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SPECIAL ISSUE PAPER

# Buried and forgotten—The non-fluvial characteristics of postglacial rivers

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## Abstract

"The systematic analysis and understanding of channel-forming processes of rivers must be expanded by including semi- and non-fluvial geomorphological processes. Such processes were particularly driven by glaciation during the Pleistocene and led to diamictic non-fluvial deposits in the post-glacial valleys. In the Holocene, rivers either covered these deposits with fluvial sediments or incised into them and exposed the non-fluvial deposits. These processes have strong and so far overlooked implications for the understanding of the genesis, morphology and sediment composition of many rivers – and thus for river utilization, ecology, restoration and management."

KEYWORDS

channel patterns, instream habitats, landscape evolution, river morphology, sediment regime

## 1 | CONTENT

In this article, we argue that the analysis and understanding of channel-forming processes of rivers must be revised because semi- and non-fluvial processes in postglacial environments have been overlooked. During the glaciation periods of the ice ages, glaciers have shaped the geomorphology of large areas around the world (Esmark, 1824, Ehlers, Gibbard, & Hughes, 2011), particularly along mountain ranges and in arctic and subarctic regions (Figure 1). These processes had decisive effects on valley and river formation. To understand river genesis in such regions, we differentiate the geomorphological process in two phases, a glacial (i) and a postglacial phase (ii).

The glacial phase (i): During the Pleistocene, enormous glaciers burst, scratched, and dug the terranes of the northern and southern Hemispheres, reshaping the surface (Ehlers et al., 2011), with local differences, however, e.g. between "cold-based glaciers" and "warm-based glaciers" moving across the landscape (cf. Hodson & Ferguson, 1999). In the Holocene, ice shields melted and glaciers retreated. Glacial tills, glaciofluvial, and colluvial deposits remained on the valley floors—mainly of diamictitic composition (Figure 2, Olsen, Fredin, & Olesen, 2013). The deposits originated from glacial and colluvial processes. They were not sorted, and they had a wide range of grain-size distribution. Partly, scoured bedrock was exposed. In addition, glaciofluvial deposits may have had sorted sediments within layers but consisted of varying sediment composition between the layers (Corner, Dalrymple, Leckie, & Tillman, 2006). Thus, the initial postglacial valley fills are considered mainly as semi- and non-fluvial sediments (Hauer & Pulg, 2018). They formed the initial stage for river genesis in the glacier-shaped valleys of the world.

The postglacial phase (ii): Below glaciers and after they were gone, rivers reshaped the diamictic sediments of the valleys by fluvial processes (Corner et al., 2006; Gilbert et al., 2017. Hauer & Pulg, 2018). Usually, discharge was significantly higher than today because large amounts of ice were melting. Partly, outburst floods occurred with high potential for erosion and sediment transport. Material was transported along mountain slopes by colluvial processes and further downstream by fluvial processes. In drainages with tectonic orogeny, sedimentary rocks, intense erosion, and high sediment yields, the young rivers became transport limited (iia). The fluvially transported sediments were deposited on top of the non-fluvial valley bottom

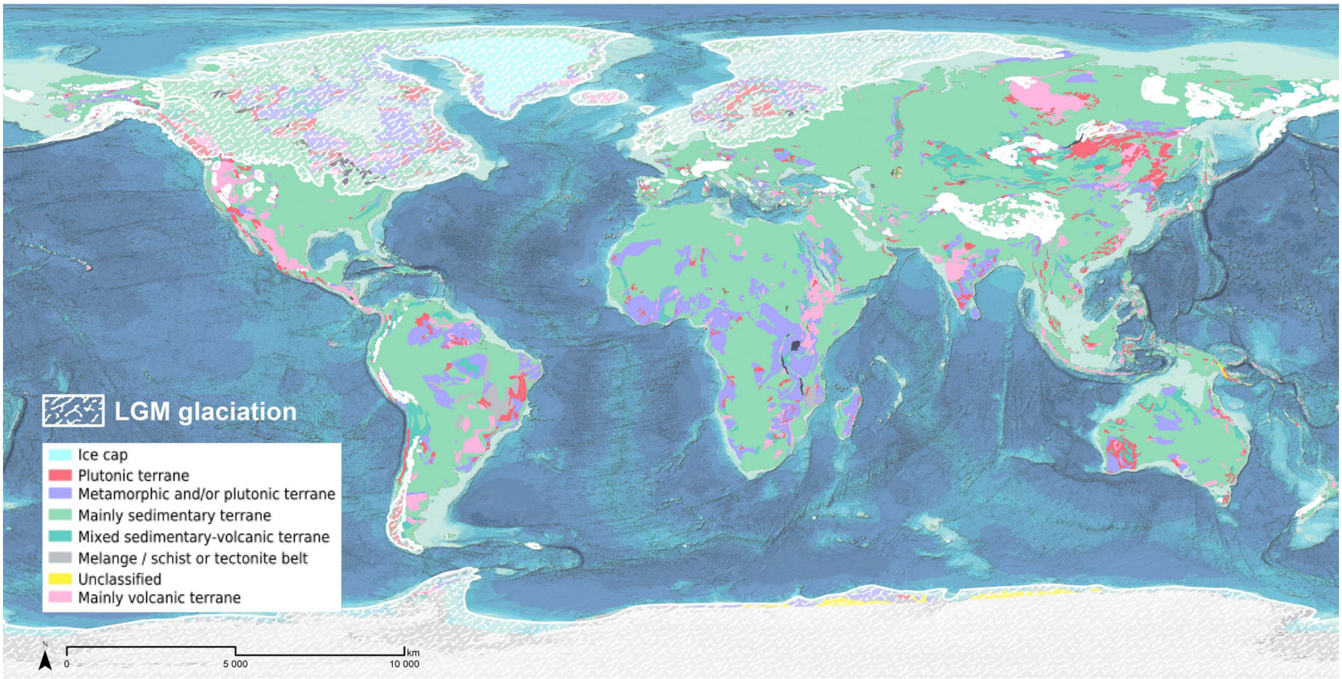


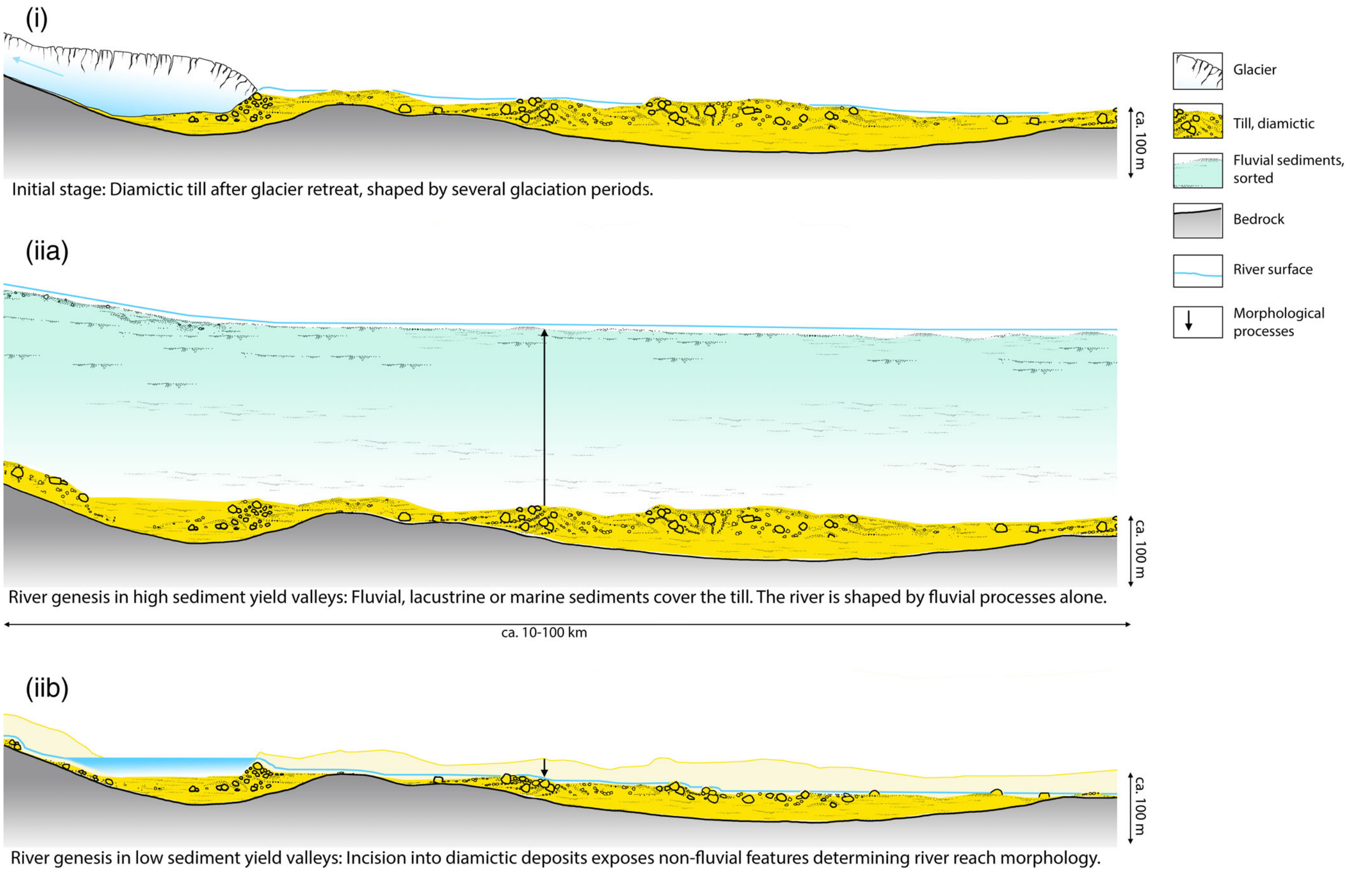
**FIGURE 1** (A) LGM plotted on simplified geologic world map with today's sea level; LGM after Ehlers et al. (2011), provided by https://crc806db.uni-koeln.de/layer/show/6 (accessed November 10th 2019). Geology after United States Geological Survey, provided by https://mrdata.usgs.gov/geology/world/(accessed November 10th 2019). LGM, last glacial maximum [Color figure can be viewed at wileyonlinelibrary.com]

sediments. In such drainages, the valleys were filled to a large extent. The largest deposition happened along major global mountain ranges, such as the Alps, the Himalaya, and the Rocky Mountains, where fluvial sediments in valleys usually reach several hundred metres thickness (Molnar & England, 1990; Preusser, Reitner, & Schlüchter, 2010). However, this did not happen in all parts of the world. Depending on the climate, tectonics, and bedrock conditions, weathering processes and thus sediment yields were limited, for example, on the metamorphic and plutonic terrane of the Scandinavian shield without recent tectonic orogeny. In such areas, initial semi- and non-fluvial deposits from the glaciation phase remained uncovered and exposed on the valley floor. Rivers often became supply limited (iib) and incised into these deposits developing a characteristic of heterogeneous highly diverse morphology with fluvial, semi-, and non-fluvial reaches (Hauer & Pulg, 2018).

Today's understanding of river genesis and river morphology classifications, however, mainly assume an entirely fluvially formed river environment (despite in confined reaches). Apart from that, they do not include non-fluvial sediments explicitly from a process-based point of view (Chin, 1998; Grant, Swanson, & Wolman, 1990; Hauer, 2015; Lisle, 1986; Montgomery & Buffington, 1997; Peterson & Mohanty, 1960; Phillips, 2002; Schumm, 1977; Wohl, 2013; Wohl & Merritt, 2008). State-of-the art analyses of river morphology can be descriptive, leading to the classification and differentiation of various channel patterns, or based on a systematic analysis of channel-forming processes (Kasprak et al., 2016). However, the traditional methods in river research have one thing in common; the fluvial channel configuration is based on an equilibrium status (described as Lane's law, Lane, 1955). Stream channels are considered in equilibrium when the sediment discharge ($Qs$) * sediment particle size ($D_{50}$) ~ streamflow ($Q_w$) * stream slope ($S$).

However, Lane's law (1955), which has become a fundamental principle in river science, is not valid in rivers systems dominated by semi- and non-fluvial sediments. Rivers running through a non-fluvially formed environment have incised mainly due to palaeo-hydraulic flood events ($Q_w$), including extraordinarily high flows due to the rapid meltdown of glaciers (Fairbanks, 1989; Figure 2). During these incision processes, sediments are washed out according to the event-based fluvial tractive forces that lead to the pavement formation of very coarse non-fluvial sediments on the river surface (Figure 2). Another geomorphological process leading to semi- and non-fluvial characteristics in rivers are colluvial rockfall and avalanches, which may not only be distributed in headwater regions but also along lower river sections (Hauer & Pulg, 2018).

Thus, the initial distribution of sediment particles that have not been fluvially transported is decisive for such rivers' genesis and morphology. Morphology and sediment composition do not reflect the event-based stream power (streamflow times the stream slope). Lane's law (1955) is therefore not valid (Figure 2b). In such rivers, neither palaeo-hydraulic approaches are applicable that claim that the largest grain sizes are in line with the hydraulic forces of the largest flood event (Church, 1978). Only if sediment supply ($Q_s$) was higher than transport capacity in the Holocene (depending on the weathering processes, tectonics, and discharge), the non-fluvial patterns were covered by fluvial sediments (iib). In these rivers, the fluvial concepts



(i) Initial stage: Diamictic till after glacier retreat, shaped by several glaciation periods.

(iia) River genesis in high sediment yield valleys: Fluvial, lacustrine or marine sediments cover the till. The river is shaped by fluvial processes alone.

(iib) River genesis in low sediment yield valleys: Incision into diamictic deposits exposes non-fluvial features determining river reach morphology.

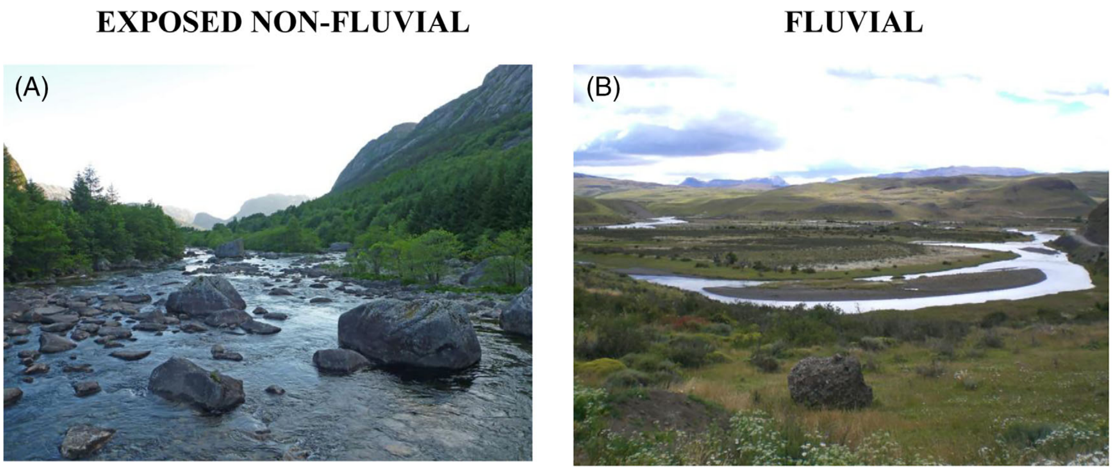
**FIGURE 2** Schematic illustration of the theory on the genesis of rivers in postglacial environments; top: initial stage (i). In the middle: the initial stage of diamictic deposits (yellow coloured) is buried by partially hundreds of metres of fluvially transported sediments (green coloured) (iia), incision of the river into the diamictic deposits after glacier retreat (yellow coloured deposit); (iib) [Color figure can be viewed at wileyonlinelibrary.com]

of river genesis such as Lane's law can be applied. Admittedly, such rivers dominate in the world because sedimentary terrain and tectonic orogeny prevail (Figure 1). Nevertheless, non-fluvial deposits can be found in their valleys, buried under fluvial sediments (Preusser et al., 2010). Yet there are also many rivers still exposing semi- and non-fluvial deposits. Such rivers are described for Norway (Hauer & Pulg, 2018) but are expected in many postglacial regions with supply-limited rivers on metamorphic and plutonic bedrock and little or no recent tectonic orogeny, such as the Eastern Canadian shield, the Scandinavian shield, and Greenland (Figure 1). The understanding of channel formation processes and the systematic analysis of river morphology must therefore be expanded.

Non-fluvial and fluvial river environments can be distinguished by grain size compositions (Figure 3). Specifically, the distributions of the largest particles at and in the riverbed reflect the form of sediment deposition (Hauer & Pulg, 2018). Fluvial-formed stretches contain minor variations in the largest sediments ($D_{max}$) and, frequently, a clear differentiation in grain sizes between the surface and subsurface layers. Non-fluvial channels exhibit a large variation in grain size and the lack of surface–subsurface layer formation. In semi-fluvial reaches such as diamictic plane beds, fluvial deposits can be found on the surface of non-fluvial sediments—a reversal of the traditional fluvial grain size distribution. Here, the grains of the surface layer ($D_{50}$), are finer than those of the non-fluvial ($D_{50}$) subsurface layer, which is the inverse of armouring (cf. Ferdowsi, Ortiz, Houssais, & Jerolmack, 2017).

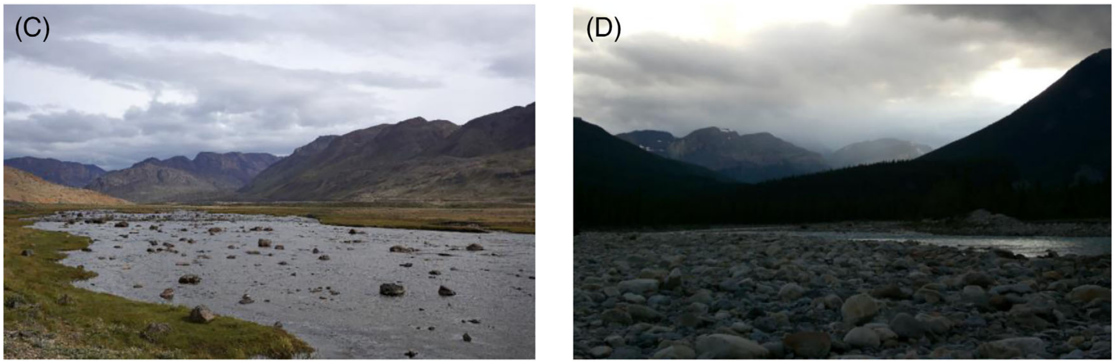
From a management perspective, semi- and non-fluvial river reaches provide different responses in terms of flood impacts and hydrological changes, including the effects of global warming. It is recommended to differentiate between morphodynamic-sensitive and non-sensitive river reaches according to fluvial and non-fluvial characteristics. Whereas non-fluvial reaches such as armoured boulder cascades and diamictic plane beds are relatively stable, fluvial reaches, such as pool-riffle types, are more exposed to discharge-triggered dynamics (Hauer & Pulg, 2018). Such implications have to be considered in a revised river classification system.

Moreover, sediment composition is an elementary habitat feature for aquatic organisms in rivers (Hauer et al., 2018; Pulg, Vollset, & Lennox, 2019; Vannote, Minshall, Cummins, Sedell, & Cushing, 1980). Semi- and non-fluvial river reaches provide characteristic highly diverse sediment compositions that consist of a grain size distribution



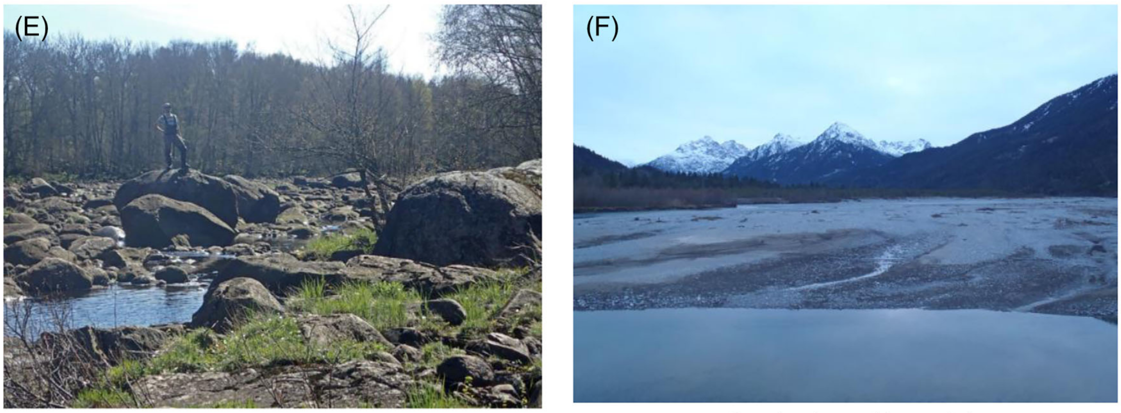
Espedalselva river (Norway)

Bifurcation river – Patagonia (Chile), non-fluvial deposited boulder in picture front



Arnangarngup Kua (Greenland)

Snaring river – Jasper National Park (Canada)



Lagan river (Sweden)

Lech river (Austria)

**FIGURE 3** Comparison of exposed non-fluvial (A,C,E) and fluvial sediments (B,D,F) in different postglacial river landscapes; photo (C) provided by Clemens Ratschan [Color figure can be viewed at wileyonlinelibrary.com]

with a large range and large maximum grain sizes and high shelter availability for fish and invertebrates. Therefore, they are likely to have a strong impact on biological diversity and production, habitat quality, connectivity, and dispersal of fish, invertebrates, and (due to their stability) algae and macrophyte growth. The ecological implications underline the need to adapt existing channel classification approaches to include semi- and non-fluvial characteristics of rivers.

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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