

The long-term hazard cascade of an unprecedented wildfire in a tropical mountain ecosystem

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Abstract. Climate change is driving wildfires to higher elevations, yet the hazard cascades that follow the burning of pristine tropical mountain ecosystems remain largely unexplored. Here, we analyse the long-term cascade following a February 2012 wildfire that burned 31 km² of forest and wetland in Uganda's Rwenzori Mountains National Park, including sections above 3800 m elevation with no major fire history in 12,000 years. Combining remote sensing, humanitarian records, field surveys and interviews, we document ten major floods since 2012, including two debris floods that required large-scale humanitarian responses. Post-fire increases in erosion and mass movement have widened the River Nyamwamba sevenfold since 2012, breaching copper-cobalt mine tailings and mobilising an estimated 744,000 tonnes of waste into the river. Slow vegetation recovery at high altitudes and positive feedbacks between hazards have prolonged this high-risk state. These findings point to an urgent need to understand where emergent tropical mountain fires can occur, how their impacts cascade downstream, and where early interventions can reduce risk.

32 **1 Introduction**

33 Climate and land-use changes are driving more frequent and intense wildfires across many tropical ecosystems worldwide
34 (Ometto et al., 2022; UNEP, 2022; Wimberly et al., 2024; Obando-Cabrera et al., 2025). In tropical mountains, fires are burning
35 at higher elevations (Mason et al., 2026; Xiao et al., 2022), which is exposing mature forests and wetlands that are not adapted
36 to burning regimes. Tropical mountain forests cover 1.8 million km² globally (FAO & UNEP, 2020), and they provide the
37 headwaters of major river systems such as the Nile, Amazon and Mekong to sustain the livelihoods of over 336 million people
38 (Encalada et al., 2019).

39
40 Hazard cascades describe networks of interconnected hazard processes, where a primary event initiates a sequence of
41 subsequent hazards through direct or indirect interactions (Gill and Malamud, 2016). Understanding cascade dynamics is
42 essential for risk assessment, as the cumulative impacts of cascading hazards often exceed those of individual events in
43 isolation (Gill and Malamud, 2016). Tropical mountains host multiple hazards, making them susceptible to multi-hazard
44 cascades (Arango-Carmona et al., 2025). Intense convectional rainfall drives flash floods (Encalada et al., 2019), whilst high
45 temperatures at lower elevations encourage the development of droughts, heatwaves and wildfires (Ometto et al., 2022). In
46 addition, their steep gradients, deeply chemically weathered soils and unconsolidated glacial and fluvial deposits also favour
47 landslides, debris flows and high rates of erosion (Arango-Carmona et al., 2025).

48
49 Multi-hazard cascades occur when two or more hazards interact through relationships characterised as *triggering*, *probability*
50 *increasing*, or *catalysing/impeding* (Gill and Malamud, 2016). Triggering interactions are typically short-term, through directly
51 sequenced hazard events such as a lightning storm triggering a wildfire. Probability increasing interactions occur when a hazard
52 affects the environmental conditions in a way that increases the likelihood of subsequent hazards occurring. Wildfires are
53 known to have probability-increasing relationships with a range of secondary hazards due to the destruction of vegetation and
54 changes to the physical, structural and biochemical properties of soil (Vahedifard et al., 2024; Boyer et al., 2022). For instance,
55 the probability of post-fire flash flooding is increased due to vegetation-loss reducing interception and thus increasing effective
56 precipitation (Stoof et al., 2012). Whilst triggering and probability increasing hazard interactions describe how one hazard
57 affects the occurrence of another hazard, catalysis/impedance relationships act upon other hazard interaction pairings. For
58 example, the increased river discharge resulting from wildfires may catalyse ‘erosion-triggered-mass movements’ by adding
59 energy and material to earth flows, and the loss of vegetation in a wildfire-affected area may impede the development of future
60 wildfires triggered by human activities (Shakesby and Doerr, 2006). In practice, hazards often share multiple of these cascading
61 interactions, and their relationships can evolve over time (Gill and Malamud, 2016).

62

63 **1.1 Post-Wildfire Hazard Cascades**

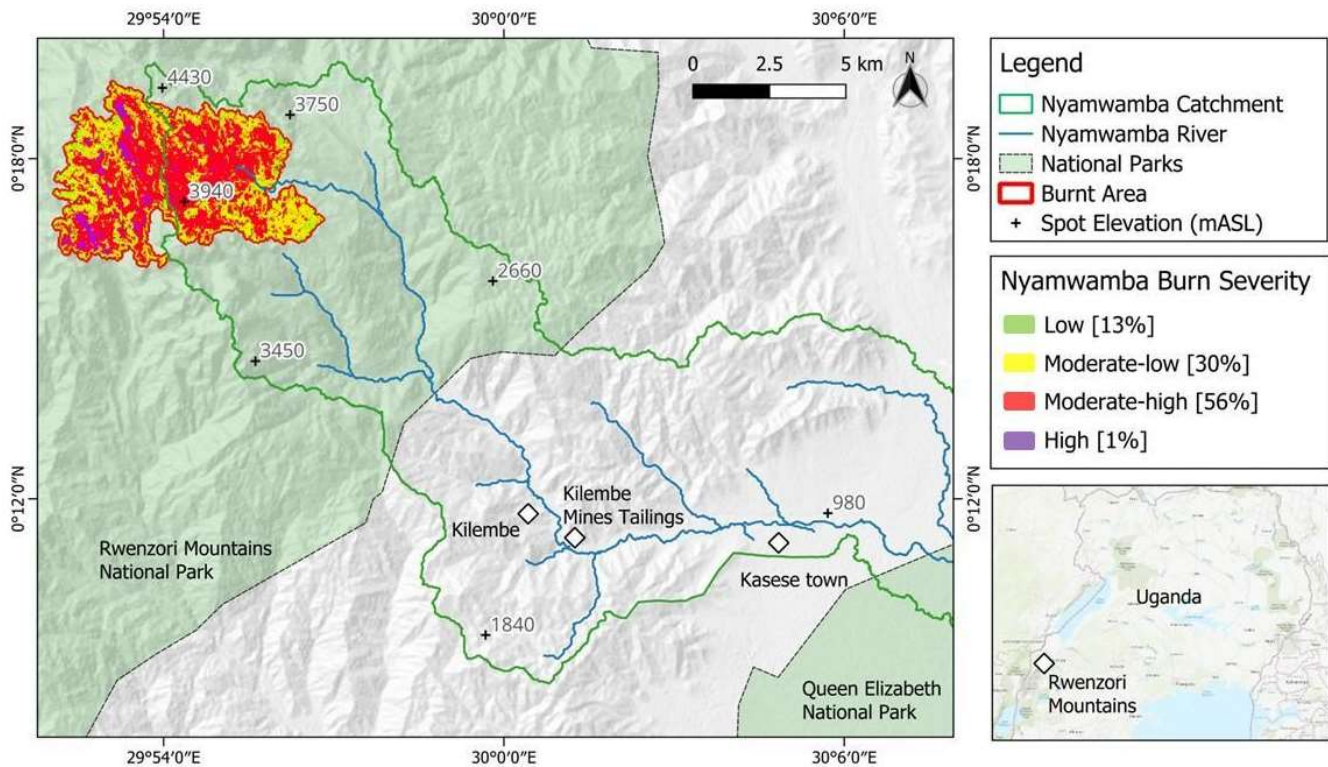
64 Despite their increasing risk, wildfire hazard cascades in tropical montane regions remain poorly understood. Most existing
65 research comes from temperate systems, where wildfires are known to amplify floods, accelerate erosion, and increase the
66 probability of landslides and debris flows by removing vegetation, altering soil properties and increasing surface runoff
67 (Belongia et al., 2023; Boyer et al., 2022; DeBano, 2000; Doerr et al., 2000; Guerriero et al., 2025; Jordan, 2016; Kemter et
68 al., 2021; Rengers et al., 2020; Swain et al., 2025; Vahedifard et al., 2024; McGuire et al., 2024).

69
70 However, there are additional factors in tropical mountains that introduce a unique risk and complexity (Moazeni & Cerdà,
71 2024; Robinne et al., 2021). First, the fires impact upon an already diverse multi-hazard landscape with many existing hazard
72 interactions (Arango-Carmona et al., 2025; Ometto et al., 2022; Sandwell et al., 2005). Second, many higher-altitude
73 ecosystems within tropical mountains have no history of wildfire, such that mature climax vegetation and pristine wetlands
74 are burned with unpredictable consequences for hydrological processes and ecosystem services (Marengo et al., 2021; Mason
75 et al., 2026; Pivello et al., 2021; UNEP, 2022). Third, a lack of wildfire history means vulnerable populations without lived
76 experience are exposed to new hazards (McCaffrey, 2004; Paton, 2003). Lastly, vegetation recovery at high altitudes is slow
77 due to cold conditions and the presence of vegetation that is not adapted to fire cycles, causing prolonged impacts (Kappelle
78 et al., 1996; Oliveras et al., 2014; Salinas et al., 2021). Given these differences, there is a need to better understand the long-
79 term cascade of tropical montane wildfires at the process level. This is especially true for multi-hazard risk management, as
80 identifying where hazards interact effectively highlights where those interactions can be proactively impeded (Aghakouchak
81 et al., 2018, Aghakouchak et al., 2020; Vahedifard et al., 2024).

82 **1.2 Rwenzori Mountains National Park 2012 Wildfire**

83 The February 2012 wildfire in Uganda's Rwenzori Mountains National Park burned 31 km² of pristine, uninhabited tropical
84 mountain forest and wetlands (Fig. 1) during a brief meteorological drought measuring -3.5 in a 1-month Standardised
85 Precipitation Index (Appendix A). The ecosystem was mature – the fire was the first to affect elevations exceeding 3800 m
86 above sea level in the Rwenzori Mountains for at least 12,000 years (Mason et al., 2026).

87
88 The wildfire was followed by unprecedented debris flooding in May 2013 that displaced more than 25,000 people, caused 13
89 deaths and over USD \$4 million in damages (Delforge et al., 2025). Local rainfall records suggested only a 6.6-year return
90 interval (6-hour duration), indicating that post-fire landscape changes drove the disaster (Jacobs et al., 2016). We present
91 evidence that, more than a decade later, the Nyamwamba catchment continues to experience flooding, debris floods, mass
92 movements, erosion and water pollution at an elevated level due to fire-induced environmental changes. Because the wildfire
93 occurred in a protected area with no burn history and little subsequent intervention (Mason et al., 2026; Norville, 2024), it
94 provides an unparalleled case for this study to characterise the long-term multi-hazard cascade of a tropical mountain wildfire.



95
 96 **Figure 1: The River Nyamwamba catchment and the delineated wildfire burn area within the Rwenzori Mountains, Uganda.**
 97 **Differenced Normalised Burn Ratio (dNBR) between pre- and post-fire Landsat-7 images were used to delineate the extent and burn**
 98 **severity of the February 2012 wildfire. Severity is classified according to the United States Geological Survey’s guide (Key & Benson,**
 99 **2006).**

100 **1.3 The Study Region**

101 The Rwenzori Mountains are an uplifted metamorphic basement block, with hard, crystalline basement geology creating steep
 102 gradients and river profiles that climb to a maximum elevation of 5,109 m (UNESCO, 2012). It is the third largest glaciated
 103 region in Africa (Hinzmann et al., 2024), with abundant quaternary deposits of unconsolidated glacial and fluvial sediment in
 104 its valleys (UNESCO, 2012; Ring, 2008). The Rwenzori Mountains National Park is a UNESCO World Heritage Site dedicated
 105 to the protection of biodiverse and unique montane flora, classified into five distinct eco-zones (UNESCO, 2012): tropical
 106 mixed broadleaf montane rainforest (<2600 m altitude); bamboo forest (2600-3000 m); an ericaceous zone characterised by
 107 dense giant heather trees, giant senecios and giant Lobelia (3000-3800 m); afro-alpine moorland and bogs (3800 – 4400 m);
 108 and the rock, snowfield and glacier zone (>4400 m).

109
 110 Higher altitudes within the equatorial mountain range have an annual precipitation of 2500 mm, with two wet seasons (March-
 111 May and September-December) where monthly precipitation values exceed 375 mm (UNESCO, 2012). The River

112 Nyamwamba is a major river in the southern part of the Rwenzori Mountains that transports water to its delta with Lake George
113 within the Queen Elizabeth National Park area (Fig. 1).

114 **1.4 Study Scope**

115 This study characterizes the multi-decadal hazard cascade profile of the Nyamwamba River catchment following a 2012
116 wildfire that burned 31 km² of pristine tropical mountain forest and wetland in Uganda's Rwenzori Mountains National Park
117 and interprets the implications for regional risk management and broader lessons for tropical montane environments globally.
118 Through an integrated mixed-methods approach combining remote sensing analysis, humanitarian records, field surveys, and
119 semi-structured interviews, we document the long-term interactions between wildfire, flooding, erosion, landslides, and
120 pollution over a 12-year period (2012-2024). The study identifies key hazard interactions using Gill and Malamud's (2016)
121 framework, evaluates entry points for management interventions to mitigate future hazards in fire-sensitive tropical mountain
122 ecosystems, and derives take-aways for the governance and resilience of tropical montane regions facing emerging fire-driven
123 risks.

124 **2 Methods**

125 We adopted a mixed methods approach to evidence changes in multi-hazard processes and risk, combining remote sensing,
126 humanitarian data, field observations and key informant interviews. Cross-validation across methods enabled an abductive
127 approach (Saunders et al., 2016), where emerging insights, such as interview reports of erosion, informed subsequent lines of
128 data collection and analysis.

129 **2.1 Remote Sensing and GIS**

130 **2.1.1 Data Acquisition and Pre-Processing**

131 Annual Landsat-7 (2006 – 2012) and Landsat-8 (2013-2024) Level-2 surface reflectance images at 30m resolution were
132 downloaded from the United States Geological Survey (USGS) earth explorer and gap corrected, cropped and cloud masked
133 for analysis (Congedo, 2021). For each year, the earliest post-January 1 image with <10% cloud cover was selected. High-
134 resolution Google Earth Pro imagery was used to measure river width, while Maxar mosaics visualised mine tailings erosion
135 (Maxar Technologies, 2025a; Maxar Technologies, 2025b; Veness & Day et al., 2026).

136 **2.1.2 Burn Severity Classification**

137 Burned area was delineated using the Normalised Burn Ratio (NBR), which combines Landsat 7 near-infrared (Band 4) and
138 shortwave-infrared (Band 7) reflectance (Key & Benson, 2006) to map and quantify the severity of a fire's impact on vegetation

139 and soil. The difference between pre- (9 January 2012) and post-fire (28 March 2012) NBR values (dNBR) provided a relative
140 severity index following USGS protocols (Key & Benson, 2006; Veness & Day et al., 2026).

141 **2.1.3 River Channel Bank Erosion Analysis**

142 Supervised minimum-distance land-cover classifications were applied to annual Landsat images from 2006 – 2024, using fixed
143 ground control points for five classes: eroded river channel, tailings, oxidised iron, vegetation, and agriculture (Congedo,
144 2021). Each image was clipped to the Nyamwamba channel, and classified areas were validated against Google Earth area
145 estimates with a relative error of 3.84% (Veness & Day et al., 2026). Cumulative lateral riverbank eroded area was plotted
146 over time, with classification maps from 2006 and 2021 shown for comparison. River width was delineated in 2010, 2014,
147 2018, and 2021, at 1 km intervals along 20 km of channel between Kilembe town and Lake George.

148 **2.1.4 Tailings Erosion**

149 Erosion of the Kilembe Mines tailings was assessed using Maxar mosaics from March 2006 and April 2023, with the 33,000
150 m² eroded footprint delineated manually. Field measurements in July 2024 using a laser rangefinder provided site dimensions,
151 from which eroded volumes were calculated (see Appendix B).

152 **2.2 Humanitarian Data Analysis**

153 Historic flood events in the Nyamwamba catchment since 2000 were compiled from multiple open sources: the Emergency
154 Events Database (Delforge et al., 2025), the Sendai DesInventar database (DesInventar, 2025), grey literature in ReliefWeb,
155 and a systematic keyword search (“Kasese” OR “Kilembe” AND “flood”) across Google, Google Scholar, and Google News
156 (Google News, 2025). While recent years benefit from expanded monitoring and reporting, the inclusion of diverse sources
157 provided confidence that all major flood events since 2000 were captured by the search.

158 **2.3 Interviews**

159 We conducted twelve in-person semi-structured interviews during field visits in 2023 and 2024, following ethical clearance.
160 Participants were identified through project partners in Kasese District, with snowball sampling to access other stakeholder
161 groups. They included 2 representatives from the Ministry of Water [M – code used to reference in the results], 2 local
162 government officials [G], 1 wildlife authority employee [W], 1 non-governmental organisation worker [N], 2 local industry
163 workers [I], 1 farmer [F], and 3 community residents [R].

164
165 Interviews followed a lightly structured topic guide covering hazard processes and causes, changing risk, existing management,
166 and potential alternatives, while remaining flexible to emergent themes (Creswell, 2009; Galletta, 2013; Mojtahed et al., 2014).
167 A full guide is provided in Appendix C. Interviews lasted 30 – 120 minutes, were audio-recorded, transcribed, and coded
168 inductively over two rounds of review, with related codes grouped into interpretive themes (Patton, 2014; Saldana, 2021).

169 While themes are not presented directly, this analysis informed interpretation of hazard processes, impacts, and management
170 options.

171 **2.4 Photographs**

172 Historic photographs of the vegetation pre- and immediately post-wildfire were taken by project partners with permission for
173 research use. Photographs in Appendices E – J were taken by the study authors during a July 2024 site visit.

174 **2.5 Cascade Visualisation**

175 Processes identified through the above methods were integrated into a conceptual diagram of the wildfire’s multi-hazard
176 cascade (Patton, 2014), following Gill & Malamud’s (2016) framework for hazard interaction types. Evidence underlying each
177 connection is documented throughout the Results and summarised in Table D1 (Appendix D).

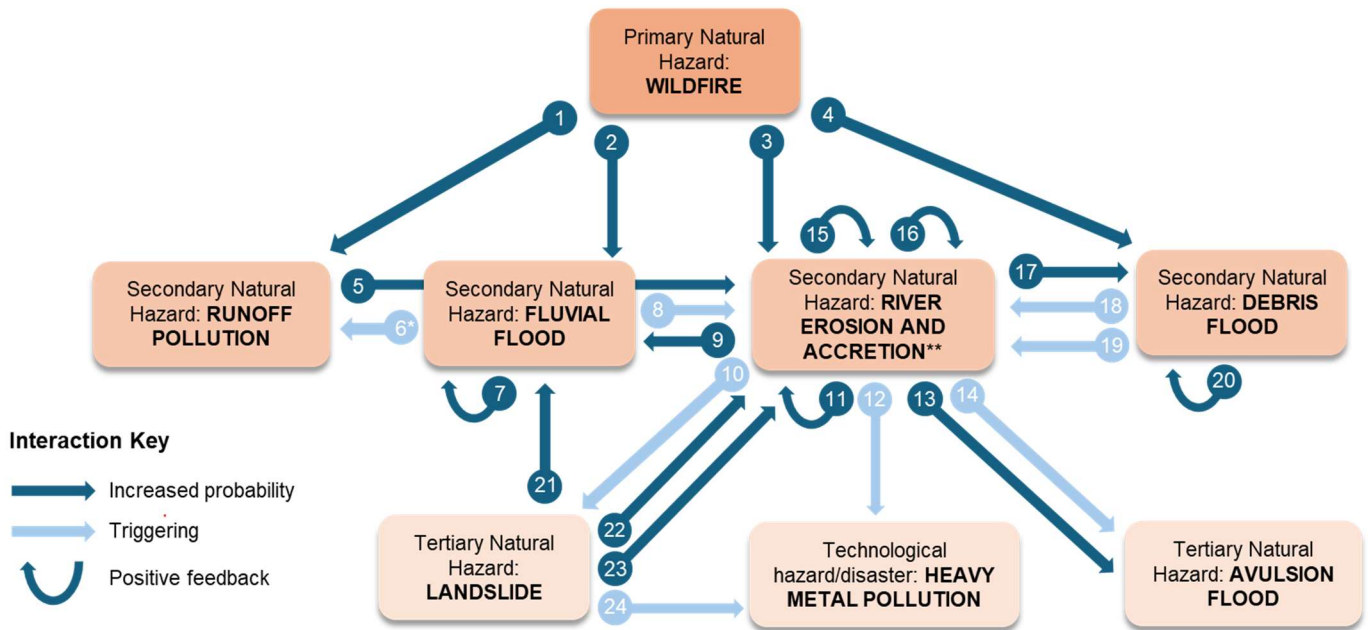
178 **3 Results**

179 We present the multi-hazard cascade caused by the 2012 Rwenzori National Park wildfire (Fig. 2). The following sections
180 describe each of the hazards involved and the interactions they drive, based on evidence from our mixed methods. Results are
181 structured by hazard type: wildfire (Sect. 3.1), flooding (3.2), landslides (3.3), erosion (3.4), and pollution (3.5). Identified
182 interactions highlight opportunities where management interventions can impede the cascade, for which we discuss practical
183 solutions at the local and global scales in Sect. 4 (Discussion). The hazard definitions follow the Hazard Information Profiles
184 (UNDRR, 2025) and are clarified in Table D1 (Appendix D). Importantly, here landslides refer to gravitational mass
185 movements directly connected to the river system as shown in Figures I1 and I2 (Appendix I).

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189

190 **Figure 2: Conceptual model of the multi-hazard cascade following the Rwenzori National Park wildfire in February 2012.**
 191 Interactions between hazards are classified as being (i) triggering, or (ii) probability increasing, following Gill and Malamud's
 192 (2016) framework, and (iii) positive feedbacks have been identified. There are numerous catalysing/impeding relationships in this
 193 context, which we omit from the visualisation for simplicity but describe key examples in the analysis text. Table 1 describes each
 194 of the interactions shown.

195 *Interaction (6) also applies for debris floods and avulsion floods as the driving hazard (Table 1), but they are grouped for
 196 simplicity in the visualisation.

197 **River channel erosion and accretion of eroded sediment are treated as one hazard in line with UNDRR's Hazard Information
 198 Profiles (HIPs), with continuously interacting processes and positive feedbacks (15, 16) along the river's reach (UNDRR, 2025).

199 **Table 1: Description of the hazard cascade interactions in Fig. 2. The study evidence for each interaction is explained in the text and**
 200 **summarised in Table D2 (Appendix D).**

Driving Hazard	Description of Interaction	Affected Hazard
Wildfire	1 Wildfire generated ash & exposed soils to surface runoff	Runoff Pollution
	2 Burning increased runoff & river discharge, causing higher peak flows	Fluvial Floods
	3 The higher peak river discharge has increased the river's erosive power	Erosion and Accretion
	4 The higher peak river discharge has increased its transport competence	Debris Floods
Runoff Pollution	5 Increased sediment loads, more material available for accretion	Erosion and Accretion
Fluvial Floods	6 Floodwaters (fluvial, *avulsion and debris floods) transport contaminants across the landscape	Runoff Pollution
	7 Each flood damages natural banks & flood defences	Fluvial Floods
	8 Higher flow velocities & turbulence during floods increase erosion	Erosion and Accretion
River Channel Erosion	9 Eroded material fills the channel, reducing its discharge capacity	Fluvial Floods
	10 Lateral erosion undercuts & destabilises hillslopes	Landslides

and Accretion	11	Lateral erosion exposes bare riverbanks to further erosion	Erosion and Accretion
	12	Direct erosion inputs Co-Cu Kilembe Mines solid tailings into the river	Heavy Metal Pollution
	13	Higher erosion rates have increased channel-switching events	Avulsion Floods
	14	Eroded sediment deposits in channel bars, diverting flow to banks	Avulsion Floods
	15	Sediment deposition narrows channel increasing erosive potential	Erosion and Accretion
	16	Eroded sediment accretes in the channel, diverting flow to erode riverbanks	Erosion and Accretion
	17	Erosion generates additional sediment for debris flood formation	Debris Floods
Debris Floods	18	Debris floods have a high erosive power	Erosion and Accretion
	19	Mobilized sediment deposits in channel, diverting flow to erode riverbanks	Erosion and Accretion
	20	Debris floods damage natural banks & flood defences	Debris Floods
Landslides	21	Landslide talus fills the channel, reducing its discharge capacity	Fluvial Floods
	22	Increased sediment loads, more material available for accretion	Erosion and Accretion
	23	Landslides increase sediment loads, increasing erosion by abrasion	Erosion and Accretion
	24	Rotational slumping of tailings inputs waste to the river channel	Heavy Metal Pollution

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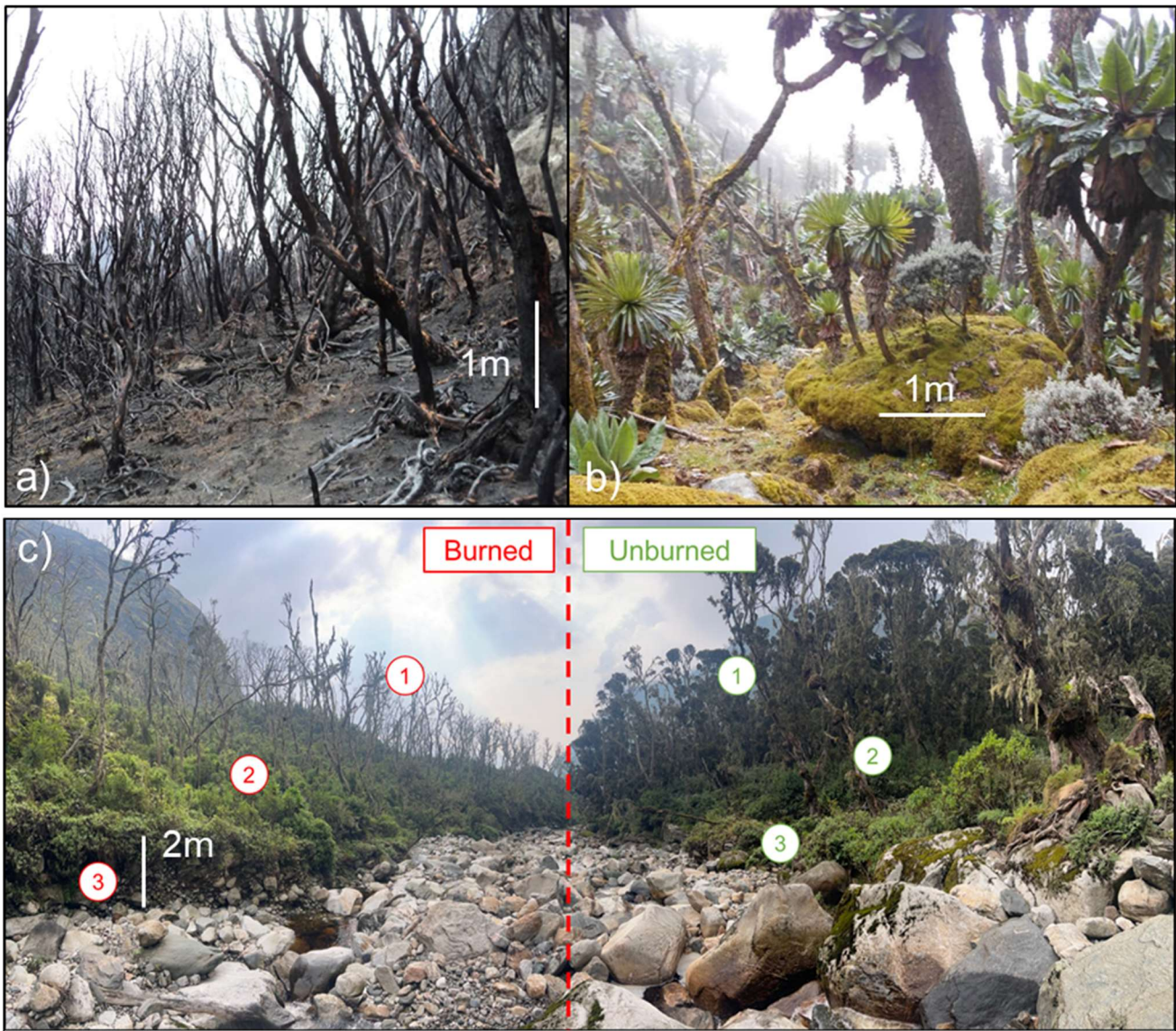
202 3.1 Wildfire

203 Remote sensing evidence shows a 30.75 km² burn area for the February 2012 wildfire (Fig. 1), with 87% of the area burned to
 204 a moderate or high severity. The fire occurred during a meteorological drought, with <0.2 mm of precipitation in the 4-weeks
 205 preceding the fire (Jacobs et al., 2016) and a one-month Standardised Precipitation Index measuring -3.5 for January 2012
 206 (Appendix A). The fire's cause of ignition is still unknown by the water and wildlife authorities [M1; M2; W1].

207

208 The fire burned between 3360 – 4400 m above sea level, burning climax 'heather zone' forest, "spongy" [R1] Afroalpine
 209 moorland, and methane-rich bogs [M1] with no recorded history of wildfires (Fig. 3a; Mason et al., 2026; UNEP, 2022).
 210 Photographs from March 2012 show indicators of high burn severity (Fig. 3b), while images from July 2024, twelve years
 211 later, reveal regrowth limited to a maximum of 2.5 m, with the upper canopy still vacant (Fig. 3c). These slow growth rates
 212 and an observed scarcity of heather in the regrowth succession indicate that natural recovery will require several decades
 213 (Wesche, Miehe and Kaeppli, 2000).

214



215

#	Attribute in c)	Burned	Unburned
1	Upper canopy	Dead ericaceous trees, vacant canopy	Mature ericaceous canopy
2	Lower canopy	Regrowth up to 2.5 m, heather scarce	Mature, dense vegetation
3	Riverbanks	Steep, unvegetated banks of exposed and unconsolidated glacial till	Sloped banks and coarse material anchored by vegetation

216

217 **Figure 3:** a) burned ericaceous ‘heather zone’ vegetation 1-month after the wildfire in March 2012; b) Mature Afroalpine moorland
 218 vegetation prior to the wildfire (March 2011); c) upper course of the River Nyamwamba at 3380 m elevation in July 2024, where the
 219 river had acted as a firebreak to provide direct comparison between unburned and recovering burned sections of the ericaceous
 220 forest. Scale bars correspond to the tree trunk in 3a, the boulder in 3b and the riverbank in 3c. The associated table describes the
 221 ecological properties of the burned and unburned areas.

223 The wildfire has unidirectional probability-increasing interactions with four secondary hazards. First, burning of soils and
 224 vegetation cover increased surface erosion and runoff to river channels, raising turbidity, carrying ash and peat, and introducing
 225 biological contaminants. Respondents recalled a strong smell “like methane” after the fire [M1; M2; R1; G1], highlighting
 226 wildfire-driven runoff pollution (#1). Second, reduced interception and infiltration capacity increased peak discharges at
 227 shorter lag times, driving a marked rise in fluvial flooding (#2; Sect. 3.2). Riverbank erosion has also accelerated due to higher
 228 discharges and loss of root cohesion (#3; Sect. 3.4), which, together with higher peak flows after the wildfire, enhanced the
 229 conditions for debris flood formation due to greater sediment supply [M1; R1] (#4, #17). These interactions (#1 - 4) are
 230 unidirectional because none of the secondary or tertiary hazards have resulted in further occurrence of wildfires in the
 231 catchment.

232

233 Additional relationships where the wildfire has catalysed other hazard interactions are numerous, but evidence for these cannot
 234 fully be established without intensive monitoring and field experimentation. Based on hydrological theory, some interactions
 235 catalysed by the wildfire’s effects would include:

236

- 237 ● *River channel erosion-triggering-landslide (#10)*: increased discharge after the wildfire (Moody and Martin, 2001)
 238 catalyses the generation of landslides caused by erosive undercutting from higher river erosion rates (Korup and
 239 Schlunegger, 2007).
- 240 ● *Landslide-increasing probability-river erosion (#23)*: increased discharge catalyses the contribution of landslides to
 241 later erosion by transporting landslide talus and using the sediment as erosive tools for abrasion (Sklar and Dietrich,
 242 2001)
- 243 ● *Debris flood-triggering-river erosion (#18)*: increased discharge catalyses erosion during debris flood events by
 244 increasing the erosive power of the flood (Stock and Dietrich, 2003)
- 245 ● *Landslide-increasing probability-fluvial flood (#21)*: increased discharge increases the volume of water
 246 accumulating in damming and bursting flood mechanisms after landslides (Costa and Schuster, 1987; Rudoy, 2002)

250

251 Although many of the other hazards in the cascade are responsible for additional catalysing relations, we only present examples
 252 for the wildfire hazard in this study. This is to emphasise that the fire has not only increased the probability of four secondary
 253 natural hazards at the start of the cascade, but it is also catalysing subsequent interactions between other hazards.

254 **3.2 Flooding**

255 All twelve respondents reported heightened flood risk in the Nyamwamba catchment. Five attributed this directly to changes
 256 in hydrological processes caused by the 2012 wildfire [M1; M2; G1; G2; R1], while others cited land use change [N1; W1;

257 R3], climate change [N1; I2], or the discontinuation of dredging [I1; R2]. A government official explained that “*the burning*
 258 *is the reason we are now having the floods annually... we know how useful wetland vegetation is in controlling floods, releasing*
 259 *water slowly*” [G1]. Similarly, a local guide described the flood-buffering role of the alpine wetlands: “*the moss was like a big*
 260 *1 m thick sponge, it soaked up all the rain... 20 or 30 km² of rock that was once boulders covered in moss is now bare*” [R1].
 261 Table 2 documents ten flood events since 2012, all exceeding in intensity the two documented events during the preceding 12
 262 years, with the 2013 and 2020 debris floods requiring international humanitarian appeals (Act Alliance, 2020; Delforge et al.,
 263 2025; Okiror, 2020).

264

265 **Table 2: Timeline of flood events of the Nyamwamba River documented by humanitarian databases and grey literature since 2000.**
 266 **The dates of the two most intense debris flood events are highlighted bold.**

Date	Area(s) Affected	Description & Impacts
1 st May 2001	Rukoki, Kilembe	1 death and 300 people affected by flooding in Kasese District (Delforge et al., 2025; DesInventar, 2025)
8 th September 2010	Rukoki, Ihandiro	A house, truck, pipeline and fields of crops destroyed by minor riverine flooding (Delforge et al., 2025).
<i>February 2012 – Wildfire burns 30.75 km² of the Rwenzori National Park</i>		
1st & 5th May 2013	Kilembe, Kasese District	Flooding and debris flooding in the Nyamwamba, Mubuku, Bulemba and Kitakena rivers displaced 25,445, with 13 deaths and US\$4,055,000 of damage (Delforge et al., 2025). Formal humanitarian response appeal of \$220,497 made by ACT Alliance (Act Alliance, 2013).
14 th May 2014	Kasese town	3,725 affected and 4 deaths in Kasese (DesInventar, 2025).
18 th June 2014	Kilembe	Flooded hospital and secondary school (Asiimwe, 2014).
18 th April 2016	Kanamba, Kanaka, Kasese District	10,000 affected and an estimated \$3,428,000 of damage following flooding of the Nyamwamba, Sebwe and Mubuku rivers between 4 th – 18 th April (Delforge et al., 2025; DesInventar, 2025; Juma, 2016).
4 th July 2017	Kilembe	4 killed in the Kilembe Valley (DesInventar, 2025).
5th May 2020	Kasese District	173,000 people affected in 24,760 houses across Kasese and Bundibugyo Districts following flooding of major rivers (Delforge et al., 2025). Debris and fluvial flooding on the River Nyamwamba submerged the Kilembe Mines hospital, with over 1,200 people displaced in Kasese town (Act Alliance, 2020; Flood List News, 2020a, 2020b). Formal humanitarian appeal for assistance made by the Ugandan Red Cross to support the displaced (Okiror, 2020)
23 rd May 2021	Kilembe	3 deaths and 134 affected following flooding and landslides in Kilembe town (Delforge et al., 2025).
18 th May 2023	Kasese District	1,016 people affected, and 23 deaths recorded between 24 th April and 18 th May due to multiple floods of the Muhokya, Mubuku, Sebwe and Nyamwamba rivers (Delforge et al., 2025).
22 nd May 2024	Kilembe, Kasese town	Sudden change of river course during high flow. Debris floods, riverine flooding and mudslides in the Nyamwamba catchment displaced 5,389 people in Kasese town (New Vision, 2024).

7 th September 2024	Kasese Town	2 deaths and extensive damage to key infrastructure including schools, roads, bridges and 120 houses. Change of course of river during high flows breached same location as the 22 nd May 2024 flood (ReliefWeb, 2024).
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268 The wildfire has increased the frequency and magnitude of fluvial flooding, but also introduced two new mechanisms of
 269 flooding, with gravity-driven debris floods and avulsion floods linked to increased mass movement (Sect. 3.3) and erosion
 270 (Sect. 3.4) in the catchment [M1; M2].

271 *Fluvial flooding*

272 Vegetation and soil loss following the wildfire reduced interception, infiltration, and water retention capacity, amplifying the
 273 river’s discharge response to rainfall. The fluvial flooding of unprecedented intensity on 5th May 2013 followed rainfall of
 274 only a 6.6-year estimated return period for a 6-hour event (Jacobs et al., 2016). Two respondents emphasise that a lack of lived
 275 experience prior to this first flood created additional vulnerability among affected communities: “2013 - that was when we
 276 were all surprised. I could not believe what I saw” [I1]; “we were not prepared because we had never experienced such
 277 magnitude” [M1]. Seven years later, an industrial worker recalled the 2020 event as “an 800 cumecs flood... higher than our
 278 professional hydrologist’s modelling of a 1000-year flood event” [I2].

279 *Debris flooding*

280 Two floods (2013 and 2020) included debris floods, confirmed in video footage and respondent testimony [M1; R1]. A water
 281 authority described “entire mahogany trees coming down as flood load” [M1], while a resident noted “moving rocks two times
 282 the size of a minibus” [R1]. Field photos (Appendix G) confirm extensive boulder deposition on the floodplain, and the river
 283 has since shifted from a pre-wildfire meandering form with vegetated banks to a braided morphology laden with coarse
 284 crystalline sediment (Appendix K).

285 *Avulsion flooding*

286 Elevated erosion rates and sediment deposition have heightened the risk of avulsions [M1; M2]. On 22nd May 2024, for
 287 example, the Nyamwamba breached its outer bank upstream of Kasese town, inundating Kiwa hot springs and displacing 5,389
 288 people [M1] (Table 2).

289 *Flood-driven Interactions*

290 High flows during fluvial and debris floods damage engineered flood defences, increasing their own probabilities of future
 291 breaches in self-perpetuating positive feedback (#7; #20; Appendix H). At the same time, their elevated velocities and
 292 turbulence generate shear stress and hydraulic action that trigger river erosion and accretion (#8; #18, #19). GIS analysis
 293 confirms that the years of greatest erosion (2013 and 2020) coincided with the largest debris flood events [M1; R1] (Sect. 3.4).

294 Fluvial, avulsion and debris floods transport contaminants across urban and agricultural landscapes, driving runoff pollution
295 (#6*; Appendix L). Additionally, debris floods deliver mobilized sediment directly into the river channel, promoting accretion
296 and progressively altering channel geometry over time (#19) [M1; M2; R1] (Figure 4).

297 **3.3 Landslides**

298 Landslides caused by lateral river erosion undercutting riverbanks and hillslopes (Jacobs et al., 2016) have accelerated since
299 the wildfire due to higher post-fire discharges and sediment loads [I1; M1; M2; R1]. In addition, the initial destruction and
300 exposure of formerly stable riverbanks during the wildfire and 2013 flood has worked to further increase the probability of
301 mass movement into the river [M1; G2]. Previously, graded banks of unconsolidated quaternary sediment were anchored by
302 climax vegetation. Now, vertical riverbanks are exposed to direct erosion and undercutting at sites throughout the river's long
303 profile. As one local government representative describes, "*when the floodwaters come down, they remove soil and grasses to*
304 *expose more boulders, and then you will have a landslide*" [G2]. This process is visible in Fig. 3c, where the riverbanks on
305 sections of the burned side are now steep, unvegetated banks of exposed and unconsolidated glacial till.

306 *Landslide-driven Interactions*

307 Landslides increase the probability of fluvial flooding by filling the channel with sediment and reducing the river's discharge
308 capacity (#21). Five respondents have also witnessed a mechanism of temporary landslide damming and bursting "*in the space*
309 *of a few minutes*" [M1] during high flow events, from which surges of sediment and discharge activate fluvial floods and debris
310 floods [G1; M1; M2; R1; W1]. As one resident recalls: "*suddenly, I heard a roar like a plane taking off at Entebbe Airport.*
311 *Two landslides cut off the river and created a dam behind it, then soon after there were entire trees pole vaulting over the*
312 *debris*" [R1].

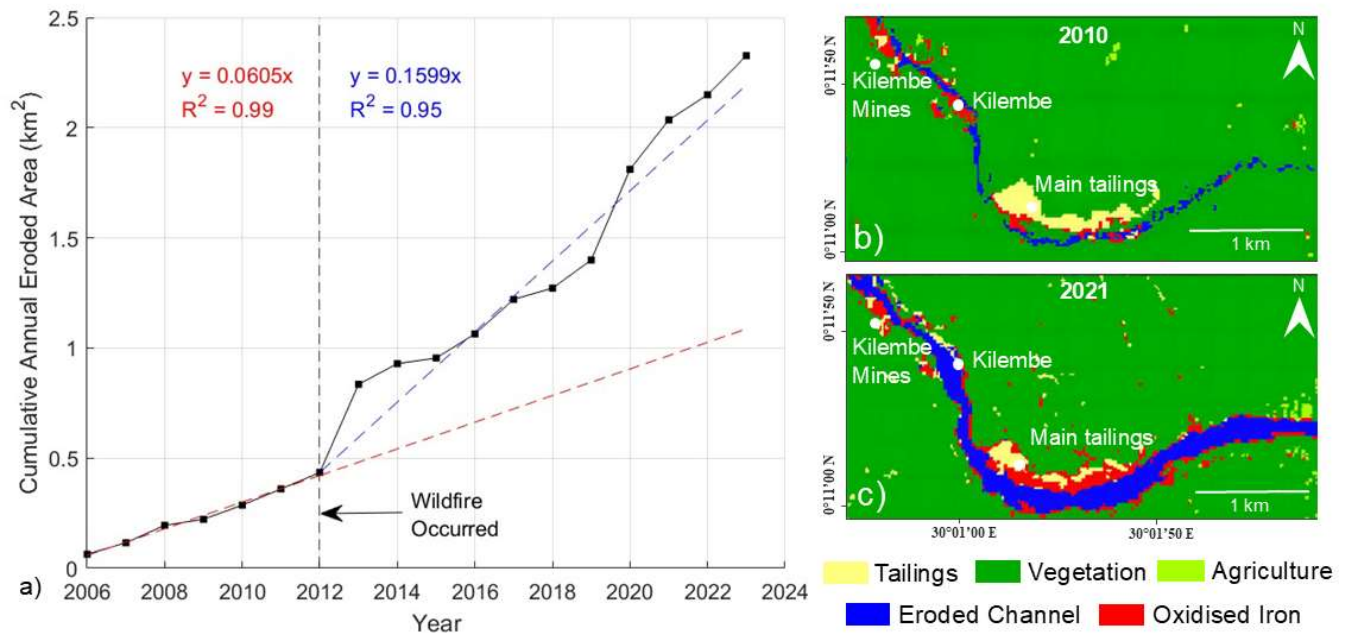
313

314 Five respondents describe landslides as being in a positive feedback process with erosion (through reciprocal interactions #23,
315 #22 and #10), whereby landslides add load to the river, accelerating accretion and lateral erosion by diverting flow to the
316 riverbanks and trigger further landslides [R1; M1; M2; I1; G2]. Landslides also trigger heavy metal pollution through the
317 rotational slumping of solid Co-Cu tailings at Kilembe Mines into the River Nyamwamba (#24; Sect. 3.5).

318

319 **3.4 River Channel Erosion and Accretion**

320 The cumulative annual eroded river channel area (Fig. 4a) shows a sustained increase in the river's rate of erosion by a factor
321 of 2.64 following the 2012 wildfire, and the average middle-lower course channel width has increased sevenfold between 2010
322 – 2021, from 16.9 m to 123 m. Rapid erosion has destroyed agricultural land [M1; M2; G1; G2], residential property, and
323 critical road infrastructure [M1].



324

325 **Figure 4: a) Annual cumulative eroded area in a 20 km mid-lower course section of the River Nyamwamba, calculated as the increase in eroded channel area between each year’s supervised classification; b) supervised classification of a February 2010 Landsat-7**
 326 **image; c) supervised classification of a February 2021 Landsat-8 image.**
 327

328 *Erosion and Accretion-driven Interactions*

329 Since the wildfire, accelerated lateral river channel erosion has shifted the river channel closer to populated areas of Kasese town and eroded debris has filled the channel via deposition, reducing its discharge capacity. Together, these erosion and
 330 accretion processes increase the probability of urban flooding in Kasese town [R1; G1; G2; M2; I2; R3] (#9). Accretion also
 331 increases the probability of avulsion flooding, as exemplified by the May and September 2024 floods, by filling the channel
 332 with sediment bars that divert flow towards riverbanks [M1] (#13), whilst directly triggering avulsion floods when it breaks
 333 through unconsolidated banks [M1; M2] (#14). Contributions of sediment to the main Nyamwamba channel also increase the
 334 probability of debris floods [M1; R1] (#17).
 335

336

337 Erosional undercutting destabilises slopes and directly triggers landslides (#10), consistent with Jacobs et al.’s (2016) mapping
 338 of 14 bank-failure slides during the May 2013 multi-hazard event. This lateral undercutting and exposure of vertical riverbanks
 339 is also described by three respondents as putting erosion in self-perpetuating positive feedback, by increasing the probability
 340 of further erosion at exposed banks [G1, G2, M1] (#11).
 341

342

342 Erosion and accretion are also coupled through reciprocal feedback (#15, #16). Sediment deposition narrows the active channel
 343 cross-section, increasing the flow velocity and erosive potential (#15), driving further channel erosion. The eroded material

344 replenishes the sediment supply available for sediment deposition (#16), sustaining this cycle. Together, these dynamics place
345 erosion and accretion in a self-reinforcing feedback loop along the river's reach.

346

347 Channel widening breached the Kilembe mine copper-cobalt tailings deposit in 2014 triggering heavy-metal pollution
348 downstream that now presents a major risk to public health (#12; Sect. 3.5).

349

350 **3.5 Pollution**

351 Immediately after the 2012 wildfire, community members reported increased turbidity and a smell "*like methane*" [M1] in the
352 river. This is still reported during high discharge twelve years later, which four respondents believe to be due to runoff (non-
353 point source) pollution through exposed bogs and organic-rich glacial sediments in the fire-affected and eroding upper
354 catchment [M1; M2; R1; G1] (#1).

355

356 Beyond this diffuse pollution, accelerated river erosion (#12) and landslides (#24) have inputted an estimated 744,000 tonnes
357 of a 15 Mt Kilembe Mines Co-Cu tailings deposit directly into the River Nyamwamba (mapped in Appendix K). Satellite
358 imagery and field photographs show erosional banks, slump scars and new channels within tailings areas, and evidence of acid
359 mine drainage from distinctive iron oxide precipitation (Fig. 3c; Appendix E). Elevated Co, Ni, Cu, Fe, Al, S, Zn, As, Cd and
360 Mn river contamination has previously been attributed to leaching of the Co-Cu mine (Abraham & Susan, 2017; Mwesigye et
361 al., 2016; Mwesigye & Lawrence, 2024; Mwongyera et al., 2014).

362

363 Five respondents identified this solid waste pollution as a major concern for public health [M2; W1; G1; G2; R1]. The river is
364 used by 38% of its adjacent population for drinking, and by many more indirectly through crop-irrigation and groundwater
365 abstraction (Abraham and Susan, 2017; Mukisa et al., 2020). In addition to waterborne risks, long-term contamination of arable
366 soils by deposited mine waste raises concern for food safety [M1; M2; G1; G2]. As one Ministry of Water official noted, "*in*
367 *Kasese District, their teeth are turning brown with yellow patches, and we have been told that many people in this region are*
368 *ailing with cancer*" [M2]. Local environmental managers also expressed concern for downstream ecosystems in Queen
369 Elizabeth National Park and Lake George, where protected flora and fauna may be affected by the pollution and vegetation
370 dieback observed in Kasese town [G2; M1, R1, W1].

371

372 *Pollution-driven Interactions*

373 Runoff pollution from the burned area transports elevated loads of fine sediment and contaminants into the river channel (#1)
374 [M1; M2; R1; G1]. This increased sediment supply promotes channel accretion as the excess sediment load settles into the
375 river channel (#5).

376 **4 Discussion: Implications for Management**

377 The intensity and persistence of the Rwenzori hazard cascade highlights how emergent wildfires in mature, fire-sensitive
378 mountain ecosystems can impose long-lasting risks on downstream communities. Recovery in these environments is slow, and
379 positive feedback mechanisms sustain elevated risk. By characterising hazard interactions in full, this study identifies entry
380 points for intervention as management approaches that systematically impede hazard interactions can help unravel cascades
381 (Gill and Malamud, 2016).

382
383 The principal way to impede this cascade is at the top (interactions #1-4), by promoting ecosystem recovery and attenuating
384 the elevated runoff and river discharge driving other hazards. In the Rwenzori, authorities implemented a mix of hard
385 engineering, community-centred and nature-based solutions in the lowlands which has saved lives (see Appendix M); however,
386 the prevailing approach to wildfire restoration has been to await natural recovery. This passivity missed a critical window to
387 implement soil stabilisation and runoff attenuation solutions such as mulching, contour felling and forest restoration
388 (Papaioannou et al., 2023; Robichaud et al., 2013; Scheper et al., 2021), and allowed lower canopy vegetation to establish
389 ahead of upper canopy tree species in the ericaceous zone (Fig. 3c). The challenge now is to develop recovery and discharge
390 attenuation solutions in a partially recovered ecosystem. Addressing this requires post-wildfire expert assessment to guide
391 restoration planning and build an evidence-base for financing solutions (Veness and Buytaert, 2025).

392
393 In the later stages of the Rwenzori cascade, erosion emerges as a key driver of multiple hazard interactions and positive
394 feedback processes. It has accelerated landslides, amplified debris floods, triggered flooding, and caused a major water
395 pollution hazard now requiring urgent investigation of its scale and health impacts. Stabilising riverbanks is a critical
396 intervention to mitigate erosion and therefore impede its cascading interactions. We recommend integrating existing dredging,
397 levee construction, and nature-based approaches to achieve this (Appendix M; MoWE, 2022). In particular, repositioning
398 coarse sediment to riverbanks can help protect eroding riverbanks, regrade unstable slopes, and create conditions for in-channel
399 vegetation to anchor finer sediments and restore soil, thus mimicking the stable, unburned riverbank morphology seen in Fig.
400 3c (Sanches Fernandes et al., 2020). These measures are urgent in the mid-catchment to protect communities and limit further
401 mobilisation of solid mine waste, but also advisable in the upper catchment to reduce sediment generation and landslide risk.

402
403 The principle of mimicking natural processes to promote post-wildfire recovery has been successfully implemented elsewhere
404 (European Environment Agency, 2025). In New Mexico, Engineering With Nature (EWN) principles were implemented
405 following the 2011 Las Conchas Wildfire to implement low-tech hillslope and in-channel structures including mulch barriers,
406 contour-felled log debris, tree-check dams, and in-channel sediment grade-control features to stabilise slopes and reduce
407 downstream sediment transport (Haring et al., 2021). In Arizona, USA, following the 2019 Museum Fire, alluvial fan
408 restoration through regrading and rock sill installation has a predicted reduction in downstream sediment transport of 70%

409 (Schenk et al., 2025). Post-fire restoration following the 2020 Cameron Peak Fire in Colorado included post-assisted log
410 structures and beaver dam analogues to attenuate peak flows and promote sediment aggradation in burned headwater streams
411 to replicate the hydrological buffering functions of pre-fire riparian systems (Wheaton et al., 2019; CPRW, 2026; Nichter et
412 al., 2026). Whilst these represent a small selection of examples, the underlying principle of designing interventions to mimic
413 pre-disturbance geomorphological and hydrological processes offers a transferable blueprint for post-wildfire management in
414 significantly altered catchments like the Nyamwamba (Haring et al., 2021; Bombino et al., 2024).

415

416 Montane environments globally, especially those without a history of fire, require greater investment in monitoring and
417 research into post-wildfire hazard cascades (Arango Carmona et al. 2025; Mason et al., 2026; Wimberly et al. 2024). The lack
418 of comparable case studies makes it difficult to determine whether the Rwenzori represents an outlier or part of a broader
419 emerging trend; however, the intensity of the Rwenzori cascade, following a burn area of just 31 km², is a signal to trigger
420 post-fire risk assessments at lower thresholds of burn area and severity when an emergent fire occurs in a fire-sensitive
421 mountain ecosystem (Mason et al., 2026). Expanding research in similar regions may help build an evidence base of
422 comparable events, common cascading interactions and best practices for their management.

423 **5 Conclusions**

424 This study has characterised a post-wildfire multi-hazard cascade in a tropical montane catchment, demonstrating how the
425 burning of a pristine, fire-sensitive mountain ecosystem can initiate cascading hazards of exceptional intensity and persistence.
426 As fire regimes continue to shift to higher altitudes under climate change, there is an emerging risk of similar hazard cascades
427 for downstream communities in tropical mountain catchments worldwide (Mason et al., 2026).

428

429 In Uganda's Rwenzori National Park, in the twelve years after a 2012 wildfire burned 31 km² of mature forest and peatland,
430 ten major floods with fluvial, debris or avulsion mechanisms occurred, with two debris floods requiring large-scale
431 humanitarian responses. Increased river discharge after the fire caused a 2.64-fold increase in erosion rates and increased the
432 probability of landslides, which have together driven a sevenfold increase in river channel width over nine years. Urban and
433 agricultural areas now face a real-time risk to public health due to the erosion and mass movement of 744,000 tonnes of copper-
434 cobalt solid tailings into the River Nyamwamba since 2014. This discrete escalation of hazards, interactions and impacts is
435 sustained by the slow recovery of vegetation poorly adapted to fire regimes, and multiple positive feedbacks between hazard
436 interactions.

437

438 The Rwenzori case highlights a need to recognise post-wildfire hazard cascades as a long-term risk in tropical mountain
439 environments, especially in newly fire-prone areas with no prior history of burning. High-income countries generally have
440 established post-fire risk assessment protocols, such as the Burned Area Emergency Response used in the USA (NICF, 2026),

441 and the Post Wildfire Natural Hazard Risk Analysis in British Colombia, Canada (Government of British Colombia, 2023).
442 Meanwhile, many low- and middle-income countries still lack standardised assessment procedures at the local or national
443 level. We recommend post-fire risk assessments and research, even for relatively small burn areas, when future fires occur in
444 previously unburned or fire sensitive mountain ecosystems. A better understanding of interactions between hazards identifies
445 intervention points, where interactions can be impeded through early actions that prevent ecosystem impacts from becoming
446 entrenched long-term. To this end, remediation of the burned zone should always be a priority to accelerate ecosystem recovery
447 and attenuate elevated runoff.

448
449 More monitoring and research of global case studies is needed to establish the prevalence and behaviour of tropical mountain
450 wildfire hazard cascades at emergent elevations, and best practices for their management. This study has additionally
451 underscored the value of integrating qualitative data and local knowledge into such studies. Interviews were critical to
452 identifying key hazard interactions that would not have been captured through physical or remote data alone. Interdisciplinary
453 research, through close partnerships between academic and local stakeholders, can improve collective visibility on this
454 emerging climate risk and accelerate the development of shared solutions.

455

456 **6 Data Availability**

457 The interview data is confidential according to ethical and data sharing restrictions. The GIS data files are available in Zenodo
458 (doi: 10.5281/zenodo.20556393).

459 **7 Competing Interests**

460 We declare no competing interests.

461 **8 Author Contributions**

462 William Veness: Writing – review & editing, Supervision, Writing – original draft, Visualization, Validation, Software, Resources, Project
463 administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization

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476 Wouter Buytaert: Writing – review & editing, Supervision, Methodology, Investigation, Project administration, Conceptualization,
477 Validation

478 **9 Acknowledgements**

479 We thank the Uganda Red Cross Society, the Ministry of Water and Environment, Kasese Municipality, and all local
480 collaborators and community members in Kasese District for their contributions to this research. We are grateful to the Uganda
481 Wildlife Authority and Rwenzori Trekking Services for facilitating access to the Rwenzori Mountains National Park. This
482 study was initiated through support from Imperial College London’s African Research Universities Alliance (ARUA)
483 partnership, which enabled collaboration with Makerere University. The Red Cross Red Crescent Climate Centre is also
484 gratefully acknowledged for its role in establishing the partnership with the Uganda Red Cross and the Ministry of Water and
485 Environment.

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827 **11 Appendices**

828 **Appendix A: 1-Month Standardised Precipitation Index Calculation for January 2012**

829 ERA5 monthly averaged reanalysis total precipitation data was downloaded from 1974 – 2024 for the pixel covering to the
830 burned area (centroid coordinates: 0.4°N, 29.8°E; Copernicus Climate Change Service (C3S), 2017). This was processed in
831 MATLAB following McKee et al.'s (1993) method to determine the monthly-SPI for January 2012.
832

833 **Appendix B: Eroded Tailings Volume Calculation**

834 The average original height of the tailings was calculated to be 23 m, assumed to be flat across the original dammed area,
835 which was calculated (32945 m²) from historic satellite imagery.

836

837 This average height (23 m) was multiplied by the eroded footprint area (m²) to get a volume, then volumetric subtractions were
838 made to account for the originally sloped (55 degrees) walls of the tailings dam and the wedges of slumped material yet to be
839 eroded at the foot of the collapsed tailings escarpments. The volume of these wedges was calculated from the slope angle and
840 height of their triangular cross-section, multiplied by their width parallel to the eroded tailings escarpment.

841

842 The tonnage of eroded tailings was then calculated by multiplying their estimated volume by their assumed average dry density
843 (1.5 t/m³) based on standard values for copper-cobalt tailings (Williams, 2015).

844

845 **Appendix C: Semi-Structured Interview Template**

846 *Background*

- 847 ● What organisation do you represent?
- 848 ● What is your role?
- 849 ● What is your experience of hazards in the Rwenzori?

850

851 *Perceptions of changing hazard risk*

- 852 ● Do you feel the risk of hazards have changed (in the Nyamwamba catchment)? How?
- 853 ● If yes, why do you feel risk is changing?
- 854 ● Do you feel the river Nyamwamba/Mubuku/other rivers have changed?
- 855 ● If yes, why do you think this change has happened?

856

857 *Awareness and efficacy of existing management strategies*

- 858 ● What existing strategies are in place to manage hazard risk in the Rwenzori?
- 859 ● Do you feel these strategies are working?

860

861 *Potential alternative management strategies*

- 862 ● What strategies do you feel would better reduce hazard risk in the Rwenzori?
- 863 ● Why do you think these have not been implemented yet?
- 864 ● Do you feel nature-based solutions could be used to manage these hazards?

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869 **Appendix D: The Multi-Hazard Cascade Interactions**

Table D1: Definitions of hazard terminology in this article from the 2025 Hazard Information Profiles (HIPs; UNDRR, 2025).

*Both avulsion flooding and debris flooding are profiled under Flooding - MH0600 (UNDRR, 2025) however further distinction using key references between these types of flooding is important here for understanding the hazard cascade and its interactions.

Hazard	HIPs 2025 Definition	HIP 2025 Identifier	Primary Source(s)
Wildfire	Any unplanned and uncontrolled vegetation fire that, regardless of ignition source, may negatively affect social, economic or environmental values, and require suppression response or other action according to agency policy (FAO, 2024).	EN0205	FAO (2024)
Runoff Pollution	Nonpoint sources of pollution refer to pollution that does not have a single point of origin or has not been introduced into a receiving freshwater or maritime environment from a specific outlet. The pollutants are generally carried off from the land by agricultural runoff, urban stormwater, atmospheric deposition or subaqueous groundwater discharges. The most common categories of nonpoint pollution are agriculture, forestry, urban areas, mining, construction, dams and channels, land disposal and saltwater intrusion.	EN0106	UNdata (2026) Admad, Sakib and Gang (2016)
Fluvial Flooding	Overflowing by water of the normal confines of a watercourse or other body of water (WMO, 2012).	MH0604	UNESCO and WMO (2012)
*Avulsion Flooding	River avulsions are an abrupt change in a rivers course to establish a new river channel. These are natural phenomena as the river migrates across the floodplain but can result in devastating avulsion floods. Whilst their mechanism is not yet fully understood, they are considered to occur when sediment depositions downstream of the avulsion location cause the existing channel to become unfavourable and so the channel switches to a route with a more efficient flow pathway (Singerland and Smith, 2004; Gearon et al., 2024).	MH0600	Singerland and Smith (2004) Gearon et al. (2024)

River Erosion and Accretion	River erosion is the removal of material from the banks and beds of rivers and streams (Lawler, 1993). River accretion is the formation of new land such as channel bars, sandbanks and deltas by sedimentation or changing river flow (after Islam and Guchhait, 2020 and Hasanuzzaman et al., 2024).	GH0404	Lawler (1993) Hasanuzzaman et al. (2024) Islam and Guchhait (2020)
Debris Flows	Debris flows are rapid, gravity-driven flows of poorly sorted material in which water and sediment form a dense slurry, typically with sediment concentrations exceeding 50% by volume (Rengers et al., 2020; Pierson, 2005). This distinguishes them from hyperconcentrated flows (approximately 20-60% sediment by volume) and water-dominated floods (below approximately 10% sediment by volume) in which flow behaviour is primarily controlled by water instead of the entrained sediment (Pierson, 2005). Debris flows behave like wet concrete, capable of holding gravel in suspension at low velocities, and transporting large boulders and woody debris at high velocities (Pierson, 2005). Due to their density and momentum, they are generally more destructive than floods or debris floods and can cause catastrophic damage through impact and burial (Pierson, 2005). Post-fire debris flows are fast moving slurries of soil, ash, rocks, burned vegetation and water, typically triggered by short-duration, high-intensity rainfall in the first few years following a fire (Oakley et al., 2025; Rengers et al., 2020).	GH0303	Rengers et al. (2020) Pierson (2005) Oakley et al. (2025)
*Debris Flooding	Debris floods are ‘very rapid flow of water, heavily charged with debris, in a steep channel...’ in which ‘the streambed may be destabilized’ (Hung, Leroueil and Picarelli, 2014) resulting in massive sediment transport over large distances (Church and Jakobs, 2020). Crucially, flow behaviour in a debris flood is still controlled by water rather than the entrained sediment (Pierson, 2005), and peak discharge remains comparable in order of magnitude to that of a water-dominated flood.	MH0600	Hung, Leroueil and Picarelli (2014) Church and Jakobs (2020) Pierson (2005)
Landslide**	A gravitational mass movement (‘landslide’) is the downslope movement of soil, rock and organic materials under the effects of gravity, which occurs when the gravitational driving forces exceed the frictional resistance of the material resisting on the slope. Such movements may be terrestrial or submarine (GH0306) (Cruden and Varnes, 1996).	GH0300	Cruden and Varnes (1996)

**Here, we define landslides as those connected to the river system.

Heavy Metal Pollution	Heavy metals are metallic trace elements with either high relative atomic weights or occurring in materials with high densities. Trace Elements is the term used for elements that are generally found in soil at low concentrations. Trace elements can become contaminants when their concentrations significantly exceed natural levels due to anthropogenic activities, such as industrial processes, mining, agriculture, and waste disposal. These contaminants can accumulate in soil, water, and biota, potentially causing adverse effects on ecosystems and human health.	CH0100	FAO and UNEP (2021)
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Table D2: Description of the hazard interactions in Fig. 2 and supporting evidence.

#	Initiating Hazard	Affected Hazard	Interaction Description	Evidence
1	Wildfire	Runoff pollution	Increased probability. Burning of soils and vegetation cover increased their erosion and runoff to the river channel. This hazard is also catalysed by higher rates of erosion increasing the delivery of soil, ash and peat to the river.	Four interview respondents describing increased turbidity immediately after the wildfire and during high flows, with a smell “like methane” [M1, M2, R1, G1].
2	Wildfire	Fluvial flood	Increased probability. Burning of vegetation has reduced interception and root uptake of precipitation, increasing surface runoff to the channel. This has increased peak discharges at reduced lag times following peak rainfall events. The burning and erosion of mature soils has also reduced their infiltration and storage capacities, therefore increasing runoff.	Humanitarian data of 10 flood events since 2012 exceeding the impacts of any documented flood in the 12 years prior (Table 1). Interviewee accounts [M1, M2, G1, G2, R1], e.g. “ <i>the burning is the reason we are now having the floods annually... we know how useful wetland vegetation is in controlling floods, releasing water slowly</i> ” [G1].
3	Wildfire	River channel erosion	Increased probability. Wildfire’s burning of vegetation and erosion of soil has increased runoff, peak river discharge, and therefore the erosive power of the river. Initial erosion and mass movement also exposed riverbanks, which is increasing the probability of (and catalysing) further erosion in a positive feedback process.	GIS analysis calculating an erosion rate increase by a factor of 2.64 due to the wildfire (Fig. 4). Photographs of exposed riverbanks within wildfire affected areas (Fig. 3c and Appendix F).
4	Wildfire	Debris flood	Increased probability. Wildfire has increased peak river discharge by the burning of vegetation and soil which modulate discharge. It has also increased sediment generation through augmented erosion and mass movement, improving the conditions for debris flood development.	Two interview respondents explain and show camera footage of 2013 and 2020 debris floods, described as unprecedented before the fire [M1, R1] (Table 1). Jacob’s et al.’s (2016) reconstruction of debris flood during the May 2013 flood. Field photographs of boulder deposition on the delta and distal flood plain (Appendix G).

7	Fluvial flood	Fluvial flood	Increased probability. Fluvial floods damage engineered flood defences, increasing the probability of future breaches.	Photos of damaged flood defences (Appendix H).
8	Fluvial flood	River channel erosion	Triggering. Higher flow velocities and turbulence during fluvial floods exert shear stress, abrasion and hydraulic action to erode riverbanks.	GIS analysis shows the years of highest erosion occurred in 2013 and 2020, the years of the largest debris and fluvial floods [M1, R1] (Fig. 4).
6*	Fluvial flood	Runoff pollution	Triggering. Fluvial floods transport materials across the urban and agricultural landscape. If pollutants are present, this results in a runoff pollution event. *This is also true of avulsion floods and debris floods	Respondents describe post-flood contamination of urban and agricultural landscapes [M1, M2]. Field photographs of contaminant transport into urban areas (Appendix L, Fig. L1).
9	River channel erosion and accretion	Fluvial flood	Increased probability. Eroded material fills and reduces the channel's carrying capacity for discharge. Erosion has also relocated active channels closer to residential areas.	Change in river morphology to a sediment-laden braided system indicating increased deposition and channel switching (Fig. 4b).
10	River channel erosion and accretion	Landslide	Triggering. Lateral and vertical erosion of riverbanks undercuts and destabilises hillslopes, increasing local shear stresses to failure.	Jacobs et al. (2016) map 14 landslides triggered by scour and bank failure from river erosion.
11	River channel erosion and accretion	River channel erosion	Increased probability. Erosion of banks exposes steep, unstable riverbanks to further erosion.	Photos of erosional riverbanks incising into hillslopes at multiple sites (Appendix F). Interviewee descriptions [G1, G2, M1]
12	River channel erosion and accretion	Heavy metal pollution	Triggering. River erosion has breached the main 15 Mt solid Co-Cu Kilembe Mines tailings deposit and other smaller deposits within the town.	Satellite images and field photographs (Fig. 4) show erosive riverbanks and new channels within the original tailings area. Field observations of downstream deposition of tailings and iron precipitates (Appendix E). Four respondents consider waste deposition a major concern for public health and a potential cause of vegetation death on the riverbanks [M2, W1, G2, R1].
14	River channel erosion and accretion	Avulsion flood	Triggering. Increased erosion of riverbanks causes channel-switching and subsequent avulsion floods.	Humanitarian data and interview respondents [M1, M2] describing the 22nd May 2024 avulsion flood impacting Kasese town (Table 1).
13	River channel erosion and accretion	Avulsion flood	Increased probability. Higher rates of upstream erosion increase downstream deposition in channel bars, diverting flow towards riverbanks.	Interview respondents [M1, M2] describing the 22nd May 2024 avulsion flood impacting Kasese town (Table 1) and the increased rate of deposition that has raised dredging and channel clearance costs since the 2012 wildfire [M1, M2, R1].
17	River channel erosion and accretion	Debris flood	Increased probability. Erosion provides additional sediment that improves the probability of debris flood formation.	GIS analysis of increased channel area and width (Fig. 3) filled with coarse sediment in a braided system (Appendix K). Two respondents describe debris floods as unprecedented before the fire [M1, R1].
15	River channel	River channel erosion	Increased probability. Sediment deposition narrows the active channel	Interview respondents describing sediment erosion and accretion processes in river channel [M1, M2,

	erosion and accretion		cross-section, increasing the flow velocity and erosive potential driving further channel erosion.	R1, G1, G2]. GIS analysis of increased channel area and width (Fig. 3) filled with coarse sediment in a braided system (Appendix K).
16	River channel erosion and accretion	River channel accretion	Increased probability. Sediment deposition narrows the active channel cross-section, increasing the flow velocity and erosive potential driving further channel erosion (#15). The eroded material replenishes the sediment supply available for sediment deposition (#16), sustaining this cycle.	Interview respondents describing sediment erosion and accretion processes in river channel [M1, M2, R1, G1, G2]. GIS analysis of increased channel area and width (Fig. 3) filled with coarse sediment in a braided system (Appendix K).
20	Debris flood	Debris flood	Increased probability. Debris floods damage engineered flood defences, increasing the probability of future breaches.	Photos of damaged flood defences (Appendix H).
18	Debris flood	River channel erosion	Triggering. Debris floods have high erosive power (Church & Jakob, 2020).	GIS analysis shows the years of highest erosion occurred in 2013 and 2020, the years of the largest debris and fluvial floods [M1, R1] (Appendix K).
19	Debris flood	River channel accretion	Triggering. Debris floods deliver mobilized sediment directly into the river channel, promoting accretion and progressively altering channel geometry over time.	Interview respondents describing the increase in channel sediment deposition following debris flood events [M1; M2; R1].
24	Landslide	Heavy metal pollution	Triggering. Rotational slumping of the soft, unconsolidated tailings into the River Nyamwamba causes heavy metal contamination of water and sediment.	Satellite images and field observations (Appendix K) show rotational slump scars throughout the affected tailings. Four respondents consider waste deposition a major concern for public health and a potential cause of vegetation death on the riverbanks [M2, W1, G2, R1].
23	Landslide	River channel erosion	Increased probability. Landslides increase sediment load and the subsequent erosive power of the river through abrasion.	Interview respondents describing the increase in channel sediment deposition following landslides [R1; M1; M2; I1; G2]. Field photographs of slump scars on riverbanks (Appendix I). Analysis by Jacobs et al. (2016) showing landslides directly entering the river system.
22	Landslide	River channel accretion	Increased probability. Landslides add increase sediment load, accelerating accretion and lateral erosion by diverting flow to the riverbanks.	Interview respondents describing the increase in channel sediment deposition following landslides [R1; M1; M2; I1; G2]. Field photographs of slump scars on riverbanks (Appendix I). Analysis by Jacobs et al. (2016) showing landslides directly entering the river system.

21	Landslide	Fluvial flood	<p>Increased probability. Landslide material fills and reduces the channel's carrying capacity for discharge.</p> <p>Landslides also increase the probability of fluvial (and debris) flooding through temporary damming and bursting mechanisms that create surges of discharge.</p>	<p>Jacobs et al. (2016) mapped 29 landslides during the May 2013 flood that directly entered the River Nyamwamba.</p> <p>Five respondents describe a mechanism of temporary landslide damming and bursting "in the space of a few minutes" [M1] during peak rainfall events in the upper-catchment [G1, M1, M2, R1, W1].</p>
5	Runoff pollution	River channel accretion	<p>Increased probability. Runoff pollution from the burned area transports elevated loads of fine sediment and contaminants into the river channel. Increased sediment supply promotes channel accretion as the excess sediment load settles into the river channel.</p>	<p>Four interview respondents describing increased turbidity immediately after the wildfire and during high flows, with a smell "like methane" [M1, M2, R1, G1].</p> <p>GIS analysis of increased channel area and width (Fig. 3) filled with coarse sediment in a braided system (Appendix K).</p>



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876 **Figure E1: Acid mine drainage at location 0.18599N, 30.01951E, 25 July 2024.**



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878 **Figure E2: Acid mine drainage at location 0.19879N, 30.01139E, 3 August 2024.**



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Figure E3: Tailings sedimentation in the Nyamwamba channel, 0.18652N, 30.01986E, 25 July 2024.



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Figure F1: Riverbank exposure at 0.29291N, 29.93596E – 28 July 2024.



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Figure F2: Riverbank style erosion of house foundations in Kilembe, 0.20603N, 30.00822E – 24 July 2024.

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Figure F3: Riverbank at 0.23742N, 23.97568E – 1 August 2024.



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Figure F4: Riverbank at 0.23715N, 29.97601E – 1 August 2024.



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905 Figure G1: 0.20285N, 30.00908E - 7 June 2023.



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Figure G2: 0.19528N, 30.01544E - 25 July 2024.



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Figure H1: 0.18981N, 30.07408E, 26 July 2024 (damaged bamboo nature-based solution).



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Figure H2: 0.21387N, 30.00558E, 7 June 2023 (damaged gabions).



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Figure 11: 0.29291N, 29.93596E – 28 July 2024.



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Figure 12: Landslide scar at 0.23758N, 29.97570E – 1 August 2024.



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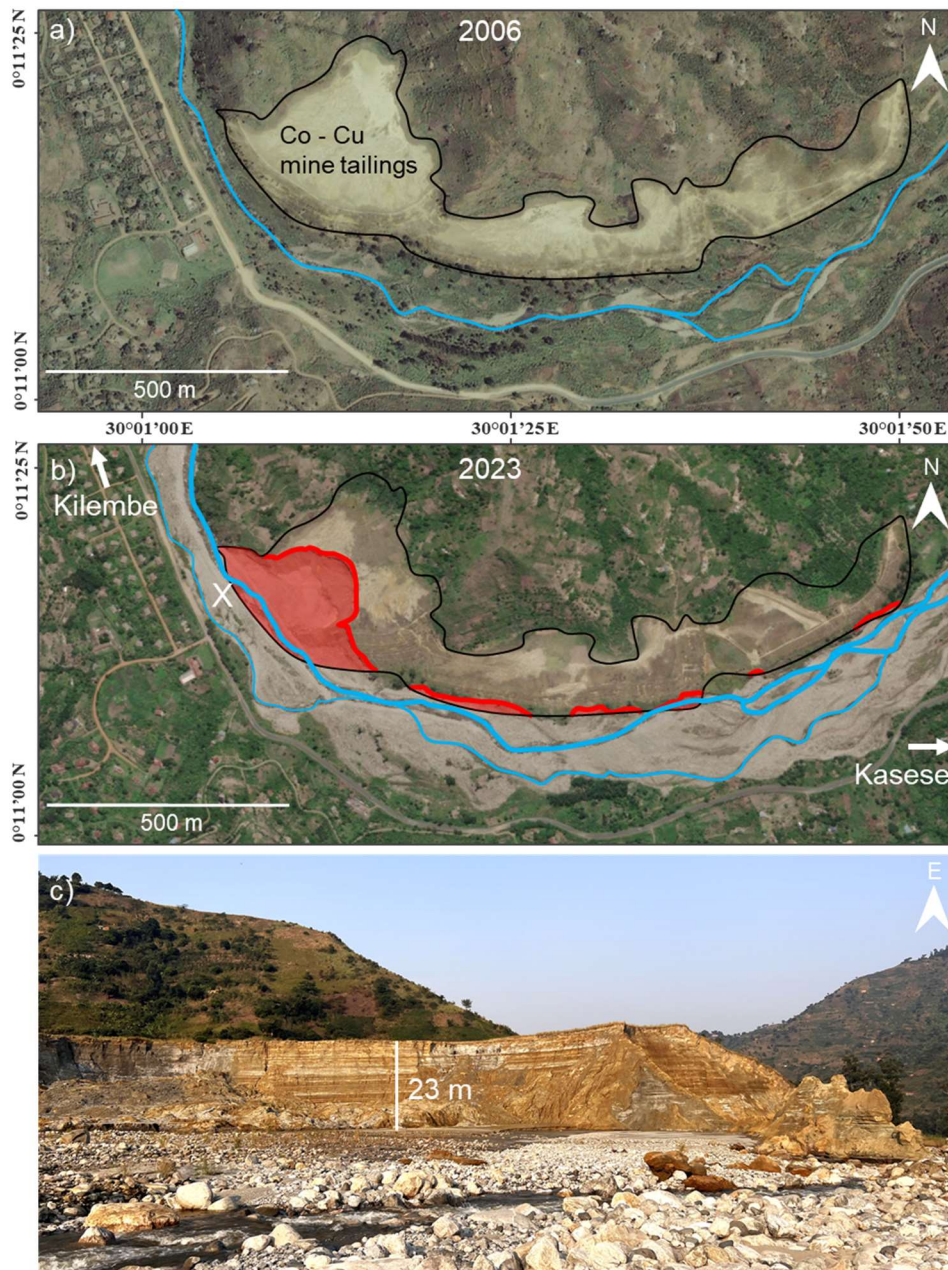
Figure J1: Deposition and acid mine drainage downstream of Kilembe Mines 0.19385N, 30.082355 E, 26 July 2024.



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Figure J2: Acid mine drainage from deposited solid tailings at location adjacent to Kasese town, 26 July 2024.



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937 Figure K1 – a) Kilembe Mines tailings on 24th March 2006 (Maxar Technologies, 2024a); b) the same location on 10th Apr 2023

938 (Maxar Technologies, 2024b) where an estimated 744,000 tonnes of solid waste have eroded into the river. The black polygon outlines

939 the original surface area of mine tailings, and the red polygon shows the area partly or fully eroded; c) photograph of a section of

940 the eroded tailings taken in July 2024 at position X (b), facing east towards Kasese town.



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943 **Figure L1: Photograph following flooding in Kasese town evidencing the inundation level and post-flood ground**
944 **contamination. Photograph provided by the Ministry of Water and Environment.**

945 **Appendix M: Management Strategies and their Evaluation**

946 The disaster risk management (DRM) strategies in Table L1 have been implemented in the Nyamwamba catchment since the
947 May 2013 floods. Whilst relocation of communities experiencing near-annual flooding is considered desirable for mitigating
948 their flood risk [M1, M2, N1], residents have opposed relocation due to existing community and land ties, lower living costs
949 on flood plain and a lack of economic opportunity in areas proposed for relocation [M1, G2, N1]. Instead, therefore, strategies
950 have focussed on protecting existing communities and informal settlements on the flood plain with hard engineering,
951 community-centred and nature-based solutions (Table L1).

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953 **Table M1 – Summary of disaster risk reduction strategies in Kasese Districts observed during field reconnaissance and described**
954 **by interview respondents.**
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Strategy		Description	Evaluation
Hard Engineering	Gabions (Figure M1a)	Installed in phases along a 2-3 km alongside Kilembe town to mitigate flooding and river channel switching.	“The Gabions have failed, they’re very weak” [R1]. Damaged by minor flood events (Appendix H), and they have failed to prevent channel overtopping into Kilembe Town during the 22 nd May 2024 flood [M2].
	Channelisation (Figure M1b)	A short 500 m channelised section of channel downstream from Kilembe, using concrete to ensure the stability of the road-bridge providing the only access route to Kilembe town.	“what they have done [at the bridge] is perfect...the narrow section never gets clogged up so the rocks pass through” [R1]. The solution has been positively received [R1, R2], but it is considered expensive, and river may switch channels if extended [M2].
	Dredging	5 km of channel is desilted (boulders are broken down and removed from the active water channels to the banks) in an irregular regime, typically funded after major floods such as those in 2013 and 2020 [M1, M2].	It costs US\$4.5 million to clear 5 km of the channel and it needs to be performed annually to maintain a cleared channel [M2]. Residents recall successful desilting by a Canadian mining company until the 1971, so it is a positively viewed activity [G1, G2, W1] but may not be economically sustainable with the currently increased sediment flux of the river [M1]. It does not take place far enough upstream of Kilembe where debris floods generate [R1, M2].
Community-Centred Solutions	Flood Early Warning Systems (Figure M1c)	Communities of Kilembe, Kasese and Mubuku given early warnings through the Ugandan Red Cross and the Ugandan Ministry of Water and Environment (MoWE) following alerts of high rainfall.	"with early warning systems, less people are dying... people are more informed with better risk communication" [N1]. However, difficulties monitoring water levels due to high sediment loads and channel switching leaves early warning dependent on rainfall forecasts that are low-confidence in a convectional mountainous region [M2]. Expansion requires greater hydrological monitoring for more accurate, confident and timely warnings [N1, M2].
	Resident Relocation	Relocation of displaced households from Kilembe and riverbanks to the Kasese lowlands, using emergency response funding following major 2013 and 2020 flood events [N1, M1]. Matched with investment to support alternative livelihoods independent of the river such as bee keeping [M1].	In most cases, residents have refused to relocate and are building informal homes [M1]. There is a need for expansion of livelihood incentives and longer-term support investments for their setup [G2]. High flood risk areas offer low-cost land, economic opportunities, free water from the river and many have attachment to lands from family history, mountain livelihoods and lived experience [N1].
	Participatory Desilting	Pilot project training individuals to convert river boulders into crafts, such as granite wash-basins to be sold to safari lodges and tourists.	It is not being completed at a scale that significantly impacts flood risk [M1], but it has been shown to successfully supplement family incomes (Ugandan Ministry of Water

			and Environment (MoWE), 2022). It requires longer-term investment and a plan for expansion and greater access to the market [N1, M1].
Nature-based Solutions (NbS)	Riverbank Stabilisation (Figure M1d)	As part of a 2021 World Bank funded project (MoWE, 2022), a 10 km length of the Nyamwamba riverbanks have been planted with 30 m thick vegetation buffers to mitigate further lateral erosion. Seedlings planted included 35,000 Asper bamboo, 2,000 mango and 4,000 Mahogany, situated within a fenced zone to deter trespassing, logging, theft and interference by animals (MoWE, 2022).	An existing pilot in Mubuku has demonstrated 20 years of successful bank stabilisation [M1], however 2021 Nyamwamba planting has faced challenges of droughts, floods, termites [W1], death of seedlings due to heavy metal contamination by mine tailings, logging, and reluctant participation by some land owners. Rapid initial growth in patches require long term monitoring and evaluation, but bamboo planting is perceived as the most promising solution for landslide and erosion mitigation in the wildfire-affected zone and around the mine tailings [R1, M1, M2, I1, I2, W1]
	Soil and Water Conservation	Awareness raised among 1,420 land owners of methods available to reduce soil erosion and runoff. 750 were trained to implement the intervention and provided equipment, with 211 hectares of land modified by the addition of trenches and hedges in 2021-2022 (MoWE, 2022). Households encouraged to harvest rainwater instead of drinking from the river.	“there was actually a gentleman that implemented it on his own land, without us telling him to.” Need for more land-owner co-operatives to share trainings, to share risk of failed implementation following land conversion, and to share tedious workloads [G2]. Rainwater harvesting reduces runoff, soil erosion on small plots and decreases heavy metal consumption from river water [M2, G2].
	Afforestation and Regrading of Hillslopes	825 hectares afforested through reforestation and agroforestry in the mid-catchment to reduce landslides, soil erosion and runoff to the river (MoWE, 2022).	Soil-water conservation trenches and soil-stabilising species increased coffee yields [F1]. Some respondents criticised soil-water conservation and afforestation efforts for focussing on the mid-catchment, when “99%” of the sediment and discharge generation is taking place in the burned national park area upstream [R1, I2]. "Until we stabilise those areas [upstream] we will have these problems" [I2].

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957 For hard engineering strategies, respondents believe that gabions are too weak to sustainably channelise the river [R1, M2]
 958 (Figure M1a), whereas there is demand for the successful concrete channelisation to be extended beyond Kilembe town centre
 959 [R1, R2, M2] (Figure M1b). Channel dredging is perceived to be a critical activity, not because of successful implementations
 960 since 2013, but due to successful historic programmes of dredging by mining companies when Kilembe mines was operational
 961 in the 1960s [G1, G2, W1, R1, M2]. For all hard engineering approaches, there is concern of an unsustainably high cost of
 962 maintenance, given the elevated rate of discharge, erosion and sediment generation in the Nyamwamba river [M1, M2].

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964 Flood early warning systems piloted in Kilembe and Kasese using 2 local rain gauges and water level sensors have faced
965 challenges of continuous automated data collection in hard-to-reach upstream locations, however, sharing of information
966 between authorities and community representatives via Whatsapp has successfully coordinated evacuations following high
967 flows and rapid dispatches of emergency respondents [N1]. A 2023 installation of a camera 5 km upstream of Kilembe, capable
968 of international photo and video transmission at 1-minute intervals (Figure M1c), is considered a useful supplementary dataset
969 for a more detailed interpretation by those with lived experience and indigenous knowledge of the river [N1, M2]. For rivers
970 with a debris-flow model of flooding, setting qualitative thresholds of perceived flood severity from imagery may have more
971 local predictive value than water levels in channels where channel location and roughness change frequently [M2].

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973 A project funded by the World Bank and implemented by the Ugandan Ministry of Water and Environment (MoWE) in 2021
974 – 2022 has installed a range of nature-based (NbS) and community-centred solutions (MoWE, 2022). The NbS of riverbank
975 stabilisation in Kasese is considered especially promising [R1, R3, W1, M1, M2], using 35,000 asper bamboo seedlings and
976 other economic crops in buffer zones on the mid-catchment riverbanks to prevent erosion. Despite challenges with drought,
977 flooding, termites and metal-contaminated soils during the early implementation [W1, M2, G2], a previous project successfully
978 stabilising the Mubuku riverbanks for 20 years [M1] and observations of stable bamboo forests in the upper catchment [R1]
979 provide optimism for the project. Respondents are more critical of other parts of the project, including soil-water conservation
980 and participatory desilting of the river (Table L1), for focussing on the mid-catchment around Kasese town, when discharge
981 and sediment generation is taking place higher in the mountains [R1, I2].

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“the assumptions made are well off beat; “99% of the water is coming from the park” – R1



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Figure M1 – Photographs taken during June 2023 field reconnaissance: a) collapsed gabions adjacent to Kilembe town (for scale: 8 m channel width); b) channelisation using concrete embankments in Kilembe town centre (10 m channel width under bridge); c) photo from a camera transmitting photos at 1-minute intervals 5 km upstream of Kilembe town centre for flood early warning; d) riverbank stabilisation adjacent to Kasese town including asper bamboo (4 m fencepost spacing).

990 Notably, there have been no DRR interventions so far in the wildfire affected area of the upper catchment, and no active
991 mitigation of mine tailing erosion into the river Nyamwamba. In both cases, a low awareness of their impacts has inhibited
992 action [M2, R1, W1, G2]. 7 of 12 interview respondents did not mention the 2012 wildfire when asked to describe factors
993 affecting local flood risk, and only one small-scale academic study has assessed water quality in the Nyamwamba since large-
994 scale erosion began in 2015 (Mukisa et al., 2020). Of the respondents aware of the wildfire [R1, W1, M1, M2, G2] and water
995 quality problems [M1, M2, G1, G2] in the Nyamwamba catchment, all recommend restoration of the wildfire-affected area
996 and urgent mitigation of further erosion into the river.