

Critical flows in semi-alluvial channels during extraordinarily high discharges: Implications for flood risk management

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Abstract

For channelized, flood-regulated rivers, morphological changes are avoided as much as possible. Extraordinarily high flows in the past, however, have demonstrated that channelized rivers may also become morphologically active, especially when a discharge exceeds the design discharge, such as in hundred-year floods. However, the morphodynamic potentials and critical flows in such cases have hardly been investigated, and the flood risk to human settlements is therefore poorly understood. The present study aims to analyse the critical flow conditions in Flåmselva, western Norway and the consequences of morphological adjustment on the Froude number from an extraordinary flood event in 2014. Based on a step-backwater modelling approach, three different high-resolution river bathymetries of Flåmselva were investigated: (i) pre-flood, (ii) post-flood and (iii) re-channelized morphology. The results showed that due to the 2014 flood, large parts that were in critical flow conditions in the pre-flood stage (>1), exhibited significantly lower Froude numbers in the post-flood stage. It turned out that the artificially created plane-bed morphologies in flood-regulated channelized rivers can act as drivers for critical flow conditions and that structural as well as non-structural measures should consider non-fluvial, semi-fluvial and fluvial sediment deposits in rivers and floodplains in terms of flood risk management.

KEYWORDS

channel adjustment, flood mitigation, hazard analysis, river basin management

1 | INTRODUCTION

Floods frequently become morphodynamically effective during extraordinarily high flows (Baker, 1977; Fuller, 2008; Kale, 2007; Magilligan et al., 1998; Miller, 1990). Flood-driven occurrences of increasing active channel widths (Hajdukiewicz et al., 2016),

overbank scouring (Harrison et al., 2015) and channel avulsions (Brizga & Finlayson, 1990) have been linked to the thresholds of hydraulic parameters, such as specific stream power (Costa & O'Connor, 1995), bottom shear stress (Carrivick, 2007) and Froude number (Grant, 1997; Hauer & Habersack, 2009). In particular, the latter is of central interest in the present study, as this research

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focuses on the effects of (super)critical flow in a high gradient semi-alluvial river. Erosional features that form in unconsolidated materials, such as alluvial channels, take the form of longitudinal grooves, channel widening and incision, stripped floodplains, anastomosing erosion channels, chute cut-offs, and erosion of impinging tributary fans (Baker, 1977; Hauer & Habersack, 2009; Krapesch et al., 2011; Stewart & La Marche, 1967; Wohl, 2013).

Critical flows are indicated by Froude numbers > 1 and are documented in terms of river steps (Wyrick & Pasternack, 2008), flow contractions (Hauer & Habersack, 2009; Reinauer & Hager, 1998) or at the toes of dam spillways or weirs (Chanson, 2001; Song & Zhou, 1999). The high kinetic energy of supercritical flows (Cartigny et al., 2014) is restricted in length and must be dissipated downstream in the form of hydraulic jumps. Hydraulic jumps occur as rapid transitions from supercritical to subcritical flow (Pagliara et al., 2008; Wyrick & Pasternack, 2008) and are controlled by variations in river bathymetry and/or flow magnitude (Mossa et al., 2003).

Grant (1997) provided a comprehensive overview of the interactions of channel morphology, critical flow and hydraulic jump formation. He presented a hypothesis that in mobile-bed river channels, interactions between channel hydraulics and bed configurations prevent the Froude number from exceeding 1 for longer distances or periods. It has been stated that near-critical flow deforms an initial planar bed into a series of antidunes that are accompanied by in-phase surface waves (Giménez & Govers, 2001; Grant, 1997). Antidunes, however, are rare, but similar scouring mechanisms due to high-roughness elements for other river types (e.g., step pools and riffle pools) were also discussed in Grant's (1997) study.

From a technical, hydraulic engineering point of view, the morphological stability of channelized rivers and reduction in damage to buildings and infrastructure due to prolonged inundation are of central interest (e.g., Rosgen, 2001; Thomson & Townsend, 1979). As long as river cross sections are stable in terms of flood flows (e.g., riprap protection/dike placements), the important aspects of targeted flood management are fulfilled. Recent history, however, has shown that extraordinary flood events in high-gradient, channelized rivers can become morphodynamically active when the design discharge (e.g., hundred-year recurrence interval) is exceeded (Beniston, 2006; Krapesch et al., 2011). Analysing the role of critical flow in such cases was ignored. Thus, there is a missing point of analysis and discussion about the role of engineered channel modifications (e.g., channelization and excavation of high-roughness

elements) on critical flow conditions (Grant's, 1997 thesis).

For natural rivers, there is a poor correspondence between a flood's recurrence interval and its immediate geomorphic effect(s) (e.g., Dury, 1973; Magilligan et al., 1998). Due to this lack of correlation of flood magnitude and morphodynamic effectiveness, flood hazard analysis developed separately from singular flood magnitude analysis as the appropriate metric for considering flow energy, expressed either as shear stress or stream power (Baker & Costa, 1987). This concept was further extended by the implications of the times at which river channels are exposed to certain flow energies that are above the critical value (e.g., stream power) to better explain the driving forces of geomorphic change (Costa & O'Connor, 1995).

The concept of Costa and O'Connor (1995), however, shows one limitation for application in western Norway, as it only addresses alluvial channels over bedrock. In western Norway and in many other postglacial river environments, non-fluvial sediments are exposed on the riverbed surface due to the glacial history of unconfined valleys (Hauer & Pulg, 2018; Hauer & Pulg, 2021) or due to avalanches and rockfall in confined valleys (Church, 2015; Montgomery & Buffington, 1997). These river reaches can be classified as non-fluvial (Hauer & Pulg, 2018) or semi-alluvial rivers (Ashmore & Church, 2001; Church et al., 1989). In addition, portions of the channel patterns that Grant (1997) used in his theory about the interaction of channel roughness elements and critical flow may contain non-fluvial elements (e.g., in step-pool systems). Thus, what is also missing in flood risk management is an adaptation of the Costa & O'Connor concept to those semi-alluvial or non-fluvial characteristics that involve hydraulic resistance and stability.

The aims of the study were (i) to investigate the role and interaction of a channelized, high-gradient, semi-alluvial river and the critical flow regime during an extraordinary flood event accompanied by an analysis of the morphological adjustments of the channel due to the flood. Focus is given to the systematic documentation of changes in flow velocity and Froude number in relation to the morphological adjustment of the river and (ii) to discuss and conceptually adapt the model of Costa and O'Connor (1995) for the semi-alluvial and non-fluvial river systems in western Norway.

The study was conducted at the Flåmselva River (western Norway), which was impacted by a well-documented, extraordinary, channel-forming flood in 2014 (Figure 1). To examine the stated objectives, high-resolution digital elevation models (DTMs) for the pre- and post-flood situations were used in combination with step-backwater modelling for analysing flood hydraulics.



(a)



(b)

FIGURE 1 Morphological adjustment of the Flåmselva/Norway due to the autumn flood in 2014; (a) floodplain stripping and building erosion (downstream view) (N60_5004500/E7_0700200), (b) overbank scouring and channel widening (downstream view) (N60_5001300/E7_0701700). (a) Foto: Tore Meek/NTB, (b) Foto: Helge Mikalsen/VG.

2 | STUDY REACH

The Flåmselva River (hereafter named ‘Flåmselva’) is a mountain river that is located on the western coast of Norway (E07°26′71″/N67°73′48″) (Figure 2). It is 52 km long with a drainage area of 282 km². Its mean annual flow is 17.2 m³s⁻¹ (1961–1990). The river enters the sea at Aurlandsfjorden, which is a part of the Sognefjorden. Ninety percent of the drainage is located between 765 m and 1764 m a.s.l. Seventy-five percent of the drainage surface is covered by rock and tundra, 13% by forest, 4% by lakes, 3% by glaciers, 0.5% by marshland and 0.4% by irrigated land. Human settlements (< 0.1% of catchment area) are concentrated along the lowest 4.8 km of the river. The average riverbed slope of the given reach is 0.0069 (data are from nevina.nve.no, accessed September 8th, 2020). The bedrock of the river drainage consists mainly of gneiss, phyllite, and Proterozoic granites (www.ngu.no, accessed 08.09.2020).

Recent tectonic dynamics are lacking, and glacial geomorphology has led to scoured bedrock valleys with low sediment supplies and fluvial, semi-fluvial and non-fluvial river reaches (Hauer & Pulg, 2018). As many rivers of western Norway, Flåmselva exhibits high morphological variation (Hauer & Pulg, 2021) without a certain sequence of gradients and morphology, as has been described for fluvial rivers (Knighton, 1998; Vannote et al., 1980).

2.1 | River hydrology

From source to sea, Flåmselva exhibits fluvial (pool-riffle reaches), semi-fluvial (diamictic plane bed reaches) and non-fluvial (cascades) characteristics. The investigated part (0–4.8 km from the mouth) consists of a semi-alluvial reach in the upper part. This includes a confined cascade in a canyon and diamictic plane bed with grain sizes between 1 and 5000 mm (4–3 km, compare to Hauer & Pulg, 2018). The downstream part exhibits mainly fluvial characteristics, such as sorted material and channel-forming sediments with sizes in the range of 1–50 mm. The pre-flood morphology exhibited continuous bank protection measures by coarse riprap along the entire study reach. In principle, the channel modification of the Flåmselva had a long history and started already with the land use activities of farmers in the valley. Technical measures by NVE (Norwegian Water and Energy Directorate) data were recorded from 1971 on. On October 28–30th 2014, a flood occurred in the Flåmselva that eroded buildings and infrastructure and led to significant morphodynamic changes along the lower 4.8 km of the river (Figure 1). Holmquist (2015) reported an instantaneous peak discharge of 247 m³s⁻¹ and maximum daily average discharge of 162 m³s⁻¹ (Figure 3). Due to this large event, the recurrence intervals and hydrological statistics had to be adjusted. These modelled flood magnitudes and recurrence periods (including the 2014 data in the statistics) are presented in Table 1 for Brekke Bru, which was the location of the gauging station until 2014 and was 2.3 km upstream of the river mouth (modelled by Holmquist, 2015 based on the official Norwegian flood guidelines Midttømme et al., 2011). Q_M is the average of the largest discharges per year over a period (1939–2014). Q_5-1000 represents the recurrence indices (number = years). NVE supplements the risk analysis with a flat 40% addition to include the risk of higher future discharges due to climate change. The 200-year reoccurrence flood is thus estimated to be 290 m³s⁻¹ and 350 m³s⁻¹ under the 20% climate scenario and 400 m³s⁻¹ under the 40% climate scenario (Table 1). After the catastrophic flood in 2014 the channel was re-regulated,

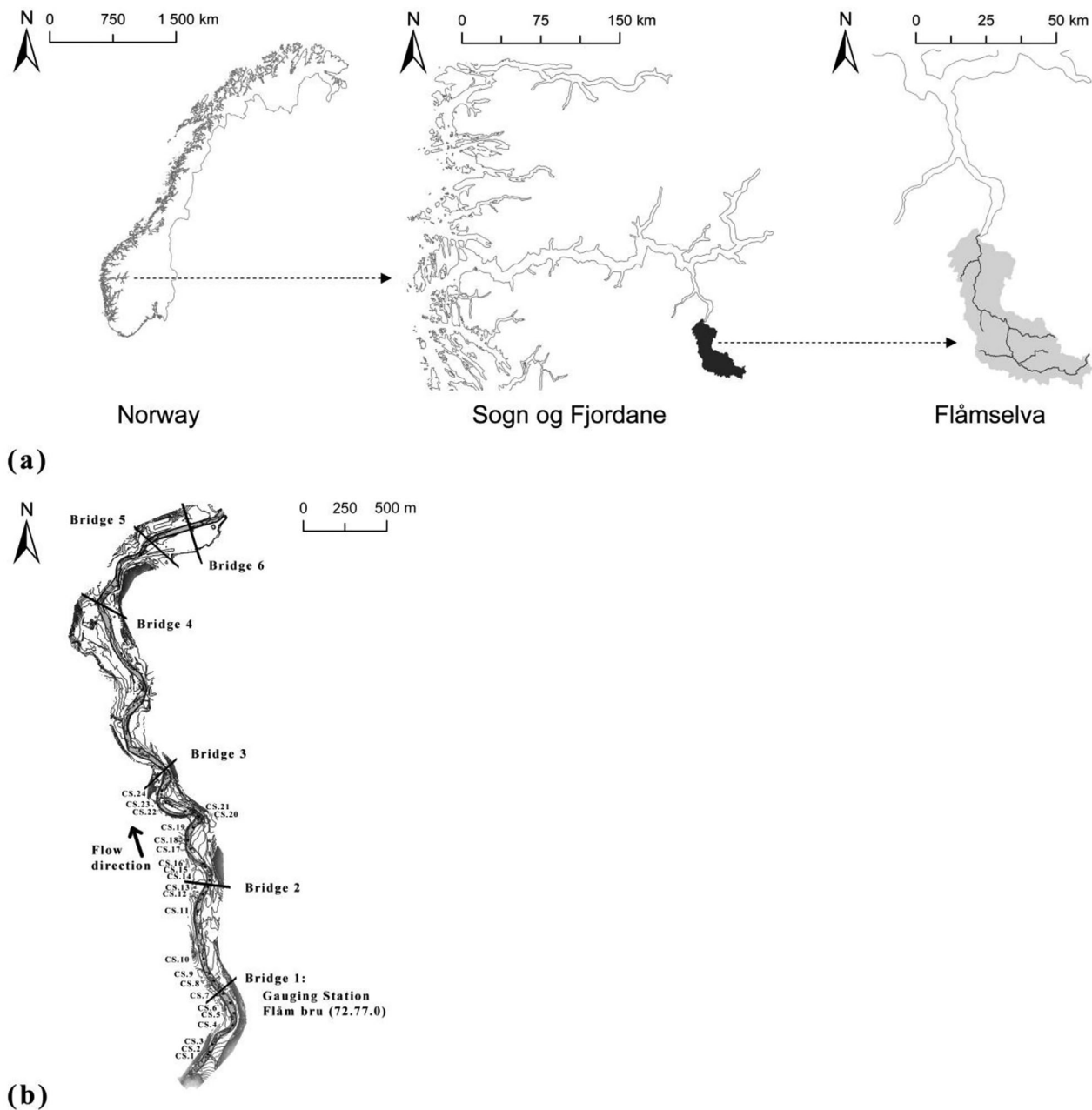


FIGURE 2 (a) Norway with the study area highlighted, (b) high resolution digital elevation model (DTM) of the Flåmselva with its floodplains until the valley margins including bridges and sites for calibrations indicated by C.S; DTM data are based on Airborne Lidar Bathymetry (ALB) in 2018

partially along the former artificial banks and partially along a new course (compare Figures 1 and 5).

3 | METHODS

The presentation of methods follows two main objectives: (i) Description of the applied approach for modelling flood forces and of the impact assessment of the documented river adjustment; and (ii) extension of the

conceptual Costa & O'Connor model for semi-alluvial rivers in western Norway.

3.1 | Hydrodynamic-numerical modelling of flood forces

The bathymetric boundaries for setting up the one-dimensional (1D) step-backwater hydrodynamic-numerical modelling were sampled in July 2014 (pre-

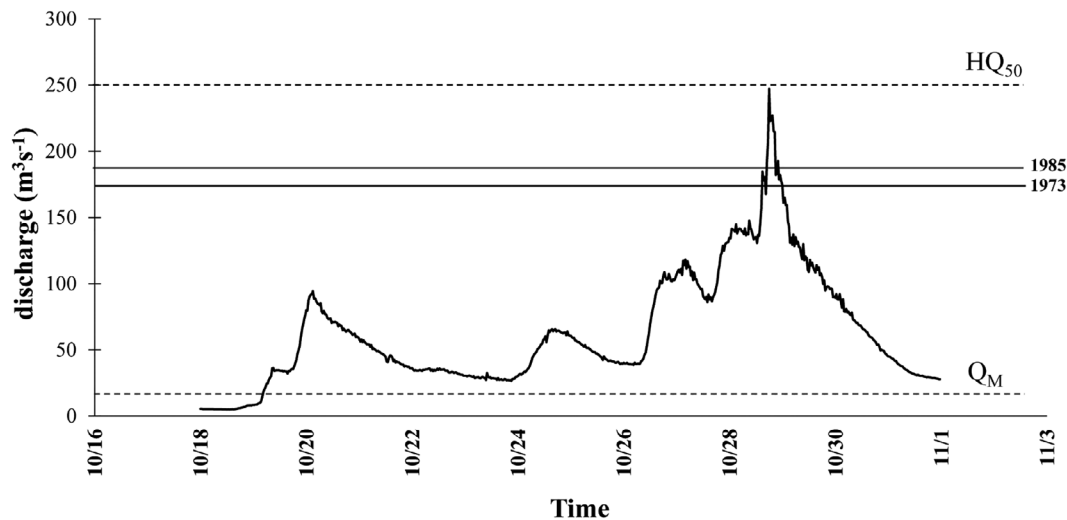


FIGURE 3 Hydrograph of the flood event at the Flåmselva in 2014; dashed lines indicating characteristic discharges of the mean-flow (Q_M) and the 50-Years flood magnitude (HQ_{50}) corrected by including the 2014 flood into hydrological statistics; solid lines indicate flood discharges of past events

TABLE 1 Hydrological characteristics for the study reach (gauging station Brekke Bro). Recurrence intervals were calculated by including the maximum discharge of the 2014 flood

	Areal km^{-2}	Q_M m^3s^{-1}	Q_5 m^3s^{-1}	Q_{10} m^3s^{-1}	Q_{20} m^3s^{-1}	Q_{50} m^3s^{-1}	Q_{100} m^3s^{-1}	Q_{200} m^3s^{-1}	Q_{500} m^3s^{-1}
72.5 Brekke bru	268.2	137	165	185	210	240	260	290	330
Climate + 20%	268.2	160	200	220	250	290	310	350	390
Climate + 40%	268.2	190	230	260	290	330	370	400	460

Note: Q_x = flood magnitude with a recurrence interval of x -years.

flood), November 2014 (post-flood) and October 2018 (implementation of river training measures). The bathymetries of the river and floodplains were derived by infrared light detection and ranging (LiDAR) accompanied by cross-sectional measurements (July 2014 and November 2014) and airborne LiDAR bathymetry (ALB) obtained in October 2018. The length of the studied reach is 4875 m from the upstream boundary at Leinarfoss (N60°49'55"/E7°07'04") to the river mouth at Aurlandsfjord (N60°51'54"/E07°07'11"). The lateral bathymetric boundaries were extended to the valley margins (Figure 2) and contained exactly the same total area of 1,033,221.60 m^2 for all applied bathymetries (number of elements = 436,178 and number of nodes = 369,389). To establish the cross-sectional-based step-backwater models, the ArcGIS® application HecGeoRas® was used (Baumann & Halaseh, 2011; Merwade, 2010). A total of 251 cross sections were extracted from the bathymetry data ($n = 3$) with varying cross-sectional lengths (e.g., 63.3 m–494.8 m; S. D. = 94.1 m) to cover the largest-ever recorded flood of 2014 ($Q = 247 \text{ m}^3\text{s}^{-1}$). Geographic Information Systems (GIS)-referenced cross

sections were used to map the (partly) variable height information (z -coordinates) for the different bathymetries (e.g., pre-flood, post-flood and channelized). Thus, it was possible to directly compare the potential changes in flood forces due to channel adjustments, namely, (i) natural changes due to the 2014 flood and (ii) anthropogenic changes due to the implementation of river regulation and bank protection measures in 2018. Flood forces were determined by the cross-sectional flow velocity and cross-sectional Froude number.

The primary procedure used by HEC-RAS to compute water surface profiles assumes a steady, gradually varied flow scenario, and is called the direct step method. The basic computational procedure is based on an iterative solution of the energy equation, which states that the total energy at any given location along the stream is the sum of potential energy and kinetic energy. The applied HEC-RAS can calculate both, sub-critical and supercritical flow conditions including the formation of hydraulic jumps. Thus, three approaches are given which can be selected by the software user; subcritical (direct step computations begin at the downstream end), supercritical

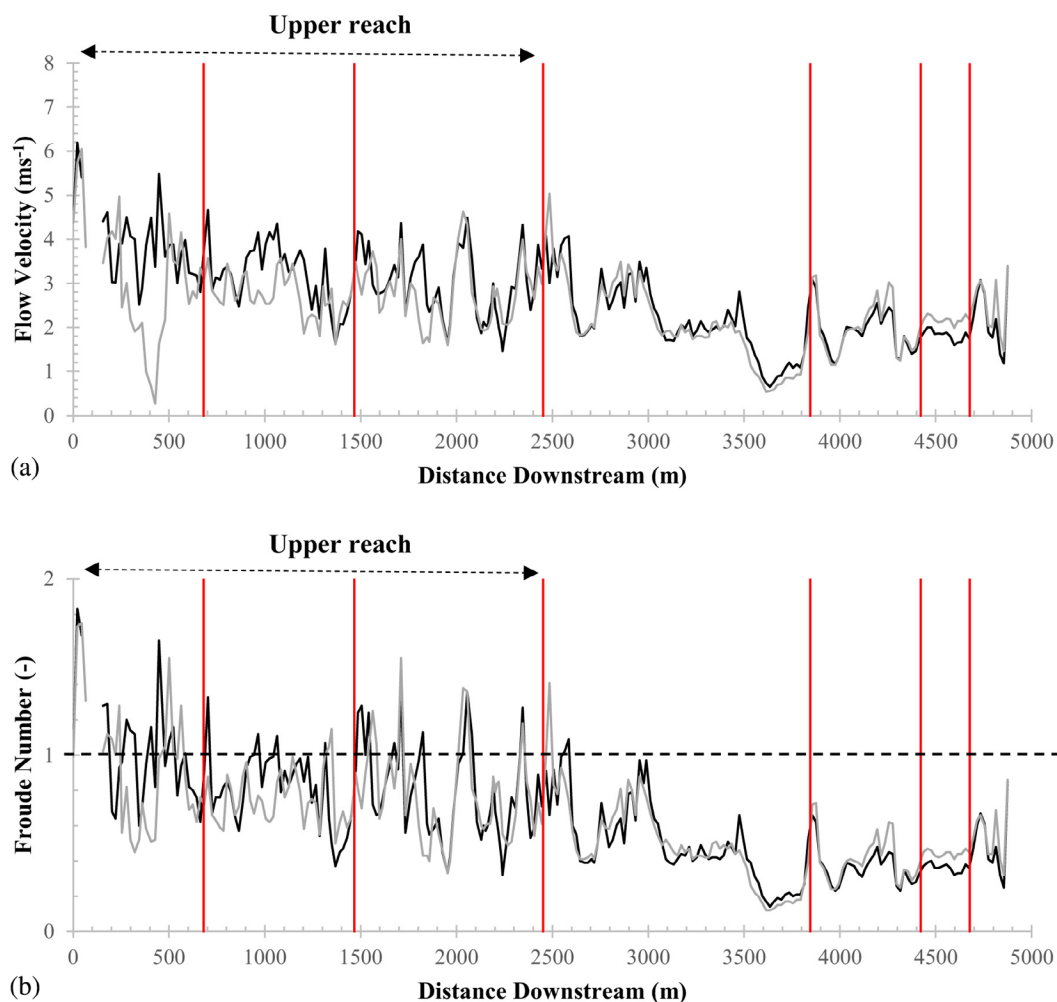


FIGURE 4 Longitudinal profile of (a) 1-D flow velocity and (b) Froude number calculated by step-backwater modelling for $247 \text{ m}^3 \text{ s}^{-1}$ (discharge of October 2014 flood); black solid line = modelling results for the bathymetry June 2014; grey solid line = modelling results for the bathymetry November 2014; red vertical lines are indicating the location of bridges

(computations begin at the upstream end and proceed downstream) and mixed flow regime (www.hec.usace.army.mil/confluence/rasdocs/rasum/latest/advanced-features-for-unsteady-flow-routing/mixed-flow-regime). The analysis was performed in a three-step procedure: (i) for the entire upper part to a downstream distance of 2500 m (for details see Figure 4); (ii) for all cross sections, kinetic energy reductions were documented; and (iii) for those cross sections only, where a transition from supercritical flow to subcritical flow was calculated due to the morphological adjustments. Manning roughness value ($\text{s}^{-1} \text{ m}^{1/3}$) was calibrated for the main channel with $n = 0.033$ by comparing water/land marks during peak flow discharge using the post-flood river bathymetry (see supplementing materials) and varied according to the field-mapped land uses in the overbank areas. Sensitivity testing of the variable main channel roughness on flow velocity and Froude number was

implemented in the study, and are here provided as supplementary material.

3.2 | Adjustment of the Costa and O'Connor concept

The adjustment of the Costa and O'Connor concept was based on the dataset of Hauer and Pulg (2018), in which river-channel patterns in Norway were classified for 53 rivers by (i) aerial pictures, (ii) LiDAR bathymetry data, (iii) sediment sampling, (iv) validation of pre-classified patterns in the field and (v) maps of geological deposits. The dataset was re-evaluated regarding the specific aspects of morphological adjustments in terms of extraordinarily high flows. These specific aspects were (i) erosional width and (ii) substrate composition. For the erosional width, the term 'corridor' was introduced to

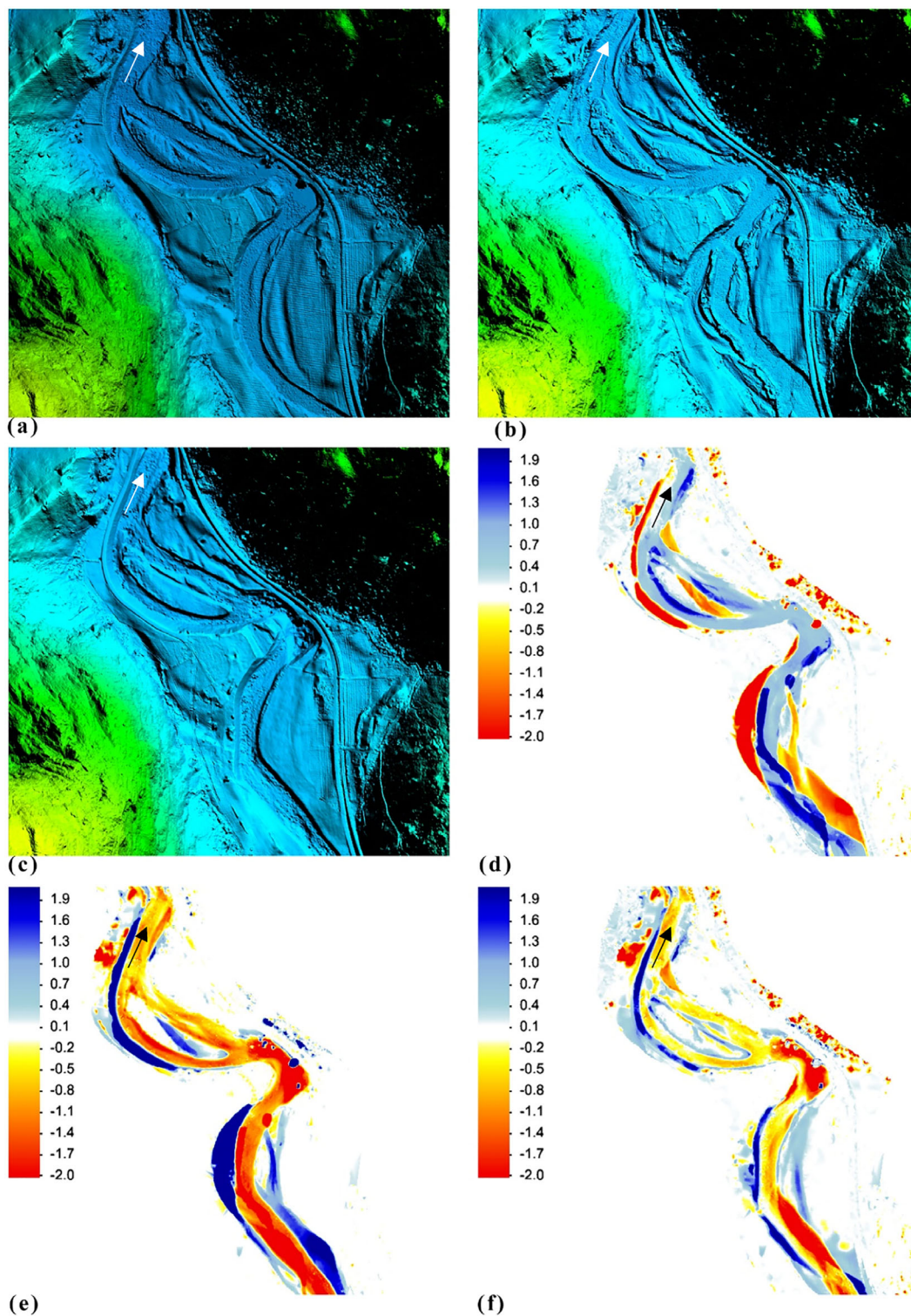


FIGURE 5 Relief shading of a specific section of the Flåmselva of channel adjustment during the 2014 flood (N60° 50' 52"/E7° 06' 55"), bathymetry data are presented for (a) September 2014, (b) November 2014 and (c) 2018. Difference plots of the elevation models: (d) 2014 (pre-flood) compared to 2014 (post-flood); (e) 2018 compared to 2014 (pre-flood); and (f) 2018 compared to 2014 (post-flood)

reflect the morphodynamically active zone. Within this 'erosional corridor', the factors of selective transport (compare to Pender et al., 2001; Gibbins et al., 2007) and geomorphic change (compare to Baker, 1977;

Fuller, 2008; Magilligan et al., 1998; Miller, 1990; Kale, 2007) were implemented into the Costa & O'Connor concept. In particular, the largest grain sizes (D_{max}) and substrate heterogeneity were addressed in the

conceptual approach, as the largest (exposed) grains deposited reflect the maximum flood forces (Sugai, 1993).

3.3 | Statistics

Statistical testing of significant differences ($p < 0.05$ level) in the mean cross-sectional averaged flow velocities and Froude numbers was applied between the various river bathymetries using a paired t -test for two independent samples. Testing for normal distributions was applied using the Shapiro–Wilk normality test (Shapiro & Wilk, 1965) and was combined with testing for homogeneity of variances using Levene's test (Levene, 1960).

4 | RESULTS

The results are presented based on the two given research aims. Figure 4 presents the longitudinal profiles of flow velocity and Froude number for the bathymetries in the pre-flood stage (June 2014) and post-flood stage (November 2014). The results demonstrate that due to the changes in cross-sectional characteristics, both flow velocity (ms^{-1}) and Froude number (–) mainly decreased after the flood event. The results highlight that in the sections that became morphodynamically active during the 2014 flood, the Froude number was reduced to below 1. The changes in cross-sectional bathymetry are presented in a planimetric view in Figure 5 and show overbank scouring, side erosion and partial channel avulsion in the selected stretch of the Flamseleva. In particular, the upper part of the studied river became morphodynamically active. In total, 70 cross-sections that experienced channel adjustments due to the 2014 flood ($Q = 247 \text{ m}^3\text{s}^{-1}$) were identified, which had a follow-up reduction in kinetic energy. In Figure 6 and Table 2, the comparative statistics of those changes in the Froude number are presented.

The variations in Froude numbers for all cross sections down to river station 2500 are presented in Figure 6a. Comparing the distribution of the calculated Froude numbers for those specific transects, non-significant differences were detected when comparing the pre- and post-flood stages ($p = 0.093$), as well as the post-flood stage and channelized bathymetry from 2018 ($p = 0.993$) (Table 2). In Figure 4b, only those cross-sections ($n = 70$) from the upper reach are presented, that exhibited a reduction in Froude number due to the adjustments of river bathymetry by the 2014 flood flow. Here, significant differences ($p < 0.05$) between the distributions of Froude numbers were calculated for both the pre- and post-flood cases ($p < 0.001$), as well as the post-flood and

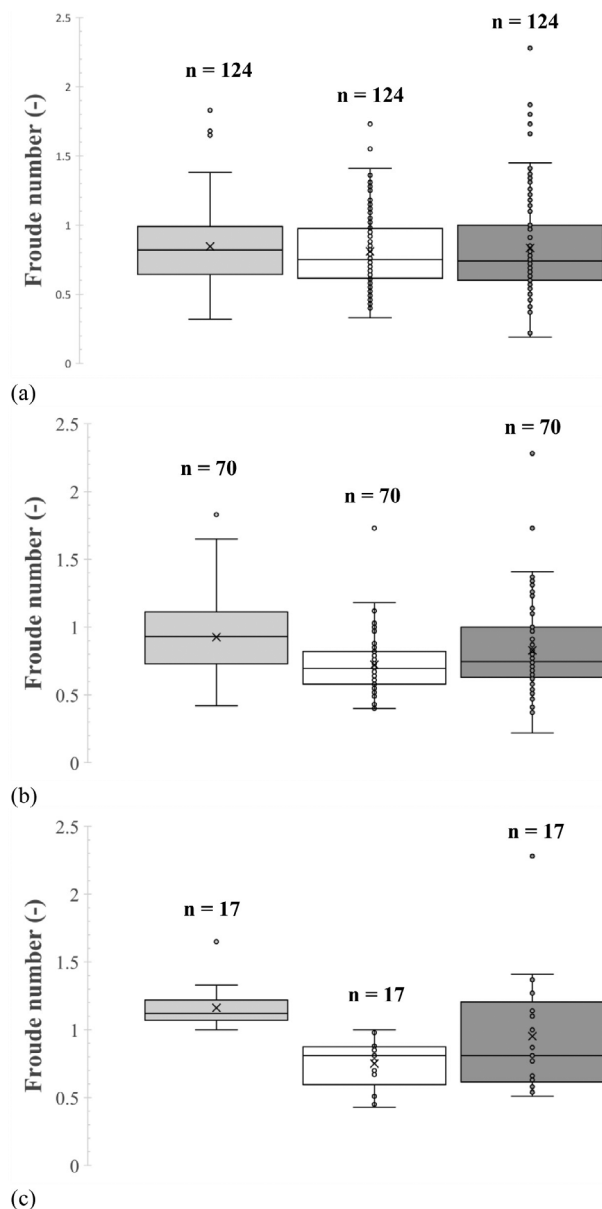


FIGURE 6 Box-plots of the cross sectional Froude numbers for (a) upper reach to downstream station 2500, (b) cross sections where a reduction in the Froude number was calculated based on the morphological adjustments by the 2014 flood, (c) cross sections which turned from a supercritical to a sub-critical flow regime; light grey = pre-flood data 2014; white = post flood data 2014; dark grey = data from 2018

the post-channelized cases (Table 2). The third comparative analysis addresses the statistical testing of those cross sections ($n = 17$) where the calculated Froude number dropped from a supercritical ($Fr > 1$) to subcritical flow regime ($Fr < 1$) due to the morphological adjustments. The analysis showed significant differences between the pre-flood and post-flood Froude numbers ($p < 0.001$) and non-significant differences for the post-flood and post flood channelized bathymetry ($p = 0.086$) (Table 2).

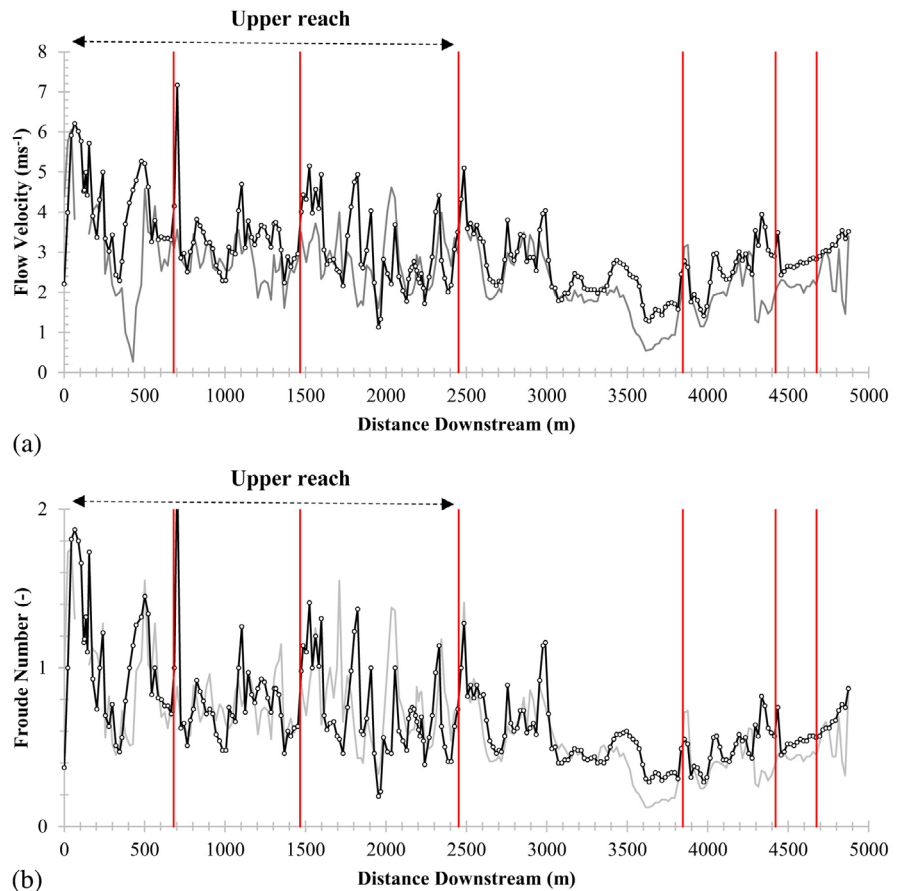
TABLE 2 Paired samples *t*-tests for the calculated Froude number using the different bathymetries of the Flåmselva ($n = 3$); – for distribution of values compare to Figure 6

		Mean	<i>t</i>	df	Sig. (2-tailed)
(1)	Froude_pre_flood – Froude_post_flood	0.03944	1.694	123	0.093
	Froude_post_flood – Froude_channelized	0.00024	0.008	124	0.993
	Froude_pre_flood – Froude_channelized	0.04419	1.673	123	0.097
(2)	Froude_pre_flood – Froude_post_flood	0.20329	9.137	69	0.000
	Froude_post_flood – Froude_channelized	–0.1061	–2.678	69	0.009
	Froude_pre_flood – Froude_channelized	0.09714	2.613	69	0.011
(3)	Froude_pre_flood – Froude_post_flood	0.41000	8.068	16	0.000
	Froude_post_flood – Froude_channelized	–0.2011	–1.828	16	0.086
	Froude_pre_flood – Froude_channelized	0.20882	2.109	16	0.051

Note: (1) all cross sections for the upstream reach ($n = 124$), (2) all cross sections where a reduction in the kinetic energy was calculated ($n = 70$), (3) all cross sections where a shift from (super-)critical to subcritical flow occurred ($n = 17$).

FIGURE 7 Longitudinal profile of

(a) 1-D flow velocity and (b) Froude number calculated by step-backwater modelling for $247 \text{ m}^3\text{s}^{-1}$ (discharge of October 2014 flood); grey solid line = modelling results for the bathymetry November 2014; black solid line with white dots = modelling results for the bathymetry in 2018 (re-channelization); red vertical lines are indicating the location of bridges



The results of the hydraulic changes due to the post-flood hydraulic engineering measures are presented in Figures 6a–c and 7. Obviously, river re-channelization once again caused an increase in kinetic energy for the selected flood discharge as represented by the magnitudes of flow velocity and Froude number. The channel bathymetry was adjusted to the pre-flood stage to a large

extent, especially for the flood-impacted river stretch. However, the discharge capacity also increased on a lower bankfull width by engineered channel adjustment, which led to even higher flow velocities compared to the modelling results using the pre-flood stage. Thus, the results demonstrate that even though the floodplain inundation aspect was considered in terms of the 2018

flood risk management (increasing discharge capacity), due to re-channelization, the future risk of a similar uncontrolled overbank scouring by critical flows, however, is still present for Flåmselva.

Concerning the second aim of the paper, for testing the Costa and O'Connor concept for the semi-alluvial and partially non-fluvial rivers of western Norway or exposed glacial deposits worldwide (compare to Hauer & Pulg, 2021), Figure 8 shows the results of the proposed concept extension. Based on the six classified river channel patterns for western Norway (Figure 8b), the conceptual model was adjusted by considering the abundance of non-fluvial and fluvial sediments. These theoretical threshold values are in line with the adjustment capacity during extraordinary flood flows. Fluvial morphology may respond in similar forms as was documented for Flåmselva in October 2014 (compare to Figure 5). For increased non-fluvial sediment depositional rates in the overbank sediment deposits, however, fewer channel adjustments are proposed due to the higher lateral stability/critical shear stress of these high-roughness elements. This means, the extended Costa and O'Connor concept could be put on top of hydrodynamic-numerical modelling, not to identify and validate driving processes like in

the present study, but to predict which rivers or river stretches (if fluvial, semi-fluvial and non-fluvial are mixed) will contain (i) selective transport and wash out of sediments or (ii) significant geomorphic adjustments in terms of floodings. In Figure 9, pictures of various channel adjustments are presented (during and after extraordinary flood events) in western Norway that include the extension of the Costa and O'Connor concepts: (i) side erosion, overbank scouring and channel avulsion for the fluvial parts (Figure 9e,f) and (ii) washouts and only local scouring effects without channel avulsion for the semi-alluvial sections (Figure 9a–e). For practical implementation, however, these threshold lines (Figure 8a) need to be adjusted by calculating flood forces (e.g., bottom shear stress and stream power) and are defined in the relationship of resistance of the deposited sediments by a site- and/or river-specific flood hazard analysis.

5 | DISCUSSION

The presented findings showed that critical flow conditions are relevant for erosional activity and morphological adjustments for the selected study river. Grant (1997) stated that natural plane bed types (for definition see Montgomery & Buffington, 1997) are insufficient to generate critical flow. In the studied Flåmselva, however, plane bed sections (with increased discharge capacity) were artificially constructed to increase hydraulic capacity for flood discharges. Channelization was conducted and plane-bed morphology was forced although the given sedimentological and hydraulic boundary conditions would result in other river types. The roughness elements were excavated or levelled out, and bar formation was prevented by (i) high transport capacity and (ii) lack of sediment supply. The high-roughness elements, which may be responsible for preventing the channel from becoming critical (Grant, 1997), especially in postglacial river environments (compare to Hauer & Pulg, 2018; Hauer & Pulg, 2021), were removed. Thus, it is hypothesised that both (i) the river training measures, which increase transport capacity and (ii) the smooth boundary walls of the channel, were the drivers of supercritical flow (Froude number > 1) in various parts of the river during the autumn flood in 2014. This has been and is still of great importance for flood risk management because the main targets of flood mitigation are to increase or maintain the discharge capacity within the active channel (Klijn et al., 2018), which can be further extended by dikes and levees along banks (Di Baldassarre et al., 2009). Roughness elements are avoided, as they increase the water surface elevation (Wohl &

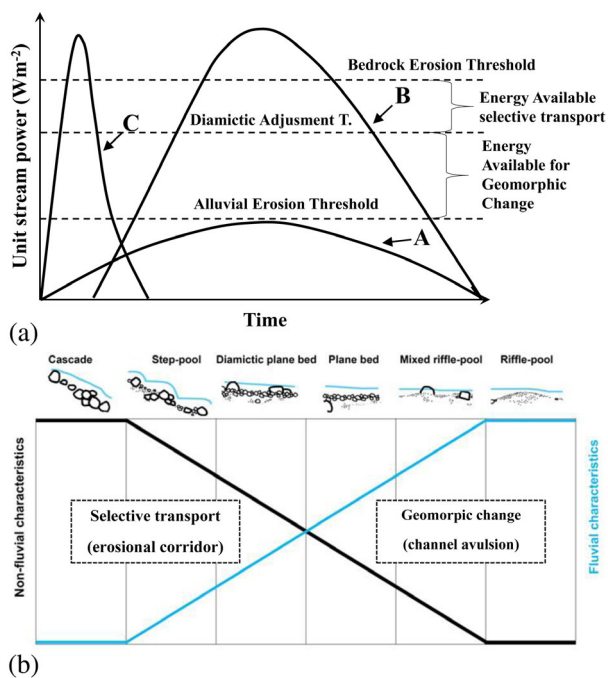


FIGURE 8 (a) Adapted Costa and O'Connor (1995) concept for semi-fluvial and fluvial river reaches in Western Norway and (b) principal fraction of non-fluvial and fluvial characteristics of different channel types classification (Hauer & Pulg, 2018) including the processes and channel responses in terms of morphodynamic active floods; black solid line = non-fluvial sediments, blue solid line = fluvial sediments



(a)



(b)



(c)



(d)



(e)



(f)

FIGURE 9 Pictures of erosional corridors in Norway (a) semi-alluvial river in Brumunddal, (b) semi-alluvial Opo river in the city of Odda, (c) semi-alluvial part of the Flåmselva, (d) semi-alluvial river in Brumunddal; note the large variety of exposed sediments, (e) fluvial river in Gudbrandsdal, (f) fluvial river in Kvam. (a) and (d) Foto: Cornelius Poppe/NTB, (b) Foto: Tore Wiers, (c) Foto: Ulrich Pulg, (e) Foto: Espen Braata/VG, (f) Foto: Håkon Mosvold Larsen/NTB.

Ikeda, 1998) and thus lead to earlier overtopping and flooding into overbank areas (Apel et al., 2009). Our results suggest that smoothing and channelizing rivers to

increase discharge capacity also increases the flood hazard risk by increasing supercritical flow and erosion potential. We argue that both factors (capacity versus

critical flow) should be analysed in flood risk management to avoid one-sided solutions that may in fact increase the total flood hazard potential.

The documented morphological adjustment of the Flåmselva after the 2014 flood fully supported the hypothesis of Grant (1997) that natural river channels avoid becoming critical over longer distances for all river types; – even for semi-alluvial postglacial river types such as Flåmselva. Giménez and Govers (2001) also documented in their experiments a slope independence of flow velocity on mobile beds, related to a feedback process between the investigated rill bed dynamics and hydraulic conditions. This slope independence has been reported in other studies as well, such as Nearing et al. (1997, 1999) or Takken et al. (1998). When the bed (rills), however, was fixed in the experiment of Giménez and Govers (2001), the velocity in the rills changed to a clearly slope-dependent state. In the present study of Flåmselva, overbank scouring, side erosion and partial channel avulsion caused such reductions in flow velocities in many morphodynamically active parts (compare to Figure 4), with consequences for the Froude number (compare to Figure 6).

The coarse bed of Flåmselva began to be ‘mobile’ only for an extraordinary flood event, when bank protection measures failed. The observed processes were similar to the interacting processes among alluvial sediments, bed roughness and flow hydraulics that were documented for experimental studies (e.g., Giménez and Govers (2001) or were reported for smaller grain sizes with loose granular material (Grant, 1997). Our results agree with those studies. The interaction between the mobile alluvial sediments in Flåmselva and flow hydraulics contained a reduction in kinetic energy and thus a reduced Froude number with a more nearly constant averaged distribution of approximately 1 along the longitudinal profile.

For consideration in flood risk management this means, if flood discharges have sufficient power to reshape the riverbed, the flow tends towards an average Froude number of 1. If the flood does not have enough power, the Froude numbers may be above 1 but with a high risk of uncontrolled erosion if the protecting material (e.g., riprap along banks) fails or is overtopped and the alluvium in the floodplain is suddenly exposed to supercritical flow (compare to Figures 1, 5 and 9). Due to the resultant deformation of the alluvium, the critical flow will establish a hydraulic jump, which is the main driver for energy dissipation. For such hydraulic jump formations, it is well-known that hydraulic forces can dramatically increase and weaken and erode solid technical structures (e.g., at the toes of dam spillways or weirs) (Vischer & Hager, 1998). The same holds true

for hydraulic jump formation in rivers, which can weaken and erode massive bank protection measures, as has already been documented for extraordinary discharges (Hauer & Habersack, 2009; Krapesch et al., 2011).

Similar to the present study, hydraulic forces in terms of flooding can be simulated. In particular, for flood risk management, application of hydrodynamic-numerical models has a long tradition from calculating water surface elevations (Schumann et al., 2007; Yan et al., 2015) and flood inundation areas (Tayefi et al., 2007; Teng et al., 2017). In addition to the one-dimensional modelling applied, more advanced depth-averaged two-dimensional unsteady flow modelling (Chen et al., 2012; Lin et al., 2006; Vojinovic & Tutulic, 2009) allows identification of spatially distinct ‘risk’ categories that were standardised under the framework of the European Floods Directive (Priest et al., 2016). Based on the findings of the present study, it is recommended that the Froude number should be used as an important parameter for risk assessment and as a type of strategic management tool in the future. In addition to the state-of-the-art analyses of flow velocity (ms^{-1}) and water depth (m) already used for the identification of ‘red zones’ or ‘yellow zones’ for flood hazard maps (Van Alphen et al., 2009).

For hydraulic engineering (measures), two relevant discharges are described for sediment transport in rivers: (i) the dominant discharge (Wolman & Miller, 1960) as the flow, which transports the greatest amount of sediments (dominantly the suspended load), and (ii) the geomorphic effectiveness discharge (Wolman & Gerson, 1978), which addresses the maximum geomorphic work for a characteristic flood discharge. This geomorphic effectiveness discharge, however, may vary at the reach scale between bedrock and alluvial areas and may vary among the semi-alluvial or non-fluvial stretches in western Norway. Focus was placed on the implementation of the discharge of the maximum geomorphic work to extend the Costa & O'Connor concept. As stated by Wolman and Gerson (1978) and summarised by Wohl (2013), floods can significantly alter channel and floodplain morphology without transporting large quantities of suspended sediment, and the effectiveness also depends on the rate of the recovery period of the channel morphology. Both mentioned aspects include specific characteristics of the western Norwegian environment. Thus, erosion or ‘erosional corridors’ (i.e., the diamictic threshold line shown in Figure 8a) should be the central focus for morphological adjustments of rivers due to floods in western Norway. However, there is one exception present along the river course. These are sensitive stretches due to aggradation, which are mainly found at

the mouth. Here, the deposited material that is due to the reduced energy slope may reduce the discharge capacity of rivers and thus lead to earlier and more severe inundation of the floodplains. Di Silvio (1994) documented that aggradation due to flooding is most serious in channels with bed slopes between 0.2% and 2%. In 2014, for Flåmselva, large amounts of gravel were deposited in the lowermost part of the river, where the slope was reduced to 0.0008.

The formation of erosion corridors also has important ecological implications for integrative river basin management. Natural bed forming processes would contribute to lowering the risk for supercritical flow and simultaneously improve the ecological status of channelized or rip-rapped rivers. Side erosion would increase sediment supply, including spawning gravel and pebbles, which are essential for the reproduction and rearing of autochthonous fish in the region, such as Atlantic salmon (*Salmo salar*) and anadromous brown trout (*Salmo trutta*, Pulg et al., 2019). This is especially important since natural lakes reduce longitudinal sediment transport in postglacial supply-limited catchments (Hauer & Pulg, 2021). Roughness can be increased by using boulders, which are typical in untouched rivers in the region and provide essential cavities and shelters for fish (Finstad et al., 2007). Increasing channel width would allow habitat restoration such as side channels, oxbows, temporary ponds and riparian vegetation.

Thus, integrated flood risk management that balances both flow capacity and hydraulic forces would also benefit environmental goals as set by the Water Framework Directive. This type of management would contribute significantly to river restoration by allowing natural bed-forming processes and reestablishment of side channels and river widening. Integrated flood control management may therefore play an important role in the UN Decade of Ecosystem Restoration (2021–2030), and flood management budgets can be used to improve both human safety and ecological conditions. Additionally, integrated flood risk assessment based on Froude number modelling, as proposed, will allow quantification of the full effects of river restoration and natural river channels for flood risk management. It is not only the flow capacities but also the reductions of critical flow and thus erosion potentials, which are essential for human safety along rivers.

Finally, how the presented findings can be implemented in flood risk management is discussed. Different concepts are addressed here to control the floods of ‘maximum geomorphic work’ that form ‘erosional corridors’ (compare to Krapesch et al., 2011), which may also be beneficial for aquatic environments. First, fluvial river types (compare to Hauer & Pulg, 2018) are presented. Here, two forms of management are addressed:

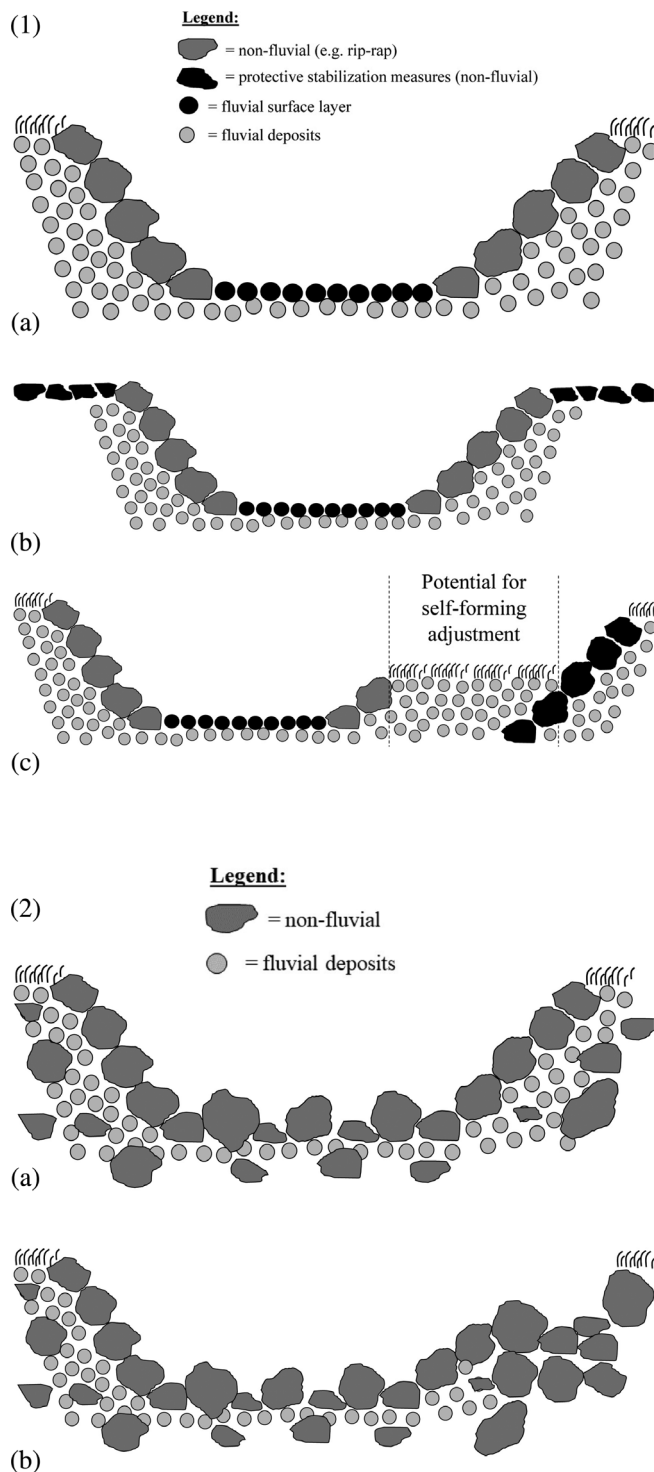


FIGURE 10 (1) Schematic cross sections of (a) an artificial channelized plane-bed river with surface layer formation and stabilisation of the banks by rip-rap, (b) an artificial channelized plane-bed type with additional protection measures along the banks and in the floodplains to avoid scouring processes (e.g., floodplain stripping) at the top of the banks, (c) channel widening of an artificial channelized plane bed type. (2) Schematic cross sections of semi-alluvial rivers (a) near-natural sediment composition with additional bank stabilisation measures, (b) artificial channel widening above mean flow with non-fluvial sediments as dominating substrate to avoid uncontrolled erosion and enabling energy dissipation on site

(i) the additional protection of overbank areas along banks (Figure 10a) to avoid uncontrolled scouring at the top of the bank protection and scouring behind the protective measures (e.g., riprap). Such a concept may be feasible in river reaches with no opportunities for implementing channel widening; (ii) the definition and implementation of an 'erosional corridor' in those sections where channelization of the riverbed led to predicted critical flow conditions. The 'pre-erosional corridors' are artificial river widenings and lowering of parts of the overbank area above the mean flow stage (Figure 10a). These types of bathymetric adjustments should avoid critical flow conditions in terms of extraordinary flooding and prevent negative impacts of reduced water levels/depths in terms of low-flow conditions as the active channel width for low discharges is not changing. Furthermore, the exposed material for reworking the channel bed should allow self-forming dynamics to develop site-specific habitat features as well as energy dissipation during on site flooding.

For the semi-alluvial river types containing higher contents of non-fluvial sediments, the adjustments mainly involve reducing the kinetic energy in the cross section by channel widening or re-implementation of high-roughness elements, which may cause similar energy dissipation mechanisms as was reported for step-pool morphologies by Grant (1997). Local acceleration above the roughness elements in terms of overtopping with critical flow conditions and hydraulic jump formation downstream may occur. Moreover, due to these adjustments of cross-sectional bathymetries with the typical landscape features due to the glacial history of Norway (Hauer & Pulg, 2018; Hauer & Pulg, 2021), important habitat features are also improved, such as shelter for juvenile fish (Finstad et al., 2007).

5.1 | Uncertainties in the modelling approach

For normal river flows and a static riverbed, the flow resistance will depend on many factors (including flow velocity and depth, section shape, plan-form, vegetation, sediment grain size and bed-forms) (Bathurst, 1985; Hey, 1979; James et al., 2004; Wilcox & Wohl, 2006). However, where significant sediment motion is taking place additional processes impact upon the flow resistance including the transient change in bed-forms in a reach (compare to Figure 8b) which will influence the form losses and the energy transferred from the water flow into the kinetic energy of the motion of large sediments. These processes imply that the Manning's n will vary during the passage of the flood. Thus, a sensitivity analysis of variable Manning's

n on the calculation of Froude number were conducted in the present study (see Supplementing Material). This sensitivity analysis underlines that in general the principal statements are valid, that due to the morphological adjustments the number of cross sections with supercritical flow regimes decrease for the investigated Flåmselva, – especially when flow resistance becomes smoother. In terms of increasing roughness up to $n = 0.04$ the differences became less visible (see supplementing material). Although the principal findings are supported by the sensitivity testing, specific uncertainties are given concerning the exact number of cross sections, which were calculated as sub- or supercritical flow, respectively.

6 | CONCLUSIONS

The present study investigates the role of critical flows on morphological adjustments during an extraordinary flood event at Flåmselva in western Norway. The results, which were based on one-dimensional step-backwater modelling, revealed that morphological adjustments in semi-alluvial, high gradient rivers led to a partially significant reduction in the Froude number with establishment of near critical conditions for post-flood river bathymetry. This was in line with previously published studies regarding morphological adjustments of rivers in terms of critical flows. Furthermore, strategies for flood risk management to reduce the impact of roughness elements increase the risk of supercritical flow over engineered stabilised plane-bed morphologies. In conclusion, various concepts were presented to improve flood hazard analyses and mitigation in the future by (i) a strong recommendation to include spatially distributed Froude number modelling in flood hazard risk analysis/maps and (ii) to implement revised engineering concepts in practice for minimising critical flows by channel widening and corridor definitions, including the use of high-roughness elements for local energy dissipation. We recommend applying an integrated flow risk assessment that balances both flow capacity and hydraulic forces indicated by critical flow. In addition to securing human lives and settlement along rivers, such a strategy would have the potential to combine river restoration and improve the ecological status and flood risk management.

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DATA AVAILABILITY STATEMENT

The 1-D modelling results including Froude number, flow velocity and bottom shear stress are available from the authors.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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