenishment consisted of four deposits that were alternately arranged on both banks. The deposit material was excavated from the adjacent alluvial forest and had an average grain size of $D_m = 57$ mm. The deposits' total volume of 1000 m^3 reduced the flow relevant channel width in the 70 m long replenishment section by half. (Stähly et al., 2019; Döring et al., 2018)

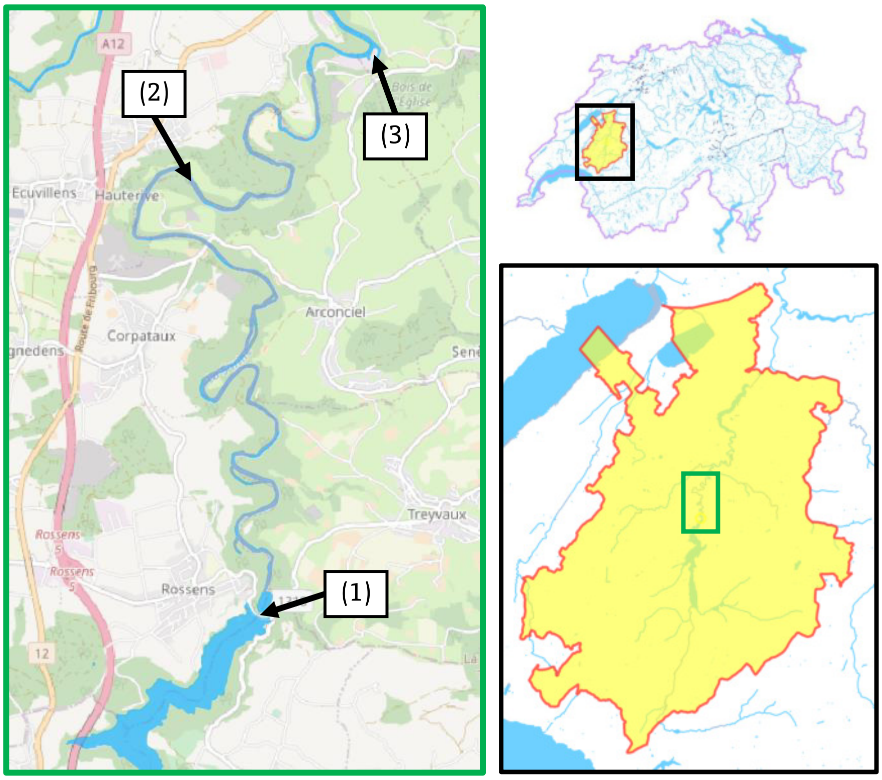

Figure 2.1: Location of the 2016 Sarine sediment replenishment in relation to Switzerland (purple outline), canton Fribourg (red outline) and the Sarine residual flow reach (green frame). Positions of Rossens dam (1), sediment replenishment (2) and powerhouse Hauterive (3) are indicated by arrows. Map data by swisstopo and openstreetmap.org

2.2. Study reaches

The evaluation of the sediment replenishment was based on a comparison between the impacted reach and a suitable control reach. This type of post-restoration evaluation is suggested for M&E surveys where sufficient pre-restoration data does not exist (Weber et al., 2019). The approach is referred to as post-treatment (PT) or control-impact design (Roni et al., 2018). Ideally, an appropriate control reach represents an untreated version of the restored reach. Hydrological and morphological conditions should be similar in both reaches and the control reach is preferentially to be located upstream of the restored reach (Roni & Beechie, 2013). In the present study, the term *replenishment reach* will be preferred over *restored reach*. The control reach is a reach that experienced only the flood and no sediment replenishment.

Figure 2.2 shows the study reaches' location within the residual flow reach. The replenishment reach's upstream limit was positioned 5 m above the uppermost sediment deposit. Its downstream limit was defined by M&E's maximum reach length of 200 m. This choice provides a maximum coverage of the replenishment's direct morphological impacts as well as its downstream bed load effects. The section of direct morphological impacts is termed *intervention section* and defined as the upstream 80 m long section of the replenishment reach. It is followed by the 120 m long *downstream section*. This subdivision of the replenishment reach is visualized in Figure 2.3. The M&E guideline prescribes a 200 m reach length limit only for four out of six Set 1 indicators. However, an identical study reach definition was applied to the entire M&E Set 1 to allow for a homogeneous analysis of results.

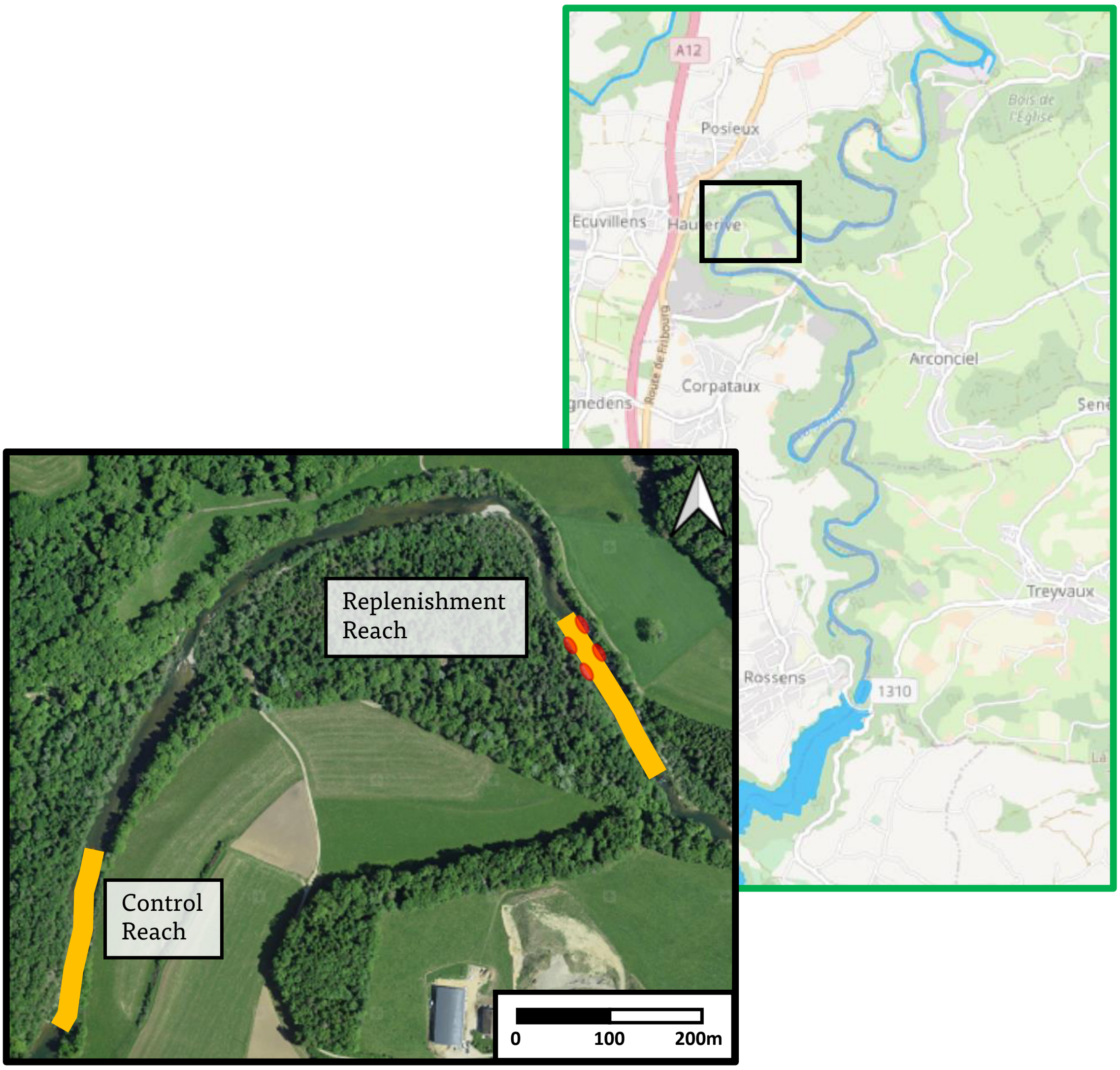

Figure 2.2: Location of the replenishment reach and its control reach in relation to the Sarine residual flow reach (green frame). Positions of the four sediment deposits are highlighted in red. Map data by swisstopo and openstreetmap.org

The main criteria guiding the selection of the control reach were the parameters channel planform, bed structure, bed slope, wetted width and floodplain and bank morphology. Geographical and hydrological proximity with upstream positioning were necessary prerequisites. The selection process consisted of a morphological analysis using the swisstopo Web-GIS as well as field observations. The most appropriate control reach that could be identified is located 1 km upstream of the replenishment reach. Its identical length of 200 m results in a 800 m clear distance in between. A description with further details of both reaches is provided in Table 2.1.

Table 2.1: Description of the replenishment reach and control reach

	Replenishment reach	**Control reach**
Coordinates upstream end	46.75804 N, 7.10333 E	46.75396 N, 7.09609 E
Coordinates downstream end	46.75650 N, 7.10468 E	46.75574 N, 7.09657 E
Length	200 m	200 m
Planform	straight, subsequent to a bend	straight, subsequent to a bend
Channel-Riffle-Rapids sequence	included (long rapids section)	included (short rapids section)
Average wetted width	24.9 m	23.1 m
Width variability (max/min)	(33.8 m/14.9 m) = 2.3	(32.9 m/13.2 m) = 2.5
Average slope	$\frac{0.7\,\text{m}}{200\,\text{m}} = 0.4\,\%$	$\frac{0.2\,\text{m}}{200\,\text{m}} = 0.1\,\%$

2.3. M&E Indicator-Set 1: Habitat diversity

The Indicator-Set 1: *Habitat diversity* constitutes the central assessment tool of FOEN's Monitoring & Evaluation guideline. It is composed of six individual eco-morphological indicators (Weber et al., 2019). In the present study, these indicators were used to evaluate the effects of the Sarine sediment replenishment on the river's habitat mosaic. Their assessment approaches are briefly outlined in the following. Further details are provided by FOEN (2019), Woolsey et al. (2005) and Hunzinger et al. (2018). Currently, no official English version of the M&E guideline has been published. The original terms of the French and German publications are listed along with this report's English translations in Appendix A.

Indicator 1.1: River bed structures The entire area of the study reach is visually examined and mapped in between bank toes. Nine river bed structures are distinguished: *Bar*, *scour*, *channel*, *riffle*, *rapids*, *backwater*, *shallow water*, *drop* and *pool*. The examination area is subdivided into polygons that are characterized by a single river bed structure. Each polygon must be delineated in such a way that its structure type is unique among adjacent polygons. In a first step, the indicator's assessment requires to calculate the reach's unit length L_u. L_u is obtained by multiplying the average river bed width $W_{b,avg}$ with factor 12. In this study, $W_{b,avg}$ was calculated as the ratio of total reach area between bank toes A_b and reach length $L_r = 200\,\mathrm{m}$. The study reach's unit length is then calculated as

$$L_u = W_{b,avg} \times 12 = \frac{A_b}{200\,\mathrm{m}} \times 12 \tag{2.1}$$

Finally, the study reach's total number of polygons is normalized by L_u, yielding the number of river bed structures per unit length. A look-up-table links the number of river bed structures per unit length to the corresponding indicator value ranging from 0 to 1.

Indicator 1.2: River bank structures The study reach's shoreline, i.e. the border line between water and land is mapped and divided into sections of homogeneous structure. A homogeneous structure is defined by having identical properties for the three attributes *Profile* (linear, convex, concave), *Composition* (permeable structures, impermeable structures, loose material, roots, rock) and *Slope* (flat, steep). The indicator is evaluated by assessing the proportion of impermeable structures (Parameter "Longitudinal obstructions", A_{long}) as well as the structural diversity of the shoreline (Parameter "Structural elements", $A_{Structure}$). A value between 0 and 1 is calculated for Indicator 1.2 as the sum of the two parameters.

$$Ind1.2 = A_{long} + A_{Structure} \tag{2.2}$$

Indicators 1.3 + 1.4: Water depth and Flow velocity In each study reach, 10 to 15 cross sections are defined at approximately regular intervals but including local peculiarities. In each cross section, water depth and flow velocity are measured for at least 10 sampling points. The distance between neighboring points is constant across all cross sections and determined by the narrowest profile. A total of 150 to 200 samples is recommended. Flow velocity is measured at height $z = 0.4 * h$ from the river bed, where $z = 0$ defines the river bed and $z = h$ the water's surface, yielding a good estimate of depth averaged flow velocity. From all measurements of a reach, the coefficients of variation (CV) are calculated for water depth and flow velocity, respectively. In the replenishment reach, CV values are additionally calculated separately for the intervention section and the downstream section from their corresponding measurements. To obtain indicator values ranging between 0 and 1, the CV values are standardized.

With the intention of creating a valuable data base for follow-up research, recommendations of the M&E guideline were followed as closely as possible for the replenishment reach. In this study reach, a total of 263 measuring points was sampled over 14 cross sections. The intended 15th cross section in proximity to the upstream reach limit could not be sampled because of water depths $> 1.6\,\mathrm{m}$. Five of the reach's 14 cross sections are attributed to the intervention section, nine to the downstream section. In the control reach, only 77 measurement points in five cross sections could be sampled due to capacity restrictions. The cross sections' placement within both reaches is visualized in Figure 2.3.

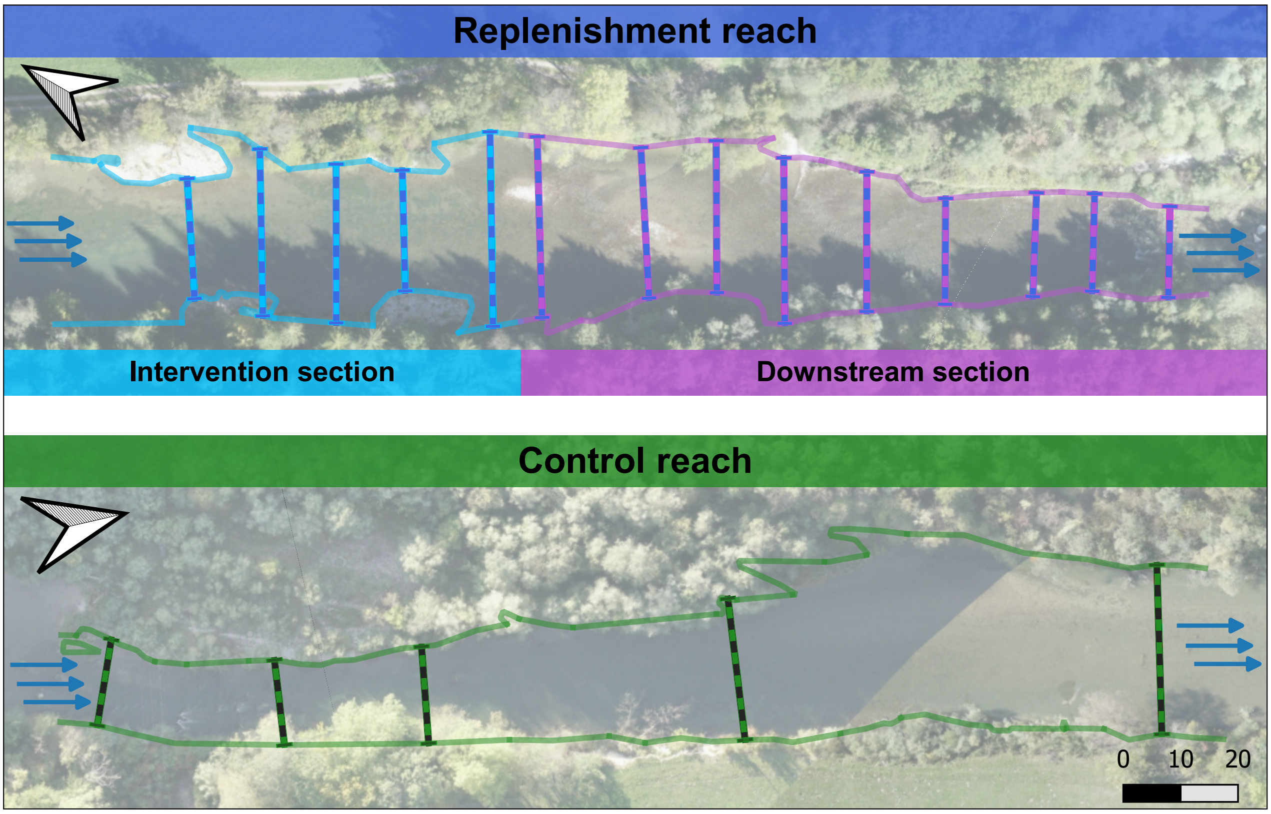

Figure 2.3: Cross section placement and replenishment reach subdivision.
Base map: © Research Group for Ecohydrology ZHAW

Indicator 1.5: Presence of cover The wetted area A_{wet} is examined for thirteen types of cover and their occupied areas are mapped as polygons. The different types are *immerged rocks*, *non-immerged rocks*, *small organic particles*, *medium-sized organic particles*, *large branches in the water*, *large roots*, *tree trunks*, *tree stumps or entire root systems*, *overhanging vegetation*, *undercut banks*, *underwater plants/floating plants*, *overhanging grass/reed*, *turbulent zones* and *scours*. The total area of cover A_{cov} can be calculated. The deviation D_{cov} of current presence of cover from a (theoretical) reference state is obtained as

$$D_{cov}\ [\%] = 100 - \left(\frac{Cov_{curr}\ [\%]}{Cov_{ref}\ [\%]} \times 100 \right) = 100 - \left(\frac{A_{cov,curr} \div A_{wet,curr}}{A_{cov,ref} \div A_{wet,ref}} \times 100 \right) \tag{2.3}$$

where Cov_{curr} is the percentage of wetted area currently occupied by cover and Cov_{ref} is the percentage of wetted area that would be occupied by cover in a reference state. In M&E surveys Cov_{ref} is usually estimated by experts. For the present study, the estimations provided by Christine Weber (Eawag) and Pascal Vonlanthen (Aquabios Sàrl) were averaged. The value of Indicator 1.5 is determined from D_{cov} by means of a look-up-table.

Indicator 1.6_A2: Substrate mobilisability In the current version of the M&E guideline, Indicator 1.6 is composed of two attributes. Attribute A1 is called "Substrate composition" and distinguishes *fine sediments*, *sand*, *gravel*, *stones*, *large stones*, *blocks*, *bedrock*, *organic material* and *artificial substrate*. Attribute A2 describes the "Substrate mobilisability" and distinguishes five qualities: *Suspended matter deposits*, *fine bed load*, *coarse bed load*, *bed material interspersed with bed load* and *coarse bed material*.

As with Indicator 1.1, the entire zone between bank toes (A_b) is examined. By visual inspection, A_b is divided into homogeneous subareas or polygons. Each polygon is characterized by a single combination of attributes A1 and A2. Currently, an assessment method only exists for attribute A2. In order to determine the score of Indicator 1.6_A2, for each of the five qualities the cumulative attributed polygon area is calculated. A bar chart of area distribution among qualities is created. The M&E guideline supplies five typical distributions with textual descriptions that are rated with indicator values between 0 and 1. The distribution or description that corresponds the most to the mapping result determines the final score of Indicator 1.6_A2 "Substrate mobilisability"

2.4. Indicator 1.6_A3: Substrate degradation

The current M&E guideline describes a mapping procedure for substrate composition but no method to assess the composition or degradation of substrate. Yet, substrate composition and degradation constitute essential factors in habitat assessment and are considered important for the interpretation of biotic indicators (FOEN, 2019). Preliminary field observations in the Sarine residual flow reach supported this consideration by revealing wide-spread substrate consolidation and colmation. It was hence considered necessary to extend the M&E Indicator-Set 1 with an additional indicator to assess the composition and degradation of streambed substrate. The resulting set of indicators is here referred to as the *Extended M&E Set 1*. The aim was to find a **method to assess the substrate's functionality in terms of its ecological role as habitat**. The method was required to make use of the existing M&E mapping procedure for substrate composition and follow the general assessment approach of M&E Set 1. By examination of each indicator's mapping procedure and assessment approach, five principal requirements for the method were identified. They are outlined in Box 2.2.

Box 2.2: Assessment method requirements (R)

R1 **Indicator range concept** compliance
- → Range from 0 to 1
  0 = artificial/degraded; 1 = near-natural

R2 **Survey concept** compliance
- → Rapid inspection procedures
- → No post-analysis in the lab

R3 **Mapping and assessment concept** compliance
- (a) Assessment by *eco-morphological properties*
  Only physical substrate appearance and characteristics are examined
- (b) Assessment of *habitat availability and quality*
  The substrate's ability to fulfill fundamental ecological habitat functions is evaluated
- (c) *Examination extent and mapping approach*
  The entire study reach is examined and homogeneous M&E substrate polygons are used.

R4 **Scientific justification**

R5 **Applicability** across Switzerland (trout zone)

Necessity for a new method A variety of methods exist to assess the degradation of substrate, which impairs the streambed's natural functionality as habitat (e.g. Schälchli et al., 2002; Barbour et al., 1999; Parzefall et al., 2014; Duerdoth et al., 2015). Some of them evaluate the degree of habitat functionality by linking physical substrate characteristics to habitat suitability criteria (Kondolf, 2000; Pulg et al., 2013). No existing method sufficiently fulfills all five requirements stated in Box 2.2. A new method is therefore proposed on the basis of several existing approaches.

Evaluation basis The assessment method of the new indicator "Substrate degradation" is based on brown trout's requirements for substrate as reproduction habitat. The choice of brown trout as reference species and the definition of substrate requirements based on the substrate's ecological function as reproduction habitat is justified by several arguments.
Generally, substrate requirements vary significantly among aquatic species and depending on the ecological habitat function considered (Kondolf, 2000; Zweig & Rabeni, 2001). The streambed substrate provides a general living habitat for a variety of benthic organisms and as such it also serves as feeding habitat for fish (Aarts & Nienhuis, 2003; Wharton et al., 2017). Gravel-spawning fish of the trout zone depend on streambed substrate as reproduction habitat and a natural streambed offers cover for different species in various situations. The presence of cover is already evaluated by M&E Indicator 1.5.
In literature, quantitative descriptions of eco-morphological substrate requirements are predominantly available for reproduction in fish (c.f. Kondolf, 2000; Pulg et al., 2013). Descriptions of eco-morphological substrate requirements of other species such as invertebrates were less comprehensive (Zweig & Rabeni, 2001) or required assessment techniques which are incompatible with a rapid field inspection procedure (Descloux, 2011). Among gravel-spawning fish of the trout zone, brown trout would be the most common species under reference conditions. Moreover, it has, among other species, the highest requirements regarding substrate quality (Pulg, 2008).

Indicator concept In analogy to Indicator 1.5 "Presence of cover", the area of currently present habitat is compared to a reference value. More specifically, the area of substrate within the study reach that is suitable for reproduction in brown trout A_{RSS} is compared to the suitable area under reference conditions $A_{RSS,ref}$. Indicator 1.6_A3 "Substrate degradation" is directly calculated as

$$Ind1.6\_A3 = \frac{A_{RSS}}{A_{RSS,ref}} \tag{2.4}$$

yielding values in between 0 (fully degraded) and 1 (near-natural).
To obtain A_{RSS} and $A_{RSS,ref}$, an additional attribute A3 is introduced to the substrate mapping procedure of the M&E guideline. The attribute A3 "Reproduction suitability" complements A1 "Composition" and A2 "Mobilisability". Mapped polygons are required to be homogeneous across all three attributes.

Attribute A3 "Reproduction suitability" distinguishes substrate according to three qualities:

1_RSS **R**eproduction-**S**uitable **S**ubstrate for brown trout without or with an acceptable level of substrate degradation.
Example: Colmation-free, unconsolidated, well submerged gravel

2_NSS-Deg **N**on-**S**uitable **S**ubstrate due to anthropogenically caused **Deg**radation or due to an artificial cover layer. All forms of substrate degradation are summarized.
Examples: Colmated gravel due to unnatural fine sediment input or an unnaturally stable flow regime, consolidated stone streambed due to lack of bed load, artificial paving on natural gravel substrate

3_NSS-Nat **N**on-**S**uitable **S**ubstrate due to water depth or due to a **Nat**ural, non-suitable substrate composition type.
Examples: Barely submerged substrate, bedrock, blocks, sand, natural fine sediment accumulation in an area of reduced flow in an otherwise dynamic environment

The proposed calculation approach for the indicator score is based on the assumption that in the natural environment of the trout zone, gravel and stone substrate in generally not critically degraded. An extended calculation approach that takes into account the uncertainties of this assumption and the uncertainties in the distinction between anthropogenically caused and natural degradation is discussed in Chapter 4. When assuming correct distinction between the two causes of degradation during the field survey, all areas of quality *2_NSS-Deg* would be degradation free and qualify as *1_RSS* in the reference state. The suitable area in a reference state can then be defined as

$$A_{RSS,ref} = A_{RSS} + A_{NSS-Deg} \tag{2.5}$$

where $A_{NSS-Deg}$ describes the substrate area described as non suitable due to anthropogenically caused degradation or artificial covering. In contrast to Indicator 1.5 the reference area does not need to be estimated. After mapping the entire study reach area between bank toes by subdivision into homogeneous A1-A2-A3 polygons, Indicator 1.6_A3 is calculated as

$$Ind1.6\_A3 = \frac{A_{RSS}}{A_{RSS,ref}} = \frac{A_{RSS}}{A_{RSS} + A_{NSS-Deg}} \tag{2.6}$$

Assessment criteria Suitable substrate for reproduction in salmonids is described as unconsolidated, non-colmated, submerged gravel (Bjornn & Reiser, 1991). Grain size and consolidation of substrate are determining factors in the construction of redds (spawning process) (Pulg, 2008). Colmation endangers egg development (embryo incubation) and is often described by concentration fine sediment. Colmation can prevent interstitial flow and thus reduces oxygen supply and metabolic waste removal (Kondolf, 2000). Sufficient water depth reduces the risk of stranding during low flow (Barlaup et al., 1994). Pulg et al. (2013) identified brown trout's main substrate requirements in a regulated pre-alpine carbonatic stream, comparable to the Sarine residual flow reach in size and bed load deficit. The requirement thresholds match data on brown trout found by other authors (Pulg et al., 2013). These thresholds form the basis for the assessment procedure of the proposed substrate degradation indicator. The assessment procedure to follow during a field survey is summarized in the form of a decision tree and visualized in Figure 2.4. The decision criteria's derivation is outlined in the following. Classification examples that clarify the distinction between natural and anthropogenic cover layer origination are provided in paragraph *Indicator concept*.

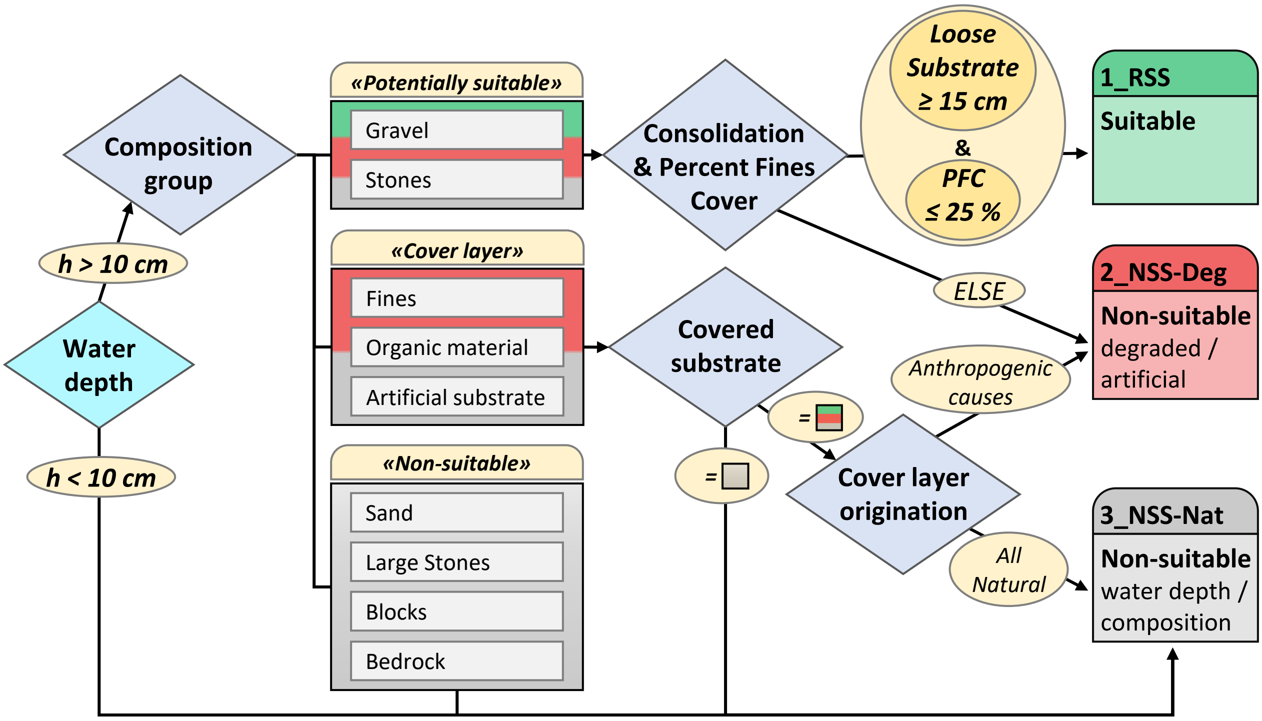

Figure 2.4: Decision tree for reproduction suitability classification in the field

The substrate requirements of brown trout described by Pulg et al. (2013) are summarized in Table 2.2. The listed criteria describe only the eco-morphological substrate requirements and some physical prerequisites for reproduction in brown trout. Actual reproduction success depends on many other factors such as hydrological conditions, water quality, temperature regime and streambed morphology. The set of criteria that determined whether substrate can be qualified as *1_RSS* is an adapted version of criteria C1 to C4. The new criteria set comprises the original M&E attribute A1 *Substrate composition* as well as three binary auxiliary attributes (X1 to X3). It is presented and compared to the original criteria in Table 2.3.

Pulg et al. (2013) found reproduction suitable substrate to have average grain sizes between 5.7 mm and 40 mm. Among other authors, descriptions of suitable grain sizes for brown trout show some variation (Peter, 1986; Bjornn & Reiser, 1991) but are usually contained within the limits of gravel and stone according to their definition in the M&E guideline (Gravel: 2-16 mm; Stones: 16-64 mm). By making use of the existing mapping of substrate composition and taking into account the rapid inspection requirement, the original criterion C1 is replaced by the requirement that

Table 2.2: Minimum substrate requirements for brown trout reproduction (Pulg et al., 2013). CF: Concentration of fine sediment (< 0.85 mm)

Criterion (C)	**Description**	**Requirement**
C1	Average grain size (D_m)	5.7 mm < D_m < 40 mm
C2	Consolidation	Top layer of loose substrate ≥ 15 cm (boot test)
C3	Colmation	$CF \leq 18.5\,\%$ of upper 20 cm layer
C4	Water depth (h)	$h > 0.1$ m
C5	Flow velocity (v)	0.2 m/s < v < 1 m/s
C6	Interstitial oxygen concentration (IO_2)	$IO_2 > 6.7$ mg/L

substrate be described as gravel or stones. The consolidation criterion C2 was adopted as such and integrated into the new assessment method as auxiliary attribute X1.

Schälchli et al. (2002) distinguishes two types of colmation, *inner colmation* and *outer colmation*. For both colmation types, rapid inspection procedures are available. Inner colmation can be assessed by the boot test (Box 2.3) and outer colmation can be quantified by visual inspection in terms of *embeddedness* or *Percent Fine Cover* (PFC) (Schälchli et al., 2002). These factors encouraged the splitting of colmation criterion C3 into sub-criteria C3-i: *Inner colmation* and C3-ii: *Outer colmation.*

Table 2.3: Indicator attributes to determine the reproduction suitability of substrate. Comparison to substrate requirements by Pulg et al. (2013)

Assessment attribute		**Required for *1_RSS***	**Original criteria covered**		**Comment**
A1	Substrate composition	Gravel or stones → visual estimation	**C1**	Average grain size (D_m)	*Range of tolerable grain sizes originally more restrictive*
X1	Consolidation	Top layer of loose substrate ≥ 15 cm → boot test	**C2** **C3-i**	Consolidation Inner colmation	*Boot test assesses not only substrate consolidation but also inner colmation (*Schälchli et al.*, 2002).*
X2	Percent Fine Cover (PFC)	$PFC \leq 25\,\%$ → visual estimation	**C3-i** **C3-ii**	Inner colmation Outer colmation	*PFC indicates outer colmation (*Schälchli et al.*, 2002). Together, X1 and X2 cover the original colmation criterion C3.*
X3	Water depth (h)	$h > 0.1$ m → visual estimation	**C4**	Water depth	*Identical requirement, no adaptation*

A basic assumption of the assessment method is that loose, unconsolidated gravel without critical fine sediment cover (outer colmation) is not affected by critical inner colmation. Consequently, unconsolidated substrate with sub-critical fine sediment cover has no or sub-critical inner and outer colmation and can therefore be considered as non-colmated, thus fulfilling criterion C3. Colmation assessment based on consolidation and embeddedness has previously been applied in a related study by Mürle et al. (2003).

A critical threshold for percent fine cover PFC was obtained in several steps from the original threshold for concentration of fine sediment in terms of weight CF. Pulg et al. (2013) describes the critical concentration of fine sediment in the upper 20 cm substrate layer at the end of the incubation period as $CF_{crit,inc} = 18.5\,\%$. During redd construction, salmonids significantly reduce fine sediment concentration in the substrate. Kondolf (2000) established an empirical relationship between fine sediment concentration before and after redd construction as

Box 2.3: How-to boot test

Substrate is classified as loose if it can easily be moved to a depth of 15 cm by small movements of the boot. Otherwise it is considered as consolidated.
Pulg et al., 2013

$$CF_{after} = 0.67 * CF_{before} \tag{2.7}$$

Fine sediment re-accumulation after redd construction can be significant but varies strongly even among potential reproduction sites within the same stream (c.f. Pulg, 2008). Therefore, the mean of full re-accumulation and zero re-accumulation was considered as best estimate for the re-accumulation effect during the incubation period in a random location. Considering both redd construction and re-accumulation, the critical fine sediment concentration for pre-spawning surveys is obtained as

$$CF_{crit,pre} = \frac{CF_{crit,inc}}{0.67 + (0.33 * 0.5)} = \frac{18.5\,\%}{0.84} = 22.2\,\% \tag{2.8}$$

Sutherland et al. (2010) found significant and high correlation between visual estimates of PFC by trained individuals and measurement results of CF (< 2 mm) from sieved core samples of the upper 20 cm substrate layer. Similar conclusions regarding the comparability of visual and measurement-based techniques are drawn by McHugh & Budy (2005). Sutherland et al. (2010) observed visual estimates of PFC to be consistently higher than measured results of CF. They quantified this overestimation in terms of a root mean squared error (RMSE) of 12.9 %. Although this relationship is based on the definition of fine sediment as < 2 mm it was considered to be a valid rough estimate for the regression coefficient in the determination of the critical PFC limit. The critical limit for visual PFC estimation in pre-spawning surveys is obtained as

$$PFC_{crit,pre} = CF_{crit,pre} \times 1.129 = 22.2\,\% \times 1.129 = 25.0\,\% \tag{2.9}$$

The auxiliary attributes X1 and X2 evaluate substrate consolidation and percent fine cover. In combination, they were considered an adequate rapid inspection replacement for the original criterion C3, which requires laborious post-analysis of sediment samples.
The water depth criterion C4 was integrated as is and became auxiliary attribute X3. Criteria C5 and C6 were not integrated into the assessment method of the new substrate degradation indicator. The flow velocity criterion C5 does not describe the substrate itself but its surroundings. Moreover, flow velocity conditions are separately assessed by M&E Indicator 1.5. Criterion C6, interstitial oxygen concentration, is not an eco-morphological descriptor. Furthermore, its measurement is not compatible with the requirement that demands rapid field inspection methods.

Requirement compliance The original criteria C1 to C4 described by Pulg et al. (2013) were adapted for compliance with the assessment method requirements R2 and R3. The combination of the final set of assessment criteria with the indicator concept provides an assessment method for Indicator 1.6_A3 "Substrate degradation" that fulfills requirements R1 to R3 by design. The method's limits with regard to requirements R4 and R5 are discussed in Chapter 4.

2.5. Survey set-up and data

For the study's field work, a digital, GNSS-supported mapping environment was conceived and set up. The set-up consisted of a survey-grade GNSS antenna that was mounted on a backpack and connected to a mobile GIS application on a field tablet. It is shown in Figure 2.5.

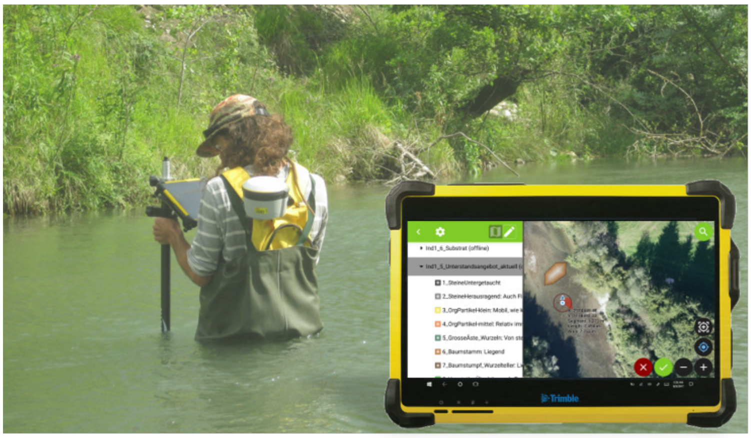

Figure 2.5: Field work set-up: GNSS antenna connected to a mobile GIS application on a field tablet

Various mobile GIS applications exist and have been successfully applied in environmental field surveys (Nowak et al., 2020). In the present study, an integrated GIS environment consisting of *QGIS* (v3.12.3) as desktop application and *QField* (v1.5.3) as its mobile counterpart was chosen (QGIS Development Team, 2020; The QField Project/OPENGIS.ch, 2020). Several reasons explain this choice. First, both programs are open source, freely accessible and thus usable in follow-up projects. Second, similar to the commercial products offered by ESRI, this environment allows for fully integrated data transfer between the mobile and desktop application and requires only one single project set-up. Third, QField offers a wide range of functionalities that were considered indispensable for efficient field work. These functionalities include GNSS-supported mapping, dynamic attribute forms, custom symbology, constraint definition and snapping. Finally, QField's ongoing rapid evolution and its successful implementation in environmental projects across Switzerland further supported the decision. (Kuhn & Bernasocchi, 2016; Nowak et al., 2020)

Pre-study data The aerial imagery that served as a base map in the QField project was provided by the Research Group for Ecohydrology of the Zurich University of Applied Sciences (ZHAW). The ZHAW research group captured drone images during summer flow conditions ($Q = 3.5\,\mathrm{m}^3/\mathrm{s}$) on

September 28, 2018. The post-processed images were provided as geo-referenced TIFF-files with a resolution of 4 cm per pixel and 6 cm horizontal positional accuracy in the CH1903+/LV95 coordinate reference system.
For a preliminary and partial validation of the new indicator's assessment method, positional data of actual trout redds from the years 2016 to 2019 was consulted. Redd data was provided by the organization *La Frayère* that monitors each year the trout spawning grounds in a reach of the Sarine that covering both study reaches. The most recent monitoring took place on December 28, 2019 (La Frayère, 2020). At each spawning site, the number of redds was counted and the position logged with consumer-grade handheld GPS devices. Horizontal position accuracy was estimated at ≈ 20 m, coinciding with accuracy analysis of consumer-grade devices in other studies (Johnson & Barton, 2004).

Mapping environment The hardware that was available to set up the study's mapping environment consisted of a *Trimble* GNSS antenna "R2" and *Trimble*'s field survey tablet "T10". The tablet can receive GNSS data from the antenna via a bluetooth connection. Accuracy augmentation of the GNSS data is achieved via Satellite-Based Augmentation Systems (SBAS) by using the tablet's mobile internet connection and *Trimble*'s "GNSS Status" application. This application can forward the corrected GNSS data stream in the form of NMEA sentences to a specified COM port. Third party applications can then connect to the tablet's COM port to receive positional data. However, the tablet runs a Windows 10 operating system, whereas at the time of this study, a fully functional version of QField was only available as Android application. Such android applications can be run in a Windows environment by using Android emulators for Windows. No freely accessible emulation software was found that is able to directly make positional data from a COM port (or the Windows location itself) available to apps within an Android environment. A custom middleware solution was hence necessary to run QField on the T10 tablet with R2 GNSS positions. The middleware's main components were an Android emulator, a network bridge, a mock position application as well as a short Linux bash script. The data flow from the R2 antenna to the QField app is shown in Figure 2.6. The emulation software chosen for this study was *MEmu*, as it is a powerful emulator that is able to connect to a bridged network (Microvirt, 2017). It can thus receive signals via TCP/IP. *MockGeoFix* is an Android app that can read NMEA sentences from the emulator's IP adress and write the positional data in the Android location (Vacek, 2016). This location is accessible by the QField app inside the emulator. To establish the link between COM port and MEmu, two virtual ethernet connections ("Loopback Microsoft KM-TEST") were created in the Windows network configuration and connected by a network bridge. The Linux Telnet Client was activated in Windows and a Linux terminal was prepared (Ubuntu 18.04 LTS). Finally, by making use of the Linux *cu* package, a short bash script was written that forwards the NMEA sentences from the COM port to the network bridge's IP adress. By connecting MEmu to the bridged network and running MockGeoFix, the corrected GNSS location was available to QField for GNSS-supported mapping.
The horizontal accuracy of position-based mapping within QField was tested prior to field work. QField's tracking mode was enabled so that walked trajectories were automatically saved as *LineString*

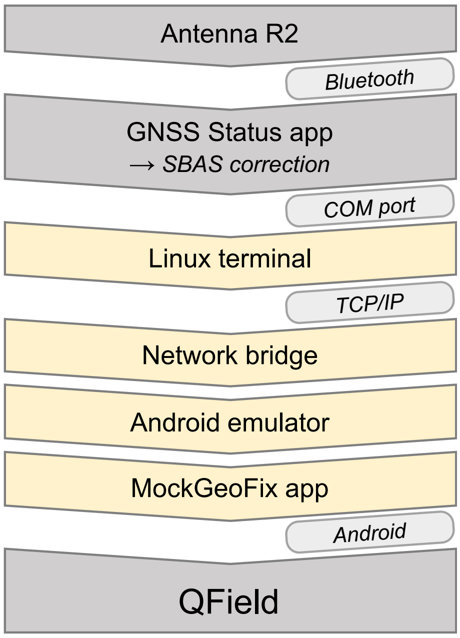

Figure 2.6: Flow of GNSS data from the antenna (Trimble R2) to the mapping application (QField). Components of the custom middleware solution are highlighted.

features in a test project. On the EPFL campus, road markings were followed and gully tops were circled. The offset between the mapped position of sharp bends of road markings or gully tops and their position on geo-referenced satellite imagery was analyzed.

GIS project A comprehensive, QField compatible project was set up in QGIS that implemented the extended M&E Indicator-Set 1. The project was developed as a general, ready-to-use template for digital M&E Set 1 surveys. Project layers, symbology, forms and settings were designed to replace analogue documents and mapping material in the field. The attribute tables' set-up allowed for efficient post-survey data analysis. Principal project characteristics are presented in Figures 2.7 to 2.10 and described in the following. Detailed instructions for implementation can be found in The QField Project/OPENGIS.ch (2020) and QGIS Development Team (2020).

Base map: A high resolution base map was obtained from the provided orthophoto TIFF-files. Since uncompressed raster data is inefficient on mobile devices, the original files were clipped to an appropriate extent around the study reaches and converted to the geopackage (GPKG) format. Pyramids were built for enhanced rendering.
Layers: Project layers were organized in four groups corresponding to their GPKG-bundling: *Base maps*, *Replenishment reach indicators*, *Control reach indicators* and *Reach definition*. Reach definition layers define the study reaches' borders, support orientation in the field and contain automatic proposals for the placement of cross sections. Each group of study reach indicators contains one separate layer for each of the indicators 1.1, 1.2, 1.5, 1.6_A2 and 1.6_A3. Indicators 1.3 and 1.4 share one layer which represents the measurement cross sections for water depth and flow velocity samples.

The cross section layer, the river bank structure layer (Indicator 1.2) and reach definition layers have *LineString* geometry. The remaining indicator layers are of type *Polygon*.

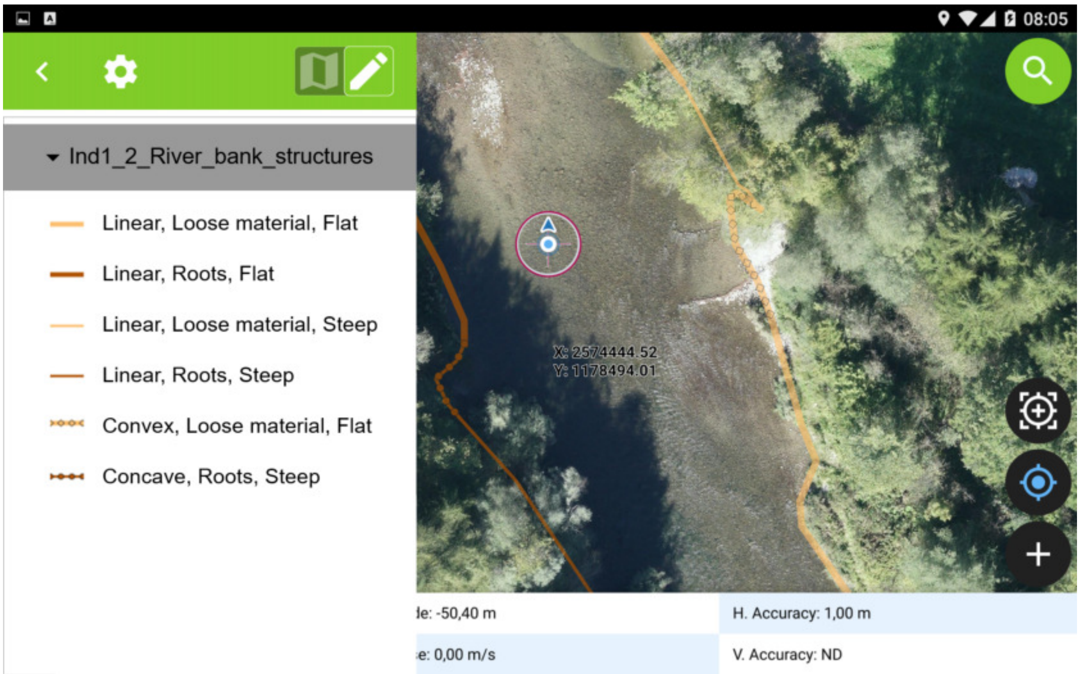

Figure 2.7: Rule-based visualization of river bank structures in QField: Bank profile is visualized by symbols (linear - no symbol, convex - squares, concave - circles), composition is represented by colors and slope by line width (flat - wide, steep - narrow).
Base map: © Research Group for Ecohydrology ZHAW

Fields and forms: For each indicator layer, fields of the attribute table were defined in which the M&E attribute values of a mapped features could be stored. Names, data types and valid values of the attribute fields were adopted from the M&E guideline as well as from descriptions provided in Section 2.4. Additional fields were created to implement decision support functionalities within QField such as pop-up explanations and example pictures. Fields were also set up for geometric properties of mapped features such as polygon size and line length. The layers' attribute forms were assembled using the QGIS drag and drop designer. Allowed field values could be predefined using the *value map* widget. For straightforward feature recognition, the feature's display names were defined by expressions that included attribute values and geometric properties.

Symbology: When mapping a new feature in a QField indicator layer, the feature's M&E attribute values must be directly selected in the attributes form. The selected attribute qualities are visualized instantly by feature symbology. Depending on the indicator, rule-based or categorized symbology was used for straightforward feature recognition. Figure 2.7 shows the example of Indicator 1.2, where river bank structure attributes are distinguished by line width, color and symbols.

Mapping-supportive symbology was also implemented in the reach definition layer. A combination of a font marker line with simple marker lines describes the distance of any position within the study reach from its downstream limit. Propositions for the placement of equally spaced measurement cross sections for indicators 1.3 and 1.4 were visualized using dynamic expression markers. The number of cross sections can be adjusted during the field survey via the layer's attributes form. Figure 2.8 displays this functionality.

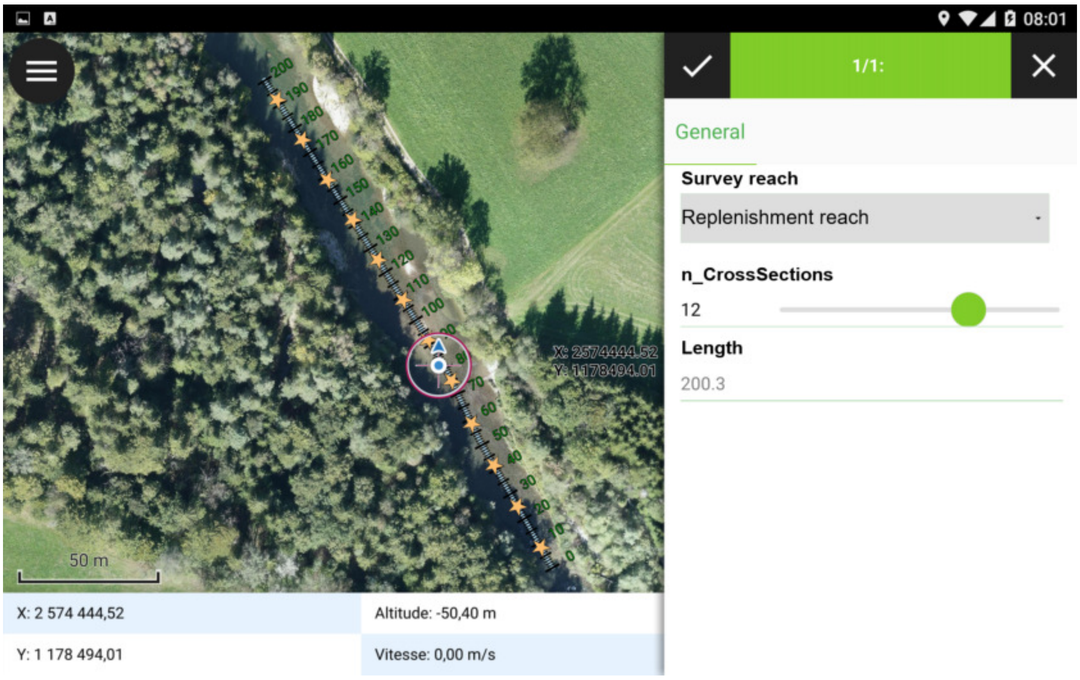

Figure 2.8: Reach definition layer in QField: Marker lines describe the distance from the study reach's downstream limit. Propositions for cross section placement are indicated by star markers. Base map: © Research Group for Ecohydrology ZHAW

Default values: In QGIS and QField, default values can be assigned to attribute fields. Default values were in particular used for the automatic calculation of feature geometry properties such as line length and polygon surface areas. This functionality accelerated post-survey data analysis and aided technical decision support.

Decision support: During field work, mapping decisions were supported by a need-specific integration of the M&E guideline into QField's attributes forms. A summary of indicator-specific guideline content is displayed in each indicator layer's attributes form and the guideline's relevant pages are previewed and linked to. Two QField functionalities were particularly useful for the implementation of decision support: Value constraints and conditional visibility of attribute form content. Value constraints were used to examine features' compliance with M&E requirements. For instance, bank structure lines were required to have a minimum length of 5 m and substrate polygons a minimum surface area of 3 m^2. QField's conditional visibility functionality was used to provide pop-up explanations based on the current selection of attribute values. Such explanations featured HTML-style text as well as images from the M&E guideline. An implementation example is provided for substrate mobilisability classification in Figure 2.9.

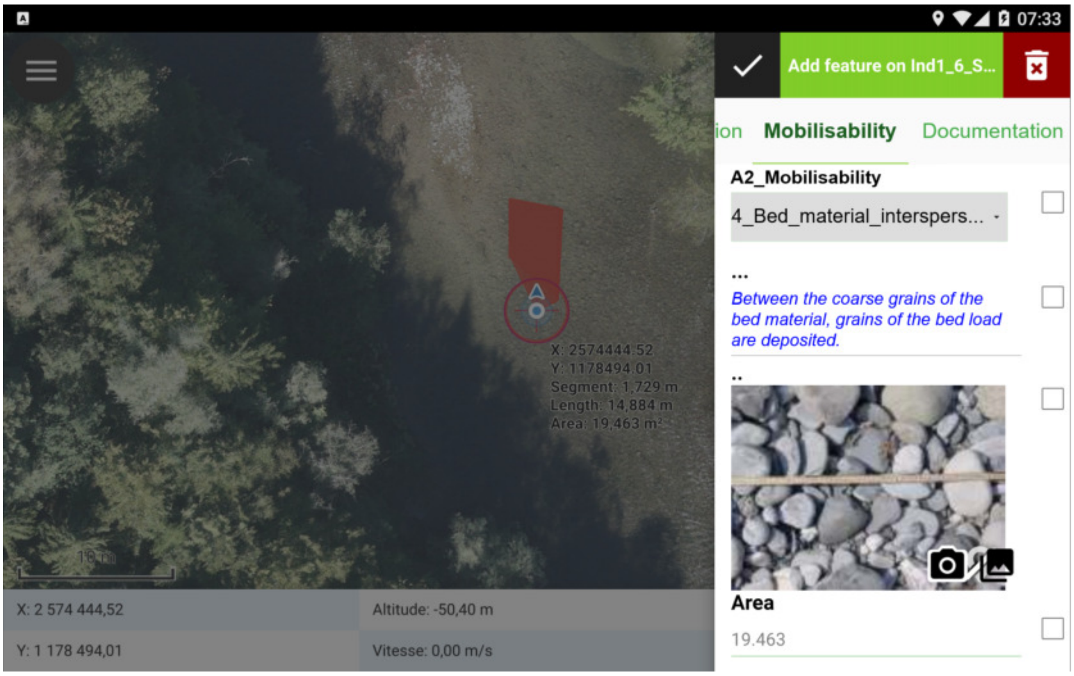

Figure 2.9: Conditional visibility fields for decision support in QField: Pop-up explanations consisting of HTML text and example images aide decision-making during mobilisability classification. Base map: © Research Group for Ecohydrology ZHAW

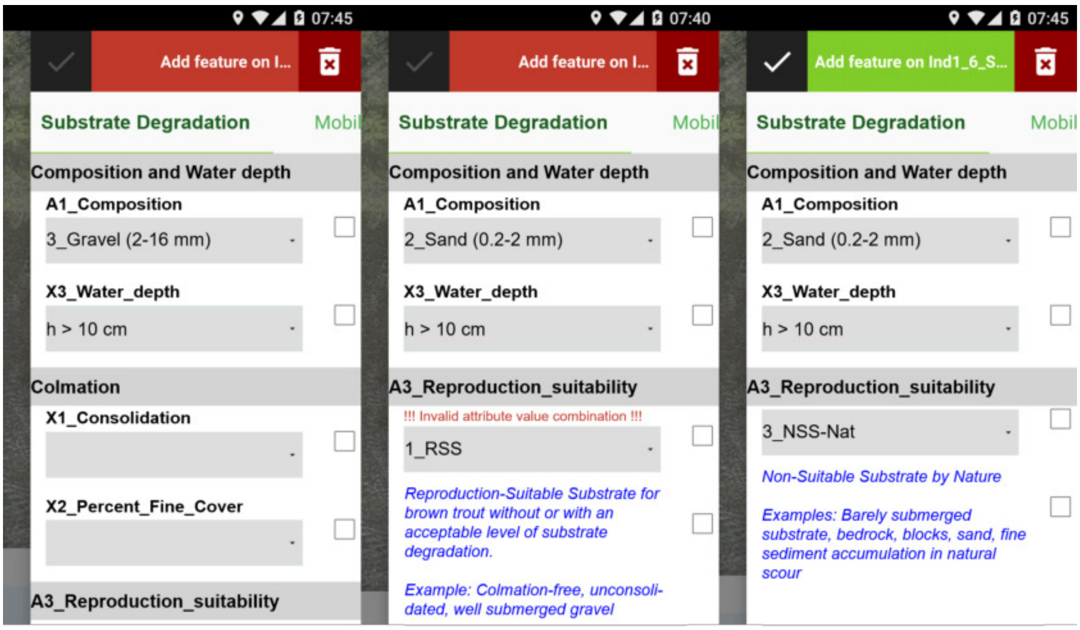

Figure 2.10: Conditional visibility and value constraints for decision tree implementation in QField: Relevant fields are shown based on previous attribute selection (left vs. center). Value constraints prohibit invalid combinations of attribute values (center vs. right).

At the time of the survey, QField did neither support live updates of default values in attribute forms nor expression-based dynamic value maps for attribute fields. The basic functionalities *value constraints* and *conditional visibility* were therefore also used to support more complex mapping decisions, e.g. by implementing the decision tree for reproduction suitability classification. Figure 2.10 demonstrates the implementation's behavior during substrate degradation assessment.
General settings: The coordinate reference system of all project layers was set to CH1903+/LV95. Snapping was enabled on vertices and segments of all layers with a snapping tolerance of 10 px. All described layers were defined as identifiable, editable and searchable in the project's general properties.

Survey conditions and equipment Field work was carried out from June 24 to July 3, 2020. Generally dry weather allowed for digital mapping with the touch screen field tablet. Constant summer residual flow ($Q = 3.5\,\mathrm{m}^3/\mathrm{s}$), sunny conditions and moderate turbidity provided good visibility of streambed substrate. Streambed substrate was assessed using a hand-crafted underwater periscope. Flow velocity measurements were taken with *SonTek*'s FlowTracker. Streambed and flow velocity assessment work is depicted in Figure 2.11.

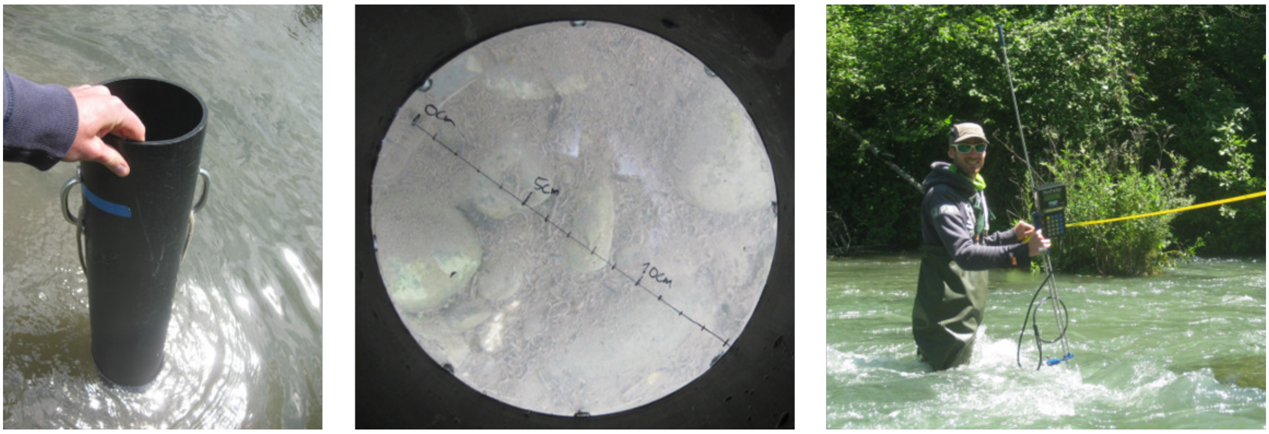

Figure 2.11: Streambed and flow velocity assessment: An underwater periscope (left) was used to estimate fine sediment cover of the streambed (center). Flow velocity was measured with SonTek's FlowTracker (right).

Post-processing Data post-processing was performed in a *Python* environment. The module *pandas* provided all necessary data analysis functionalities for this study (The pandas development team, 2018; McKinney, 2010).

3. Results

Field work data was analyzed separately for the replenishment reach (RR), its intervention section (IS), its downstream section (DS) and for the control reach (CR). An overview of the results is given in Section 3.1, followed by a detailed analysis for each M&E indicator. Each indicator analysis is guided by a standardized, three-subplot "performance dashboard", which summarizes spatial survey data and visualizes intermediate steps of indicator score calculation. Substrate degradation results are presented separately in Section 3.2 along with a validation of the proposed assessment method. Section 3.3 summarizes the results of the efficiency and accuracy analysis of the digital mapping approach.

3.1. Eco-morphological habitat assessment by M&E Indicator-Set 1

The indicator scores of all four study reaches and sections are plotted in Figure 3.1. Neither the replenishment reach nor the control reach has a global tendency to score higher than the other.

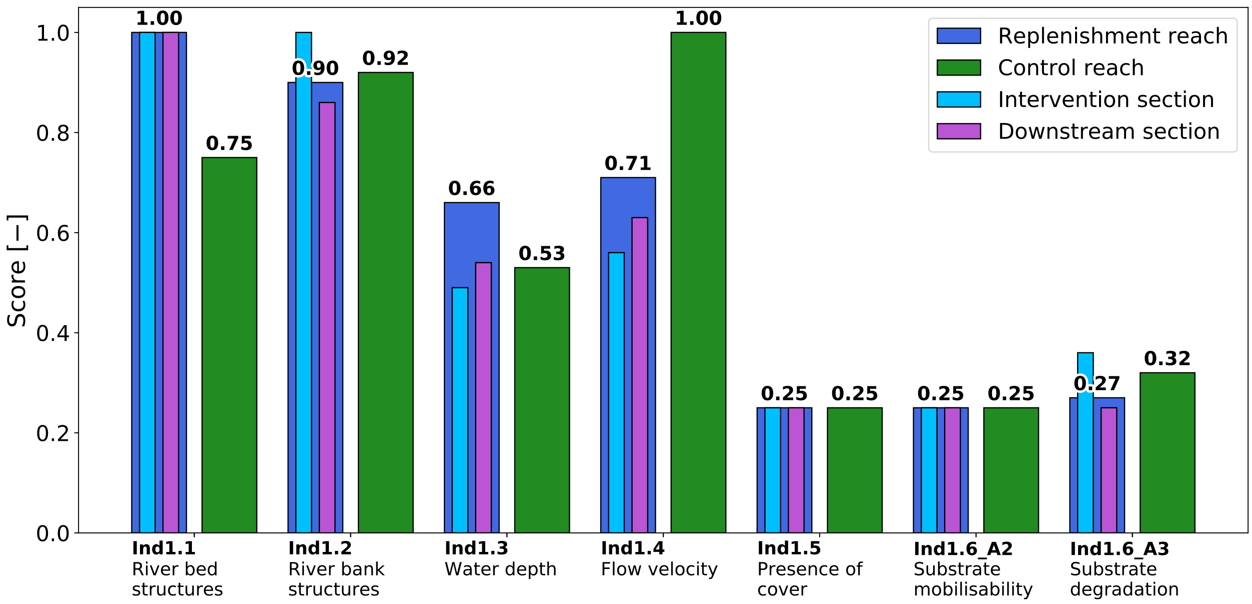

Figure 3.1: Result overviw: Indicator Scores of the extended M&E Set 1

All four study reaches and sections obtain higher scores for indicators 1.1 to 1.4 (river bed structures, river bank structures, water depth and flow velocity) than for indicators 1.5, 1.6_A2 and 1.6_A3 (presence of cover, substrate mobilisability and substrate degradation). The replenishment 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, substrate degradation). The intervention section and the downstream section obtain scores equal to the replenishment reach for three indicators (river bed structures, presence of cover, substrate mobilisability) and lower scores for both hydraulic indicators (water depth, flow velocity). For the remaining indicators (river bank structures, substrate degradation), the score of the replenishment reach is in between the scores of the intervention section and the downstream section.

3.1.1. River bed structures

The performance dashboard for Indicator 1.1 "River bed structures" is shown in Figure 3.2. The locations and types of the mapped structures are shown in the appendix' Figure B.1.

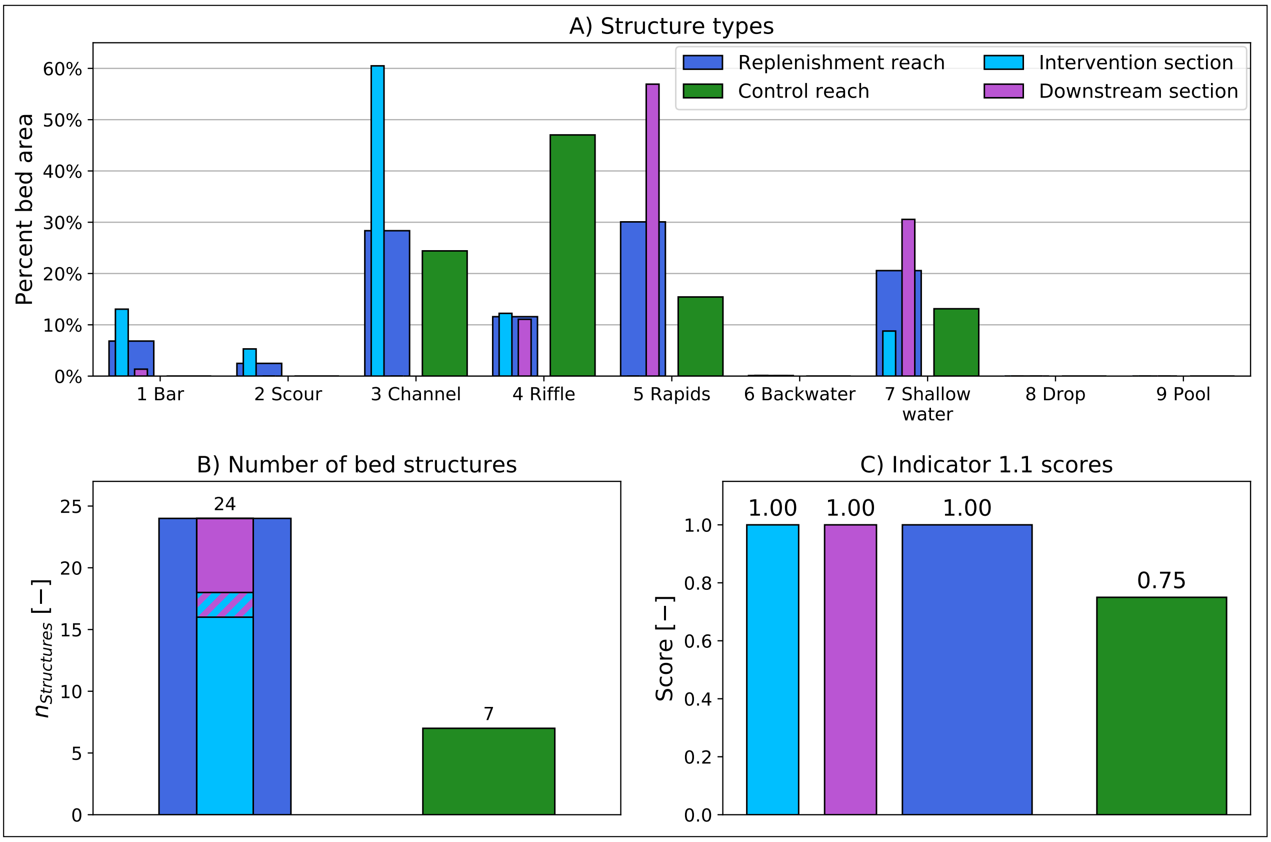

Figure 3.2: Results for Indicator 1.1: River bed structures

A) Bars and scours are structure types that are non-present in the control reach but represented in the replenishment reach. Bars are found in both the intervention section and the downstream section whereas scours are only present in the intervention section, on the downstream side of the sediment deposits.

B) The replenishment reach has a larger number of structures compared to the control reach ($N_{Structures}(RR) = 24$, $N_{Structures}(CR) = 7$). Two structures in the replenishment reach traversed the border line between the intervention section and the downstream section. They are represented as hatched area in the stapled bars of the two sections.

C) The replenishment reach obtains the maximum indicator score $Ind1.1\ (RR) = 1.0$ and the control reach a lower score of $Ind1.1\ (CR) = 0.75$. Scores of the intervention section and the downstream section are identical to the score of the entire replenishment reach $Ind1.1\ (IS) = Ind1.1\ (DS) = Ind1.1\ (RR) = 1.0$.

3.1.2. River bank structures

The performance dashboard for Indicator 1.2 "River bank structures" is shown in Figure 3.3. The mapping results of the river bank classification are shown in the appendix' Figure B.2.

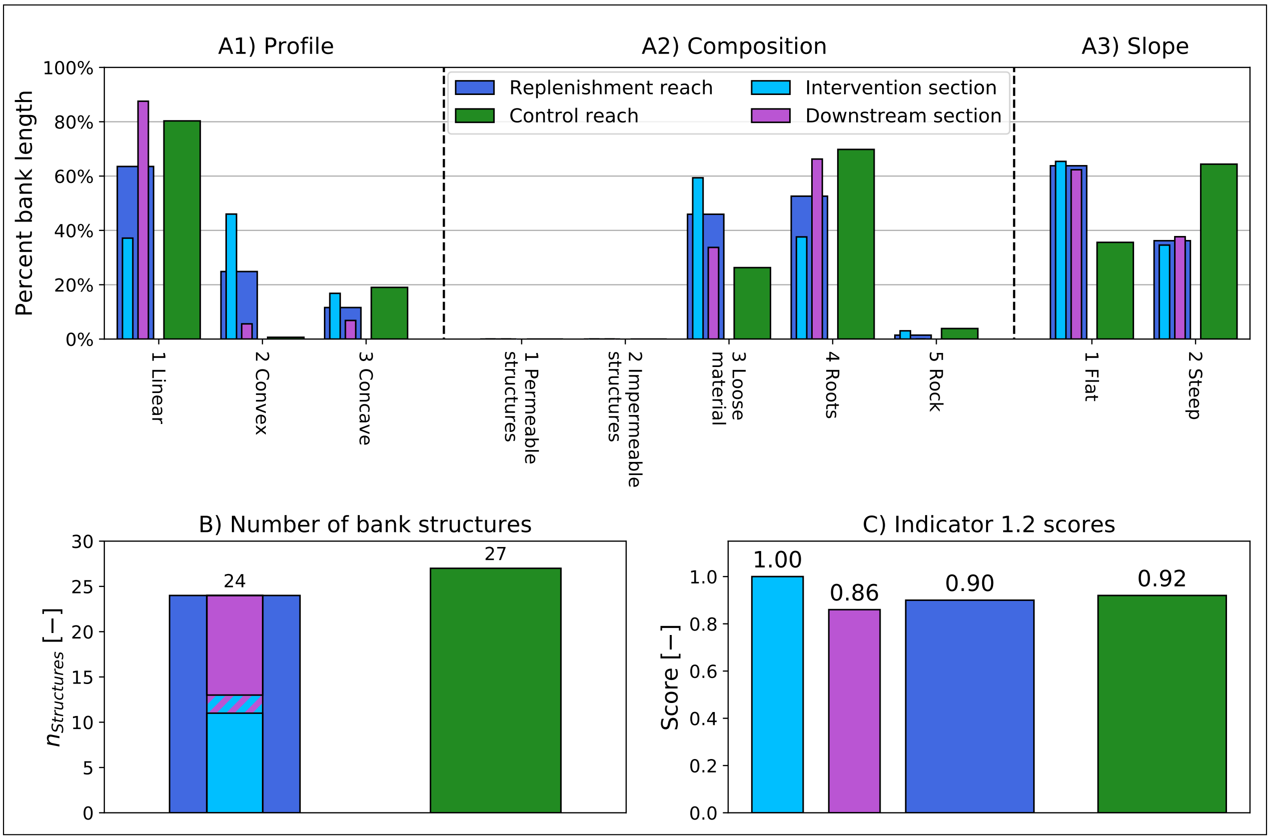

Figure 3.3: Results for Indicator 1.2: River bank structures

A) The intervention section's sediment deposits contributed to its large share of convex, loose material bank lines compared to the downstream section and the control reach (A1, A2). River banks were generally steeper in the control reach than in the replenishment reach (A3).

B) The replenishment reach has a smaller number of structures compared to the control reach ($N_{Structures}(RR) = 24$, $N_{Structures}(CR) = 27$). Two structures in the replenishment reach traversed the border line between the intervention section and the downstream section. They are represented as hatched area in the stapled bars of the two sections.

C) The replenishment reach obtains an indicator score of $Ind1.2\ (RR) = 0.90$ and the control reach a slightly higher score of $Ind1.2\ (CR) = 0.92$. The intervention section obtains the maximum indicator score $Ind1.2\ (IS) = 1.00$ whereas the downstream section scores lowest at $Ind1.2\ (DS) = 0.86$.

3.1.3. Water depth

The performance dashboard for Indicator 1.3 "Water depth" is shown in Figure 3.4.

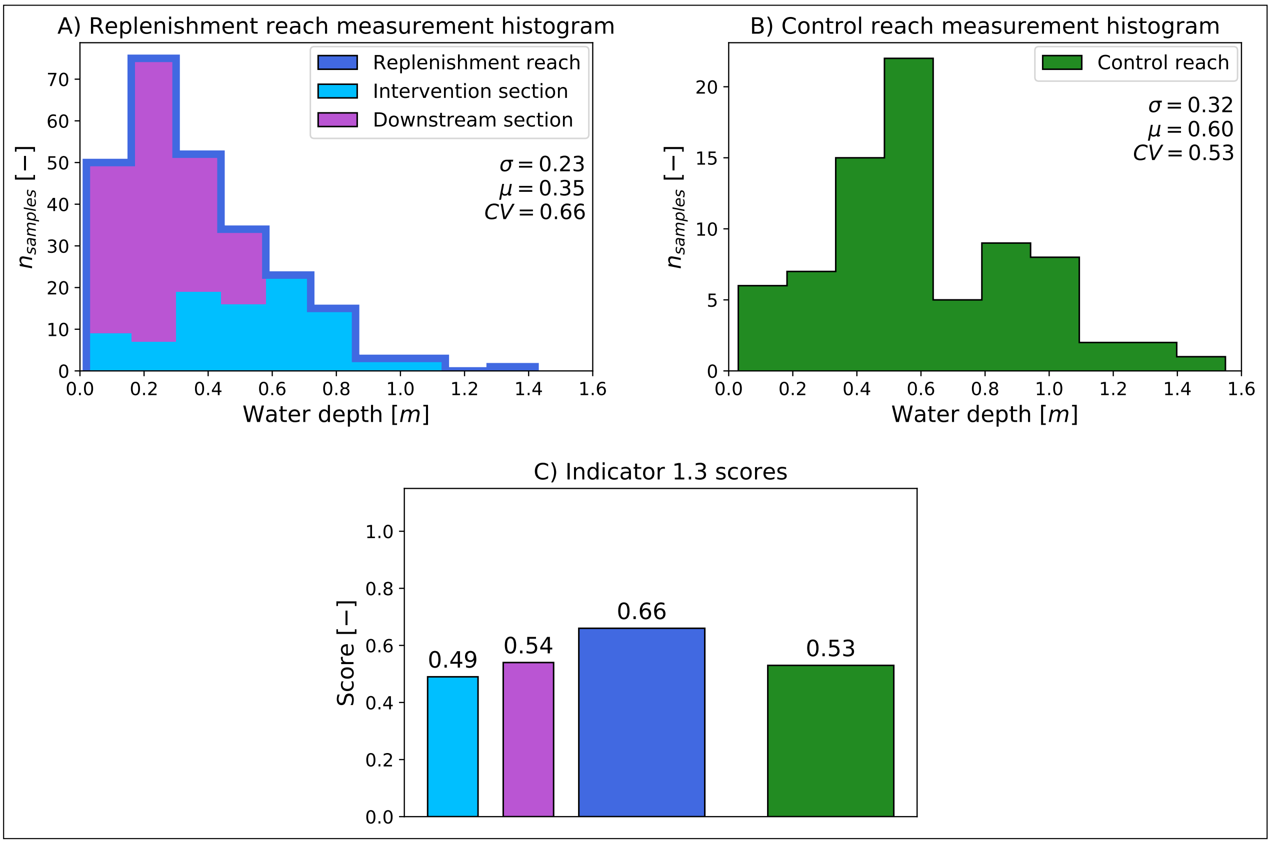

Figure 3.4: Results for Indicator 1.3: Water depth. The scaling of the histograms' y-axes differs. The y-axis is scaled to the histogram's maximum sample number per bin.

A,B) The water depth histogram of the downstream section is dominated by shallow water depths (h) with $h_{max}\ (DS) = 0.57\,\text{m}$. In the intervention section as well as in the control reach, water depths $> 1.4\,\text{m}$ 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 histogram compared to the downstream section. All coefficients of variation (CV) of water depth measurements stayed within the range from 0 to 1 so that CV values directly translated to indicator scores.

C) The replenishment reach obtains an indicator score of $\mathit{Ind1.3}\ (RR) = 0.66$ and the control reach $\mathit{Ind1.3}\ (CR) = 0.53$. The intervention section scores at $\mathit{Ind1.3}\ (IS) = 0.49$ whereas the downstream section scores slightly higher at $\mathit{Ind1.3}\ (DS) = 0.54$.

3.1.4. Flow velocity

The performance dashboard for Indicator 1.4 “Flow velocity” is shown in Figure 3.5.

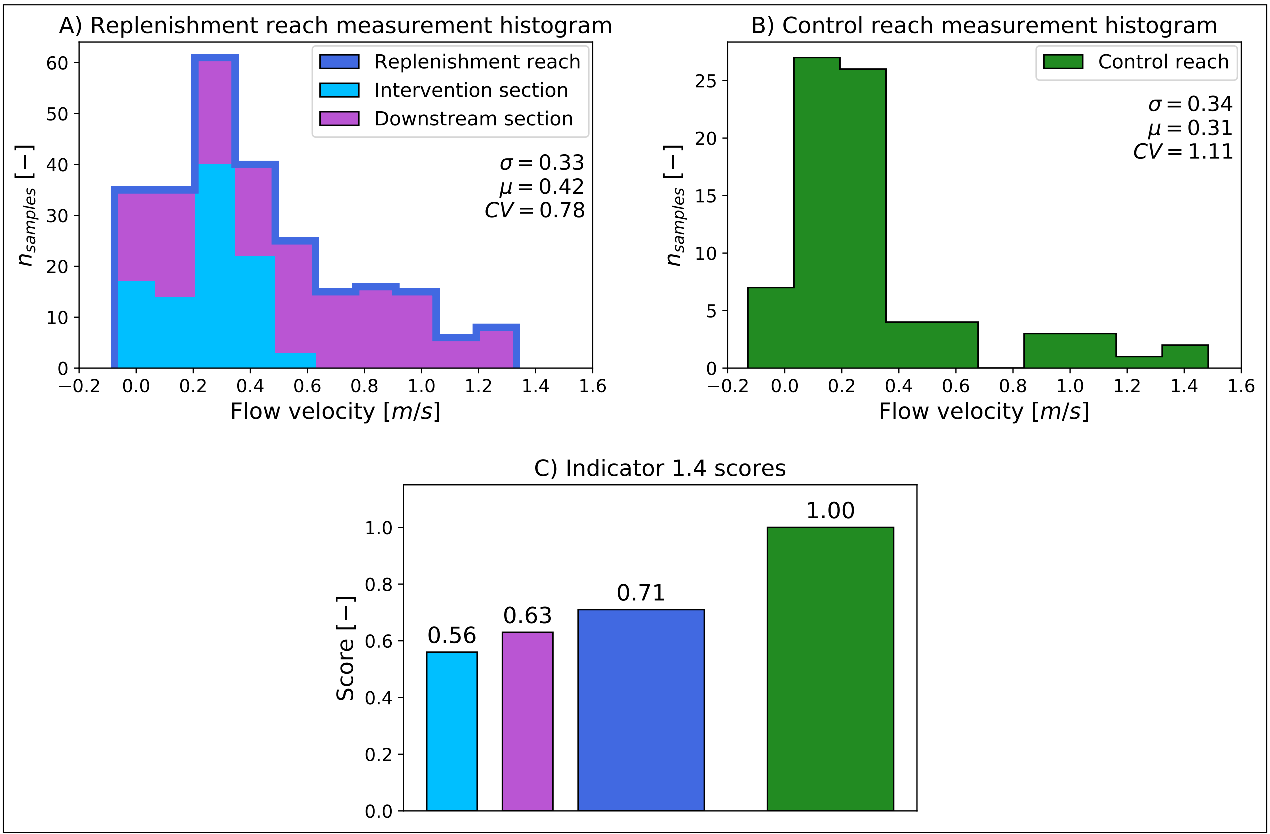

Figure 3.5: Results for Indicator 1.4: Flow velocity. The scaling of the histograms’ y-axes differs. The y-axis is scaled to the histogram’s maximum sample number per bin.

A,B) The flow velocity histogram of the intervention section is dominated by relatively slow flow velocities (v) with $v_{max}\ (IS) = 0.54\,\mathrm{m/s}$. In the *rapids* zones of the downstream section and the control reach, flow velocities up to $v_{max}\ (DS) = 1.33\,\mathrm{m/s}$ and $v_{max}\ (CR) = 1.48\,\mathrm{m/s}$ 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 histogram compared to the downstream section.

C) The replenishment reach obtains an indicator score of $\mathit{Ind1.4}\ (RR) = 0.71$ whereas the control reach achieves the maximum score $\mathit{Ind1.4}\ (CR) = 1.00$. The intervention section scores lowest at $\mathit{Ind1.4}\ (IS) = 0.56$, the downstream section scores slightly higher at $\mathit{Ind1.4}\ (DS) = 0.63$.

3.1.5. Presence of cover

The performance dashboard for Indicator 1.5 "Presence of cover" is shown in Figure 3.6. The location and types of the mapped covers are shown in the appendix' Figure B.3.

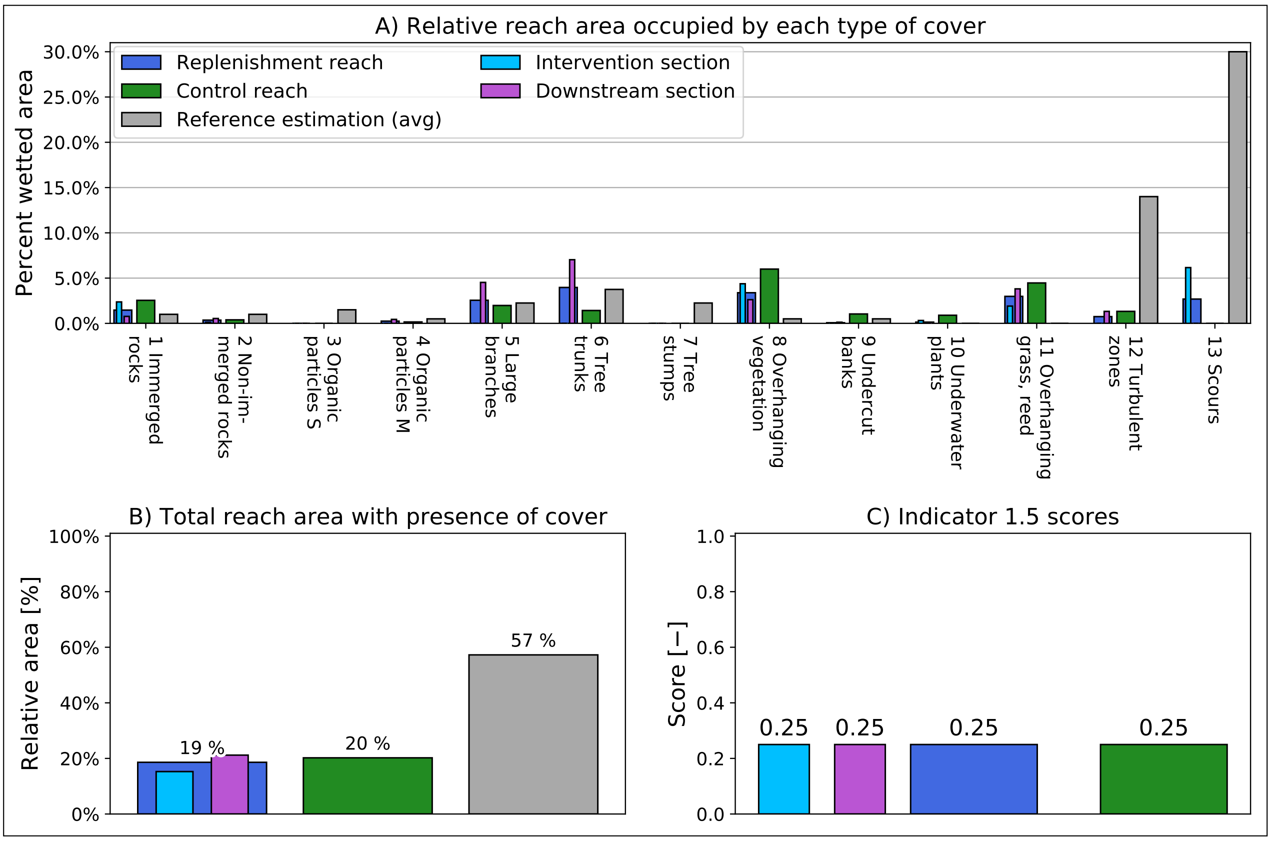

Figure 3.6: Results for Indicator 1.5: Presence of cover

A) The cover types with the largest deviations between reference estimation and mapping results are *12 turbulent zones* and *13 scours*. Under reference conditions, scours are estimated to be the largest contributor to the presence of cover. During the field survey, scours were only identified within the intervention reach. In contrast to turbulent zones and scours, the relative reach area covered by types *8 overhanging vegetation*, *10 underwater plants and floating plants* and *11 overhanging grass and reed* was consistently greater in all study reaches and sections than under reference conditions.

B) According to the experts' averaged estimation, under reference conditions the relative reach area with presence of cover (Cov_{ref}) is $Cov_{ref} = 57\,\%$. Mapping results indicate a current presence of $Cov_{curr} \approx 20\,\%$ in both study reaches.

C) The replenishment reach, its intervention section, its downstream section as well as the control reach all obtained the identical indicator score of $Ind1.5 = 0.25$.

3.1.6. Substrate mobilisability

The performance dashboard for Indicator 1.6_A2 "Substrate mobilisability" is shown in Figure 3.7. Substrate mapping results are shown in the appendix' Figure B.4.

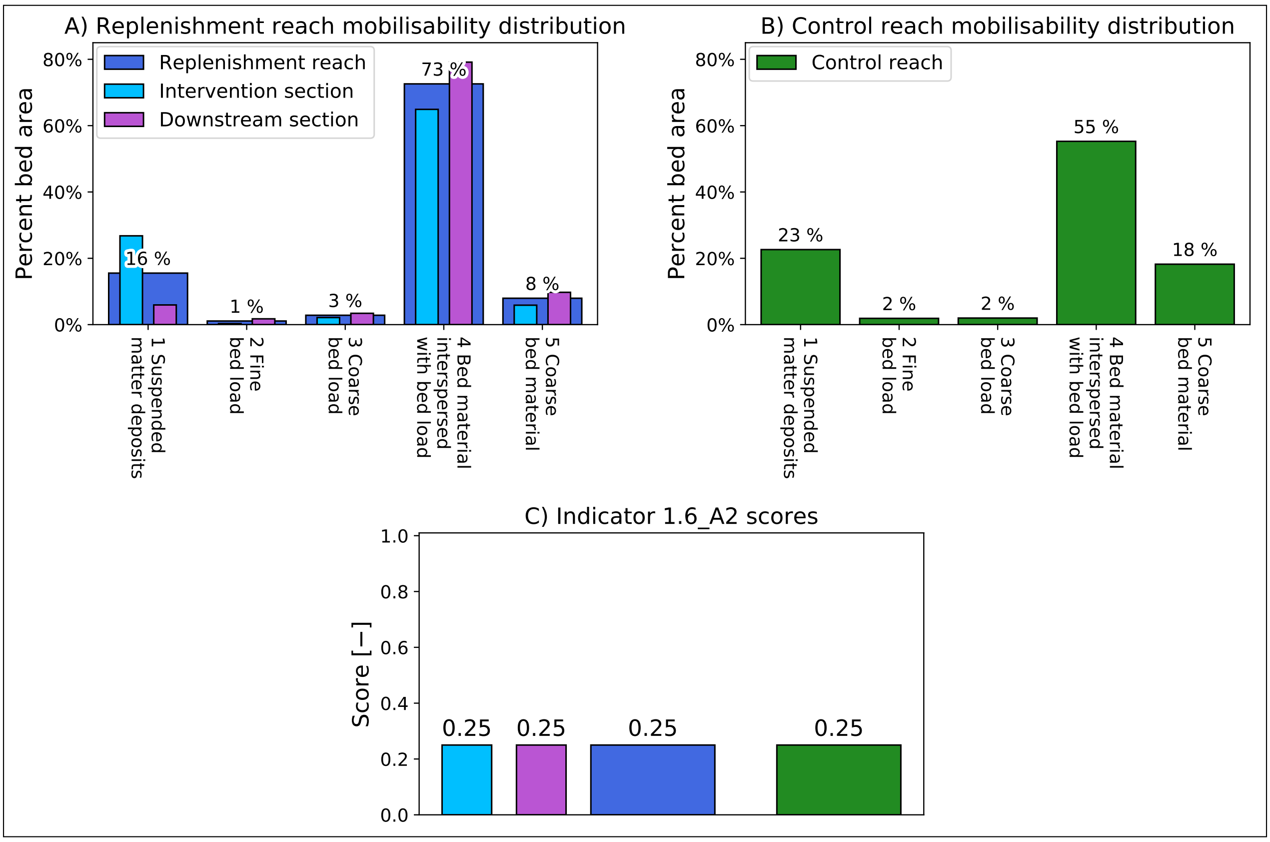

Figure 3.7: Results for Indicator 1.6_A2: Substrate mobilisability

A,B) The share of streambed area predominantly covered by bed load (fine + coarse) is limited to 4 % for both the replenishment reach and the control reach. Fine sediment accumulations (suspended matter deposits) are most dominant in the intervention section (27 % bed area) but have a higher share of bed area in the control reach (23 %) than in the replenishment reach (16 %). Most areas of the study reaches' streambed was covered by coarse bed material. The bed material was usually interspersed by finer grains which, although immobile during survey observations, were described as bed load.

C) The assessment of Indicator 1.6_A2 was based on the textual description of score categories provided by the M&E guideline. The description of score category $Ind1.6\_A2 = 0.25$ best matched the survey observations: "Mainly coarse and tiled bed material, partly interspersed with bed load. Small areas with bed load deposits.". All study reaches and sections obtained the identical indicator score of $Ind1.6\_A2 = 0.25$.

3.2. Substrate degradation assessment by Indicator 1.6_A3

3.2.1. Assessment method validation

The approach of the assessment method to determine the reproduction suitability of streambed substrate based on criteria described in scientific literature was preliminarily validated by data of trout redd locations. Figure 3.8 shows the substrate reproduction suitability classification of the study reaches' streambed together with logged positions of trout redds, which were mapped between 2016 and 2019.

Four logged positions of trout redds are located within the study reaches' limits. The horizontal position accuracy ϵ of logged positions had been estimated as $\epsilon = 20\,\text{m}$. When plotting ϵ as an accuracy radius around logged positions, three of the four historic redd locations coincide with

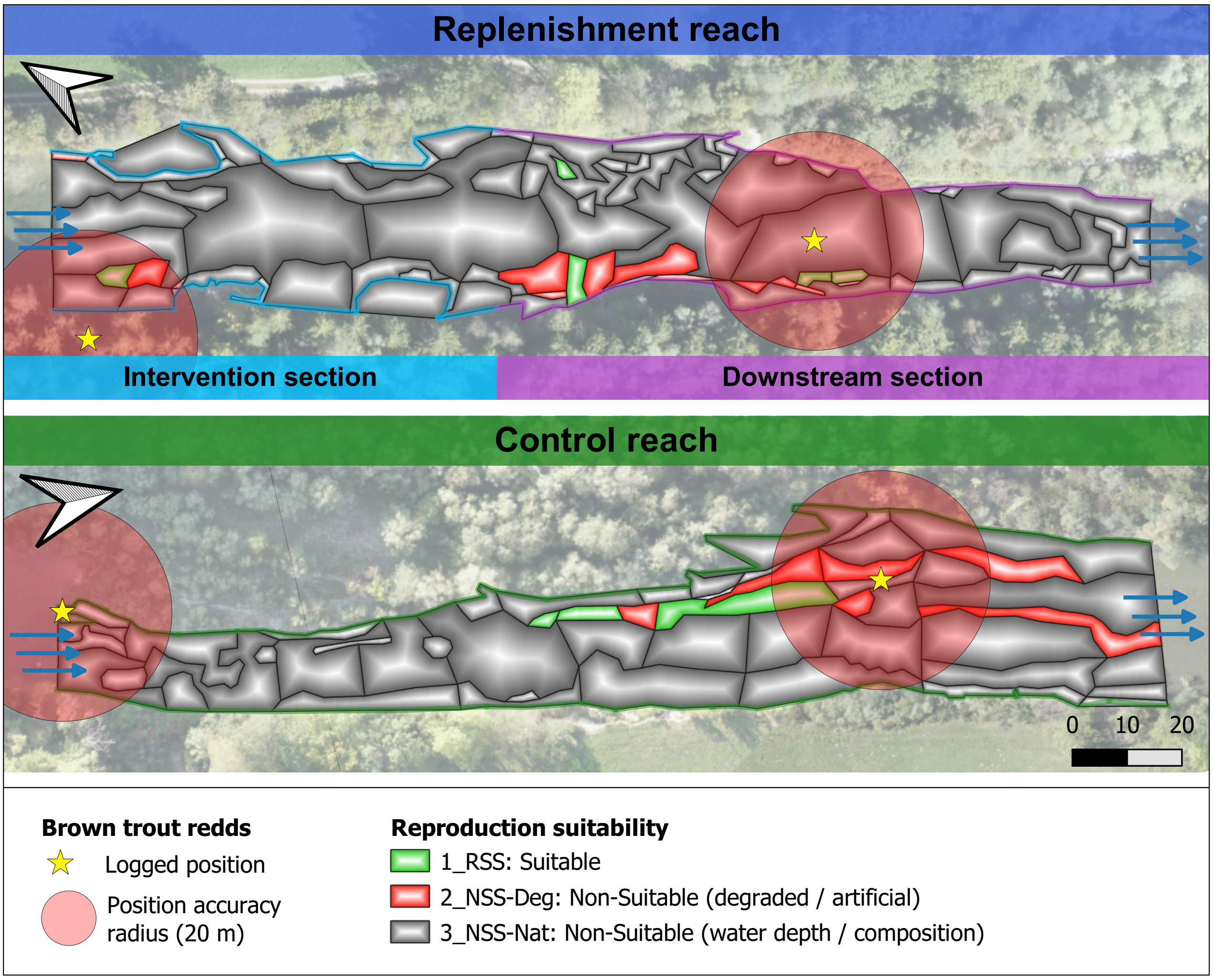

Figure 3.8: Preliminary validation of the assessment method for Indicator 1.6_A3: Mapped positions (2016-2019) of actual trout redds are in the direct proximity of substrate qualified as suitable for trout reproduction.
Base map: © Research Group for Ecohydrology ZHAW | Trout redd data: La Frayère (2020)

locations of substrate qualified as suitable for reproduction (*1_RSS*). The fourth redd location (control reach, upstream) might be considered to lie outside of the study reach's limits. There exist no logged redd position that would contradict the reproduction suitability classification scheme or the substrate mapping results.

3.2.2. Substrate composition and degradation

The performance dashboard for Indicator 1.6_A3 "Substrate degradation" is shown in Figure 3.9. Substrate mapping results are shown in the appendix' Figure B.4.

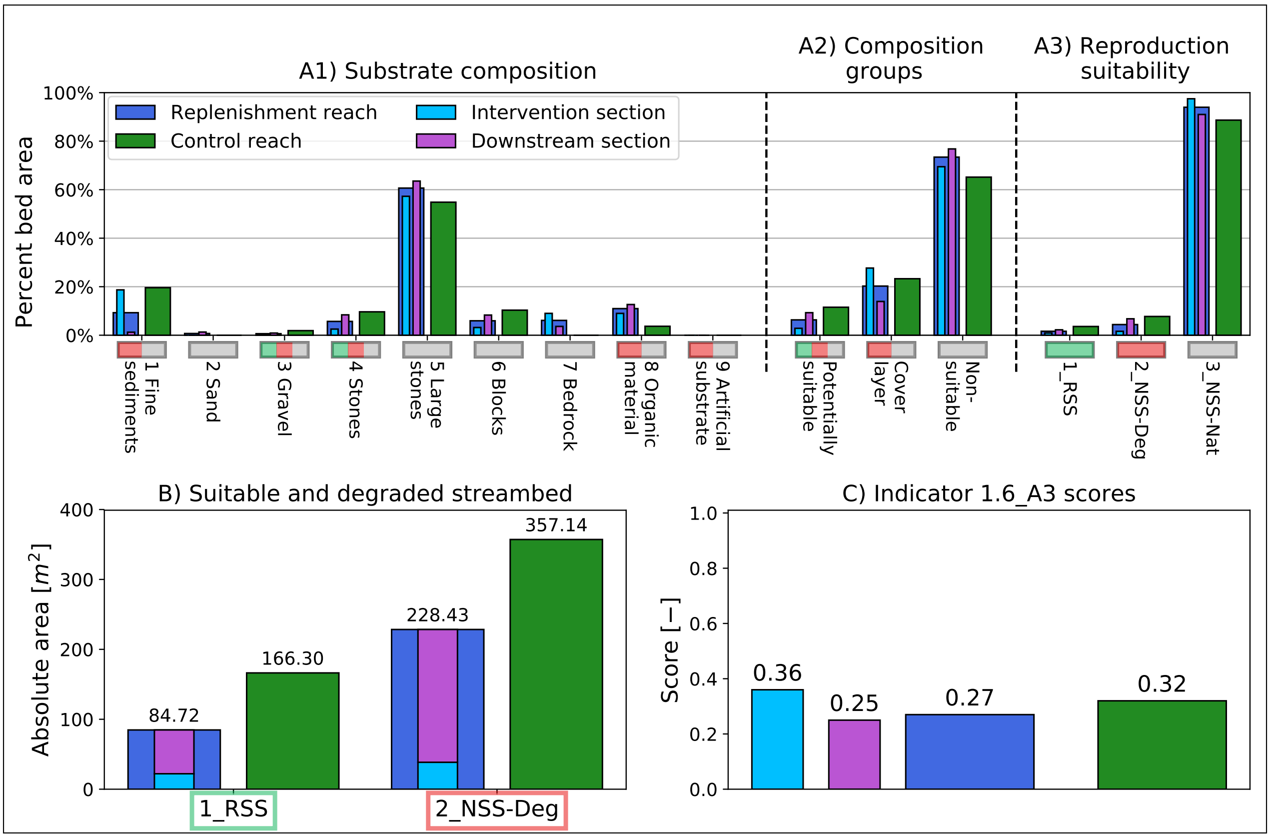

Figure 3.9: Results for Indicator 1.6_A3: Substrate degradation. Areas covered by a certain composition type are attributed to its composition group (A1 to A2) and eventually to a reproduction suitability type (A2 to A3). The total areas of suitable and degraded substrate (B) form the basis for the indicator scores (C). Color coding of x-axis labels according to the decision tree in Figure 2.4.

A) In both study reaches, the streambed was primarily dominated by the group of non-suitable substrate types for reproduction in brown trout. Its main contributor were large stones (64 – 250mm). In the replenishment reach, 61 % of streambed area were attributed to this type and 55 % in the control reach. Blocks (> 250mm) were another naturally non-suitable composition type with important

presence in both the replenishment reach (6 %) and the control reach (10 %). Areas where streambed was completely eroded to the underlying bedrock were only present in the replenishment reach, where they occupied 6 % of its streambed. Areas of bedrock were mainly concentrated in the proximity of the left, downstream sediment deposit as well as in the rapids section.
Cover layers dominated 20 % of the replenishment reach streambed and 23 % in the control reach. Its main contributor were fine sediment accumulations. Fine sediment accumulations occupied 9 % of the replenishment reach's streambed area and 20 % in the control reach. In the replenishment reach, fine sediment accumulations were mainly concentrated in the proximity of the sediment replenishment deposits. In the intervention section, the share of streambed covered by fine sediment is 19 % and almost as high as in the control reach. In both study reaches, most areas of fine sediment accumulation covered a naturally non-suitable substrate type and were thus qualified as *3_NSS-Nat* during reproduction suitability classification. All areas of composition type organic material (e.g. tree trunks, branches, reed) were attributed to reproduction suitability group *3_NSS-Nat*.
Only 6 % of the replenishment reach's bed area was dominated by substrate considered as potentially suitable for reproduction (gravel and stones), most of it being concentrated in the downstream section. In the control reach, 12 % of streambed area was attributed to gravel and stones. In both study reaches, around 70 % of potentially suitable streambed area for trout reproduction was qualified as non-suitable due to degradation.

B) Substrate degradation by consolidation and colmation as well as low water depths in some parts reduced the absolute area of substrate qualified as reproduction suitable *1_RSS* to $84.72\,\mathrm{m}^2$ in the replenishment reach. In the control reach, streambed qualified as *1_RSS* in an area of $166.30\,\mathrm{m}^2$. The areas of streambed that were qualified as non-suitable due to degradation *2_NSS-Deg* exceeded the suitable area by a factor of 2.7 in the replenishment reach ($A_{NSS-Deg}(RR) = 228.43\,\mathrm{m}^2$) and by a factor of 2.1 in the control reach ($A_{NSS-Deg}(CR) = 357.14\,\mathrm{m}^2$). The low degradation ratio in the intervention section of 64 % is relativized by the presence of potentially suitable substrate on less than 3 % of its streambed, the lowest share among all study reaches and sections.

C) The replenishment reach obtains an indicator score of $Ind1.6\_A3\ (RR) = 0.27$ and the control reach scores slightly higher at $Ind1.6\_A3\ (CR) = 0.32$. The intervention section obtains the highest score with $Ind1.6\_A3\ (IS) = 0.36$, the downstream section obtains the lowest score with $Ind1.6\_A3\ (DS) = 0.25$.

Degradation analysis In both study reaches, streambed substrate was impacted by substrate consolidation, colmation and armor layer formation (Figure 3.10). Lime coagulations from onkoid formations were observed to contribute to the widespread consolidation of substrate in both study reaches (Figure 3.11). Fine sediment accumulations were often accompanied by extensive algae growth and mostly covered naturally non-suitable substrate for trout reproduction, such as large stones and blocks.

Figure 3.10: Examples of substrate degradation in the study reaches: Areas of gravel and stones are consolidated by inner colmation and lime coagulations (left). Fine sediment accumulations cover large stones and blocks (center). In many places large stones and blocks are tiled, forming a streambed armor layer (right).

The decision criteria that guided the degradation assessment of streambed substrate were its degree of consolidation and fine sediment cover. The combination of these two criteria yields three principal reasons to classify otherwise suitable streambed substrate as *2_NSS-Deg*. Substrate can be qualified as non-suitable due to a critical level of consolidation, due to a critical level of fine sediment cover or due to critical levels of both criteria. The share of each of these degradation types on the streambed's area that was qualified as *2_NSS-Deg* is visualized for all study reaches and sections in Figure 3.12.

Figure 3.11: Substrate consolidation by lime coagulations from onkoid formation: Onkoids develop on grains of the streambed substrate in the Sarine residual flow reach (left). Lime coagulations from onkoid formation barely cover unexposed surfaces (center). In places with armor layer formation, smaller-sized, clean grains are often present underneath (right). The samples in the center and right image were fully dried before being photographed.

All streambed areas, which were qualified as *2_NSS-Deg*, had exceeded a critical level of consolidation. In the control reach and in the replenishment reach's intervention section, 24 % of the degraded area additionally presented a critical level of fine sediment cover. In the downstream section, critical levels of fine sediment cover were not observed on gravel or stone substrate at water depths > 0.1 m. Within both study reaches' limits, no areas of unconsolidated gravel or stone substrate were observed which exhibited a critical level of fine sediment cover. Most consolidated streambed areas were affected by both lime coagulations and inner colmation. Lime coagulations were observed using the underwater periscope, inner colmation was indicated by increased water turbidity following the boot test.

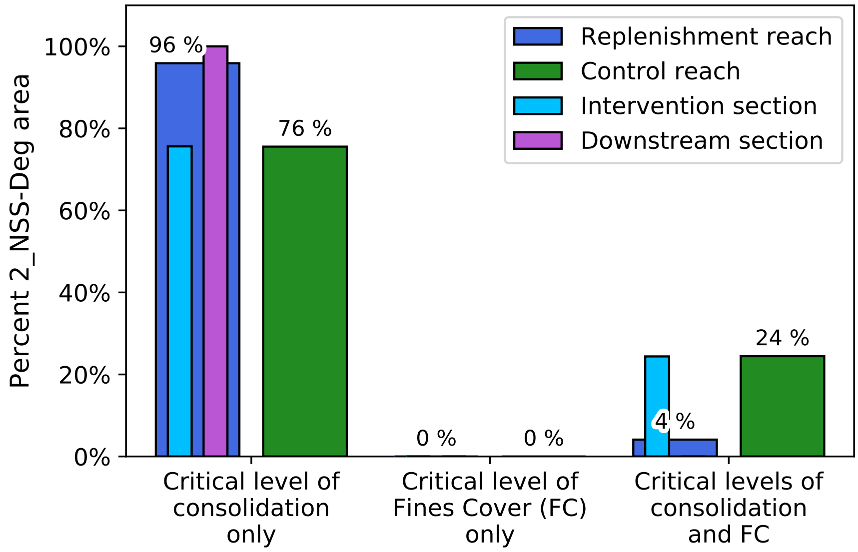

Figure 3.12: Analysis of Indicator 1.6_A3 results: Shares of degradation types on *2_NSS-Deg* areas

3.3. Accuracy and efficiency of GNSS-supported digital mapping

Throughout field work, SBAS accuracy augmentation consistently provided a horizontal position accuracy $< 3\,\mathrm{m}$ according to Trimble's GNSS Status application. Regularly, sub-meter accuracy was reported. The accuracy performance during field works was consistent with pre field work testing. Horizontal position accuracy during pre field work testing is shown in Figure 3.13. Mapping results could be directly transferred into the QGIS desktop environment without accuracy losses by post-survey digitization. Implemented value constraints and geometry requirements worked as expected in the field and eliminated the error source of invalid mapping by mistake.

High resolution aerial imagery in combination with GNSS-supported digital mapping guaranteed permanent and accurate orientation in the field. The mapper's position could be directly used to create nodes of polygons, eliminating time-consuming positioning decisions of a traditional analogous mapping approach. The snapping functionality allowed reusing previously mapped elements in different layers. For instance, bank lines were mapped once for Indicator 1.2 and could be snapped to during the mapping of polygons for all other indicators.

In addition to efficiency gains during field work, a digital mapping solution with automatized data analysis also eliminates time-consuming tasks in the aftermath. Time expenditure estimations for a traditional survey approach are provided by the M&E guideline. Table 3.1 compares the time expenditures for M&E surveys using a traditional and a digital survey approach. The estimations for

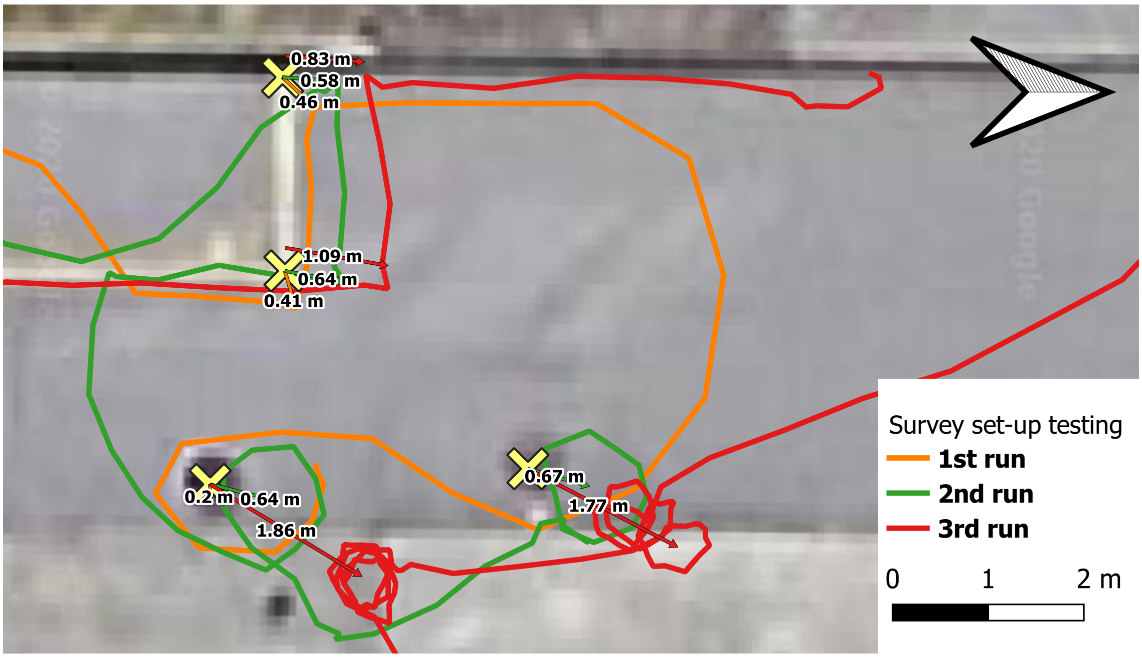

Figure 3.13: Horizontal position accuracy during pre field work testing: Labeled arrows indicate the positional deviation between the actual position of road markings or gully tops (yellow crosses) and the SBAS corrected, GNSS antenna positions (test run lines)
Base map: © Google

the digital survey approach are based on the assumption of equal time expenditure for data collection in both approaches and full automation of data post-processing in the digital approach. Under these assumptions digital surveying can provide relative time savings between 43 % and 50 %.

Table 3.1: Time savings in M&E surveys with a digital survey approach: Time expenditure estimations for a traditional survey approach are provided by FOEN (2019). Estimations for the digital survey approach are based on the assumption of equal time expenditure during data collection and full automation of digitization and post-processing tasks.

	Traditional survey approach		**Digital survey approach**	
	Lower limit	Upper limit	Lower limit	Upper limit
Survey preparations	2 h	2 h	2 h	2 h
Ind 1.1 and 1.2 data collection (per km)	5 h	10 h	5 h	10 h
Ind 1.1 and 1.2 digitization (per km)	5 h	8 h	0 h	0 h
Ind 1.3 to 1.6 data collection	10 h	30 h	10 h	30 h
Ind 1.3 to 1.6 digitization	8 h	16 h	0 h	0 h
Post-processing	4 h	8 h	0 h	0 h
Total time expenditure	34 h	74 h	17 h	42 h
Relative time expenditure (digital/traditional)	-	-	50 %	57 %
Relative time savings	-	-	50 %	43 %

4. Discussion

4.1. The 2016 Sarine sediment replenishment as a restoration measure

Four years after the artificial flood, the Sarine sediment replenishment continues to affect certain components of the residual flow reach's habitat mosaic. The most noticeable difference between the replenishment reach and the control reach is the increased diversity of river bed structures and bank structures in proximity to the partially eroded sediment deposits. Convex and concave bank lines are formed by the four sediment deposits and reduce the intervention section's share of linear bank lines to the smallest value among all studied reaches and sections. The sediment replenishment created river bed structures such as bars and scours that are not present in the control reach. In the natural riverscape, scours are an important type of cover, so that their presence in the intervention section might be interpreted as a contribution towards a locally more natural presence of cover. On the other hand, scours and the channelization of flow in the center line between the four partially eroded sediment deposits favored lateral fine sediment accumulation upstream, downstream and in between the partially eroded deposits. Among the studied reaches and sections, suspended matter deposits have the highest presence in the intervention section due to these areas of near-zero flow velocities. In the replenishment reach, indicator results for variation in water depth and flow velocity were lower for each of the subsections compared to the entire reach. This result suggests that a similar distribution of cross sections over principal river bed structures might be necessary for comparability between reaches. Due to varying sampling strategies and different proportions of river bed structures such as channel, riffle and rapids between the study reaches, the sediment replenishment's medium term effects on hydraulic habitat suitability is difficult to interpret.

There is no significant difference between the replenishment reach's and the control reach's availability of bed load. Fine and coarse bed load cover approximately 4 % of each reach's streambed area. The availability of potentially suitable substrate for reproduction in brown trout was lowest in the intervention section and highest in the control reach. Remains of the four sediment deposits were dominated by large stones and blocks. They were attributed to the mobilisability category bed material and did not classify as bed load. The average grain size of the substrate used for the sediment deposits ($D_m = 57\,\mathrm{mm}$) is larger than the maximum grain size suitable for trout spawning grounds ($D_m < 40\,\mathrm{mm}$, Pulg et al., 2013). Under summer residual flow conditions ($Q = 3.5\,\mathrm{m^3/s}$), bed substrate was generally immobile in both reaches.

The degradation ratio between areas covered by degraded substrate and areas covered by reproduction suitable substrate is high in both the replenishment reach ($\frac{A_{NSS-Deg}}{A_{RSS}} = 2.7$) and the control reach ($\frac{A_{NSS-Deg}}{A_{RSS}} = 2.1$). This result suggests that without further measures neither the 2016 artificial flood event nor its coupling with the sediment replenishment are effective against substrate degradation in the medium and long term. Substrate consolidation testing and visual observations of the extent of onkoid and armor layer formation suggest that there is no significant difference in streambed dynamics or bed load transport between the replenishment reach and the control reach.

In the replenishment reach, the availability of mobile substrate was as low as in the control reach. The sediment replenishment seems to promote fine sediment accumulation in zones of low flow velocity due to the incomplete erosion of the sediment deposits. Four years after the flood, the 2016 Sarine sediment replenishment functions rather as a structurization measure than as a sediment regime restoration measure. The replenishment's medium term effects are mostly concentrated around the partially eroded deposits in the intervention section. Medium term benefits of the replenishment include a locally increased structural richness. Drawbacks are an increased accumulation of fine sediment accompanied by algae growth as well as a decreased availability of suitable grain sizes for reproduction in brown trout in the intervention section. The benefits and drawbacks affect different aspects of the residual flow reach's habitat mosaic.

More than two decades ago, Stanford et al. (1996) already stated that yearly artificial floods of varying size are necessary to restore a functional habitat mosaic in regulated rivers below dams. Mürle et al. (2003) support the argumentation for regular flooding with their findings, where three consecutive floods within two years were significantly more effective in terms of substrate decolmation than a single flooding event. The present study's results support such considerations and confirm the concerns that positive effects on streambed substrate quality by the artificial flood and the coupled sediment replenishment are not persistent.

Where dams cannot be removed, annual flooding events should be considered a necessary instrument to promote sediment dynamics and a functional habitat mosaic in residual flow reaches. Coupling the artificial flood events with a sediment replenishment might improve the quality of some habitat mosaic components. Depending on its design and without regular flooding, it can reduce the quality of other habitat mosaic components. The ecological or eco-morphological objectives of a sediment replenishment should be clearly stated in advance to allow for a comprehensive evaluation of its achieved effects by a defined protocol. The general design and the choice of an appropriate grain size distribution for the sediment deposits should be based on the stated objectives.

To stimulate sediment dynamics in between artificial floods in the Sarine residual flow reach, a promising hydropower mitigation measure could be the replacement of the stable residual flow regime by a dynamic ecological flow regime (environmental flows, E-flows). The ecological flow regime could be coupled with continuous bed load feeding below the dam. Bed load feeding below dams can compensate for bed load deficits and help restoring a functional sediment regime (c.f. Weiss, 1996). Ecological flow regimes mimic a river's natural flow regime and thereby promote sediment dynamics and a functional habitat mosaic (c.f. Suen et al., 2008; Davies et al., 2014; Al Zaghal, 2010).

4.2. Performance of the M&E Indicator-Set 1 in the Sarine case study

The Indicator-Set 1 of FOEN's Monitoring and Evaluation guideline proved to be an informative assessment tool kit in the eco-morphological evaluation of the 2016 Sarine sediment replenishment. Although the M&E guideline is dedicated to revitalization projects, it was found to be a transferable assessment protocol, suitable for the studied type of hydropower mitigation measures. A major strength of the M&E Set 1 lies in the evaluation approach itself that considers a diverse set of components of the river's habitat mosaic. In contrast to a targeted, objective-oriented evaluation, the holistic approach of the M&E Set 1 also captures unforeseen or unintended secondary impacts, such as impacts on river bank structures. The M&E Set 1 constitutes a defined assessment procedure that might offer the potential for cross-project learning in sediment regime restoration measures.

In the present study, the sediment replenishment was assessed by post-restoration survey data due to missing pre-restoration data. Such a control-impact design requires the definition of a control reach. Naturally, a control reach can never perfectly represent all characteristics of the restored reach before restoration. This limitation called for particular attention during the interpretation of results.

Streambed observations in the study reaches suggested that the currently published version of the M&E Set 1 might have to be extended with an assessment method dedicated to substrate colmation and consolidation when used to evaluate a sediment regime restoration measure. For the present study, the M&E Set 1 provided a good base and an extendable framework that allowed for the smooth integration of a substrate degradation assessment method.

4.3. Potential and limits of Indicator 1.6_A3: Substrate degradation

The M&E guideline was developed for the comprehensive evaluation of river revitalization measures. For revitalization measures, a principal objective is to improve the ecological functionality of different components of the habitat mosaic. For hydropower mitigation measures that focus on sediment dynamics, the reduction of streambed degradation constitutes an important objective. The extension of the M&E Indicator-Set 1 by the substrate degradation Indicator 1.6_A3 resulted in an assessment approach that considers essential components of the habitat mosaic and at the same time provides important information on a restoration measure's effects on streambed degradation. The proposed assessment method might constitute a valuable component for the evaluation of different types of restoration measures and in particular for the evaluation of hydropower mitigation measures that are similar to the investigated sediment replenishment.

The assessment approach of Indicator 1.6_A3 is based on rapid inspection methods that rely only on readily available equipment. The entire bed area of the study reach is examined and assessed. Such an exhaustive examination proved to be useful in the Sarine residual flow reach where the proportion of areas dominated by gravel and stone substrate was marginal. These areas might not be analyzed when examination sites are randomly sampled. The proposed assessment method can be directly applied in residual flow reaches, where the extent of wetted streambed remains relatively constant over time. By focusing on ecological functionality rather than on physical formation patterns, the Indicator 1.6_A3 offers a simultaneous evaluation of different forms of degradation. Anthropogenically caused types of streambed degradation, such as substrate consolidation by onkoid formation under a stable sediment regime or artificial streambed paving, are not considered by assessment approaches that focus exclusively on colmation.

The quality of streambed habitat can be severely impaired by colmation. In the M&E guideline, the mapping of fine sediment accumulations constitutes an essential part of the mapping procedures. Yet, in the currently published assessment methods of the guideline, high rates of fine sediment accumulation are not (yet) penalized. The proposed Indicator 1.6_A3 addresses this assessment gap. The indicator's assessment method was developed for a seamless integration into the M&E Set 1 to reduce the added survey effort for substrate degradation assessment to a minimum.

Ecologically functional streambed substrate is composed of natural grain sizes and has a degree of degradation that is within acceptable limits. The M&E Indicator 1.6_A2 "Substrate mobilisability" can be interpreted as a measure for the degree to which different natural grain sizes are available in the streambed. Indicator 1.6_A3 "Substrate degradation" assesses the degradation of the streambed substrate that is currently present. By assessing both aspects of habitat functionality, the combination of indicators 1.6_A2 and 1.6_A3 can offer a comprehensive assessment of streambed habitat.

In its current version, the proposed assessment method for substrate degradation has certain limits. A study reach obtains the indicator value 1 only when the substrate of all streambed areas covered by gravel or stones can be described as loose and non-colmated. It might be argued that even under reference conditions a critical degree of colmation can be observed in some places. A possible solution to this limit of the proposed indicator might be to standardize the indicator value by means of a look-up-table. In analogy to the assessment method for M&E Indicator 1.5, a study reach could for example obtain the indicator value 1, when the proportion of reproduction suitable substrate over all potentially suitable areas is greater than 90 %. The proportion of 90 % corresponds to $Ind1.6\_A3 = 0.9$ in the described version of the proposed assessment method.

In the proposed assessment method, the functionality assessment of streambed habitat is primarily based on requirements of gravel-spawning fish in the trout zone. Although the assessment criteria describe streambed characteristics that are found in a natural environment, some adaptations to threshold values and assessment criteria might be required when focusing on other aquatic species, such as macroinvertebrates. Adaptations could also be necessary when considering the fact that the described threshold value for fine sediment cover is based on studies outside of Switzerland. It might be interesting to examine how this threshold value might vary under different environmental conditions across Switzerland.

Fine sediment cover thresholds were derived from a regression function which had originally been established using a definition of fine sediment as grain sizes < 2 mm. The threshold for fine sediment concentration which served as input for the regression function used a definition of fine sediment as grain sizes < 0.85 mm. This inconsistency might constitute a source of inaccuracy. Further study is required to investigate the relationship of visual PFC assessment and CF($D < 0.85$ mm) sieve measurements in a representative selection of Swiss rivers. Given the very high and significant correlation between visual assessment and measurements in the original study by Sutherland et al. (2010), it can be assumed that trained experts are able to distinguish between acceptable and unacceptable levels of fine sediment concentration with sufficient accuracy by visual estimation and boot testing.

To integrate Indicator 1.6_A3 into the M&E Set 1, the assessment criteria described in scientific literature had to be simplified and adapted in some cases. The preliminary partial validation of the assessment method's approach by trout redd data is not sufficient to prove the ecological significance of indicator scores. Future research that investigates the correlation of indicator scores or the extent of reproduction suitable substrate with young-of-the-year (YOY) recruitment of brown trout (c.f. Schager et al., 2007) might provide a more comprehensive validation of the assessment method. The correlation analysis should ideally eliminate the influence of other environmental disturbance variables. Such a targeted correlation analysis can be based on sample pairs whose principal difference is the extent of areas of reproduction suitable and degraded substrate. Sample pairs could for instance be composed of survey data in the same reach before and after spawning ground restoration (c.f. Vonlanthen et al., 2018).

The grayling zone constitutes Switzerland's second most important river zone and is, just like the trout zone, populated by gravel-spawning fish species. From a methodological point of view, it should be possible to apply the proposed assessment method for substrate degradation also to river reaches in the grayling zone. Varying requirements of grayling zone gravel-spawners might require some adaptions of assessment criteria and threshold values.

4.4. Advantages and disadvantages of digital mapping for M&E surveys

Digital, GNSS-supported mapping provided significant efficiency and accuracy gains in the Sarine case study. Workflow improvements by task automation and elimination yielded estimated time savings between 43 % and 50 %. Similar time savings of approximately 40 % have been reported from other ecological field surveys using a QGIS and QField environment (Bell, 2019). During field work, enhanced orientation, position-based mapping, snapping across different layers, pop-up explications and drop-down value selection significantly improved workflow efficiency. In a traditional survey approach, time-consuming preparatory work might be necessary to prepare for unplanned challenges during field work, such as the readjustment of study reach limits. When implementing a digital surveying approach, such tasks can be immediately and smoothly carried out in the field without additional preparations. Challenging tasks, such as the even distribution of measurement cross sections, can be guided by implementing automatic placement proposals and an instant visualization of registered cross sections in QField.

The digital survey approach provided a quantifiable and reliable horizontal position accuracy that was consistently < 3 m and regularly in the sub-meter range. Streambed area of study reaches covered

5200 m^2 in the replenishment reach and approximately 4600 m^2 in the control reach. When areas of such dimensions are mapped using a traditional mapping approach, spatial data can be assumed to be considerably less accurate. The quantification of accuracy gains from the implementation of a digital mapping approach for M&E surveys requires further research. In M&E surveys, the reliability of spatial data by digital mapping might enhance indicator value calculation. For instance, the M&E variables *mean wetted width* and *mean wetted area* of a river reach might be more accurately determined from the continuously mapped area in between shorelines instead of by averaging discrete lengths of measurement cross sections.

In the Sarine case study, the digital mapping approach did not cause noticeable inconveniences. In other projects and settings, the implementation of digital surveying could have certain drawbacks that should be considered upfront. Digital mapping might require financial investment in technical equipment and adds the responsibility for potentially expensive and sensitive equipment during field work. In digital surveying, there is a higher risk of interruption due to sudden technical failure.

Digital mapping provides a great potential for the future of M&E field surveys. Current developments in mobile and desktop GIS applications promise to further increase workflow efficiency and data accuracy in ecological surveying. The implementation of full NMEA support in QField will allow for a comprehensive accuracy assessment of mapped features. A dedicated QGIS plugin could provide an automation of the entire workflow for M&E surveys from the pre-survey project set-up to the post-survey data analysis.

5. Conclusions

Coupling a sediment replenishment with an artificial flood can locally improve structural aspects of the riverscape's habitat mosaic in the medium term. The study's results do not indicate improved sediment dynamics in the reach impacted by the 2016 Sarine sediment replenishment compared to the control reach. Four years after the flood event, the degree of substrate degradation in the reach affected by the sediment replenishment is just as alarming as it is in the upstream control reach. The replenishment's medium term effects on the variety of water depth and flow velocity could not be evaluated due to the inherent limitations of the study's control-impact approach and due to the simplified sampling strategy in the control reach.

The Indicator-Set 1 "Habitat diversity" of FOEN's Monitoring and Evaluation guideline provided a good basis for a comprehensive evaluation of the Sarine sediment replenishment's intended and secondary effects on the residual flow reach's habitat mosaic. It was found that a restoration measure that aims at restoring sediment dynamics can be more comprehensively evaluated when the currently published version of the M&E Set 1 is extended by a complementary indicator for substrate degradation. The assessment method for substrate degradation proposed by the present study was an effective tool in the Sarine case study and might offer important insights on streambed habitat quality, when applied in the evaluation of other river restoration projects in the alpine region.

It was shown by this study that digital, GNSS-supported surveying based on a mobile GIS application like QField can significantly improve overall efficiency and help to quantify data accuracy of M&E surveys. The digital surveying approach developed for this study provides a reusable GIS project template for river restoration projects in Switzerland and might even be adapted to other evaluation protocols in environmental surveys.

The study's results support concerns that the positive effects of a single flood event on the habitat mosaic are not persistent in the medium term. Under a non-dynamic residual flow regime, a coupled sediment replenishment might locally affect some components of the habitat mosaic positively and others negatively in the medium term. To permanently improve sediment dynamics and substrate quality in a residual flow reach, other studies have shown that annual flood events, E-flows and continuous bed load feeding are effective hydropower mitigation measures. To restore a functional habitat mosaic in the Sarine residual flow reach, the implementation of such measures should be explored.

Recently, a follow-up artificial flood has been released from the reservoir on October 22, 2020. First observations in the Sarine residual flow reach a few days after the flood event suggest wide-spread decolmation of streambed substrate by the artificial flood. Considering that similar observations had been made after the 2016 flood event, it can be assumed that these positive effects will again not persist in the medium term. A more committed and far-sighted restoration strategy is necessary to restore the vital conditions for a healthy eco-system in the Sarine residual flow reach.

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A. Glossary of Translations

Table A.1: Glossary of translations of the extended M&E Indicator-Set 1: Habitat diversity

EN	DE	FR
Legend	**Legende**	**Légende**
Indicator	Indikator	Indicateur
Attribute	Attribut	Attribut
Quality	Ausprägung	Caractéristique
Assessment parameter	Bewertungsparameter	Paramètre d'évaluation

Term *Description*	**Bezeichnung** *Beschreibung*	**Notion** *Description*
Ind 1.1 "River bed structures"	Ind 1.1 "Sohlenstruktur"	Ind 1.1 "Structure du fond du lit"
Structure	Struktur	Structure
1 Bar	1 Bank	1 Banc
2 Scour	2 Kolk	2 Fosse
Secondary flows, eddies	*Sekundärströmungen, Wirbel*	*Courants secondaires, tourbillons*
3 Channel	3 Rinne	3 Chenal
4 Riffle	4 Furt	4 Plat
Low bed gradient	*Geringes Längsgefälle*	*Pente longitudinale faible*
5 Rapids	5 Schnelle	5 Radiers
High bed gradient	*Starkes Längsgefälle*	*Pente longitudinale importante*
6 Backwater	6 Hinterwasser	6 Écoulement secondaire
Wetted area connected to the main channel with stagnating water during low flow conditions "dead end"	*Benetzter Bereich, bei Niedrigwasser nicht durchströmt (Sackgasse)*	*Zones mouillée, mais sans écoulement en période de débit faible (impasse)*
7 Shallow water	7 Flachwasser	7 Eaux peu profondes
Area of weak current	*Schwach durchströmte Zone*	*Zone de faible courant*
8 Drop	8 Stufe	8 Seuil
Natural or artificial drop preceeding a pool	*Absturz*	*Chute*
9 Pool	9 Becken	9 Mouille
Big scour behind a drop	*Kolkloch*	*Affouillement (creusement)*

Ind 1.2 "River bank structures"	Ind 1.2 "Uferstruktur"	Ind 1.2 "Structure des rives"
A1 Profile	A1 Linienführung	A1 Sinuosité
1 Linear	1 Linear	1 Linéaire
2 Convex	2 Konvex	2 Convexe
3 Concave	3 Konkav	3 Concave
A2 Composition	A2 Beschaffenheit	A2 Nature
1 Permeable structures	1 Verbauung durchlässig	1 Aménagement perméable
2 Impermeable structures	2 Verbauung undurchlässig	2 Aménagement imperméable
3 Loose material	3 Lockermaterial	3 Substrat meuble
4 Roots	4 Wurzelwerk	4 Racines
5 Rock	5 Fels	5 Roches
A3 Slope	A3 Neigung	A3 Pente
1 Flat	1 Flach	1 Plat
2 Steep	2 Steil	2 Pentu
Along	Averb	Along
Parameter Longitudinal obstructions	*Parameter Längsverbauung*	*Paramètre aménagement longitudinal*
Astructure	Astruktur	Astructure
Parameter Structural elements	*Parameter Strukturelemente*	*Paramètre éléments de la structure*
Ind 1.3 "Water depth"	Ind 1.3 "Wassertiefe"	Ind 1.3 "Profondeur d'eau"
Ind 1.4 "Flow velocity"	Ind 1.4 "Fliessgeschwindigkeit"	Ind 1.4 "Vitesse d'écoulement"
Ind 1.5 "Presence of cover"	Ind 1.5 "Unterstandsangebot"	Ind 1.5 "Offre en abris"
Type of cover	Unterstandstyp	Type d'abri
1 Immerged rocks	1 Untergetauchte Steine	1 Pierres immergées
2 Non-immerged rocks	2 Nicht untergetauchte Steine	2 Pierres non immergées
also areas behind rocks	*auch Flächen hinter Felsen*	*également surfaces se trouvant derrière les rochers*
3 Small organic particles	3 Kleine organische Partikel	3 Petites particules organiques
mobile, like small branches, accumulations of leaves, grass	*mobil, wie kleine Äste, Ansammlungen von Blättern, Gras*	*mobiles, p. ex. petites branches, tas de feuilles, herbe*
4 Medium-sized organic particles	4 Mittlere organische Partikel	4 Particules organiques de taille moyenne
relatively immobile, e.g. fine roots, bryophytes 5-20 cm diameter	*relativ immobil, z.B. feine Wurzeln, Bryophyten 5-20 cm Durchmesser*	*relativement mobiles, p.ex. racines fines, bryophytes, diamètre compris entre 5 et 20 cm*
5 Large branches, large roots	5 Grosse Äste, grosse Wurzeln	5 Grosses branches, grosses racines
in the water, from standing trees alongside the water course	*im Wasser, von stehenden Bäumen am Gewässer*	*dans l'eau, d'arbres se trouvant au bord de l'eau*
6 Tree trunks	6 Baumstämme	6 Troncs d'arbres
lying	*liegend*	*couchés*

7 Tree stumps	7 Baumstümpfe	7 Souches
Tree stumps or entire root systems, lying	*Baumstümpfe oder ganze Wurzelteller, liegend*	*Souches ou système racinaire entier, couchées*
8 Overhanging vegetation	8 Überhängende Vegetation	8 Végétation surplombante
dead or alive, up to max. 50 cm above the water surface	*tot oder lebend, bis max. 50 cm über der Wasserfläche)*	*morte ou vivante, jusqu'à max. 50 cm au-dessus de la surface de l'eau*
9 Undercut banks	9 Unterspülte Ufer	9 Rive creusée
10 Water plants	10 Wasserpflanzen	10 Plantes aquatiques
floating underwater plants, floating plants	*schwimmende Unterwasserpflanzen, Schwimmpflanzen*	*plantes aquatiques, plantes flottantes*
11 Overhanging grass / reed	11 Überhängendes Gras / Schilf	11 Herbe surplombante / roseaux
12 Turbulent zones	12 Turbulente Wasserzonen	12 Zones d'eau avec turbulences
13 Scours	13 Kolke	13 Affouillements
different scour types are grouped	*verschiedene Kolkentypen werden zusammengefasst*	*différents types d'affouillements sont rassemblés*
Ind 1.6 "Substrate"	Ind 1.6 "Substrat"	Ind 1.6 "Substrat"
A1 Composition	A1 Beschaffenheit	A1 Nature
1 Fine sediments: <0.2 mm	1 Feinsedimente: <0.2 mm	1 Sédiments fins: <0.2 mm
2 Sand: 0.2-2 mm	2 Sand: 0.2-2 mm	2 Sable: 0.2-2 mm
3 Gravel: 2-16 mm	3 Kies: 2-16 mm	3 Graviers: 2-16 mm
4 Stones: 16-64 mm	4 Steine: 16-64 mm	4 Pierres: 16-64 mm
5 Large stones: 64-250 mm	5 Grosse Steine: 64-250 mm	5 Grandes pierres: 64-250 mm
6 Blocks: >250 mm	6 Blöcke: >250 mm	6 Blocs: >250 mm
7 Bedrock	7 Fels	7 Roches
impermeable	*undurchlässig*	*Imperméable*
8 Organic material	8 Organisches Material	8 Matériaux organiques
e.g. Grass, reed, roots, branches, dead wood, etc.	*z.B. Gräser, Schilf, Wurzeln, Äste, Totholz, usw.*	*p. ex. herbe, roseaux, racines, bois mort, etc.*
9 Artificial substrate	9 Künstliches Substrat	9 Substrat artificiel
e.g. Bed stabilization structures	*z.B. Verbauung der Sohle*	*p. ex. aménagement du fond du lit*
A2 Mobilisability	A2 Mobilisierbarkeit	A2 Capacité à la mobilisation
1 Suspended matter deposits	1 Schwebstoffablagerungen	1 Dépôts de matières en suspension
Sand, Silt	*Sand, Silt*	*Sable, silt*
2 Fine bed load	2 Feingeschiebe	2 Matériaux charriés fins
Finer parts of the regularly transported bed load	*Feinere Anteile des regelmässig transportieren Geschiebes*	*Parties les plus fines du matériau charrié régulièrement*
3 Coarse bed load	3 Grobgeschiebe	3 Matériaux charriés grossiers
Coarser parts of the regularly transported bed load	*Gröbere Anteile des regelmässig transportieren Geschiebes*	*Parties les plus grossières du matériau charrié régulièrement*

4 Bed material interspersed with bed load	4 Sohlenmaterial mit Geschiebe durchsetzt	4 Matériaux du fond du lit mêlés à des matériaux charriés
Between the coarse grains of the bed material, grains of the bed load are deposited.	*Zwischen den grossen Körnern des Sohlenmaterials sind Körner des Geschiebes abgelagert.*	*Des grains charriés sont déposés entre les grains grossiers des matériaux du fond du lit.*
5 Coarse bed material	5 Grobes Sohlenmaterial	5 Matériaux du fond du lit grossier
Coarse grains are dominant in the bed material. They are often tiled, forming an armour layer.	*Grosse Körner des Sohlenmaterials dominieren. Sie sind oft dachziegelartig gelagert.*	*Les gros grains dominent dans les matériaux du fond du lit. Ils sont souvent déposés les uns sur les autres à la manière des tuiles.*
A3 Reproduction suitability	A3 Reproduktionseignung	A3 Aptitude à la reproduction
1_RSS	1_RSS	1_RSS
Reproduction-Suitable Substrate for brown trout without or with an acceptable level of substrate degradation	*Geeignete Substrateigenschaften für die Fortpflanzung von Salmo Trutta*	*Substrat propice à la reproduction de la truite*
2_NSS-Deg	2_NSS-Deg	2_NSS-Deg
Non-Suitable Substrate due to anthropogenically caused degradation or due to an artificial cover layer	*Ungeeignete Substrateigenschaften aufgrund anthropogen versursachter Degradierung oder aufgrund einer künstlichen Deckschicht*	*Substrat non propice en raison d'une dégradation d'origine anthropique ou d'une couche couvrante artificielle*
3_NSS-Nat	3_NSS-Nat	3_NSS-Nat
Non-Suitable Substrate due to water depth or due to a natural, non-suitable substrate composition type	*Ungeeignetes Substrat aufgrund zu geringer Wassertiefe oder aufgrund der natürlichen, ungeeigneten Substratbeschaffenheit*	*Substrat non propice en raison de sa nature ou d'une profondeur d'eau insuffisante*

B. Mapping results

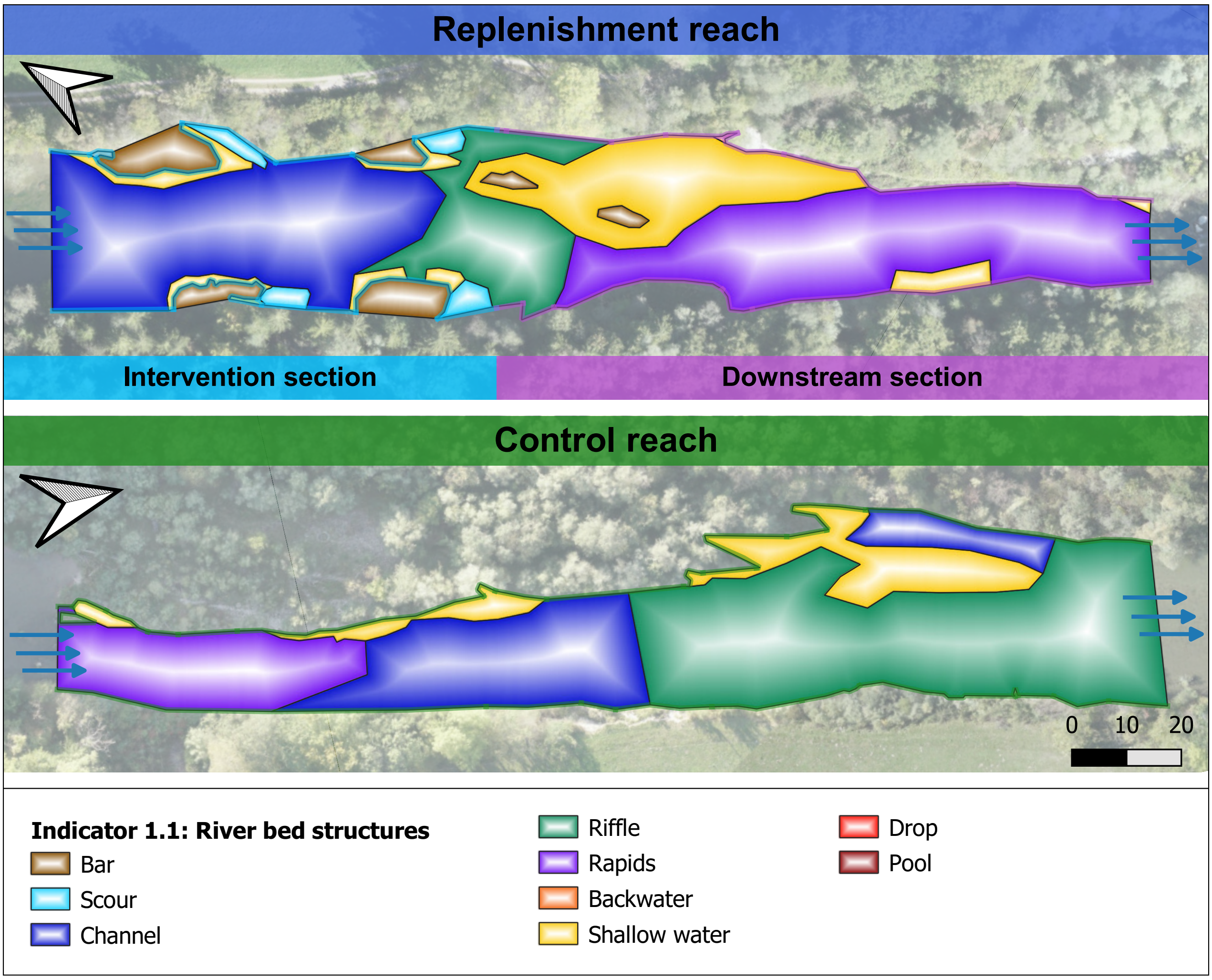

Figure B.1: Mapping results for Indicator 1.1: River bed structures
Base map: © Research Group for Ecohydrology ZHAW

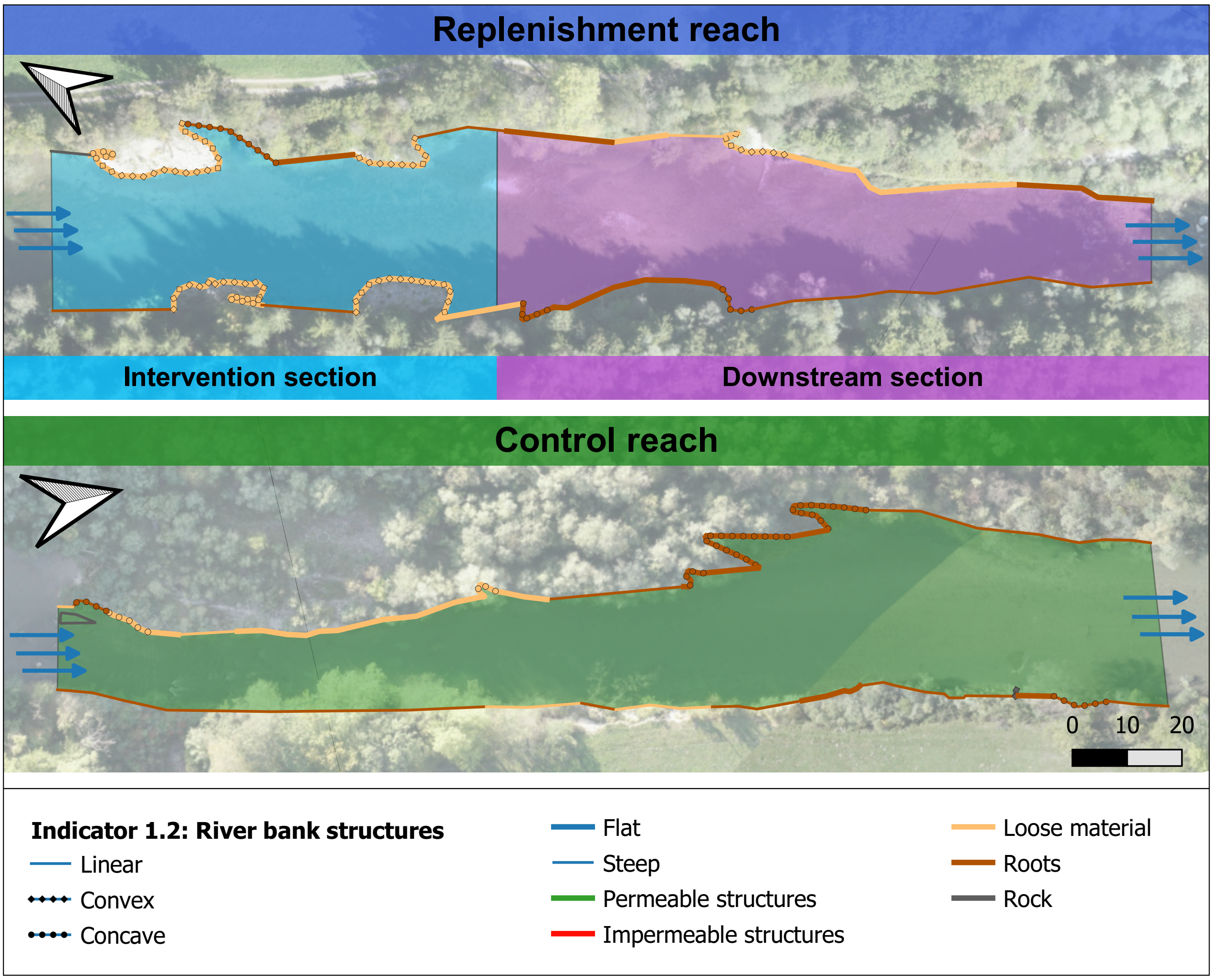

Figure B.2: Mapping results for Indicator 1.2: River bank structures
Base map: © Research Group for Ecohydrology ZHAW

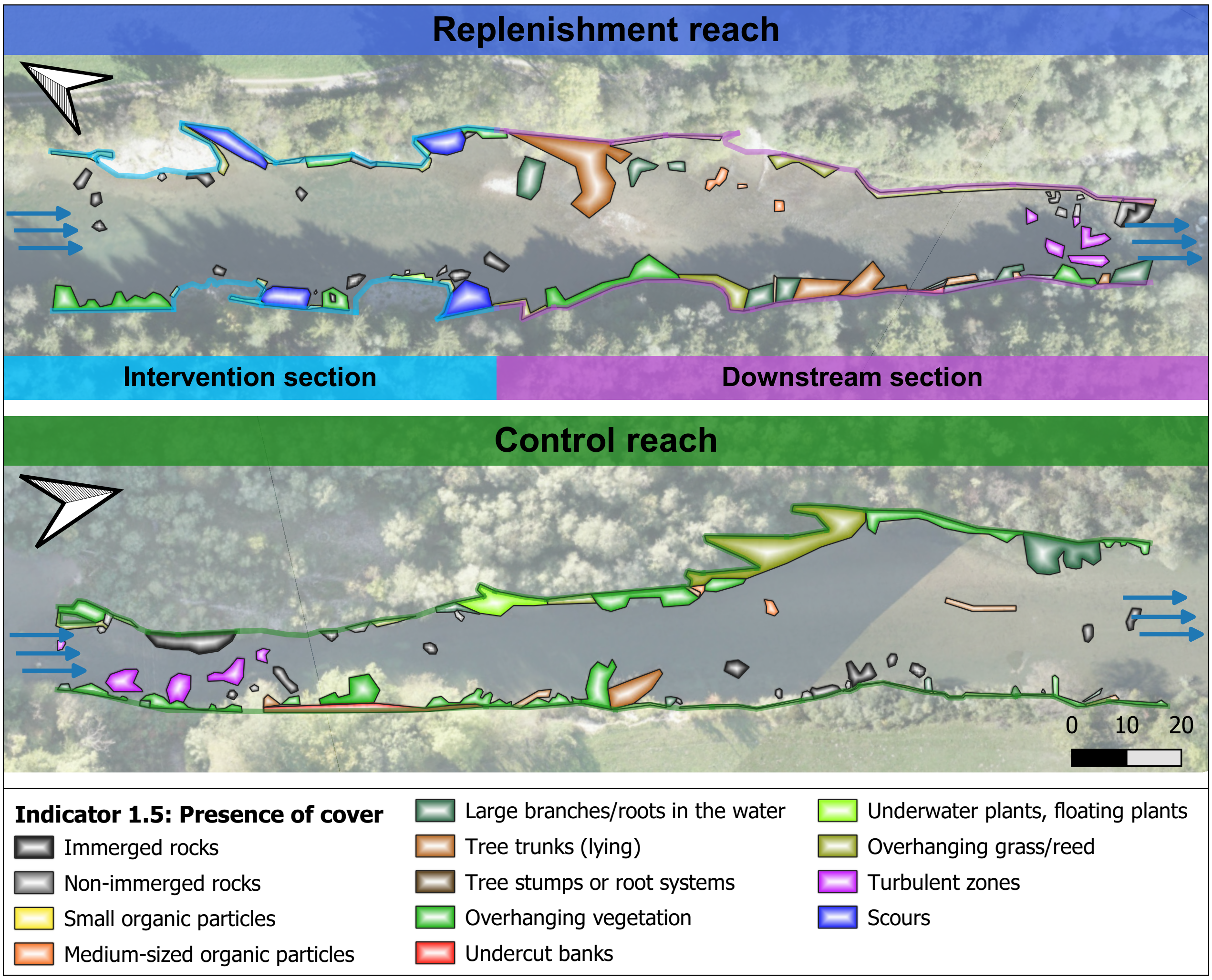

Figure B.3: Mapping results for Indicator 1.5: Presence of cover
Base map: © Research Group for Ecohydrology ZHAW

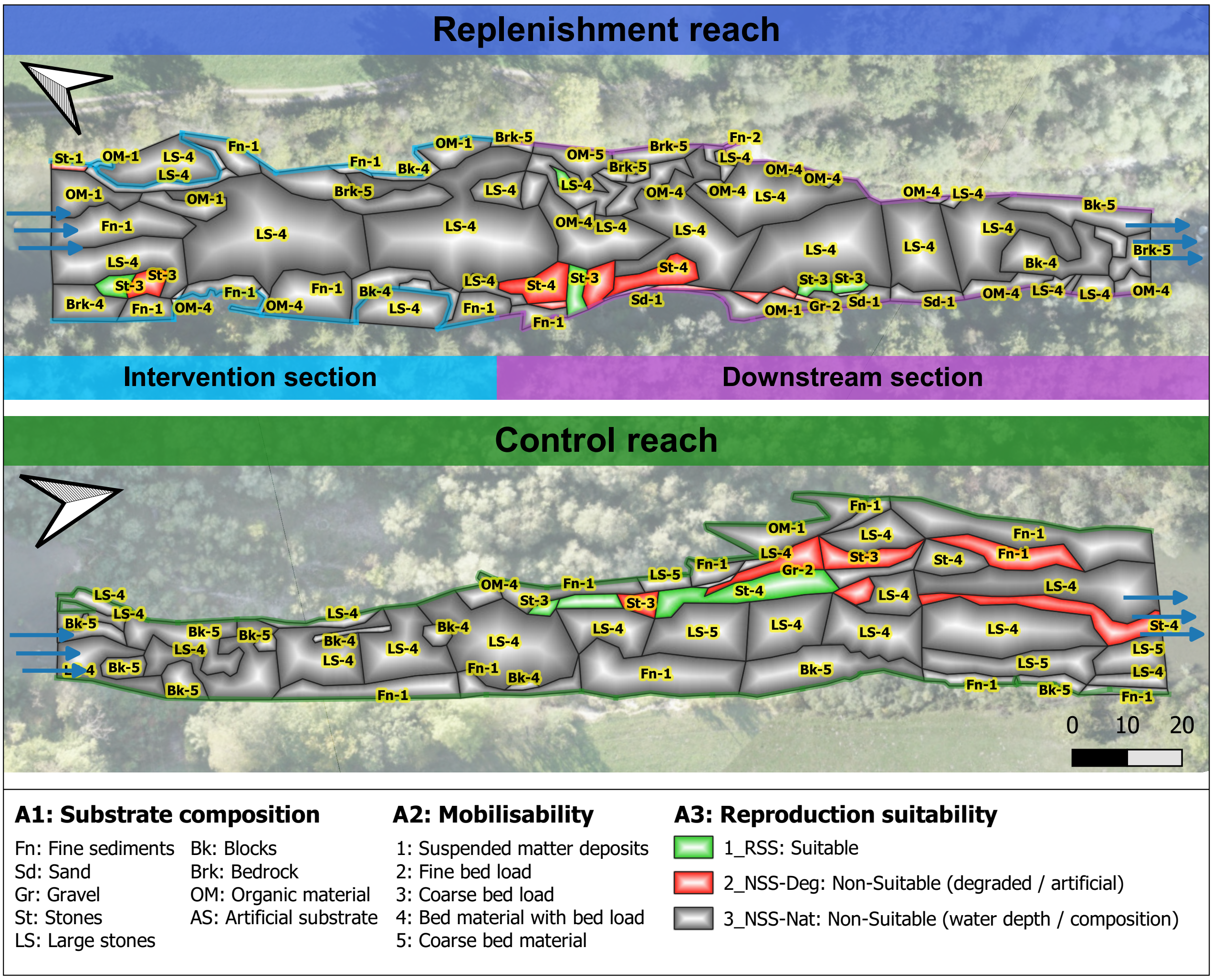

Figure B.4: Mapping results for Indicators 1.6: Substrate composition, mobilisability and degradation
Base map: © Research Group for Ecohydrology ZHAW

Declaration of Own Work

I confirm that this Master Thesis is the result of my own work, except where otherwise acknowledged. This Master Thesis was not previously presented to another examination board and has not been published.

Robin Schroff

Lausanne, 2020-10-29