Quantifying spatio-temporal changes in hydrological connectivity using historical and contemporary maps

Quantification des changements spatio-temporels de la connectivité hydrologique à l'aide de cartes historiques et contemporaines

Marta Antonelli[1], Victoria Scherelis[2,3], Christine Weber[1]

[1] Department of Surface Waters Research and Management, Swiss Federal Institute of Aquatic Science and Technology (Eawag), Seestrasse 79, CH-6047, Kastanienbaum, Switzerland (e-mail: marta.antonelli@eawag.ch; christine.weber@eawag.ch).
[2,3] Institute of Natural Resource Sciences, Zurich University of Applied Sciences (ZHAW), Grüentalstrasse 14, 8820, Wädenswil, Switzerland, and Department of Geography, University of Zurich (UZH), Winterthurerstrasse 190, 8057, Zurich, Switzerland (e-mail: vscherelis@gmail.com).

RÉSUMÉ

La connectivité hydrologique est une propriété fondamentale des bassins versants, nécessaire au maintien d'écosystèmes d'eau douce sains. Cependant, au cours de l'histoire, la connectivité hydrologique a été largement altérée par des activités humaines telles que le développement urbain et la modification des paysages, ce qui peut avoir des effets durables sur les écosystèmes d'aujourd'hui. C'est pourquoi il est essentiel de comprendre comment les rivières et les paysages ont évolué au fil du temps pour améliorer la conservation et la gestion de l'environnement. Dans cette étude, nous caractérisons et comparons la connectivité passée et présente dans dix bassins versants suisses. Pour ce faire, nous dérivons une série de métriques hydro-morphologiques à partir de cartes historiques (~1880) et contemporaines (~2024) et les utilisons comme indicateurs de la connectivité hydrologique de surface. Les observations préliminaires sur deux des dix bassins versants étudiés montrent des changements considérables dans la quantité et la qualité de la connectivité au sein des bassins versants, soulignant le rôle des activités humaines dans l'influence de la connectivité au sein des bassins versants (par exemple, les pratiques d'irrigation historiques, la mise sous terre, et la canalisation).

ABSTRACT

Hydrological connectivity is a fundamental catchment property, necessary for sustaining healthy freshwater ecosystems. However, throughout history, hydrological connectivity has been extensively altered by human activities such as urban development and landscape modification, which can have long-lasting effects on today's ecosystems. For this reason, understanding how the rivers and landscapes have changed through time is pivotal for improving environmental conservation and management. In this study, we characterise and compare past and present patterns of connectivity within ten Swiss catchments. To achieve this, we derive a series of hydro-morphological metrics from historical (~1880) and contemporary (~2024) maps and use them as proxies of surface hydrological connectivity. Preliminary observations on two of the ten investigated catchments show considerable changes in the quantity and quality of connectivity within the catchments, highlighting the role of human activities in influencing connectivity (e.g., historical irrigation practices, culverting and channelisation).

KEYWORDS

Environmental drivers, historical river network, hydro-morphological metrics, landscape change, large-scale hydrological connectivity

Connectivité hydrologique à grande échelle, évolution des paysages, facteurs environnementaux, métriques hydro-morphologiques, réseau fluvial historique

1 INTRODUCTION

Hydrological connectivity – the "water-mediated transfer of matter, energy, and organisms within or between elements of the hydrological cycle" (Pringle, 2001) – is fundamental for the preservation of the ecological integrity of catchments. The spatio-temporal patterns of hydrological (dis-)connectivity within a catchment determine the resilience of aquatic ecosystems, i.e., their ability to resist and recover from both natural and human-induced disturbances (Wohl, 2017), for instance by facilitating species recolonization or preventing the spread of pollutants. For this reason, many restoration and conservation efforts increasingly focus on maintaining or restoring functional patterns of (dis-)connectivity across sub-catchments. However, in the course of history, the natural patterns of hydrological connectivity have been extensively modified by anthropogenic landscape modification, including urban development, farming, industrialisation, and the construction of dams. This has altered water flow and led to habitat fragmentation and loss (Vörösmarty et al., 2010). Because historical landscape change can exert a long-lasting effect on riverine ecosystems structure and functions, its consideration and integration into freshwater management and research is pivotal to achieve effective restoration and biodiversity conservation (Higgs et al. 2014). For example, past connectivity patterns can serve as a basis for designing and assessing river restoration projects. Additionally, they can help identify relatively undisturbed water bodies and catchments, guiding the prioritization of conservation strategies. In this study, we quantify and compare the historical and contemporary spatial patterns of surface hydrological connectivity across ten Swiss catchments with distinct physical, geographical, and climatic characteristics to understand what drives the change and its ecological implications.

2 METHODOLOGY

Switzerland's Siegfried map (topographic map developed between 1870 and 1926) was employed to delineate and quantify the historical spatial patterns of surface hydrological connectivity in the ten catchments. The swissTLM3D model (topographic landscape model of Switzerland) was used to retrieve the contemporary patterns. The quantification of hydrological connectivity was achieved through the derivation of a set of hydro-morphological metrics to be used as a proxy of longitudinal or lateral connectivity (Table 1). A set of landscape variables (i.e., lithology, topography, and land use and cover) were also calculated and used to explore the landscape drivers of the spatial distribution of surface hydrological connectivity in the past and today (through regression analyses). The derivation of the hydro-morphological metrics and the delineation of the land use and cover variables required the conversion of the hydrological features (e.g., streams, rivers, lakes, and wetlands) and of the landscape features (e.g., forest and buildings) on the Siegfried map into vector format. This was achieved using a machine-learning approach applied to the scanned map. Lithological and topographic variables of the different catchments were extracted from the hydrogeological map of Switzerland and from a digital elevation model (DEM), respectively.

Table 1: Hydro-morphological metrics used as proxies of surface hydrological connectivity and their ecological relevance.

Surface hydrological connectivity	Hydro-morphological metrics	Relevance	
		Hydrological	Ecological
Longitudinal	Drainage density (1/km) [network length per unit area] Confluence density (N/km^2) [number of confluences per unit area] Stream order (maximum and mode; N) [Strahler order]	Physical connection within the catchment, network complexity, confluence effect	Habitat provision and complexity, transport of nutrients and organisms, species dispersion and recolonization
Lateral	Shoreline length (km) and density (1/km) [shoreline length per unit area] Shoreline interface (%) [length of the shoreline which shares a border with different landscape features i.e., forested areas, wetlands, buildings and settlements, grasslands, agricultural fields, and sediment]	Input/ exchange of water and sediment, heterogeneity of the inputs/ exchange	Habitat provision and complexity, heterogeneity of the input/ exchange of nutrients, organisms

3 PRELIMINARY RESULTS AND DISCUSSION

We report here the preliminary results from the spatio-temporal comparison of three metrics of surface hydrological connectivity for two of the ten Swiss catchments in our study: Glatt (located in a pre-Alpine area) and Suhre (located in the Swiss Plateau) (Figure 1).

3.1 Longitudinal surface connectivity

In the left panel of Figure 1, the spatial distribution of drainage density for the historical and contemporary hydrological network is shown. In Glatt, the contemporary pattern of drainage density shows a generally higher longitudinal connectivity in the upper catchment compared to the historical pattern (Figure 1 b). This area is characterised by higher elevation and steeper slopes, inherently more difficult to map in the past. Because of this, we believe that the observed differences can be mostly due to the different quality of the two maps we employed. On the other hand, we do not observe a drastic change of longitudinal connectivity in the lower catchment, where the catchment shows flatter topography and wider valleys. This is the area that has historically been more anthropised and where now reside the largest settlements. In fact, in the lower catchment a considerable fraction of the hydrological network has been nowadays culverted. Despite the longitudinal connectivity being retained, culverting can alter the natural flow of water and disrupt aquatic habitats and hamper species movements (Frankiewicz et al., 2021). In the Suhre catchment, we observe a similar situation concerning the culverting, once again in the areas of the catchment characterised by the wider valleys. However, in this catchment we also observe a dramatic reduction in drainage density in these areas (compare Figure 1 c and d). This is due to the historical presence of “Wässermatten”, a dense network of ditches used for irrigation (see map snippet in Figure 1), which have been now completely drained and mostly replaced by buildings and settlements. These observations can provide important insights into the history of human activity within the catchment and its contemporary legacy (e.g., repercussion on water and soil quality).

3.2 Lateral surface connectivity

The right panel of Figure 1 shows the results from the comparison of the historical and contemporary quantification of shoreline length (upper graph) and shoreline interface (lower graph). In accordance with what was observed before, the total length of the shoreline in the Glatt catchment has increased, while it has decreased in the Suhre catchment. However, in both cases the shoreline of rivers (i.e., flowing water bodies > 5m width) decreased. This seems to be mostly attributable to the straightening of some river sections – especially in the lower Suhre catchment – and to water withdrawal for energy production, especially in some areas of the Glatt catchment (not shown). This leads to a reduction of lateral connectivity concerning the larger water bodies (~ -28% and -42% for Glatt and Suhre, respectively). The proportion of shoreline bordering forested areas has increased in both catchments. The proportion of shoreline bordering grasslands and fields has decreased, while the shoreline bordering buildings has remained practically unchanged or has only slightly increased in the two catchments. We believe this to be the effect of a high proportion of the network flowing in culverts which are mostly located in areas where cultivated fields and settlements are present. These observations can provide information on how lateral connectivity has changed in time in term of quantity and quality.

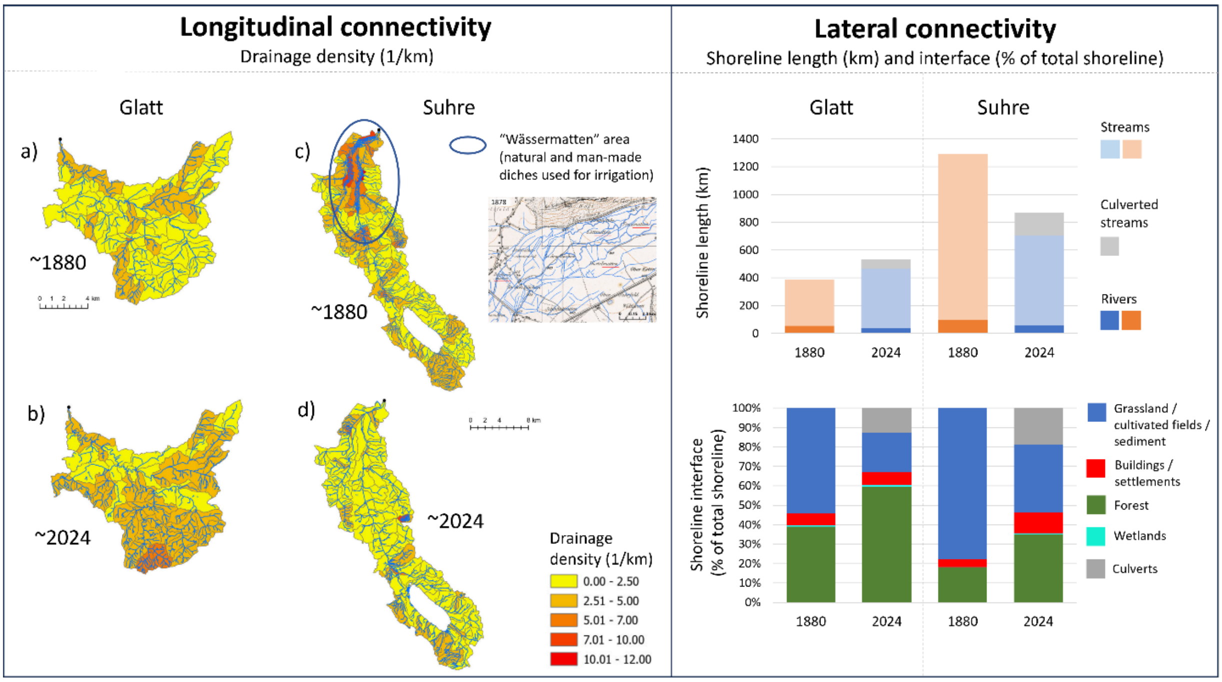

Figure 1: Spatio-temporal comparison for the hydro-morphological metrics of drainage density (left panel) and shoreline length and interface (right panel).

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