Evaluating river restoration outcomes using landscape metrics

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submitted by

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Preface

Acknowledgements

First and foremost, I would like to thank Dr. Christine Weber and Lucie Sprecher, my advisors from the River Restoration research group at Eawag, for giving me this incredible opportunity and making this whole project possible. Their support and encouragement were invaluable, especially in the early stages, where they regularly provided critical feedback for the development of the methodology and the presentation of the results. I also want to show sincere appreciation for my supervisor Dr. Gudrun Wallentin. I learned a lot from her scientific expertise and very thorough feedback, helping me to improve the structure and scientific rigor of my thesis. Finally, I am very grateful to my friends and family for their continuous encouragement. A special thanks goes to my sister Nola Behnsen for proof-reading at various stages of the thesis.

Thesis Framework

I have chosen to carry out a manuscript-based thesis to challenge myself and gain experience in academic writing. The thesis contains two main components: the manuscript and the technical report that provides details on materials and methodology. The manuscript was written according to the requirements set for submitting an article to the *River Research and Applications* journal. After coming across this journal multiple times during my literature review, I learned that it frequently publishes applied research associated with river management and restoration and is therefore highly relevant to my study of exploring a new method for evaluating river restoration outcomes. The chosen journal requires manuscripts to have a maximum of 10 figures and tables and a wordcount limit of 6000, including captions and references. As there are many constraints to the length of the manuscript, the technical report serves to provide a deep dive into the workflow of this research project.

Manuscript

Evaluating river restoration outcomes using landscape metrics

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Abstract Switzerland is investing 40 million CHF annually to restore a quarter of its degraded rivers by 2090. To support the effective allocation of these funds, the Federal Office for the Environment has developed a framework to standardise the outcome evaluation of river restoration, consisting of two components: STANDARD and EXTENDED. The framework generates high-resolution spatial data, allowing advanced approaches in evaluating river restoration.

This study applies landscape metrics to evaluate river restoration outcomes, addressing their limited use in riverscapes, particularly in small watercourses. Nine project pairs from the EXTENDED outcome evaluation dataset were analysed, each consisting of a restored reach and a nearby channelised control. The objectives were to assess the effects of restoration on habitat heterogeneity and ecological diversity, and to evaluate the applicability of landscape metrics within the STANDARD outcome evaluation by (i) quantifying differences in class- and landscape-level metrics between restored and channelised reaches, and (ii) examining relationships between landscape-level landscape metrics and macroinvertebrate taxonomic richness.

Landscape metrics proved effective for evaluating river restoration outcomes and show strong potential for future applications in Switzerland, especially at the landscape level. Restored reaches exhibited increased habitat heterogeneity, but no meaningful relationships were found with macroinvertebrate richness. At the class level, the limited sample size prevented definitive conclusions. The approach is especially promising for future STANDARD outcome evaluations, which will include pre- and post-restoration data. The larger dataset will further support the use of class-level metrics and enable more thorough analyses of correlations between landscape metrics and biodiversity.

Keywords landscape metrics, river restoration, restoration outcome evaluation, small watercourses, macroinvertebrates

Introduction

Humans have been altering river channels for over a century, which has degraded riverine ecosystems with wide ranging environmental, social, and economic implications (Kurth & Schirmer, 2014). River restoration, a globally accepted method for protecting these ecosystems and the services they provide, refers to the measures taken to enhance river process and form (Wohl et al., 2015). While the number of river restoration projects has been increasing in recent decades, many lack a proper post-project evaluation to determine if the goals have been achieved, limiting the information available to guide decision makers in planning future river restoration projects and implementing adaptive management (Han et al., 2023; Kurth & Schirmer, 2014; Morandi et al., 2014).

Switzerland has a strong need for thorough restoration evaluations. The government has agreed to invest 40 million Swiss Francs annually until 2090 to restore 4000km of degraded rivers (Kurth & Schirmer, 2014). The Federal Office for the Environment (FOEN) has been working with the Swiss Federal Institute of Aquatic Science and Technology (Eawag) to develop a national framework for the outcome evaluation of river restoration in Switzerland, consisting of standardised surveys for multiple indicators (Weber et al., 2019). The data collected will be used to provide specific recommendations of action, making future projects more effective in terms of lowering costs and achieving ecological and social objectives (Weber et al., 2019). The framework consists of two components – STANDARD and EXTENDED outcome evaluations. In the STANDARD evaluation, data are collected before and after restoration for a large number of projects to assess typical goals of restoration measures (Weber et al., 2019). The EXTENDED outcome evaluation is carried out for a subset of projects and compares restored reaches to nearby channelised control reaches to answer practice-specific questions (Weber et al., 2019). This study applies a landscape metrics approach to the EXTENDED outcome evaluation.

A Landscape Metrics Approach

In landscape ecology, landscapes are often categorised into distinct patches of habitat or land use, forming a mosaic (Frazier & Kedron, 2017). Landscape metrics quantify the composition of these patches and their configuration or spatial arrangement (Frazier & Kedron, 2017). It is a common notion that patterns are strongly related to processes, making such metrics suitable for gaining a deeper insight into complex ecosystems (Uuemaa et al., 2013).

River researchers started adopting landscape ecology approaches in the late 20th century (Datry et al., 2016). Wiens (2002) described the three main ways in which rivers were considered within the context of landscape ecology: 1) rivers were treated as components of larger landscapes, 2) rivers were seen as sub-units that are linked to terrestrial landscapes via flows of energy and material across ecosystems, and 3) rivers have their own internal heterogeneity and can be thought of as “riverscapes”.

Recent river research has increasingly adopted Wiens’ second approach, viewing rivers as links to terrestrial ecosystems. Many studies have explored these connections by examining how spatial patterns, quantified using landscape metrics, influence water quality at various spatial and temporal scales (Aalipour et al., 2022; Aalipour et al., 2024; Aalipour et al., 2023; Cheng et al., 2023; Liu et al., 2024; Rajaei et al., 2017; Wu & Lu, 2021; Xu et al., 2019; Xu et al., 2022; Xu et al., 2023; Yu et al., 2024). Others have used landscape metrics to understand how changes in land patterns and land use impact ecohydrological and hydrological processes (Boongaling et al., 2018; Chiang et al., 2019; Miller et al., 2020). Landscape metrics have even been used to predict hydrological connectivity between wetlands and streams (Epting et al., 2018) and quantify floodplain heterogeneity (Iskin & Wohl, 2023), further showcasing their diverse application in river research.

Over the last two decades, river research has increasingly adopted Wiens’ third approach, which conceptualizes rivers as “riverscapes” that have their own internal heterogeneity (Torgersen et al., 2022). This development can be attributed to the growing availability of computerised mapping and remote sensing technologies, which enable visualisation of physical and biological properties of rivers at very high resolutions (Torgersen et al., 2022). The rise in technology has also driven a shift from patch-based (vector) to gradient-based (raster) models, vastly expanding the range of applications (Erős & Lowe, 2019). Riverscape approaches are also becoming increasingly popular since they help bridge the gap between research and management, making them especially useful in river habitat studies (Torgersen et al., 2022). By defining the composition and configuration of habitats, these approaches play a key role in the management and conservation efforts of species (Dugdale et al., 2015; Le Pichon et al., 2009; Torgersen et al., 2022; Wagner & Woellner, 2022). Beyond habitats, the riverscape approach has been applied to map geomorphic units – the building blocks of a river mosaic – as a new method for river monitoring (Belletti et al., 2017). Riverscape research has further developed through the application of graph theory for connectivity and the inclusion of temporal dynamics (Erős & Lowe, 2019). Since the riverscape approach is so useful for management applications, it is also well-suited for implementing conservation, monitoring, and restoration programs (Torgersen et al., 2022).

Only few studies have applied landscape metrics to river restoration. Rohde et al. (2004) calculated landscape metrics for riparian habitat for restored, degraded and near-natural reaches, while Tamagnone et al. (2020) combined landscape metrics with hydraulic models to understand the ecological consequences of restoration. Similarly, Taddeo and

Dronova (2020) used open source remote sensing to understand wetland response to restoration. Landscape metrics have also been used to help prioritize areas for river restoration (Glassic et al., 2024; Stieger & McKenzie, 2024). So far, no research has been carried out on applying landscape metrics to riverscapes in small watercourses. Thus, the purpose of this study is to determine if landscape metrics can be used to evaluate the outcomes of river restoration in small watercourses and determine if this is a valuable approach for the upcoming STANDARD outcome evaluation.

Objectives

The specific objectives of this study are to assess how river restoration influences habitat heterogeneity and ecological diversity, and to evaluate the applicability of landscape metrics within the STANDARD outcome evaluation framework by:

a) quantifying differences in class- and landscape-level metrics between restored and channelised (control) reaches; and

b) examining relationships between landscape-level landscape metrics and macroinvertebrate taxonomic richness.

Materials and Methods

This study uses a subset of the data collected for the FOEN's EXTENDED restoration outcome evaluation. The subset includes the spatial data from Indicator Set 1 – Habitat Diversity, and the number of macroinvertebrate species from Indicator Set 6 – Macroinvertebrates, for nine restoration projects. Indicator Set 1 comprises 1.1 Riverbed Structures (polygons), 1.3 Water Depth (point), 1.4 Flow Velocity (point), 1.5 Presence of Cover (polygon), and 1.6 Substrate (polygon). Figure 1 provides an abstract representation of the spatial data used in this study, while Table 1 describes their classes.

Table 1: Summary of classes per indicator

Indicator	Classes
Riverbed Structures	bar, pool, glide, riffle, run, backwater, shallows, step, plunge pool, artificial bed
Water Depth	< 0.00, 0.00 – 0.45, 0.45 – 0.75, 0.75 – 1.15, >1.15 (Leitgeb, 2019)
Flow Velocity	<0.05 (1), 0.05 < V < 0.25 (3), 0.25 < V < 0.75 (5), 0.75 < V < 1.5 (4), > 1.5 (2) (Plattform Wasserqualität VSA, 2021)†
Presence of Cover	submerged boulders, non-submerged boulders, small organic particles, medium organic particles, large branches/roots in the water, tree trunks, tree stumps, overhanging vegetation, undercut banks, submerged plants, overhanging grass, turbulent water zones, pools
Substrate	silt (3), sand (2), gravel (5), stones (6), large stones (6), boulders (10), rock (1), organic material (7), artificial substrate (1) †

† numbers in brackets indicate suitability value from the modular stepwise procedure, where higher values represent better suitability (Plattform Wasserqualität VSA, 2021)

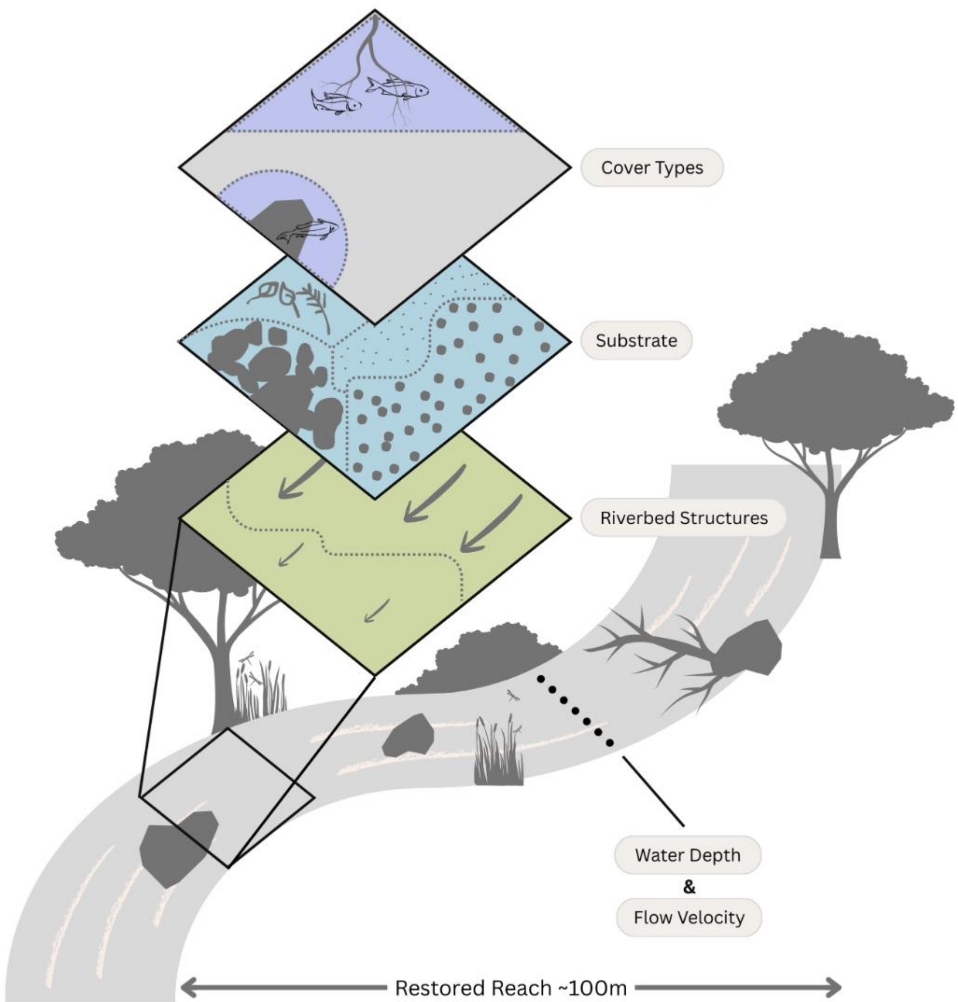


Figure 1: Abstract representation of the spatial data collected for each control and restored reach

The nine projects were selected based on data completeness. Restored lengths vary from 100 to 170m and ages range from 5 to 11 years. The watercourses are small, with the average depth ranging from 0.1 to 1m, while average width varies between 0.9 and 3m. The most common restoration measures implemented include river widening, removal of bank structures, riverbed restoration, bed structuration, and bank flattening.

Data Preparation

The spatial data were transformed from vector to raster with a resolution of 0.15m, four times smaller than the smallest unit (0.09m^2) (Congalton, 1997). A methodology adapted from Merwade et al. (2005) was used to interpolate the depth and velocity transect data, as it addresses the curvilinear and anisotropic properties of the watercourses. For this method, both the transect points and a regular point grid placed over the reach were given a new coordinate system (s, n) to straighten the data (Merwade et al., 2005). n was calculated from the closest distance to a reference line, while s represents the distance along the reference line at this location. Figure 2 provides a visual representation of this method. Following the straightening, the data were transformed, where possible, to resemble a more normal distribution and then interpolated using ordinary kriging with the *Gstat* package in R. Ordinary kriging was selected as it has been found to perform well for interpolating both depth and velocity from cross sections (Hasníková et al., 2015; Wu et al., 2019). Finally, the point grid was given its original coordinates, transformed to raster, and classified according to the depth and velocity classes in Table 1.

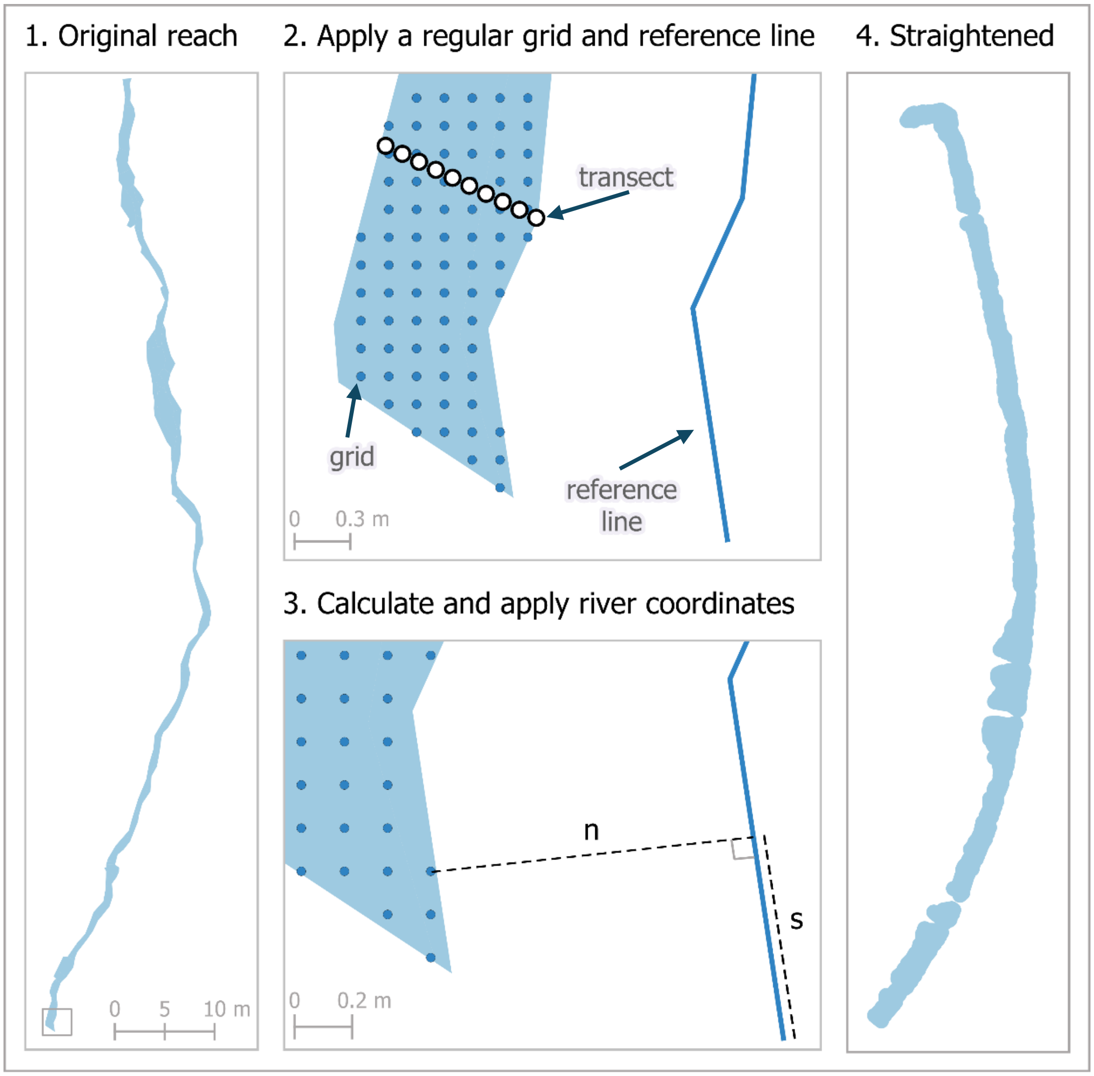


Figure 2: Visual representation of the methodology for "straightening" the reach before interpolation. 1) The original reach before straightening. 2) Prepare data: regular grid, reference line, grid 3) calculate s, n coordinates, where n = shortest distance to the reference line, and s = distance to the reference line. 4) the regular grid with the new coordinates s, n.

Additionally, a habitat suitability layer for macroinvertebrates was created from the substrate and velocity layers. The substrate classes were reclassified to match those of the modular stepwise procedure (MSP) to make them compatible with the velocity data (Table 1). The MSP classes of the two layers were added together, resulting in a suitability range of 2 to 15, where higher values represent better suitability for macroinvertebrates.

Landscape Metrics Analysis

Landscape metrics were selected based on metrics commonly used in river research (Aalipour et al., 2022; Aalipour et al., 2024; Aalipour et al., 2023; Boongaling et al., 2018; Cheng et al., 2023; Cortes et al., 2011; Datry et al., 2016; Iskin & Wohl, 2023; Liu et al., 2024; Miller et al., 2020; Rajaei et al., 2017; Rohde et al., 2004; Taddeo & Dronova, 2020; Tamagnone et al., 2020; Wu & Lu, 2021; Xu et al., 2019; Xu et al., 2022; Xu et al., 2023; Yu et al., 2024). The selection was narrowed down to describe the composition and configuration at class and landscape level, making sure to avoid redundancy (Tamagnone et al., 2020). The final metrics are shown in Table 2.

Table 2: Selection of landscape metrics and their interpretation

Metric	Level	Category	Interpretation
% of Total Area	Class	Area and Edge; Composition	Provides information on habitat availability, which strongly influences populations (Rohde et al., 2004).
Patch Density	Class; Landscape	Aggregation	The number of patches per unit area can provide an indication to the degree of fragmentation (Han et al., 2023).
Mean Shape Index	Class; Landscape	Shape	More complex shapes are an indicator of more natural conditions (Tamagnone et al., 2020); the shape of patches can also impact the number of organisms that can exist in them (Rohde et al., 2004)
Edge Density	Class; Landscape	Area and Edge	There is a direct correlation between edge density and the degree of habitat heterogeneity and fragmentation (Tamagnone et al., 2020)
Interspersion & Juxtaposition Index	Class; Landscape	Configuration; Aggregation	Degree of interspersion is especially important for species that have multiple habitat requirements; they should be well interspersed so that habitat types are easily accessible (Rohde et al., 2004).
Mean Euclidean Nearest Neighbour	Class	Configuration; Connectivity	A measure of connectivity between patches and fragmentation (Tamagnone et al., 2020)
Shannon's Diversity Index	Landscape	Composition; Diversity	Measure of patch diversity in the landscape (Yu et al., 2024)

To get a better understanding of the differences in landscape metrics between restored and control reaches, the effect size was calculated using the response ratio (Δr) developed by Osenberg et al. (1997):

$$\Delta r = \ln\left(\frac{\bar{X}_T}{\bar{X}_C}\right)$$

where $\bar{X}_T$ and $\bar{X}_C$ represent the means of the treatment (restored reach) and control (channelised reach), respectively (Kail et al., 2015). The response ratio has successfully been used as a standardised effect size for restoration outcomes (Kail et al., 2015).

A Brunner Munzel test was used to test the significance of the differences in landscape metrics between control and restored reaches. This test was chosen as it is non-parametric and works on small sample sizes that can have different distributions (Neubert & Brunner, 2007).

Results

Interpolation Assessment

The interpolation of the transect points resulted in a significant loss of classes that are present in the original data. The velocity classes 0.05<V<0.25 m/s and 0.75<V<1.5 m/s are particularly affected. Comparatively few classes are missing from the depth rasters, with depths between 0.45 and 0.75m being most impacted.

Landscape-Level Metrics

Figure 3 shows the distribution of effect size per metric for each of the five indicators from Set 1 with the addition of the macroinvertebrate habitat suitability map.

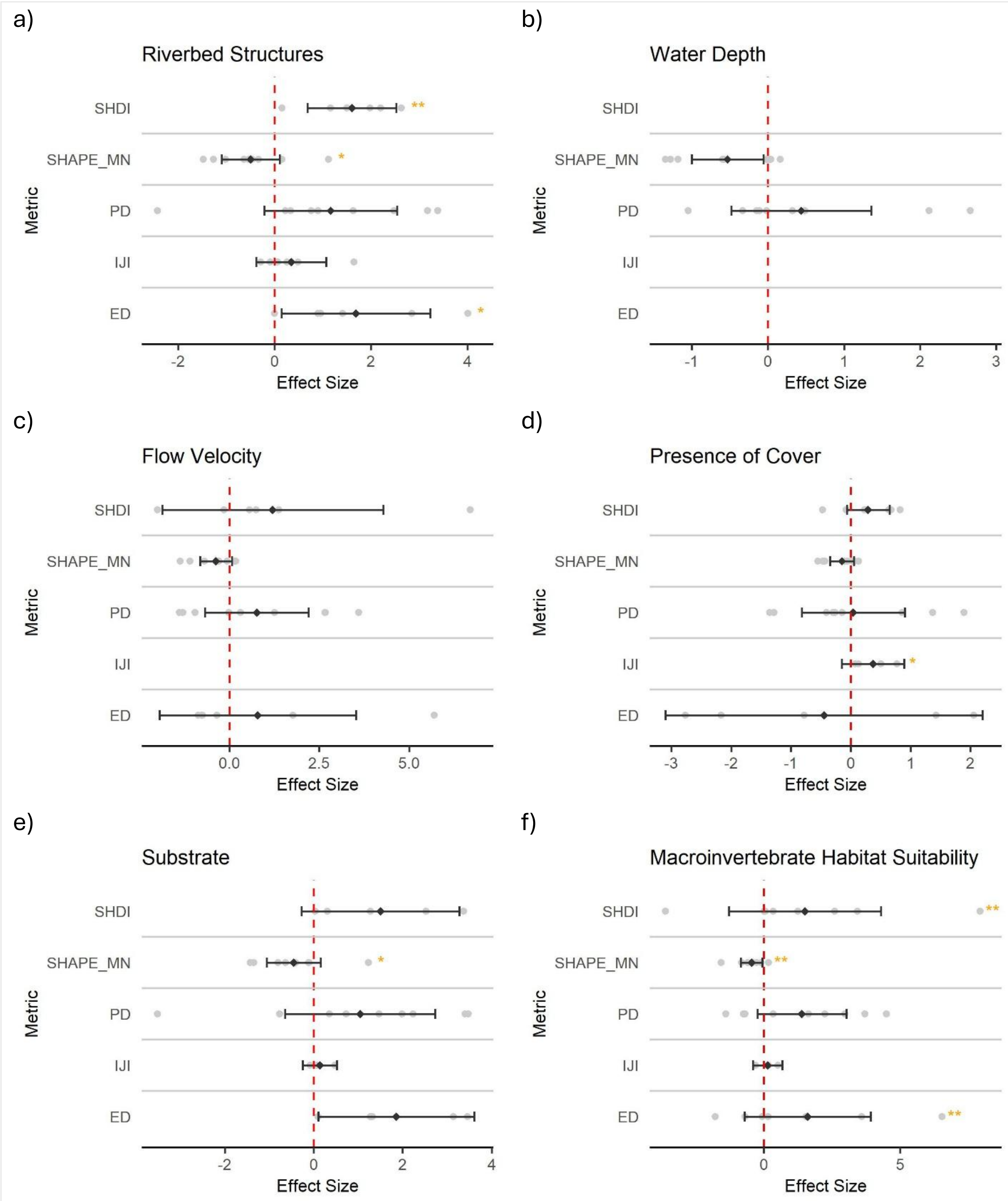


Figure 3: Effect size of landscape-level landscape metrics comparing restored to control reaches. Points represent individual projects, while diamonds show mean effect size. Error bars represent ± 95% confidence intervals. Dashed line represents no effect. Asterisks (orange) denote significance levels from Brunner–Munzel tests (**p* < 0.05, ***p* < 0.01, ****p* < 0.001). Metric abbreviations: SHDI = Shannon's Diversity Index, PD = Patch Density, SHAPE_MN = Mean Shape Index, IJI = Interspersion and Juxtaposition Index, ED = Edge Density

Shannon's diversity index has a mostly positive effect size across all six layers and shows statistically significant differences between the reaches for riverbed structures and macroinvertebrate habitat suitability (Figure 3). A similar pattern can be observed for edge density, but effect size is more negative for presence of cover (Figure 3). Patch density is also frequently positive, but negative effect sizes are more common and the differences between reaches is not statistically significant. Effect sizes for the interspersion and juxtaposition index are usually spread between positive and negative values for all layers except for presence of cover, where values are mostly positive and the differences between the reaches is statistically significant. Mean shape index generally has a negative effect size and shows a statistically significant difference between reaches for the habitat suitability, riverbed structures, and substrate layers (Figure 3).

Class-Level Metrics

The distributions of effect size per metric for the different classes are shown in Figures 4-7. Several classes were missing from one or both reaches, producing no results for these classes. Additionally, 95% confidence intervals tend to be quite large, frequently exceeding the data distribution.

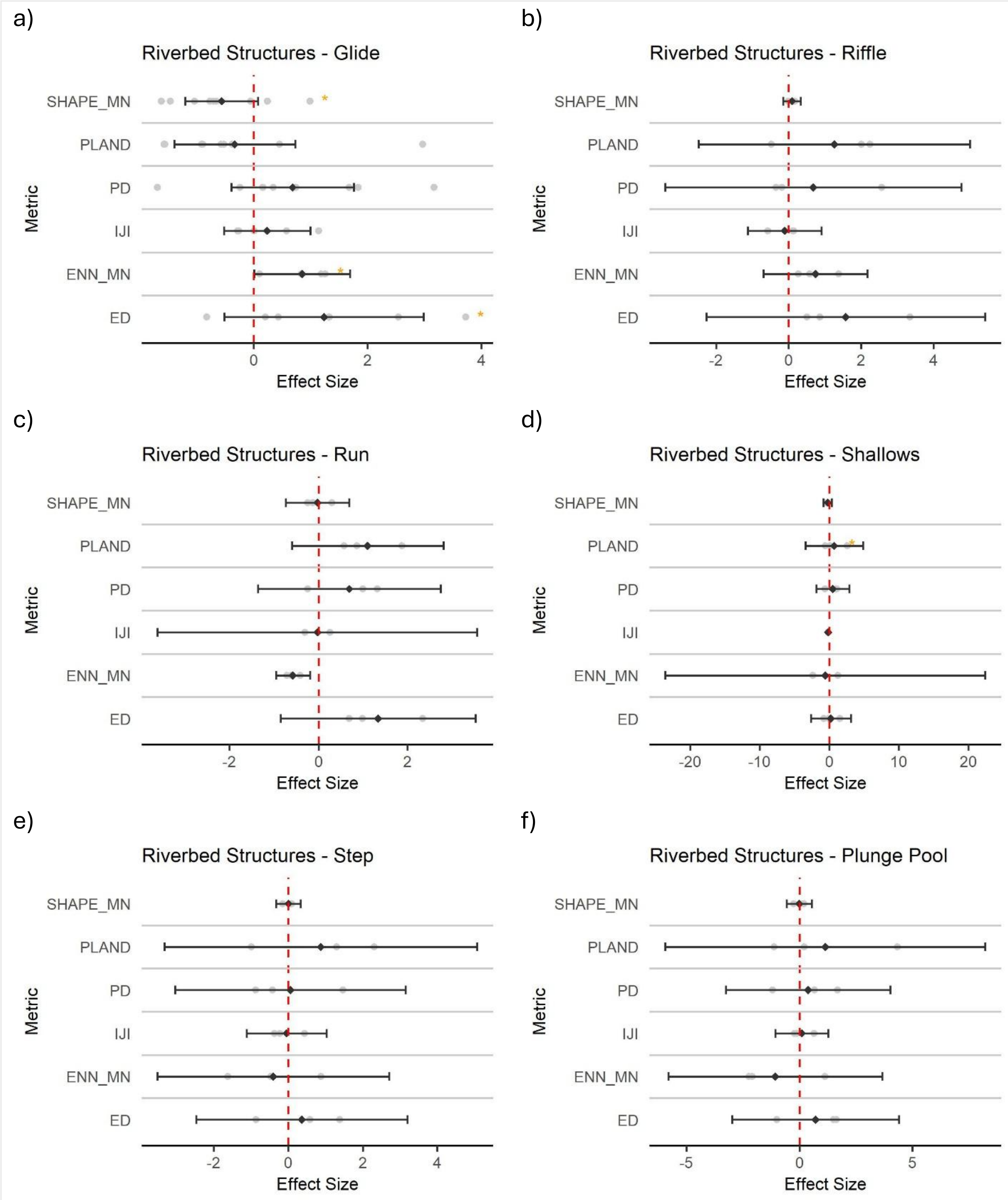


Figure 4: Effect size of class-level landscape metrics of riverbed structures comparing restored to control reaches. Points represent individual projects, while diamonds show mean effect size ± 95% confidence intervals. Dashed line represents no effect. Asterisks denote significance levels from Brunner–Munzel tests (**p* < 0.05, ***p* < 0.01, ****p* < 0.001). Metric abbreviations: SHAPE_MN = Mean Shape Index, PLAND = % of Landscape, PD = Patch Density, IJI = Interspersion and Juxtaposition Index, ENN_MN = Mean Euclidean Nearest Neighbour, ED = Edge Density

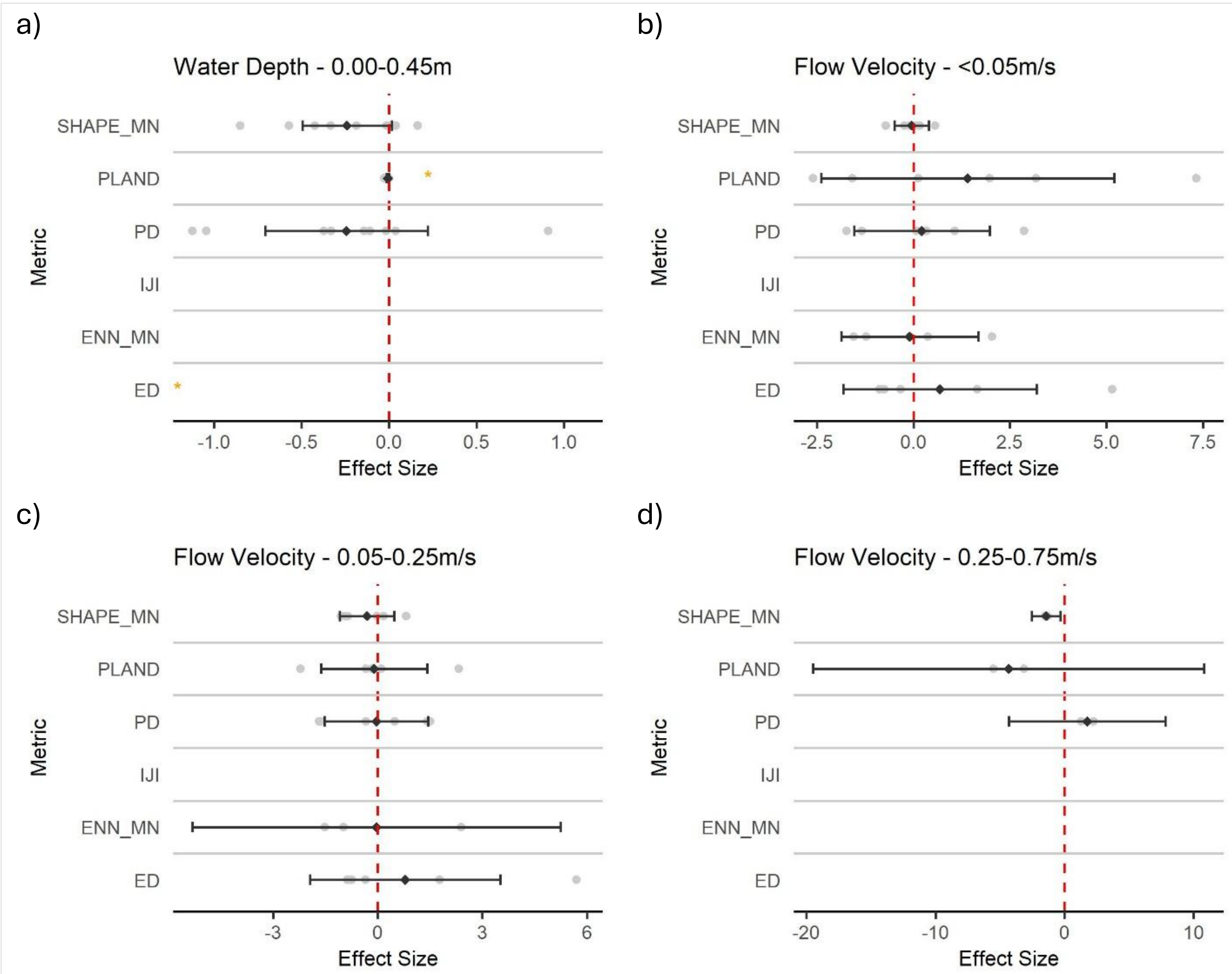


Figure 5: Effect size of class-level landscape metrics of water depth and flow velocity comparing restored to control reaches. Points represent individual projects, while diamonds show mean effect size with ± 95% confidence intervals. Dashed line represents no effect. Asterisks (orange) denote significance levels from Brunner–Munzel tests (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). Metric abbreviations: SHAPE_MN = Mean Shape Index, PLAND = % of Landscape, PD = Patch Density, IJI = Interspersion and Juxtaposition Index, ENN_MN = Mean Euclidean Nearest Neighbour, ED = Edge Density

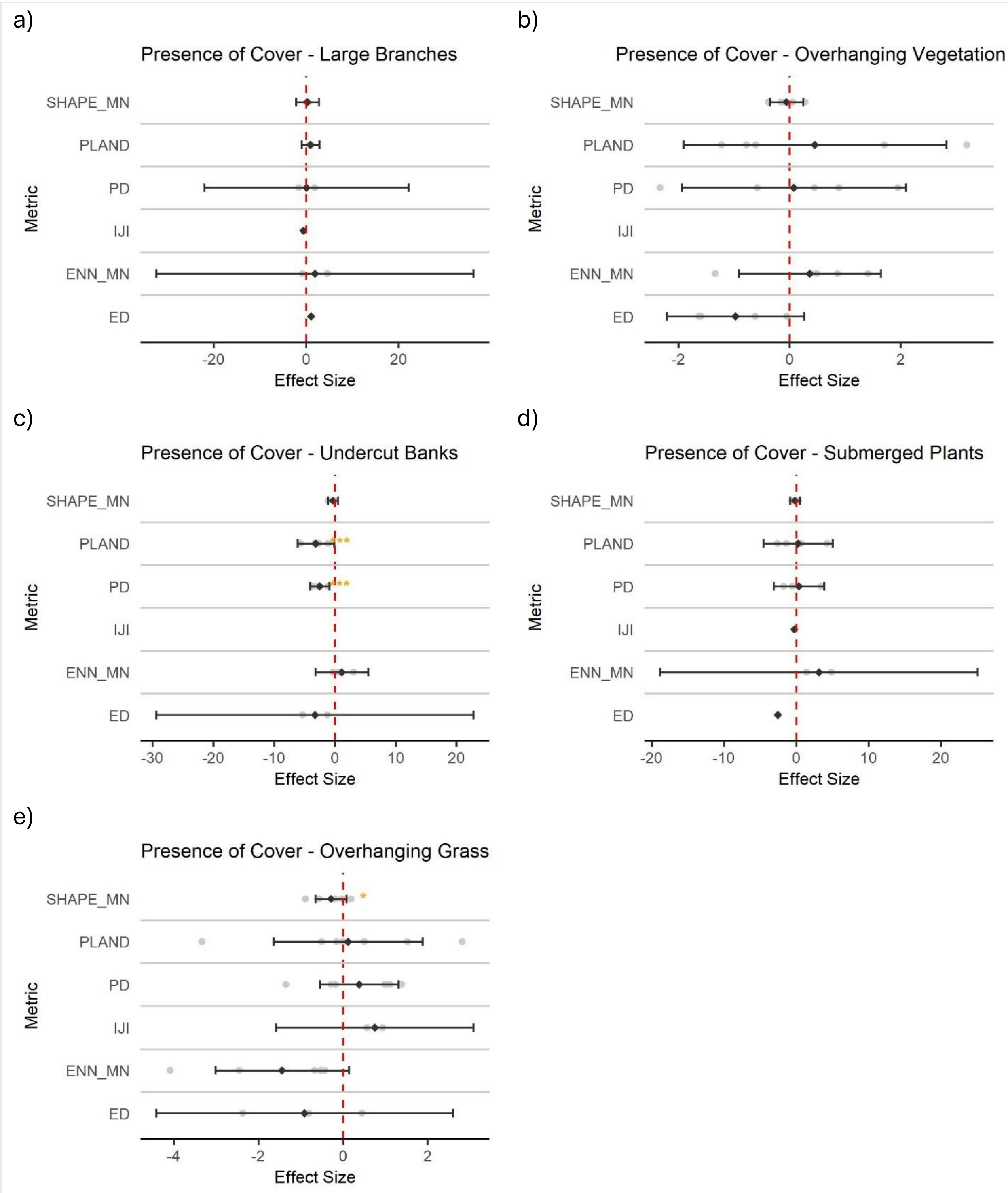


Figure 6: Effect size of class-level landscape metrics of presence of cover comparing restored to control reaches. Points represent individual projects, while diamonds show mean effect size with ± 95% confidence intervals. Dashed line represents no effect. Asterisks (orange) denote significance levels from Brunner–Munzel tests (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). Metric abbreviations: SHAPE_MN = Mean Shape Index, PLAND = % of Landscape, PD = Patch Density, IJI = Interspersion and Juxtaposition Index, ENN_MN = Mean Euclidean Nearest Neighbour, ED = Edge Density

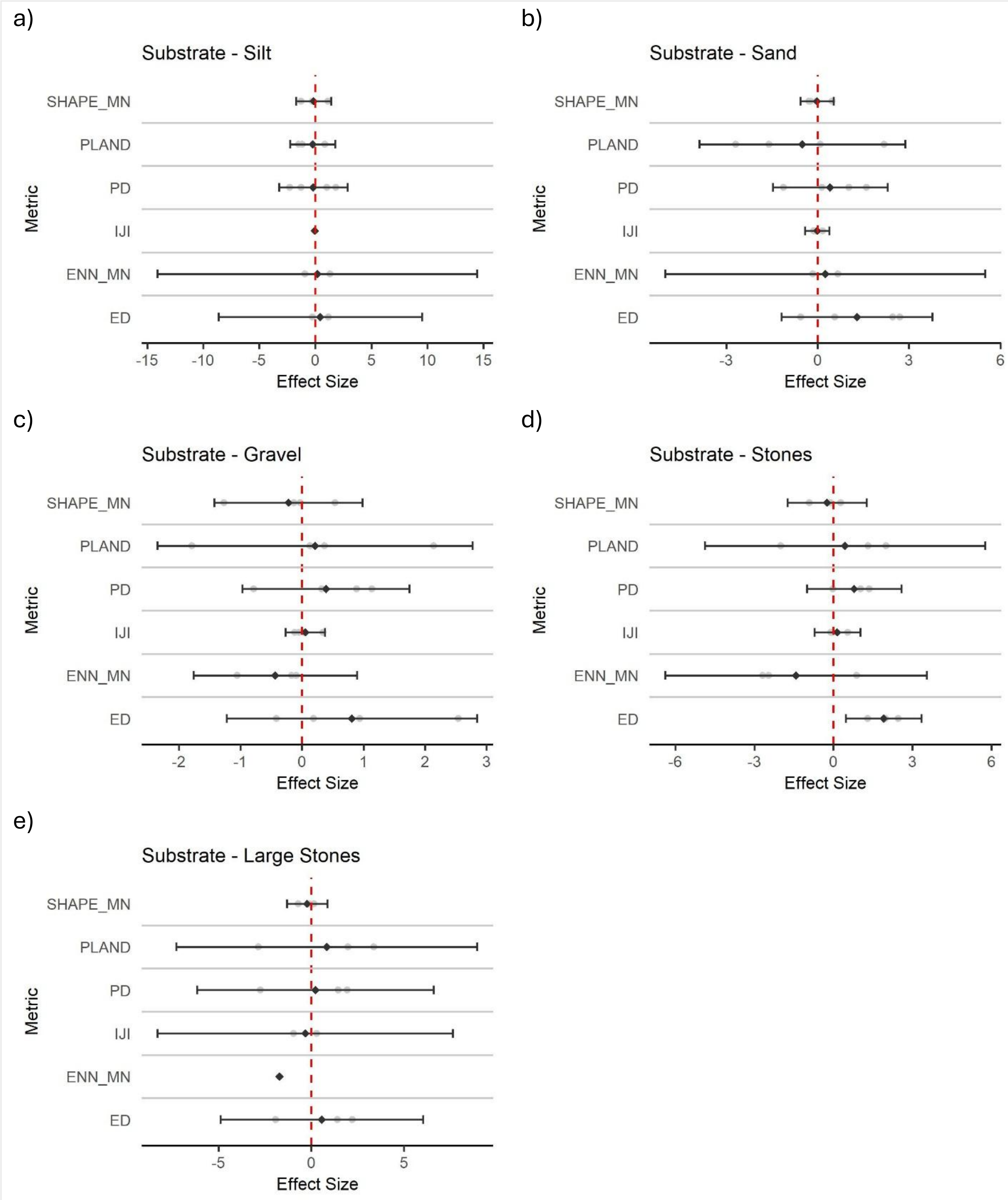


Figure 7: Effect size of class-level landscape metrics of substrate comparing restored to control reaches. Points represent individual projects, while diamonds show mean effect size with ± 95% confidence intervals. Dashed line represents no effect. Asterisks (orange) denote significance levels from Brunner–Munzel tests (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). Metric abbreviations: SHAPE_MN = Mean Shape Index, PLAND = % of Landscape, PD = Patch Density, IJI = Interspersion and Juxtaposition Index, ENN_MN = Mean Euclidean Nearest Neighbour, ED = Edge Density

Figure 4 shows the effect size for the classes of the indicator riverbed structures. Effect sizes for riffle (b), shallows (d), step (e), and plunge pool (f) are distributed between positive and negative values, showing no clear trends. Classes glide (a) and run (c) show similar patterns except for a few metrics. Glide structures have mostly positive effect sizes for edge density and mean Euclidean nearest neighbour, and negative effect sizes for mean shape index, with all three metrics showing statistically significant differences between the two reaches. On the other hand, run structures have negative effect sizes for mean Euclidean nearest neighbour, but no statistical significance (Figure 4).

The effect size distributions for water depth and flow velocity classes are shown in Figure 5. Like riverbed structures, the effect sizes are generally distributed between positive and negative values, indicating no clear patterns.

Figure 6 portrays the distribution of effect size for presence of cover classes. Most metrics for the various classes show no clear patterns. However, undercut banks (c) have statistically significant negative effect sizes for percentage of landscape and patch density. Additionally, overhanging grass (e) shows a negative effect size for mean Euclidean nearest neighbour and mean shape index, but only the latter has a statistically significant difference between the reaches. Overhanging vegetation (b) shows negative effect sizes for edge density, with no statistical significance (Figure 6).

Effect size distributions for substrate classes are portrayed in Figure 7. Like with most other classes, effect size is well distributed between positive and negative values for most metrics, resulting in no clear patterns. Only stones show a positive effect size for edge density, but the differences between the reaches are not statistically significant (Figure 7).

Correlation Analysis

A spearman's correlation test between the number of macroinvertebrate taxa and the landscape-level metrics showed almost no statistical significance, except for a few metrics for the flow velocity layer. The correlation test shows a moderate positive correlation between the number of macroinvertebrate taxa and Shannon's diversity index (rho: 0.70088, p-value: 0.035437). Patch density showed a similar correlation (rho: 0.672293, p-value: 0.047275). On the other hand, mean shape index (rho: -0.73112, p-value: 0.025215) and mean patch area (rho: -0.67229, p-value: 0.047275) showed moderate negative correlations.

Discussion

Landscape-Level Metrics

The results of the calculated landscape-level metrics generally suggest improvements in the restored reaches. Positive effect sizes Shannon's diversity index and interspersion and juxtaposition index indicate restored reaches are more diverse in terms of habitat types available and these habitats are well dispersed in the riverscape (Yu et al., 2024). Additionally, the negative effect size for shape index across all layers suggests that restored reaches have more natural patch shapes, and thus more natural conditions (Tamagnone et al., 2020). Nevertheless, positive values of patch density and edge density for riverbed structures, habitat suitability, and substrate could indicate higher degrees of fragmentation (Han et al., 2023; Tamagnone et al., 2020). However, it is expected that these metrics have higher values when the patch density increases and the riverscape is divided into smaller patches, making it more heterogeneous.

Class-Level Metrics

Across only nine projects, not all classes were represented in the original data. Moreover, many classes were only present in one of the two reaches and thus, did not produce results when calculating effect size, severely limiting the outputs at the class-level and frequently produced very large 95% confidence intervals. At the class level, the landscape metric results were too variable to draw definitive conclusions. Significantly more data from additional projects would be needed to gain deeper insight into how river restoration influences riverscape heterogeneity at the class level.

Relationship with Biological Indicators

The regression analysis conducted to examine the correlation between landscape-level landscape metrics and the number of macroinvertebrate taxa did not show any valuable results. All indicators besides flow velocity showed no correlation, and existing correlations were quite weak. Moreover, since velocity classes were often missing after interpolation, the correlations for flow velocity are likely unreliable.

Nevertheless, this approach remains valuable, as it is important to assess whether any improvements in landscape metrics between restored and control reaches are also reflected in increased biodiversity. Applying this type of regression analysis to a larger number of projects and extending it to additional biological indicators could provide deeper insight into these relationships.

Limitations

Several limitations should be considered when interpreting the results. Firstly, only nine restoration projects were included, resulting in a small sample size and often uneven representation of indicator classes, which could limit the robustness of the conclusions drawn. Additionally, restored and channelised conditions were compared across different reaches, rather than pre- and post-restoration on the same reach, making it harder to evaluate the impact of restoration. Furthermore, potential human error in field surveys may have affected the accuracy of the polygon boundaries. The transformation from vector to raster introduced further error into the accuracy of the class boundaries, which may have an impact on the results. However, the greatest source of error can be attributed to the method used for interpolating water depth and flow velocity, where classes were frequently missing from the output.

Future Improvements

Future research could enhance and extend the proposed methodology by applying it to a larger number of restoration projects, which would ensure that the different classes are more frequently represented. This approach would be particularly effective if applied to the STANDARD outcome evaluation datasets, which include both pre- and post-restoration conditions for the same river reach, as this would allow for a more reliable assessment of restoration effectiveness (Rohde et al., 2004).

In addition, future studies could calculate landscape metrics of riparian areas to explore their response to restoration, since these zones are high in biodiversity and are a critical interface between aquatic and terrestrial ecosystems, providing numerous ecosystem services (Stieger & McKenzie, 2024). It may also be valuable to calculate landscape metrics within the watershed to assess how surrounding land use influences restoration success, analogous to the methodologies commonly applied in water quality studies (Aalipour et al., 2022; Xu et al., 2019).

In the upcoming years, high resolution remotely sensed data may become more readily available, which would greatly benefit this area of research. Landscape metrics derived from remotely sensed data could possibly be used to evaluate the response of rivers to restoration efforts, as demonstrated by Taddeo and Dronova (2020) in wetland ecosystems. Moreover, such data could support the development of hydrological models that could more accurately predict water depth and flow velocity (Kastdalen et al., 2024).

Conclusion

Landscape metrics proved to be an effective method for evaluating river restoration in small streams and show strong potential for future applications in Switzerland, especially at the landscape level. Across the nine projects studied, landscape-level metrics indicated improvements in habitat heterogeneity in restored reaches. However, no meaningful correlations were found with the number of macroinvertebrate taxa. Due to the difficulties in accurately interpolating the water depth and flow velocity data, the use of landscape metrics should be limited to riverbed structures, presence of cover, and substrate until an improved interpolation methodology has been found. The approach suggested in this study is particularly promising for the upcoming STANDARD outcome evaluation, containing both pre- and post-restoration data. In addition, the larger dataset expected from this evaluation will improve the applicability of class-level metrics and enable a more thorough analysis of relationships between landscape metrics and biodiversity.

Technical Report

1. Materials

This master thesis was conducted as a part of a larger project carried out by the River Restoration group of the Swiss Federal Institute of Aquatic Science and Technology (Eawag). The River Restoration group has been working with the Federal Office for the Environment (FOEN) on evaluating the outcomes of river restoration projects using a standardised framework to gain insights into best practices to make future projects more cost-effective (Weber et al., 2019). The framework has two components: the STANDARD and the EXTENDED outcome evaluations.

The STANDARD outcome evaluation will be carried out for many projects across Switzerland, comparing values from a large selection of indicators before and after restoration (Weber et al., 2019). The pre-restoration data have been collected, and the post-restoration collection will follow in the coming years.

The EXTENDED outcome evaluation was conducted on project pairs consisting of a restored reach and a nearby channelised control reach (Weber et al., 2019). Only a subset of indicators and projects were used for this evaluation as the goal was to answer practice-specific questions (Weber et al., 2019).

For this thesis, nine projects were selected from the EXTENDED outcome evaluation dataset based on data completeness. The location of the projects cannot be shared, but Table 3 provides a summary of some project characteristics.

The dataset used in this thesis contains data from two indicator sets: Set 1 – Habitat Diversity and Set 6 – Macroinvertebrates. The data from both indicator sets were collected according to the specifications outlined in the official practice documentation (Federal Office for the Environment, 2019a, 2019b)

Table 3: Characteristic of the nine project pairs used in this study

ID	Reach	Reach Length (m)	Average Width (m)	Average Depth (m)	Age
1	Restored	123	2.99	0.54	8
	Control	100	1.60	0.93	
2	Restored	101	1.10	0.3	5
	Control	101	0.96	1	
3	Restored	170	0.92	0.8	6
	Control	105	0.91	0.9	
4	Restored	109	2.18	0.42	11
	Control	100	1.11	0.21	
5	Restored	119	2.76	0.72	11
	Control	100	1.16	0.41	
6	Restored	103	1.52	0.26	7
	Control	100	1.00	0.1	
7	Restored	101	1.20	0.58	8
	Control	101	0.78	0.26	
8	Restored	109	1.35	0.28	7
	Control	120	1.23	0.35	
9	Restored	102	2.28	0.8	9
	Control	101	1.34	0.58	

1.1 Habitat Diversity

The habitat diversity indicator set includes 6 abiotic indicators (Table 4). For some indicators, the vector data were collected over the entire reach, while for others the data only cover a characteristic subsection of the reach. Figure 9 provides an overview of the raw data used. In this study, all indicators were used except for 1.2 Riverbank Structures.

Table 4: Summary of the abiotic indicators from Indicator Set 1 – Habitat Diversity (Federal Office for the Environment, 2019a)

Indicator	Type	Extent
1.1 Riverbed Structures	Polygon	Entire reach
1.2 Riverbank Structures	Line	Entire reach
1.3 Water Depth	Point	Subsection
1.4 Flow Velocity	Point	Subsection
1.5 Presence of Cover	Polygon	Subsection
1.6 Substrate	Polygon	Subsection

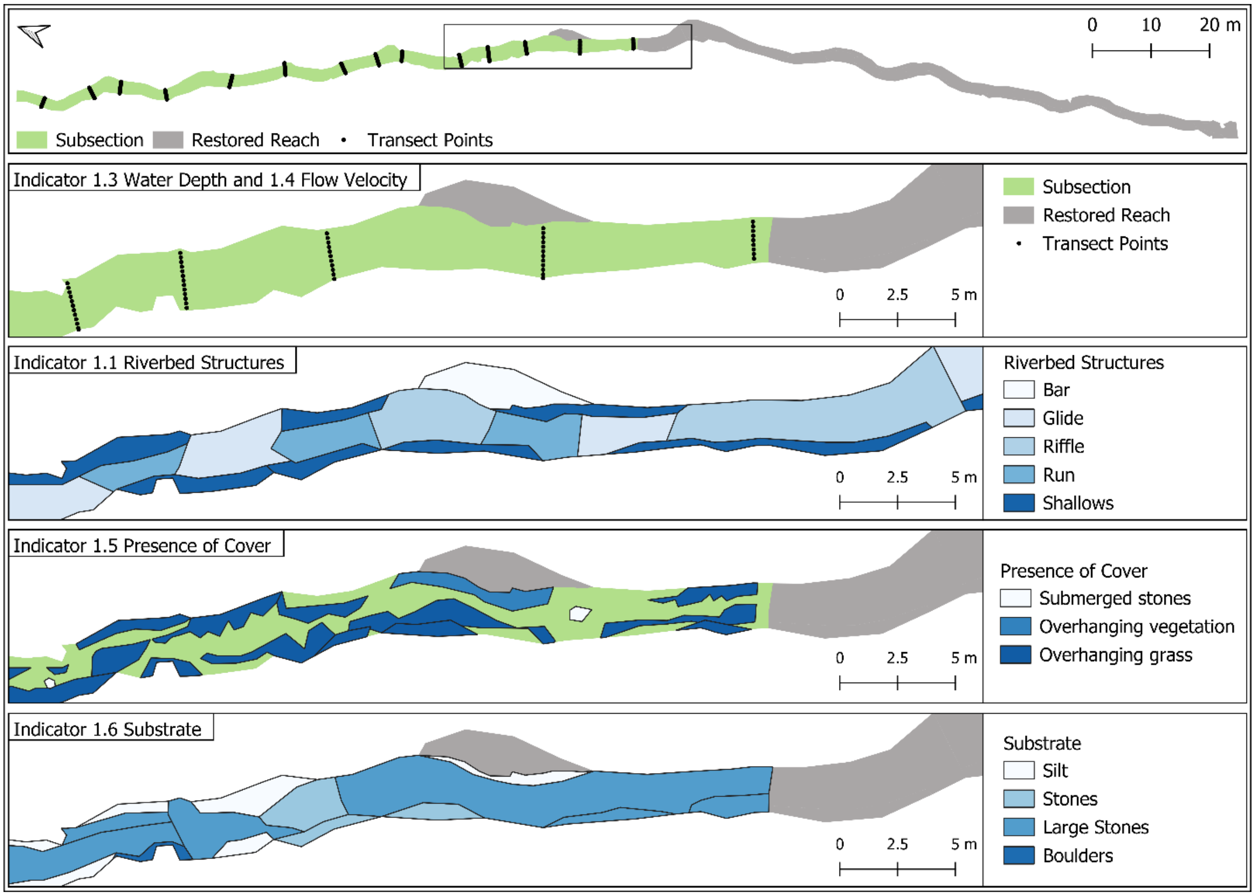


Figure 8: Examples of the raw spatial data layers in a restored reach

Riverbed structures (Indicator 1.1) were digitized in the field across the entire bed width, including dry areas like sand banks, with a minimum polygon area of 0.5m^2 (Federal Office for the Environment, 2019a). The classifications of the riverbed structures and their definitions can be found in Table 5.

Table 5: Definitions of classes from indicator 1.1 Riverbed Structures (Federal Office for the Environment, 2019a)

No.	Structure	Description
1	Bar	Local sediment deposit, not submerged during low-flow conditions, in the middle of the river or along the bank
2	Pool	Local deepening of river bed due to erosion by secondary currents and/or eddies
3	Glide*	Elongated, deep channel section with slow current. Wetted width/depth ratio low (<10–12).
4	Riffle*	Broad, elevated portion of river bed with slow current, with a low gradient. Wetted width/depth ratio higher (>10–12).
5	Run*	Steep channel section with swift current, with a high gradient
6	Backwater	Wetted area with no current during low-flow conditions ("dead end")
7	Shallows	Low-current zone along the bank or along a gravel bar
8	Step**	Natural or artificial drop followed by a pool. The step begins at the point in the upper waters where flow is accelerated towards the drop and ends where the jet enters the lower waters; here the pool begins.
9	Plunge pool**	Larger depression following a step
0	Artificial bed	Local artificial stabilisation of the river bed, which is not mapped as a step

* Glide, riffle and run together form a sequence typical of low-gradient rivers (gradient <3%).
** Step-pool sequences are natural features of steep waters (gradient >1%), which appear as a result of artificial sills, but also in more gently sloping rivers.

Water depth and flow velocity were measured at the same points at 10 to 15 cross-sections at regular intervals along the subsection. The cross-sections were taken at right angles to the river axis, and points were spaced about 0.2m apart (Federal Office for the Environment, 2019a). Both water depth and flow velocity were measured to the cm level. Flow velocity was measured at 40% water depth (Federal Office for the Environment, 2019a). The classes are presented in Table 1 above.

The presence of cover describes places where a fish of 25-30cm length can seek refuge (Federal Office for the Environment, 2019a). Based on discussions with my supervisors at Eawag, this would be equivalent to an area of about $0.09m^2$ (30x30cm). The various types of cover are defined in Table 6.

Table 6: Indicator 1.5 Presence of Cover class definitions (Federal Office for the Environment, 2019a)

No.	Cover type
1	Submerged stones or boulders
2	Non-submerged stones or boulders (also areas behind rocks)
3	Small organic particles (mobile, e.g. small branches, collections of leaves, grass)
4	Medium-sized organic particles (relatively immobile, e.g. fine roots, bryophytes 5–20 cm in diameter)
5	Large branches in the water, large roots (from trees standing along the waterside)
6	Tree trunks (lying)
7	Tree stumps or intact root plates (lying)
8	Overhanging vegetation (dead or living, up to a maximum of 50 cm above the water surface)
9	Undercut banks
10	Submerged plants, floating plants
11	Overhanging grass / reeds
12	Turbulent water zones
13	Pools (various pool types are combined)

Substrate was characterised according to composition and mobilizability (Table 6). The smallest polygon area measured was also $0.5m^2$ (Federal Office for the Environment, 2019a).

Table 7: Indicator 1.5 Substrate class definitions (Federal Office for the Environment, 2019a)

Attribute	No.	Quality	
Composition	1	Silt/fine sediment	<0.2 mm
	2	Sand	0.2–2 mm
	3	Gravel	2–16 mm
	4	Stones	16–64 mm
	5	Large stones	64–250 mm
	6	Boulders	>250 mm
	7	Rock	impermeable
	8	Organic material	e.g. grasses, reeds, roots, branches, woody debris
	9	Artificial substrate	e.g. engineered bed
Mobilisability	1	Deposits of suspended particles	Sand, silt
	2	Fine bedload	Finer-grained portions of regularly transported bedload (*)
	3	Coarse bedload	Coarser portions of regularly transported bedload (*)
	4	Bed material mixed with bedload	Bedload grains are deposited between the large grains of bed material (*)
	5	Coarse bed material	Large grains of bed material predominate, often arranged in an imbricated structure (*)

1.2 Macroinvertebrates

Benthic macroinvertebrates were sampled in the spring by means of kick-sampling (Federal Office for the Environment, 2019b). Samples were collected at 8 different combinations of substrate and flow velocity. The Ephemeroptera, Plecoptera and Trichoptera (EPT) taxa were identified to the species level (Federal Office for the Environment, 2019b). For this thesis, I used the total number of EPT species present per reach.

2. Methodology Diagram

Figure 9 provides a short overview of the methodology used.

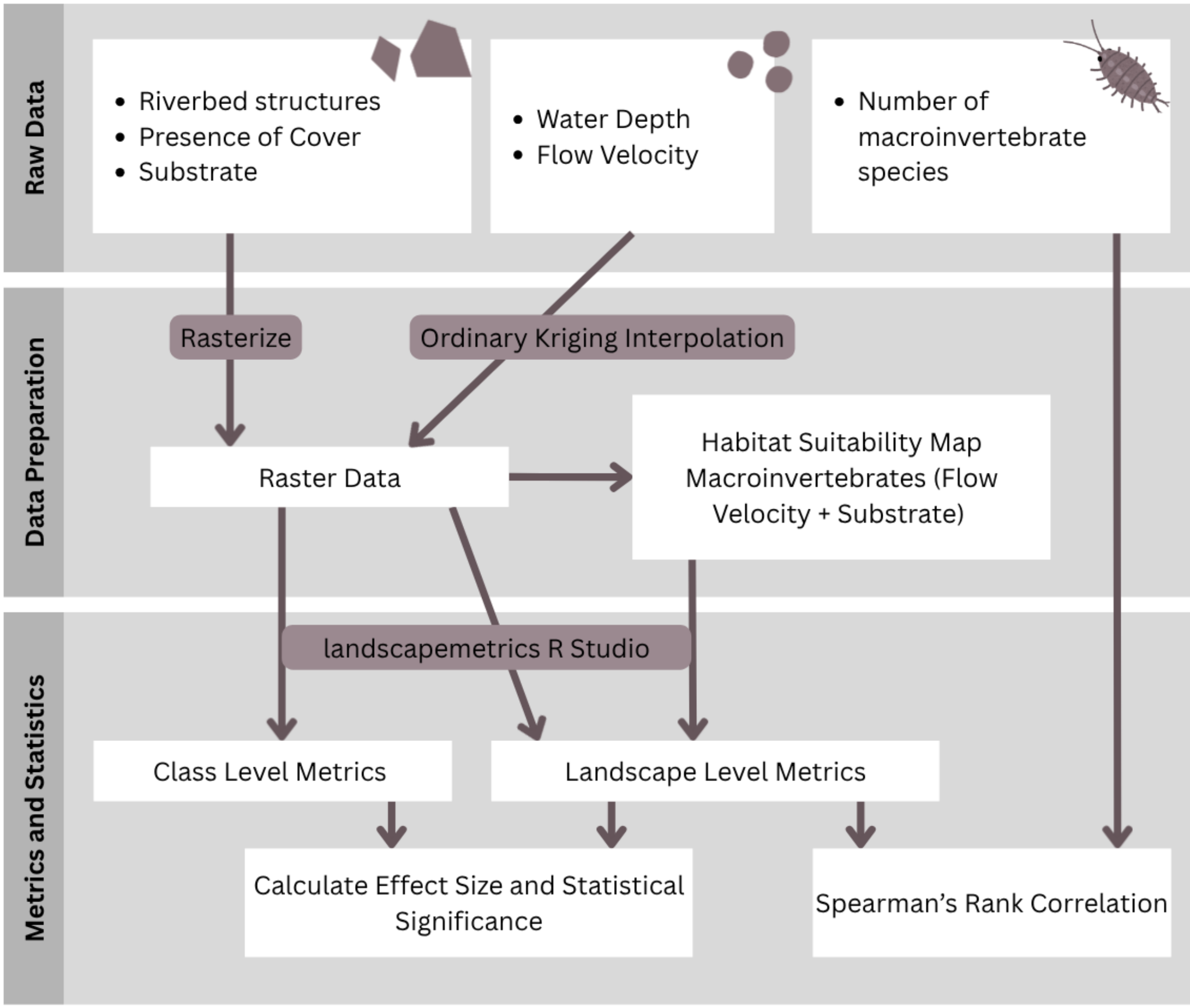


Figure 9: Overview of methodology

3. Metrics Selection

A list of landscape metrics was compiled based on those used in river research literature (Aalipour et al., 2022; Aalipour et al., 2024; Aalipour et al., 2023; Boongaling et al., 2018; Cheng et al., 2023; Cortes et al., 2011; Datry et al., 2016; Iskin & Wohl, 2023; Liu et al., 2024; Miller et al., 2020; Rajaei et al., 2017; Rohde et al., 2004; Taddeo & Dronova, 2020; Tamagnone et al., 2020; Wu & Lu, 2021; Xu et al., 2019; Xu et al., 2022; Xu et al., 2023; Yu et al., 2024). The metrics occurring at least two times in the reviewed literature are shown in Table 8, along with the total occurrence, the type of metric, its level, and a short description of what it calculates.

Table 8: List of most used landscape metrics in river research and their descriptions (Aalipour et al., 2022; Aalipour et al., 2024; Aalipour et al., 2023; Boongaling et al., 2018; Cheng et al., 2023; Cortes et al., 2011; Datry et al., 2016; Iskin & Wohl, 2023; Liu et al., 2024; Miller et al., 2020; Rajaei et al., 2017; Rohde et al., 2004; Taddeo & Dronova, 2020; Tamagnone et al., 2020; Wu & Lu, 2021; Xu et al., 2019; Xu et al., 2022; Xu et al., 2023; Yu et al., 2024). Highlighted metrics were those selected for this study.

Metric Name	Occurrence in Literature	Type	Level	Description (Hesselbarth, 2025)
Patch Density (PD)	12	Aggregation	Landscape; Class	Describes class/landscape fragmentation; is standardised allowing comparison between landscapes of different sizes
Interspersion and Juxtaposition Index (IJI)	10	Aggregation	Landscape; Class	Describes the intermixing of classes. Low values represent less intermixing
Largest Patch Index (LPI)	10	Area and Edge	Landscape; Class	Percentage of landscape covered by the largest patch, measuring dominance
Aggregation Index (AI)	8	Aggregation	Landscape; Class	A measure of how often patches of the same class are adjacent to each other
Percentage of Landscape (PLAND)	7	Area and Edge; Composition	Class	Percentage of the total landscape area covered by a class
Edge Density (ED)	7	Area and Edge	Landscape; Class	Describes the ratio of total edge and landscape area
Landscape Shape Index (LSI)	7	Aggregation	Landscape; Class	Describes the ratio between the actual edge length and a hypothetical minimum edge length for a class

Metric Name	Occurrence in Literature	Type	Level	Description (Hesselbarth, 2025)
Mean Shape Index (SHAPE_MN)	7	Shape	Landscape; Class	Describes how different the patch shape is compared to a square
Contiguity Index (CONTIG)	4	Shape	Landscape; Class	Measures the spatial connectedness of cells in a patch
Patch Cohesion Index (COHESION)	4	Aggregation	Landscape; Class	Describes the connectedness of patches in a class
Shannon's Diversity Index (SHDI)	4	Diversity	Landscape	Measure of diversity considering number of classes and abundance of each class
Fractal Dimension Index (FRAC)	5	Shape	Landscape; Class	A measure of patch complexity
Related Circumscribing Circle (CIRCLE)	3	Shape	Landscape; Class	Describes the compactness of a patch
Perimeter-Area Fractal Dimension (PAFRAC)	3	Shape	Landscape; Class	A scale-independent measure of patch complexity
Number of Patches (NP)	3	Aggregation	Landscape; Class	A measure of class or landscape fragmentation
Contagion (CONTAG)	3	Aggregation	Landscape	Describes probability of two cells belonging to the same class
Percentage of Like Adjacencies (PLADJ)	2	Aggregation	Landscape; Class	Describes how often patches of two different classes are next to each other
Clumpiness Index (CLUMPY)	2	Aggregation	Class	A measure of class aggregation
Perimeter-Area Ratio (PARA)	2	Shape	Landscape; Class	A non-independent measure of patch complexity; not standardised to a shape

Metric Name	Occurrence in Literature	Type	Level	Description (Hesselbarth, 2025)
Total Edge (TE)	2	Area and Edge	Landscape; Class	An absolute measure of fragmentation
Patch Area Standard Deviation (AREA_SD)	2	Area and Edge	Landscape; Class	Describes differences among patches of the same class
Mean Euclidean Nearest Neighbour (ENN_MN)	2	Aggregation	Class	Distance to nearest neighbouring patch of the same class from edge to edge; measure of connectivity
Patch Area Coefficient of Variation (AREA_CV)	2	Area and Edge	Landscape; Class	Describes differences among patches of the same class; scaled to mean

The metrics selected should describe both the composition and configuration of the landscape (Cheng et al., 2023; Xu et al., 2023). Therefore, they should generally contain a combination of shape, area and edge, and aggregation metrics (Tamagnone et al., 2020). Additionally, the metrics should be selected to avoid redundancy (Tamagnone et al., 2020). An average of 7 metrics were selected per study based on the reviewed literature.

In this study, I selected the most used metrics in river research literature, making sure to include metrics to describe area and edge, shape and aggregation. Thus, for area and edge metrics I chose percentage of landscape (PLAND) to describe the composition of the riverscape at the class level, and edge density (ED) at both levels, as this metric is directly related to the degree of fragmentation and heterogeneity (Tamagnone et al., 2020). For aggregation, I selected the interspersion and juxtaposition index (IJI) to get an understanding of how classes are intermixed, and patch density (PD) to further determine how fragmented the landscape is (Table 8). IJI and PD were chosen as class and landscape level metrics. I selected mean shape index (SHAPE_MN) at both levels as the shape metric, as this can also provide an indication of how natural the landscape is (Tamagnone et al., 2020). Since the context of the study is habitat heterogeneity, I also decided to include Shannon's diversity index (SHDI) to provide an insight into the general diversity of the landscape (Table 8). SHDI was also selected as it provides information on the composition of the riverscape at the landscape level. Finally, I decided to include a measure of connectivity at the class level to get a more thorough understanding of habitat fragmentation, so I selected the mean Euclidean nearest neighbour (ENN_MN) (Tamagnone et al., 2020). This resulted in a selection of 7 metrics, presented in Table 2 above.

4. Data Preparation

4.1 Data Cleaning

Despite the extensive guidelines for collecting data, small errors were present in the shapefiles. These had to be corrected before the data could be used. Prior to the start of this study, I helped develop a methodology to detect errors in geometry and attribute tables. This involved doing geometry and topology checks in QGIS and testing the values and column names in the attribute tables using a python script. Most errors were handled internally at Eawag, but some files had to be sent back to the data collectors for correction.

4.2 Vector to Raster Transformation

The *landscapemetrics* package in R was chosen to calculate the metrics because it contains a wide range of metrics at all levels (Hesselbarth et al., 2019). Additionally, it allowed me to keep most of my workflow within R. Since this package requires raster data as input, the raw data had to be transformed (Hesselbarth et al., 2019). To do so, the extent and cell size had to be determined and the point data from the transects (water depth and flow velocity) had to be interpolated.

4.2.1 Selecting the extent

Some data were only available for a subsection of the reach. To ensure the same extent for all layers, the substrate polygons were intersected with the riverbed polygons to create an extent polygon. This extent was used for all layers except for the riverbed polygons, where the entire reach was kept to avoid loss of complexity.

4.2.2 Selecting cell size

When selecting the cell size, I wanted to ensure not too much data were lost during the transformation from polygon to raster, especially since metrics like edge density are highly dependent on patch perimeter. O'Neill et al. (1996) suggest selecting a cell size that is 2-5 times smaller than the smallest unit. By using this suggestion and taking into consideration the smallest measured area of 0.09m^2, the recommended cell size was between 13.4-21.2 cm.

To select an appropriate cell size for this study, a small exploration was conducted comparing the perimeter of patches at different resolutions to the original vector patch perimeter. Two project pairs were chosen for this exploration, one with narrow reaches (ID

3) and the other with wider reaches (ID 1). The data were further subset by using only the riverbed structures and presence of cover layers, since the former covers the entire reach, while the latter is only found in subsections of the riverbed and could potentially have more varied shapes and sizes. Thus, the exploration was conducted on a total of 8 shapefiles.

The shapefiles were transformed to raster with different cell sizes using the polygon ID as the raster value. Patch perimeters were calculated using the *landscapemetrics* package. The calculated perimeters were joined to the original attribute tables of the shapefiles using the ID and the differences between the raster patch perimeters and vector patch perimeters were calculated. The results are shown in Figure 10, grouped by indicator and reach type (control versus restored).

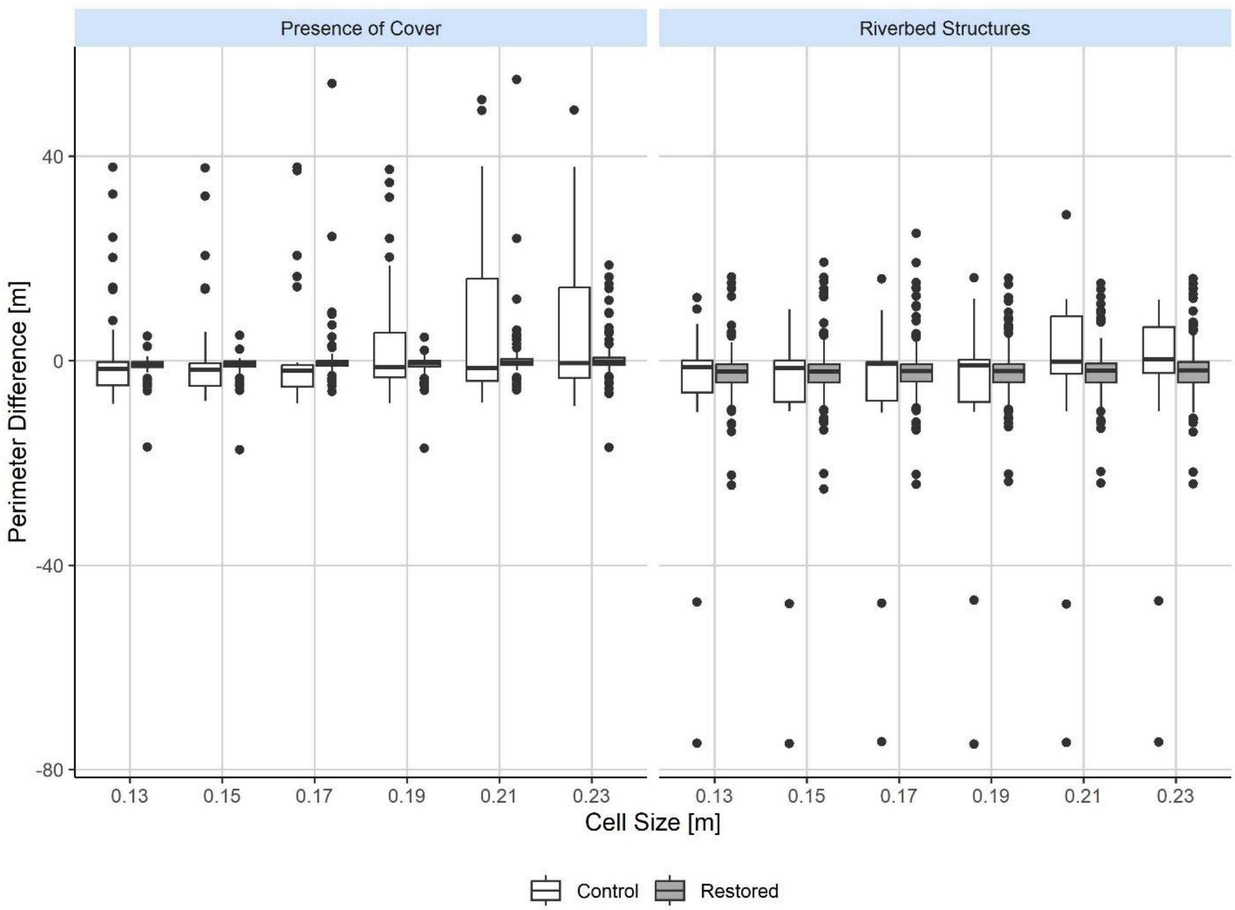


Figure 10: Difference in perimeter of patches as vector versus raster at various spatial resolutions, comparing presence of cover and riverbed structures using two project pairs. Each pair consists of a channelised control reach (white) and a restored reach (grey)

Based on Figure 10, a cell size of 0.15m was chosen, as this was the largest cell size that still resulted in lower differences in perimeter. Additionally, this was 4 times smaller than the smallest unit.

4.3 Interpolating Depth and Velocity

The interpolation of the water depth and flow velocity cross-section measurements was a great challenge due to anisotropy and the curvilinear nature of the streams. Merwade et al. (2005) developed a method that resolves some of these challenges. The method involves straightening a regular point grid that has been placed over the reach, and interpolating onto the straightened grid before joining it back to the original grid (Merwade et al., 2005). Figure 2 above shows the input data required for this method, which includes a regular grid over the reach (spaced at 0.15cm to match the spatial resolution of the raster data), the point layer for the water depth and flow velocity data, and reference line that follows the length of the reach.

The reference line was used to straighten the channel by converting the coordinates of both the depth points and the grid into a new coordinate system (s, n), which is based on distances to the reference line (Merwade et al., 2005). The n coordinate represents the direct distance to the reference line (meeting at a 90-degree angle), whereas s describes the distance along the reference line (Merwade et al., 2005). These distances were calculated in QGIS using the following formulas:

$$n = \mathrm{distance}(\mathrm{overlay\_nearest}('\mathrm{reference}', \$\mathrm{geometry})[0], \$\mathrm{geometry})$$

$$s = \mathrm{line\_locate\_point}(\mathrm{overlay\_nearest}('\mathrm{reference}', \$\mathrm{geometry})[0], \$\mathrm{geometry})$$

After changing the coordinates from x, y to s, n, ordinary kriging was performed in R using the *gstat* package for both the water depth and flow velocity data. Ordinary kriging was chosen as the interpolation method because it has been shown to perform the best for interpolating both depth and velocity from cross sections (Hasníková et al., 2015; Wu et al., 2019). To perform ordinary kriging, the raw water depth and flow velocity data were transformed, where possible, to resemble a more normal distribution. This was particularly challenging as a lot of the data were strongly positively skewed (Figure 11), making it difficult to achieve a normal distribution with transformation.

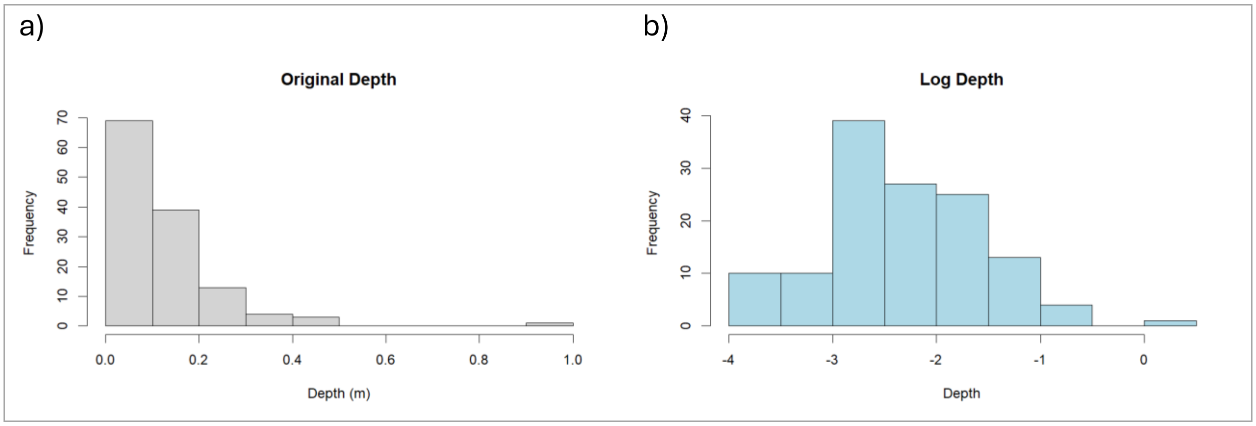
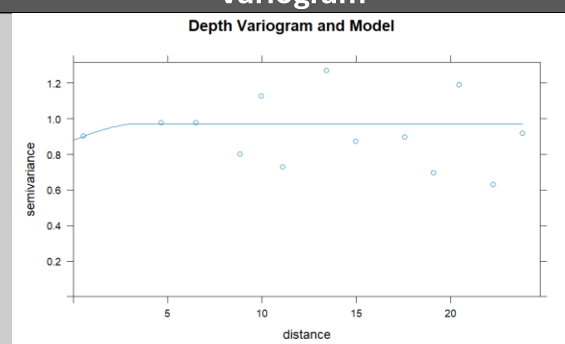
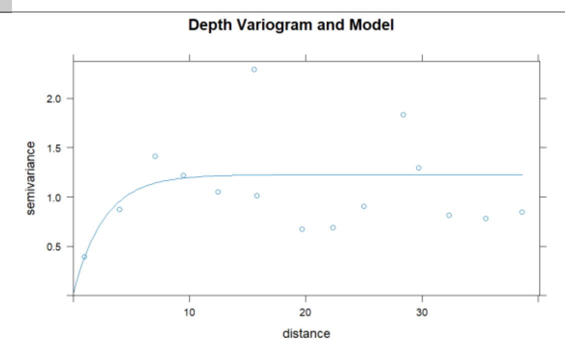
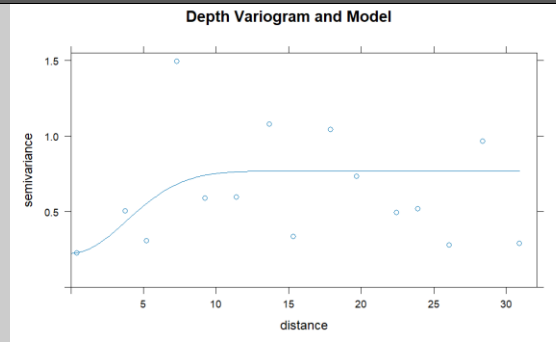
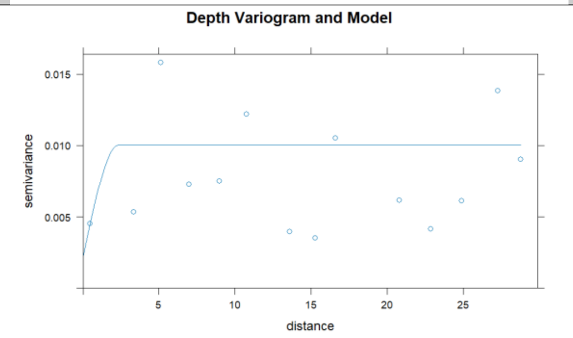
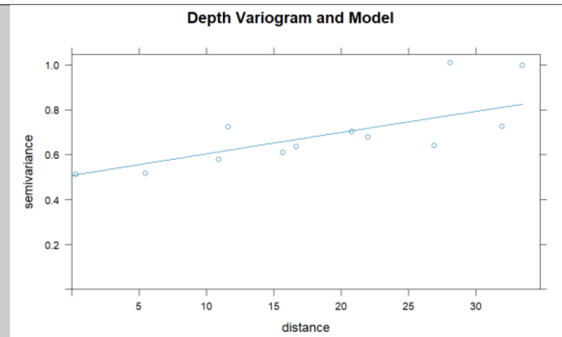
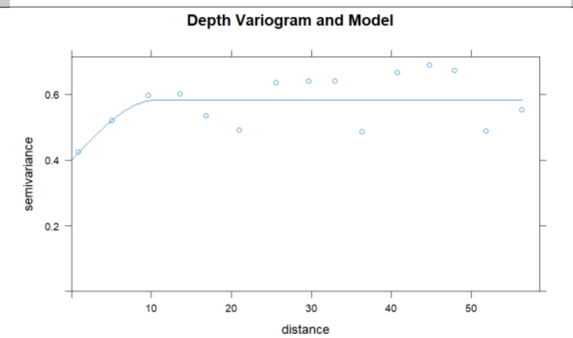


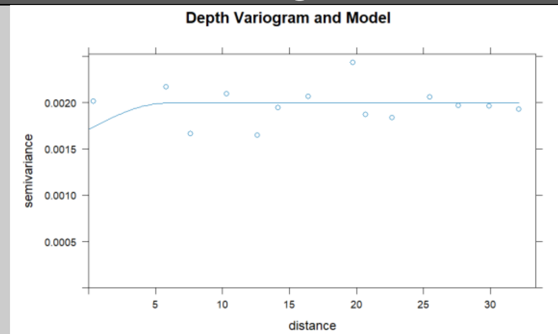
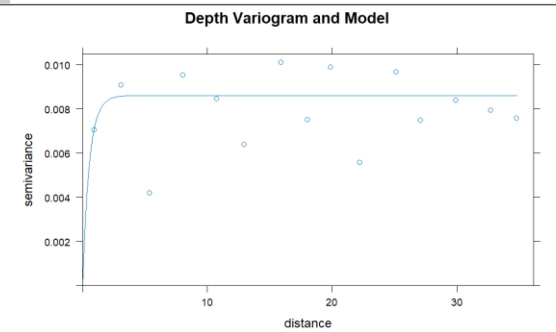
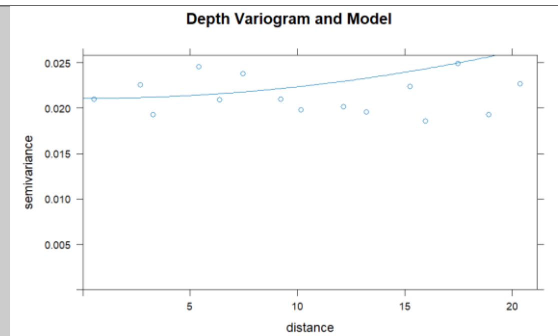
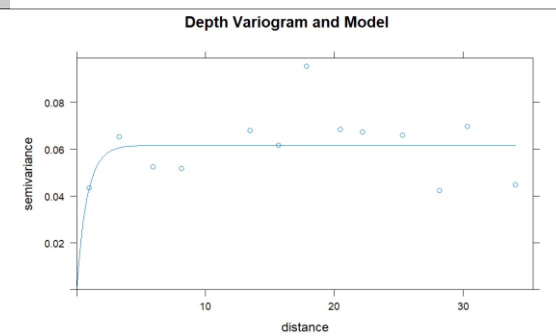
Figure 11: Example of the distribution of water depth in a channelised reach before (a) and after (b) applying a log transformation

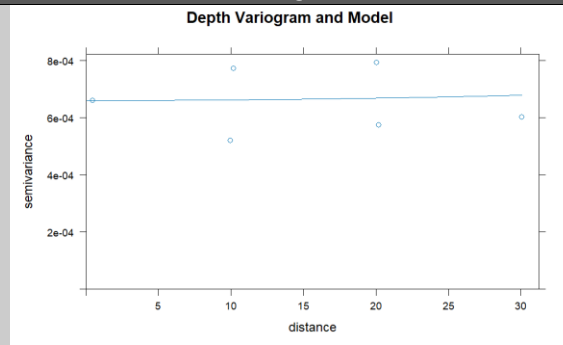
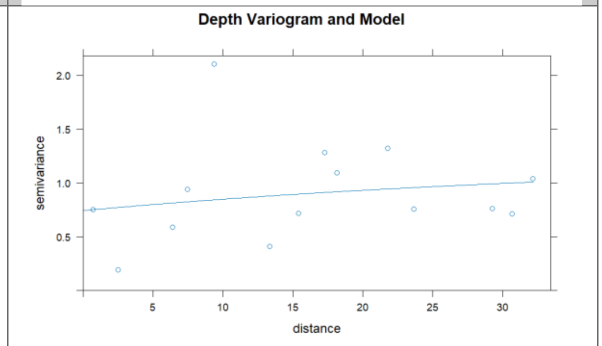
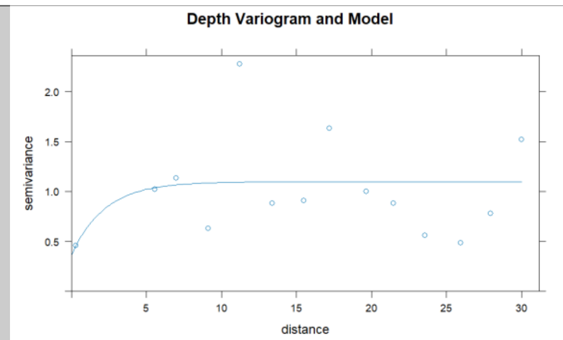
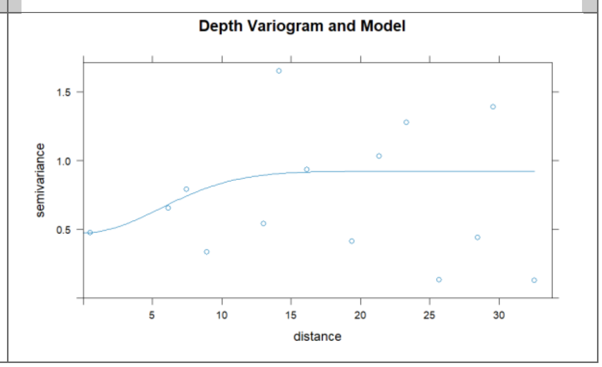
The empirical variograms were plotted, and estimates were made for the nugget, range, and partial sill. Using these estimates, various models were fit with anisotropy in the 0° direction. The model with the lowest sum of squares error (RMSE) and most reasonable fit was selected (Merwade et al., 2006). However, this process was challenging because the raw data were usually very skewed and there were limited data points, making it difficult to accurately fit a model. The final selection of parameters, the fitted model and the transformations applied are found in Table 9 for water depth and Table 10 for flow velocity.

Table 9: Original kriging parameters and variograms for Indicator 1.3 Water Depth per reach

ID	Reach	Kriging Parameters	Variogram
1	Control	Transformation: Yeo-Johnson Partial sill: 0.09351755 Range: 3.438289 Nug: 0.87803551 Model: “Sph” Anis: (0, 0.01)	
1	Restored	Transformation: Yeo-Johnson Partial sill: 1.2081966 Range: 2.666232 Nug: 0.0176218 Model: “Exp” Anis: (0, 0.01)	

ID	Reach	Kriging Parameters	Variogram
2	Control	Transformation: Log Partial sill: 0.5453411 Range: 5.406512 Nug: 0.2250739 Model: “Gau” Anis: (0, 0.01)	
2	Restored	Transformation: Square root Partial sill: 0.007826018 Range: 2.354208 Nug: 0.002198476 Model: “Sph” Anis: (0, 0.01)	
3	Control	Transformation: Yeo-Johnson Partial sill: 5.245735 Range: 757.0017 Nug: 0.506655 Model: “Ste” Anis: (0, 0.01)	
3	Restored	Transformation: Log Partial sill: 0.1835973 Range: 10.63265 Nug: 0.3992403 Model: “Sph” Anis: (0, 0.01)	

ID	Reach	Kriging Parameters	Variogram
4	Control	Transformation: NONE Partial sill: 0.000283321 Range: 5.784873 Nug: 0.001709968 Model: “Sph” Anis: (0, 0.01)	
4	Restored	Transformation: NONE Partial sill: 0.008607072 Range: 0.5491563 Nug: 0 Model: “Exp” Anis: (0, 0.01)	
5	Control	Transformation: NONE Partial sill: 123.19660495 Range: 3103.072 Nug: 0.02106952 Model: “Gau” Anis: (0, 0.01)	
5	Restored	Transformation: Square root Partial sill: 0.06171052 Range: 0.8182486 Nug: 0 Model: “Exp” Anis: (0, 0.01)	

ID	Reach	Kriging Parameters	Variogram
6	Control	Transformation: NONE Partial sill: 0.9325665083 Range: 6749.763 Nug: 0.0006603206 Model: “Gau” Anis: (0, 0.01)	
6	Restored	Transformation: Yeo-Johnson Partial sill: 0.2852334 Range: 15.12195 Nug: 0.7518558 Model: “Gau” Anis: (0, 0.01)	
7	Control	Transformation: Yeo-Johnson Partial sill: 0.7346064 Range: 2.227524 Nug: 0.3622802 Model: “Exp” Anis: (0, 0.01)	
7	Restored	Transformation: Yeo-Johnson Partial sill: 0.4483028 Range: 7.821436 Nug: 0.4749511 Model: “Gau” Anis: (0, 0.01)	

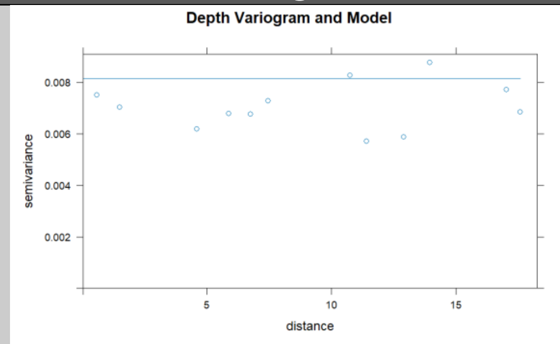
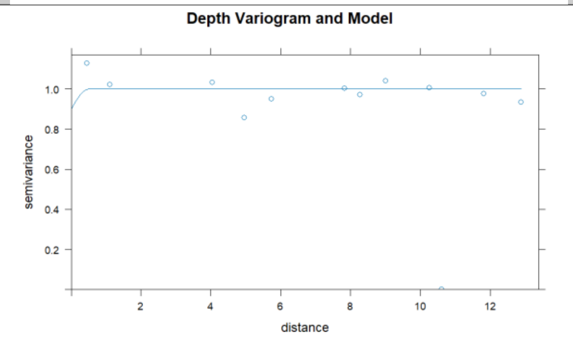
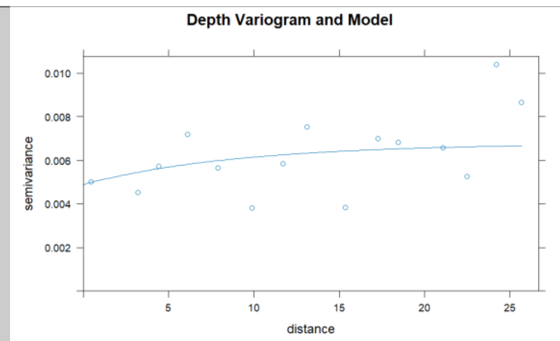
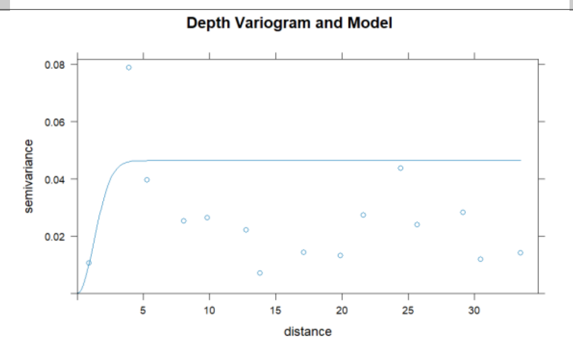
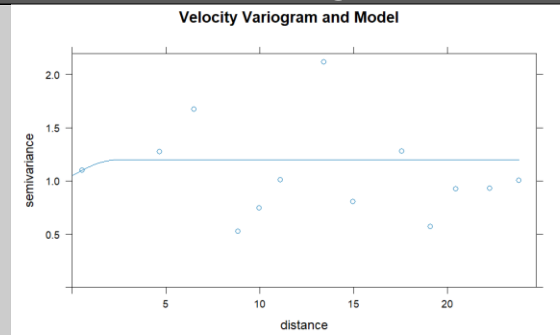
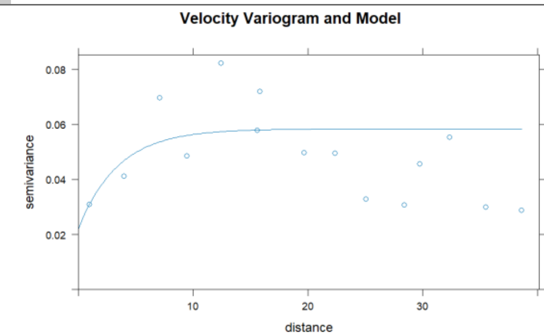
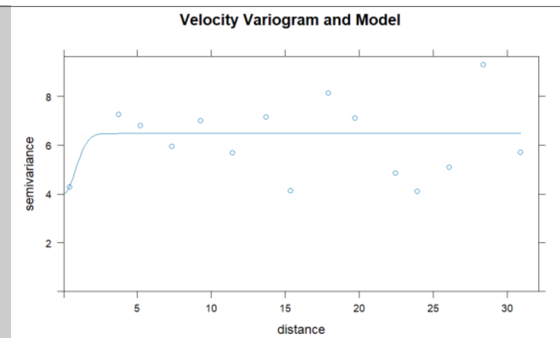
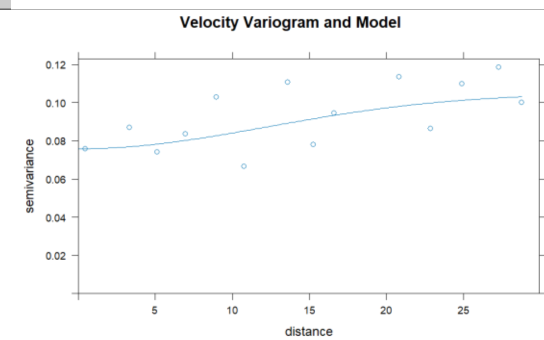
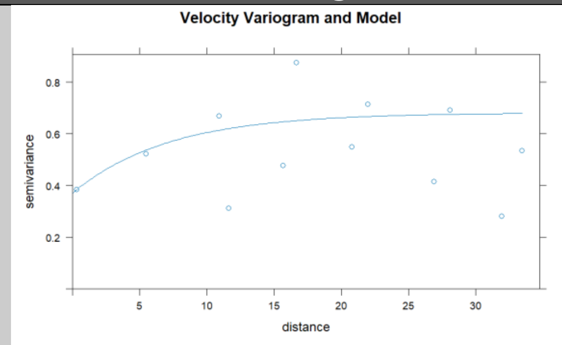
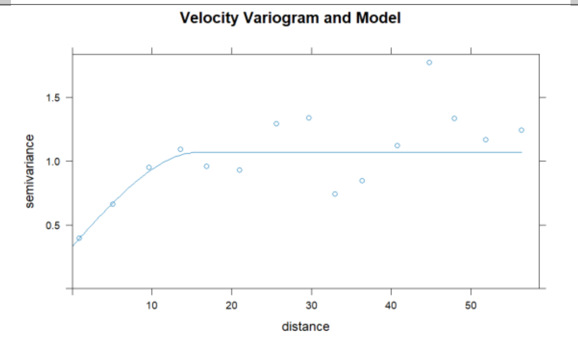
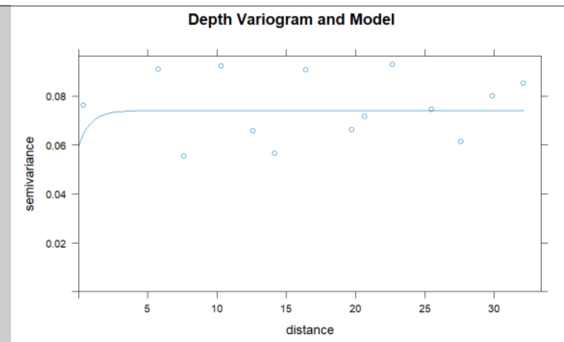
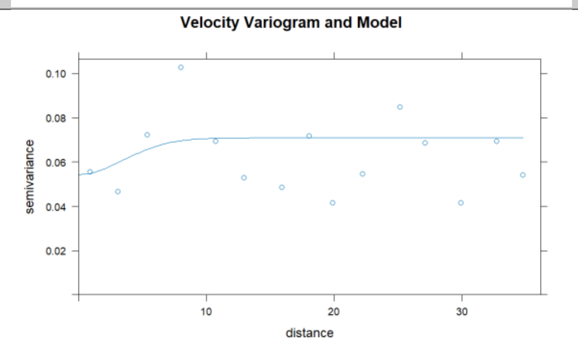
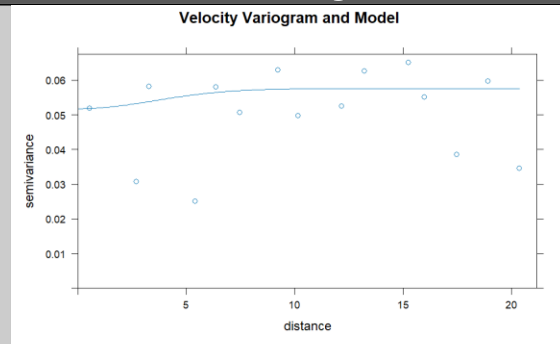
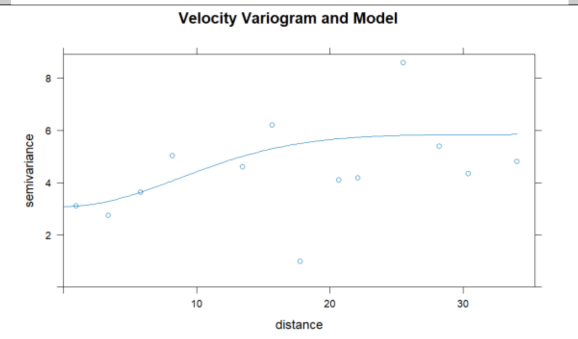
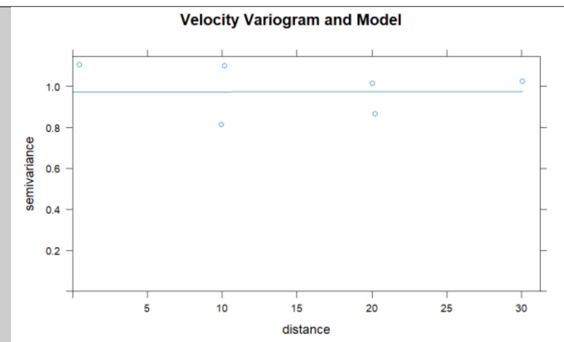
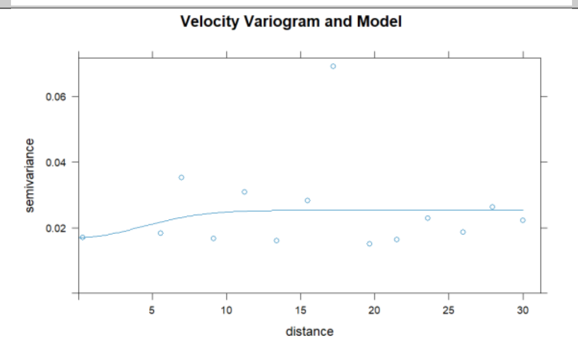
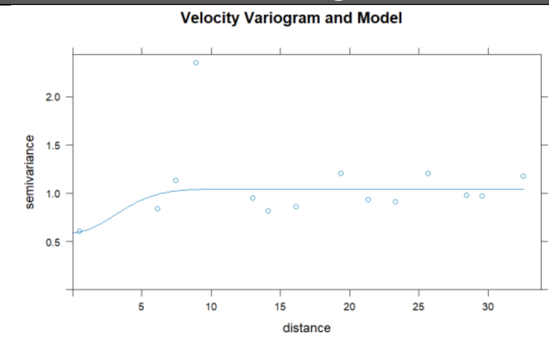
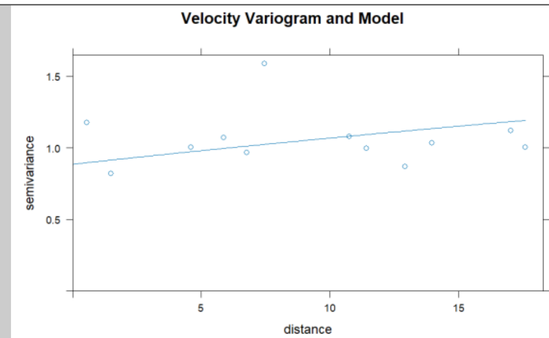
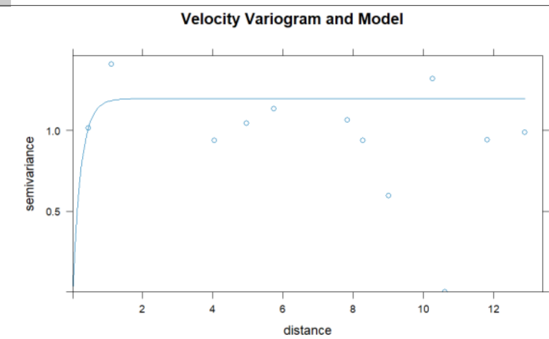
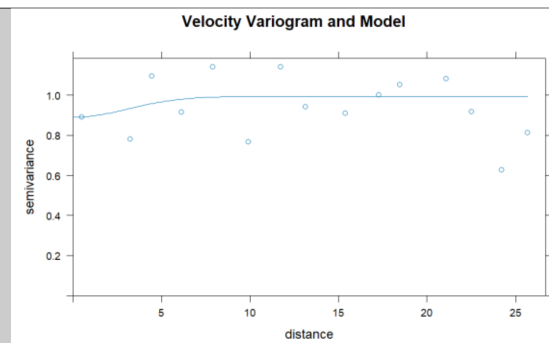
ID	Reach	Kriging Parameters	Variogram
8	Control	Transformation: NONE Partial sill: 0 Range: 3 Nug: 0.008134258 Model: “Exp” Anis: (0, 0.01)	
8	Restored	Transformation: Yeo-Johnson Partial sill: 0.1 Range: 0.5 Nug: 0.9 Model: “Sph” Anis: (0, 0.01)	
9	Control	Transformation: NONE Partial sill: 0.001889012 Range: 9.102855 Nug: 0.004889688 Model: “Exp” Anis: (0, 0.01)	
9	Restored	Transformation: Square root Partial sill: 0.04641732 Range: 1.795937 Nug: 0 Model: “Gau” Anis: (0, 0.01)	

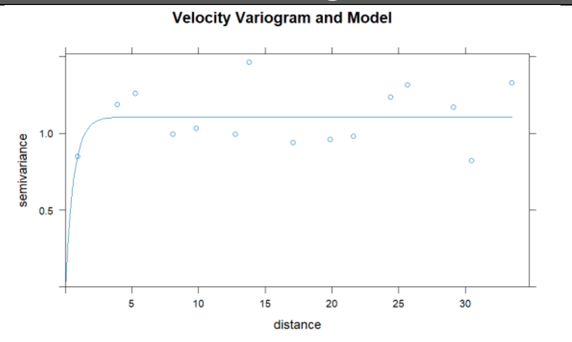
Table 10: Original kriging parameters and variograms for Indicator 1.4 Flow Velocity per reach

ID	Reach	Kriging Parameters	Semivariogram
1	Control	Transformation: Yeo-Johnson Partial sill: 0.1493192 Range: 2.351242 Nug: 1.0475982 Model: “Sph” Anis: (0, 0.01)	
1	Restored	Transformation: Square root Partial sill: 0.03643935 Range: 3.484489 Nug: 0.02194931 Model: “Exp” Anis: (0, 0.01)	
2	Control	Transformation: Log Partial sill: 2.475396 Range: 1.132914 Nug: 4.005905 Model: “Gau” Anis: (0, 0.01)	
2	Restored	Transformation: Square root Partial sill: 0.02903813 Range: 17.31935 Nug: 0.07584297 Model: “Gau” Anis: (0, 0.01)	

ID	Reach	Kriging Parameters	Semivariogram
3	Control	Transformation: Log Partial sill: 0.3109642 Range: 7.140648 Nug: 0.3704539 Model: “Exp” Anis: (0, 0.01)	
3	Restored	Transformation: Yeo-Johnson Partial sill: 0.7384227 Range: 16.00273 Nug: 0.3311660 Model: “Sph” Anis: (0, 0.01)	
4	Control	Transformation: NONE Partial sill: 0.01464993 Range: 1.239632 Nug: 0.05945923 Model: “Ste” Anis: (0, 0.01)	
4	Restored	Transformation: Square root Partial sill: 0.01648901 Range: 5.016336 Nug: 0.05436587 Model: “Gau” Anis: (0, 0.01)	

ID	Reach	Kriging Parameters	Semivariogram
5	Control	Transformation: Square root Partial sill: 0.005815032 Range: 4.985842 Nug: 0.051749945 Model: “Gau” Anis: (0, 0.01)	
5	Restored	Transformation: Log Partial sill: 2.759637 Range: 12.34227 Nug: 3.085595 Model: “Gau” Anis: (0, 0.01)	
6	Control	Transformation: Yeo-Johnson Partial sill: 0.003144731 Range: 11.71943 Nug: 0.971439915 Model: “Exp” Anis: (0, 0.01)	
6	Restored	Transformation: NONE Partial sill: 0.008276067 Range: 6.017946 Nug: 0.017008821 Model: “Gau” Anis: (0, 0.01)	
7	Control	NONE	NONE – all 0 values

ID	Reach	Kriging Parameters	Semivariogram
7	Restored	Transformation: Yeo-Johnson Partial sill: 0.4504136 Range: 4.26332 Nug: 0.5928824 Model: “Gau” Anis: (0, 0.01)	
8	Control	Transformation: Yeo-Johnson Partial sill: 1.4683333 Range: 75.29348 Nug: 0.8868059 Model: “Exp” Anis: (0, 0.01)	
8	Restored	Transformation: Yeo-Johnson Partial sill: 1.19616 Range: 0.238988 Nug: 0 Model: “Exp” Anis: (0, 0.01)	
9	Control	Transformation: Yeo-Johnson Partial sill: 0.1045455 Range: 4.328845 Nug: 0.8887378 Model: “Gau” Anis: (0, 0.01)	

ID	Reach	Kriging Parameters	Semivariogram
9	Restored	Transformation: Yeo-Johnson Partial sill: 1.106306 Range: 0.6337096 Nug: 0 Model: “Exp” Anis: (0, 0.01)	

After performing ordinary kriging, any transformations applied were reversed before the straightened grid was rejoined to the original grid with x, y coordinates and transformed to raster. The rasters for both water depth and flow velocity were then classified. For flow velocity, the classes were selected based on a habitat suitability raster from the Modular Stepwise Procedure (MSP), a set of methodologies used in Switzerland for monitoring the state of waterbodies, as these classes were used to sample the macroinvertebrates (Plattform Wasserqualität VSA, 2021). The depth classes were chosen based on the master thesis by Leitgeb (2019), who also worked in the river restoration research group at Eawag, meaning these classes were specifically applicable to the project. Both water depth and flow velocity classes are represented in Table 1.

Figure 12 shows an example of the resulting depth and velocity classes after interpolating for a restored reach.

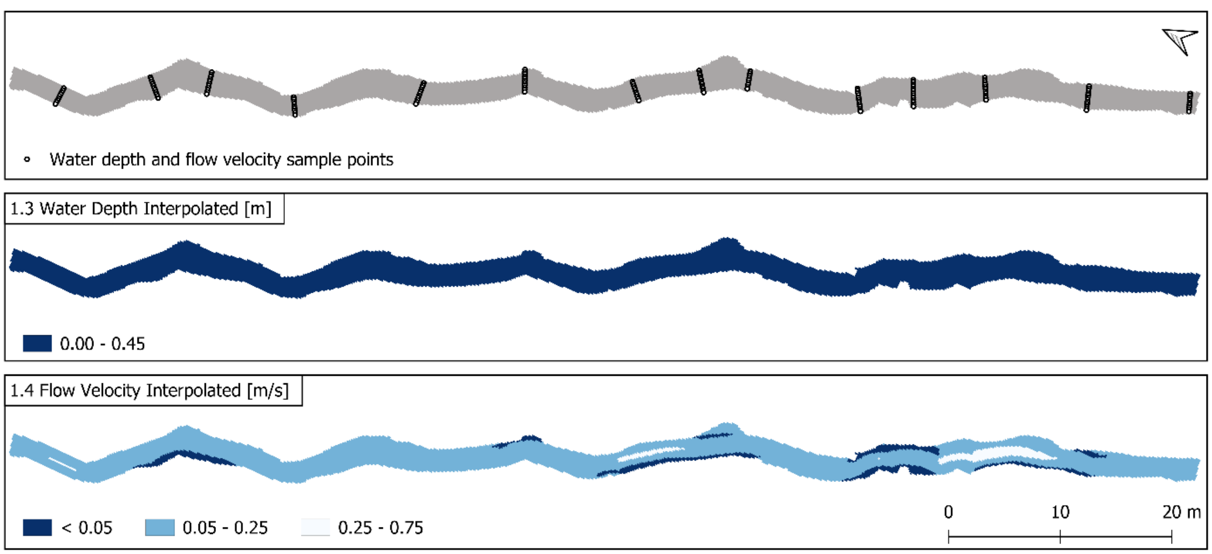


Figure 12: Sample of resulting classes in a restored reach after interpolating water depth and flow velocity from transects

However, comparing these resulting patches to the raw data showed that several classes were not represented anymore after interpolation. The missing classes per layer are shown in Table 11.

Table 11: Missing water depth and flow velocity classes after interpolation per reach

ID	Reach	Transect Points	Missing Depth Classes	Missing Velocity Classes
1	Control	81	2	3
	Restored	144	NA	NA
2	Control	129	2,3	3,4
	Restored	143	3,4,5	NA
3	Control	174	2,3	3
	Restored	307	2,3	3
4	Control	157	NA	1,2,4
	Restored	149	NA	4
5	Control	145	NA	4
	Restored	168	NA	3
6	Control	50	NA	1,2,4
	Restored	78	NA	NA
7	Control	119	NA	3
	Restored	159	NA	4
8	Control	83	NA	3
	Restored	75	NA	3
9	Control	106	NA	1,2,4
	Restored	140	NA	4

4.4 Macroinvertebrate Habitat Suitability Mapping

Since the macroinvertebrate data were collected at spots with various combinations of flow velocities and substrates, I decided it would be interesting to also create a habitat suitability map from the combination of these two layers. The habitat suitability classes from the MSP were used for substrate and flow velocity, where higher values indicate increased suitability for macroinvertebrates (Plattform Wasserqualität VSA, 2021). These classes are shown in Table 1. The original substrate classes from Indicator Set 1 were reclassified to assign an MSP suitability value, which was then added to the class values of the flow velocity layer. The final values could range from 2-15, where higher values represent better suitability. An example of the output is shown in Figure 13.

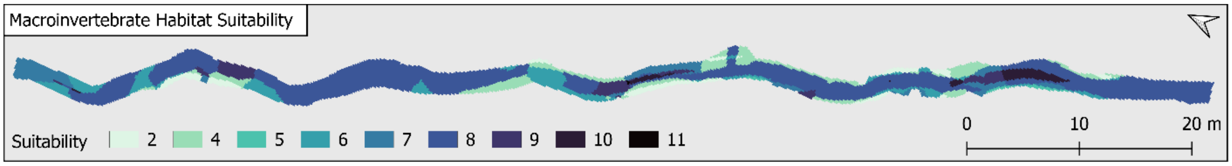


Figure 13: Macroinvertebrate habitat suitability map for a restored reach, with higher values (darker) representing better suitability

5. Calculating Landscape Metrics

The landscape metrics were calculated in R using the *landscapemetrics* package. The R functions and formulas for the selected landscape-level metrics can be found in Table 12, and Table 13 for class-level metrics.

Table 12: Selected landscape-level landscape metrics and their functions and formulas from the *landscapemetrics* package (Hesselbarth, 2025)

Landscape Metric Name	Function	Formula
Interspersion and Juxtaposition Index	lsm_l_iji	$IJI = \frac{-\sum_{i=1}^{m}\sum_{k=i+1}^{m}\left[\left(\frac{e_{ik}}{E}\right) ln\left(\frac{e_{ik}}{E}\right)\right]}{\ln(0.5[m(m-1)])} \times 100$ where e_{ik} represents unique adjacencies of classes, m is the number of classes, and E is the total landscape edge
Patch Density	lsm_l_od	$PD = \frac{N}{A} \times 10000 \times 100$ where N is the number of patches and A is the landscape area in square metres
Edge Density	lsm_l_ed	$ED = \frac{E}{A} \times 10000$ where E is the total edge in m and A is the area of the landscape in square metres
Mean Shape Index	lsm_l_shape_mn	$SHAPE_{MN} = mean\left(SHAPE\left[patch_{ij}\right]\right)$ where SHAPE describes the ratio between the perimeter and area of a patch
Shannon's Diversity Index	lsm_l_shdi	$SHDI = -\sum_{i=!}^{m}(P_i \times lnP_i)$ where P_i is the proportion of the class i

Table 13: Functions and formulas for the selected class-level landscape metrics (Hesselbarth, 2025)

Landscape Metric Name	Function	Formula
Interspersion and Juxtaposition Index	lsm_c_iji	$IJI = \frac{-\sum_{k=1}^{m}\left[\left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}}\right) ln\left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}}\right)\right]}{\ln(m-1)} \times 100$ where e_{ik} represents unique adjacencies of all classes, m is the number of classes
Patch Density	lsm_c_od	$PD = \frac{n_i}{A} \times 10000 \times 100$ where n_i is the number of patches and A is the landscape area in square metres
Edge Density	lsm_c_ed	$ED = \frac{\sum_{K=1}^{m} e_{ik}}{A} \times 10000$ where e_{ik} is the total edge in m and A is the area of the landscape in square metres
Mean Shape Index	lsm_c_shape_mn	$SHAPE_{MN} = mean(SHAPE[patch_{ij}])$ where SHAPE describes the ratio between the perimeter and area of a patch
Percentage of Landscape	lsm_c_pland	$PLAND = \frac{\sum_{j=1}^{n} a_{ij}}{A} \times 100$ where a_{ij} is the area of each patch and A is the area of the entire landscape
Mean Euclidean Nearest Neighbour	lsm_c_enn_mn	$ENN_{MN} = mean(ENN[patch_{ij}])$ where $ENN[patch_{ij}]$ is the Euclidean nearest neighbour distance from each patch from edge to edge

6. Statistics

6.1 Standardising Results

The response ratio (Δr), developed by Osenberg et al. (1997), was calculated to standardise the results, allowing for a better understanding of the differences between control and restored reaches:

$$\Delta r = \ln\left(\frac{\bar{X}_T}{\bar{X}_C}\right)$$

Where $\bar{X}_T$ and $\bar{X}_C$ represent the means of the treatment (restored reach) and control (channelised reach), respectively (Kail et al., 2015). The response ratio has successfully been used as a standardised effect size for restoration outcomes (Kail et al., 2015). An effect size of 0 would indicate no difference between restored and control reaches, while a positive value would mean that there is a higher metric value in restored reaches.

6.2 Determining Statistical Significance

To determine whether any differences between the reaches is statistically significant, a Brunner-Munzel test was used as it is non-parametric and suitable for small sample sizes where the two distributions may have different shapes (Neubert & Brunner, 2007). The significant results are shown in Tables 14 (landscape level) and 15 (class level).

Table 14: Statistically significant Brunner Munzel (BM) Test statistics for landscape-level landscape metrics

Metric	Indicator	BM Statistic	P-value
Edge Density	Riverbed Structures	2.91	0.01139
Mean Shape Index	Riverbed Structures	-2.48	0.02596
Shannon's Diversity Index	Riverbed Structures	3.02	0.00916
Interspersion and Juxtaposition	Presence of Cover	2.67	0.02047
Edge Density	Substrate	2.55	0.02739
Shannon's Diversity Index	Substrate	2.47	0.02779
Mean Shape Index	Substrate	-2.40	0.03141
Mean Shape Index	Habitat Suitability	-3.27	0.00484
Shannon's Diversity Index	Habitat Suitability	3.27	0.00514
Edge Density	Habitat Suitability	3.16	0.00712

Table 15: Statistically significant Brunner Munzel (BM) Test statistics for class-level landscape metrics

Metric	Indicator	Class	BM Statistic	P-value
% of Landscape	Riverbed Structures	Shallows	3.00	0.01994
% of Landscape	Water Depth	0.00-0.45m	-2.53	0.03527
% of Landscape	Presence of Cover	Undercut Banks	-9.19	0.00002
Edge Density	Riverbed Structures	Bar	3.54	0.03249
Edge Density	Riverbed Structures	Glide	2.35	0.03303
Edge Density	Water Depth	0.00-0.45m	2.53	0.03527
Mean Euclidean Nearest Neighbour	Riverbed Structures	Glide	2.67	0.04116
Mean Shape Index	Riverbed Structures	Glide	-2.21	0.04315
Mean Shape Index	Presence of Cover	Overhanging Grass	-2.52	0.02531
Patch Density	Presence of Cover	Undercut Banks	-5.20	0.00063

6.3 Spearman's Correlation with Macroinvertebrate Species Richness

Landscape metric results can suggest improvements in the habitat heterogeneity, and I was interested in finding out if any improvements could also be correlated with an increase in biodiversity. To explore this, a Spearman' rank correlation was used to determine the presence of any correlation between the number of macroinvertebrate species and the landscape-level landscape metrics. This test was chosen as it is non-parametric.

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