Catena 171 (2018) 83–98

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

The non-fluvial nature of Western Norwegian rivers and the implications for channel patterns and sediment composition

Christoph Hauer[a,*], Ulrich Pulg[b]

[a] CD-Laboratory for Sediment Research and Management, Institute of Water Management, Hydrology and Hydraulic Engineering, Department of Water, Atmosphere and Environment, University of Natural Resources and Life Sciences Vienna, Muthgasse 107, 1190 Wien, Austria

[b] UNI Research Miljø LFI, Laboratorium for Freshwater Ecology and Inland Fisheries, Nygårdsgaten 112, 5006 Bergen, Norway

ARTICLE INFO

Keywords:
River morphology
Channel pattern classification
Sediment dynamics
Glacial deposits
Glacial tills

ABSTRACT

Fluvial processes are considered decisive for the formation of river channel patterns. The concepts of fluvial morphology contain a functional relationship between catchment area, local bed slope and grain size that leads to characteristic channel patterns. In the postglacial landscapes of Western Norway, however, the channel patterns are highly diverse, do not follow the traditional concepts of fluvial models and are distributed seemingly randomly over the river environments. The objective of this study was to investigate whether Western Norwegian rivers have a characteristic morphology determined by non-fluvial features and whether existing fluvial morphology concepts must be supplemented to represent these characteristics. River channel patterns in Western Norway were classified for 53 rivers on the basis of (i) aerial photos, (ii) LiDAR bathymetry data, (iii) sediment sampling, (iv) validation of pre-classified patterns in the field and (v) maps of geologic deposits. Sediment composition was sampled using a novel, modified Wolman–Count method, focusing on the distribution of the largest grains (D_{max}). The results show that Western Norwegian rivers are dominated by glacial and colluvial deposits and partly bed rock. These non-fluvial features determine the longitudinal profile shape, bed slope and channel patterns. The collected data allow the definition of two novel types of channel forms: (i) the 'diamictic plane bed', with a large variation in sediment size, and (ii) the 'mixed riffle-pool type', with pool riffle morphology but boulder elements related to post-glacial or colluvial processes. It is presumed that the characteristic morphology evolved during the Holocene due to riverbed incision and low fluvial sediment yields, which are typical for the region and caused by the lack of dynamic tectonics and by rock resistance to weathering. The results are in contrast to the fluvial channel formation processes observed in many rivers of the world. The study thus contributes to an improved understanding of river morphology and channel pattern formation in a post-glacial landscape. It was concluded that the non-fluvial nature of the rivers studied has significant implications for flood protection measures, hydropower utilization, river ecology and ecological restoration since it determines sediment characteristics and channel stability.

1. Introduction

The classification and analysis of river patterns and processes is essential for understanding river dynamics and genesis (Kellerhals et al., 1976). River morphology patterns reflect the processes that formed them (Kasprak et al., 2016). Various morphological classification systems for natural river systems and channel patterns exist (e.g., Grant et al., 1990; Peterson and Mohanty, 1960; Phillips, 2002; Chin, 1998; Wohl, 2013; Montgomery and Buffington, 1997; Wohl and Merritt, 2008; Keller and Melhorn, 1978; Lisle, 1986; Schumm, 1977; Hauer, 2015). The classification of river patterns at the river basin scale can be performed with respect to the channel evolution over time (Davis, 1899), channel planform (Eaton et al., 2010), flow regime (Hannah et al., 2005) or stream ordering (Strahler, 1952).

To classify river processes, empirical studies that investigate the channel geometry and dynamic response of a river in relation to discharge (e.g. Leopold et al., 1964) and sediment dynamics (e.g. Eaton et al., 2004; Hey and Thorne, 1986) are required. Fundamental for the morphological characterization of rivers is the distinction among (i) alluvial, (ii) bedrock and (iii) semi-alluvial rivers (Kellerhals and Church, 1989). This process-based approach enables predicting channel formation and determining channel-controlling factors. On the river

Abbreviations: LiDAR, light detection and ranging

* Corresponding author.
E-mail addresses: christoph.hauer@boku.ac.at (C. Hauer), ulrich.pulg@uni.no (U. Pulg).

https://doi.org/10.1016/j.catena.2018.06.025
Received 4 October 2017; Received in revised form 14 June 2018; Accepted 25 June 2018

basin and reach scale, the river morphology is mainly controlled by the grain-size of the sediment supply (Friend, 1993) including large anthropogenic sediment sources if present (Langedal, 1997). In Norway, sediment dynamic research primarily addresses suspended load transport, including the transport rates during major flooding (Bogen, 2006), transfer and accumulation processes (Liermann et al., 2012), and the impact of climate change (Bogen, 2008). Bogen (2015) concluded that postglacial sediment yields are usually low ($< 15\,t\,km^{-2}$), despite those catchments still being dominated by sediment supply of active glaciers.

According to Wohl's (2013) criterions river environments in the western part of Norway can be defined as mountain rivers. Studies regarding bed load transport, substrate size and variability in substrate resistance according to stream power are lacking, but they are indeed important agents controlling river morphology (Leopold et al., 1964). In particular, in steep-gradient mountain rivers, sediments and grain size variability are important controlling parameters that determine the turnover rates in river morphology (Phillips, 2002; Ruhiman and Nutter, 1999). However, there are several studies that indirectly approach river morphological aspects in Norway with a focus on the ecological or hydraulic assessment of rivers exhibiting a high variation of substrate and mesohabitat types (Borsányi et al., 2004; Finstad et al., 2007; Barlaup et al., 2008; Fjeldstad et al., 2012)

Beside those general characteristics and studies regarding instream hydraulics and habitat quality, there is a lack of understanding of the genesis of the rivers in Norway during the Holocene. The landscape of Norway was formed mainly by the glacial dynamics of the last ice ages and Holocene neoglacial episodes (Olsen et al., 2013). Typical glacial landforms, such as fjords, U-shaped valleys and moraines, are clearly developed on the west coast of Norway and it was here that the ice ages and their effect on geomorphology were "discovered" (Esmark, 1824; Hestmark, 2017). Due to not only glacial and glacio-fluvial transport but also colluvial rockslides, a large amount of material was transported and deposited during the retreat of the glaciers (Ballantyne and Benn, 1994; Grove, 1972). These processes are likely to affect the morphology of rivers, but this has not been addressed directly in research up to now. Instead, rivers in Western Norwegian valleys are generally described as glacio-fluvial and fluvial landforms (Geological Survey of Norway, NGU, http://geo.ngu.no/kart/geokronologi_mobil/ accessed August, 23rd 2017, Fergus 1997).

The objective of this paper is to contribute to a process-based understanding of the genesis of rivers in landforms shaped by glacial dynamics and postglacial sediment yields. By studying river morphology patterns on the reach scale, typical characteristics of these rivers are compiled. Both understanding the river's genesis and a suitable morphological typology would be important for river basin management (e.g., Hering et al., 2010), designing flood protection (e.g., Nienhuis and Leuven, 2001) and environmental mitigation (Acreman and Ferguson, 2010).

2. Study area

The study is based on data from 53 rivers, 51 located on the west coast of Norway and two in the eastern part (Fig. 1, Table 1). The rivers were chosen since they all are located in landforms shaped by glaciers and have catchments with low postglacial sediment yields. Additionally, these rivers could be studied since they belong to the research group's (Uni Research LFI) monitoring programme, which usually includes conducting Atlantic salmon spawner counts, fish sampling or habitat mapping. All the rivers originate in alpine regions above 800 m a.s.l. and descend to the fjords (0 m a.s.l.) through valleys that were formed by glacial processes in the last ice ages (Olsen et al., 2013). In contrast to many European rivers, the watersheds are not dominated by agricultural (< 10%) or urban land use (< 3%) but rather by forest, alpine tundra and bedrock (> 90%) (Norwegian water authorities, NVE, http://nevina.nve.no). The bedrock consists mainly of Proterozoic granite and gneiss, with minor parts cambrosilurian phyllite and amphibolite (Geological Survey of Norway, NGU, http://geo.ngu.no/kart/geokronologi_mobil/ August 2017). Though some small active glaciers still are present in the region, none of them dominated sediment yields in the rivers included in this study (Fig. 1). The lengths of the rivers range from 8.6 km (Forsandana, Rogaland) to 308 km (Drammensvassdraget, mean for all: 29.6 km, S.D. 16.9 km). The average natural water discharge is $0.7\,m^3\,s^{-1}$ to $314\,m^3\,s^{-1}$ (mean: $25.9\,m^3\,s^{-1}$, S.D. $11.9\,m^3\,s^{-1}$). The natural drainage area ranges from $15\,km^2$ to $17.094\,km^2$ (mean: $200\,km^2$, S.D. $214\,km^2$). 21 of the 53 rivers have been regulated for hydropower use. The main regulation effects are caused by changes in run-off (high head hydropower plants in side-channels or bypass tubes) leading to reduced water discharge and a minor wetted area in parts of the rivers as well as minor changes in size of some drainage areas. Physical alterations (such as bank stabilization and channelization) are usually found in the lower parts of the rivers. However, for the present study, only those parts of the rivers with natural morphology have been considered when classifying the channel pattern. The lower parts of the rivers are inhabited by anadromous Atlantic salmon (*Salmo salar*) and anadromous brown trout (*Salmo trutta*). In addition, three spined sticklebacks (*Gasterosteus aculeatus*) and European eels (*Anguilla anguilla*) can be found. Above the lowest migration barrier, which is usually a waterfall on bedrock, resident brown trout are common; in some lakes, Arctic char (*Salvelinus alpinus*) are also abundant (Borgstrøm and Hansen, 2000).

3. Methods

The morphological assessment of the Norwegian rivers was performed based on two main methodological components: (i) classification of channel patterns and (ii) sediment sampling to characterize the grain size distribution in the various channel forms.

3.1. Channel pattern classification

The morphological assessment of river channel patterns was based on aerial photos (resolution: 0.1–0.5 m; provider: norgeibilder.no) and LiDAR terrain data (measurement 8 points m^{-2}, reduced to 1 point m^{-2}). Aerial photos were used for preliminary analysis according to the classification of various channel patterns (Table 2) on the reach scale. The reach scale was determined for river stretches with a minimum length of 98 m and a maximum length of 691 m (mean = 249 m/S.D. = 130 m), though the morphological pattern could be longer. In a second step, these preliminary results were validated in the field during the period of April–December 2016. Based on the classified and validated channel patterns (morphological types), GIS analyses of the hydrological characteristics of the various river stretches (n = 53) were performed, using a public domain hydrological platform from the Norwegian water authorities (NVE, *http://nevina.nve.no*, Table 1) to extract the (i) global coordinates, (ii) height above sea level, (iii) catchment size (upstream river length to the source), (iv) mean annual precipitation and (v) run-off for the investigated channel patterns at the reach scale. Moreover, based on the high-resolution LiDAR bathymetry (1 point per m^2), longitudinal profiles of the river gradient were extracted in GIS and analysed for the (vi) site-specific bed slope (m/m) for the different channel patterns at the reach scale. The bed slope was computed as the highest minus lowest elevation divided by reach length based on the LiDAR bathymetry data using ESRIs ARC-MAP 10.3.1, 3D-Analyst (functional surface mapping). To classify the sediment sources in the various stretches, the GIS database of the Geological Survey of Norway (NGU, http://geo.ngu.no/kart/losmasse_mobil/ January–June 2017) was used.

3.2. Sediment sampling

Sediment sampling was performed for 17 reaches in 11 rivers