Flash Flood warning in context: combining local knowledge and large-scale hydro-meteorological patterns

Agathe Bucherie[1,2,3], Micha Werner[2], Marc van den Homberg[3], Simon Tembo[4]

[1] The International Research Institute for Climate and Society (IRI), Columbia University, New York, 10964, USA
[2] IHE Delft Institute for Water Education, Delft, 2611AX, The Netherlands
[3] 510, an initiative of The Netherlands Red Cross, The Hague, 2593 HT, The Netherlands
[4] Malawi Red Cross Society, Lilongwe, 30096, Malawi

Correspondence to: Agathe Bucherie (agathe.bucherie@gmail.com)

Abstract. The small spatial and temporal scales at which flash floods occur make predicting events challenging, particularly in data-poor environments where high-resolution weather models may not be available. Additionally, the uptake of warnings may be hampered by difficulties in translating the scientific information to the local context and experiences. Here we use social science methods to characterise local knowledge of flash flooding among vulnerable communities along the flat Lake Malawi shoreline in the district of Karonga, northern Malawi. This is then used to guide a scientific analysis of the factors that contribute to flash floods in the area using contemporary global datasets; including geomorphology, soil and land-use characteristics, and hydro-meteorological conditions. Our results show that communities interviewed have detailed knowledge of the impacts and drivers of flash floods (deforestation, sedimentation), early warning signs (changes in clouds, wind direction and rainfall patterns), and distinct hydro-meteorological processes that lead to flash flood events at the beginning and end of the wet season. Our analysis shows that the scientific data corroborates this knowledge, and that combining local and scientific knowledge provides improved understanding of flash flood processes within the local context. We highlight the potential in linking large-scale global datasets with local knowledge to improve the usability of flash flood warnings.

1 Introduction

Weather-related hazards are responsible for 78% of the economic losses and 38 % of the fatalities related to disasters worldwide, with a drastic increase in the number of events in the last 35 years attributed to global climate change. Hydrological events show the highest increase globally with a rise of a factor of four, while meteorological catastrophes have increased a factor of three (Hoeppe, 2016). Although these events affect the entire globe, exposure to hydrological events and vulnerability of those affected are not uniformly distributed, and climate risk disproportionately affects the

world's poorest (Byers et al., 2018). For example, the impact floods have is greater in developing countries. Indeed, 95% of people are affected by floods, and 73% of the total direct damages every year occur in Asia and Africa (Alfieri, et al., 2017). Aiming at reducing the global impacts of natural hazards, the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) calls for increased adoption of multi-hazard early warning systems.

35 A recent survey of the development of operational forecasting systems for floods (Perera et al, 2020) shows that in many countries and river basins good progress has been made, though such progress is often limited in least developed countries, hampered by a lack of monitoring networks as well as human and technical capacities. These also often focus on large space and time scale riverine floods, which have attracted most attention of the flood forecasting, warning and response research community (Alfieri, et al., 2018, Kauffeldt, et al., 2015, Sai, et al., 2018). Flash floods, in contrast, occur at smaller spatial

40 and temporal scales, resulting in severe damage to infrastructure and the environment, and are more deadly than riverine floods (Jonkman, 2005). Flash flood events are characterized by very rapid runoff generation and the sudden rise of water levels out of the riverbanks. They can be caused by a combination of high local precipitation rates (Doswell, 1995), adverse antecedent hydrological conditions (Hill and Verjee, 2010) and the geomorphological disposition of the catchment to flash flooding (Georgakakos, 1986).

45 Flash flood warning is challenging due to the response times of the catchments that flash floods occur in. These are often shorter than the time needed for decision making, thus preventing efficient flash flood warning responses (Drobot and Parker, 2007). Additionally, the development of effective warnings for flash floods is hampered by the spatial and temporal incoherence between the understanding of the atmospheric and geomorphological processes that leads to flash floods, and observation data availability, even in countries with well-developed hydro-meteorological networks (Creutin and Borga,

50 2003). Recent decades have, however, seen significant progress in developing warning systems in flash flood prone catchments (Hapuarachchi, 2011; Braud, 2018), though these rely extensively on the availability of high-resolution quantitative precipitation estimates and forecasts, in particular helped by the availability of radar-based precipitation estimates and nowcasts (Creutin and Borga, 2003; Werner and Cranston, 2009; Javelle et al., 2010). Such weather radars are practically non-existent in developing countries. Medium to high-resolution numerical weather prediction (NWP) models

55 may, however, be available and are applied in selected cases, such as in the Flash Flood Guidance System for Southern Africa (Poolman et al., 2014). Flash Flood Guidance relies on geomorphological indicators (Azmeri, et al., 2016, Smith, 2003) of the susceptibility of a catchment to flash floods and triggers. Several approaches to establish triggers have been developed across the globe; based on forecasting river discharge (Drobot and Parker, 2007), or rainfall thresholds (Alfieri, et al., 2015, Georgakakos, 2005). These also rely on the availability of hydrological observation data for calibration and

60 validation of triggers and have reached a high level of complexity. Availability of these data is not equally distributed around the world, compounding the difficulty of making flash flood predictions in data poor countries, which are often also developing countries. Global and continental scale flood forecasting systems are increasingly being developed with the availability of global meteorological forecast and reanalysis datasets as well as satellite-based precipitation data (Emerton et al. 2016), and these provide an opportunity to fill the gap where national and regional forecasting systems are not available.

65 However, although these offer the advantage of providing consistent datasets to areas otherwise poorly served, the limited resolution of global and continental scale NWP datasets means they are inadequate to support flash flood forecasts (Emerton et al., 2016), and may be limited only to the forecasting of larger scale weather patterns.

Despite these technical challenges, increasing the ability to anticipate the occurrence and impacts of flash floods stands to benefit communities at risk and organisations involved in disaster relief, potentially leading to faster response and better
70 allocation of emergency flood relief effort. However, to be effective, the early warning needs to have not only a technical basis, but also a human-centred approach, commensurate with the knowledge of the people at risk (Basher, 2006). Local communities have shown to have a complex knowledge cutting across the full disaster risk management cycle (Šakić Trogrlić, et al., 2019) and the climatic conditions that lead to extreme (flood) events (Lefale, 2010; Orlove, 2010). Integration of both local and scientific knowledge is recommended in all steps of early warning system design (Martin,
75 2012), and can contribute to closing the "usability" gap (Vincent et al. 2020). Plotz et al, 2017 suggest two approaches to integration of local knowledge and the knowledge derived from contemporary forecasts systems; either through validating local knowledge based on scientific datasets, or through combining the local and scientific data into a consensus forecast that considers both knowledge. The evolving people-centred paradigm to early warning also recognises that community engagement, integration of local perceptions and information tailored to those at risk is important to the fostering of trust in
80 warning information, thus increasing the potential of its uptake (WMO, 2015, 2018). Impact-based forecasting, follows this paradigm, recognizing that early action by those at risk is more likely to be taken where warning messages recognise people's local understanding of the hazard, environmental and social cues (Calvel et al., 2020), and potential impact (Luther et al., 2017, Meléndez-Landaverde, 2020).

In this paper we explore local knowledge and science-based information on the occurrence of flash floods in rural
85 communities in Karonga District in northern Malawi. We hypothesize that local knowledge can complement the information contained in larger scale global datasets, and that the combination of local and scientific knowledge can contribute to the development of meaningful and trustworthy early warning, within the context of the people-centred early warning framework (WMO 2015, 2018). This framework recognises that effective early warning builds on four key interrelated elements; (i) risk knowledge; (ii) monitoring and warning; (iii) dissemination and communication; and (iv) response
90 capacity. North Malawi is an example of an area with high flash flood risk where the population is extremely vulnerable due to low coping capacities. Through interviews with impacted communities, we develop a shared knowledge of risk through a joint understanding of the root causes of flash floods in the area, the impacts these have and where these are more likely to occur. In the interviews we also consider the local knowledge of meteorological and hydrological signs communities recognize as precursors to flash flood events. We then interrogate available information on catchment geomorphology and
95 hydro-meteorological conditions derived from large-scale global models and satellite datasets to examine if these provide useful information congruent to that local knowledge. Our aim is to reconcile these scientific data with local knowledge of flash floods to inform the implementation of people-centred flash flood warnings and foster the taking of early action by communities.

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2 Study area

Malawi is a Sub-Saharan landlocked country in South-East Africa, sharing its borders with Zambia, Mozambique, and Tanzania. It has an elongated orientation, following Lake Malawi, with its physiography dominated by the rift valley geology. The subtropical climate, and highly seasonal precipitation variability, result in Malawi being prone to weather-related disasters (McSweeney et al., 2010). Two main seasons exist: a wet austral summer season (Nov-April) and a dry season (May-Oct). Perhaps more importantly than its disposition to weather-related hazards, the most severe impacts from disasters result from the high vulnerability of the population, estimated at around 16.5 million, with a poverty Index of 57.9 %.

Karonga is the northernmost district of Malawi, sharing a border with Tanzania. It is located along the Lake Malawi shore, has a surface of 3355 km2 and an estimated population of 380,000 in 2020. The district is characterized by a steep rift escarpment separating the hills and plateau area from the lake-shore plain (see Fig. 1). Characterised by strong erosion of the crystalline base rock, filling the rift valley with quaternary sediments, Karonga soil types are primarily sandy. Land use along the flat lake shore is almost entirely cropland (mainly rice, maize and cassava) while the hills and plateau are covered by bushes and open forest. The population of Karonga is rural, and is distributed mainly on the flat lake shore in small communities. The economy depends upon subsistence agriculture and fishing. With a poverty incidence of 57.1 % (IFPRI, 2019), Karonga district is poorer than the average of Malawi.

Being one of the most vulnerable to floods, Karonga is the focus of several projects of the Malawi Red Cross Society that aim to improve preparedness, early action and disaster response in Malawi. Flood events recur annually and are particularly damaging in Karonga due to poor infrastructure, growing population, increase of farming in flood risk areas, and difficulties for the population to receive warnings due to lack of access to communications. Large scale damaging events can occur in the district of Karonga, like the floods of 12-16 April 2018, affecting 4069 people, destroying 433 houses, and killing 4, as reported by the Department of Disaster Management Affairs of Malawi (DoDMA). Smaller scale and isolated flash floods have also impacted the district, like the event of the 1st of February 2018, affecting 1175 persons and damaging 42 houses and 397 hectares of crops in the small village of Mwenelupembe according to DoDMA.
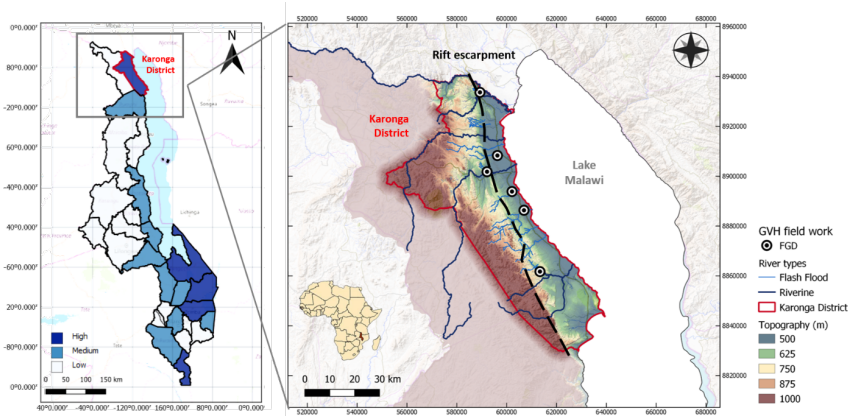
Figure 1: Karonga district location on - (left) Malawi flood recurrence map based on observed flood frequency in the period 2000-2013 generated by DoDMA (ICA 2014) - (right) Topography map showing the rift escarpment, the main rivers, and the six visited villages where Focus Group Discussion were conducted for the research.

130 ## 3 Materials and methods

3.1 Building common knowledge of flash flooding

To develop a common understanding of what constitutes a flash flood in the perception of local communities in Karonga District, a primary data collection campaign was conducted at national, district and community levels through a series of semi-structured Key Informant Interviews (KII) and Focus Group Discussions (FGD), following a systematic protocol (see

135 Section 3.1 of supplementary materials). The KIIs at national and district level, and FGDs held at community level followed a similar questioning pattern allowing for an alignment and comparison of the results obtained. We ensure that all KII and FGD were prepared to comply with the COREQ qualitative research criteria (Tong et al., 2007)

KII refers to qualitative in-depth interviews with people from a range of sectors selected for their knowledge on the specific topic (USAID, 1996). For the KII at national and district levels, we approached actors from a wide range of institutions,

140 including representatives of disaster, meteorological and hydrological governmental institutions, universities, and disaster practitioners from locally active NGO. As a results, we were able to carried out six KII in English at the national level; including identified experts from the Malawi Red Cross Society, the Department of Disaster Risk Management, the Ministry of Finance Economy and Development, the Department of Climate Change and Meteorological Services, the Ministry of Agriculture Irrigation and Water Development, and Mzuzu University. At the Karonga district level, local actors such as

145 members of the district civil protection committee, a reporter from Nyasa Times news agency, and NGOs active in the

district (Salvation Army, Focus and Self-Help Africa) were interviewed. Based on these interviews, we identified twelve communities that are recognised to have a higher flash flood risk in Karonga District, located on different river basins across the district.

Focus Group Discussions (FGD) were carried out with six of these communities (communities are identified as a Group Village Head, GVH) represented as circles in Fig. 1. FGD interviews bring together a group of persons from a similar background guided by a facilitator. We made sure that at least four persons in the FGD were above 50 years old, with at least one participant having spent more than 50 years in the community in each group. These were conducted and recorded in the local languages, Nkhonole and Chichewa; and subsequently transcribed and translated into English. A community drawing exercise was held in each village, resulting in a map gathering information about historical flash flood frequency, impacts, and perceptions of flash flood risk in different areas of the community. This was followed by a transect walk through the most affected part of the community. In addition, information about historical flash flood occurrence and their impacts was collected from each community. From all KII and FGD interview transcripts, local knowledge was extracted through quotes and coded into thematic analysis following five themes; (i) Flash flood definition; (ii) occurrence of flash flood events; (iii) impacts of flash floods (iv) risk perception, and (v) the signs leading to flash floods. These themes were identified partly based on deductive coding (literature study) inspired by the dimensions of local knowledge of the flood risk management cycle identified by Sakic Trogrlic et al. (2019), and partly based on inductive coding of the transcripts.

We complement these primary data with secondary data on historical flash flood events, their location, date and recorded impacts. These were extracted manually from five different sources of information: Disaster reports from Humanitarian Actors (IFRC GO, n.d.; UNICEF Malawi, n.d.), existing global disaster (EM-DAT, n.d.; Munich RE, 2004), government data, online news-briefs (FloodList, n.d.; ReliefWeb, n.d.) and national online media (Nyasa Times, n.d.; The Nation, n.d.). All datasets were filtered and consolidated into an event database at three levels of spatial granularity: Karonga District, Traditional Authority (TA) and community levels (GVH). A total of 142 records of flash flood events affecting the district from 2000 to 2018 were gathered (Bucherie, 2021). This included 48 events reported at district level, and 38 events at TA level. Only 18 events are reported to affect the six communities of interest, covering the period 2004-2018.

3.2 Mapping flash-flood susceptibility based on scientific data.

The susceptibility of an area to be affected by flash flood depends on the geo-morpho-metric and surface characteristics (Horton 1945, Patton, 1976), which have a strong influence on catchment hydrologic response to heavy rains, and therefore on runoff generation. Here we map the relative susceptibility to flash flooding of the twelve communities identified to have the highest flash-flood risk in Karonga District. For each of the 12 communities, hydrological catchments are delineated, using the global SRTM 90m Digital Elevation Model (DEM) v4.1 (Jarvis et al., 2008). Geomorphological indicators related to surface and morphometric characteristics known to characterize flash flood risk are identified (Bajabaa, et al., 2013, Farhan, et al., 2016, Rogelis and Werner, 2014), with some linked to the local knowledge (such as indicators related to slope, soil type, land or vegetation cover). The identified indicators and references are described in Table 1.

For each catchment, geomorphological indicators are calculated and classified according to four categories characterizing
the geometry, the hypsometry, the drainage network, and surface of the catchments (Appendix A). While the first three
categories of catchment indicators are extracted from the DEM analysis only, the surface characteristics indicators are
derived from the Malawi government soil type and Land-use Land-cover (LULC) data, and the Normalized Difference
Vegetation Index (NDVI) Copernicus Global Land Service 300m product (Roujean et al., 2018). All geomorphological
indicators are normalised from 0 to 1 according to their contribution to susceptibility to flash flooding.

Different methods of weighting the influence of each geomorphological parameter can be used depending on the context
and the scale of each case study (Azmeri, et al., 2016). Some studies use equal weighting (Zogg & Deitsch, 2013), or
weighting based on the indicator ranking (Karmokar & De, 2020). Here we apply a weighted method based on Principal
Component Analysis (PCA) to reduce the dimensions in each class (Chao & Wu, 2017, Rogelis & Werner, 2014). Based
on the four Principal Component results, a ranking of flash flood susceptibility of the 12 catchments is calculated,
following Eq. (1), representing the inherent potential of each catchment to generate a flash flood in case of heavy rain.
PC[name] refers to principal components related to geometry, hypsometry, surface and drainage network. The linear
coefficients a,b,c and d are the weights applied to each of these classes.

$$FF_{Suscept} = a \times PC_{[geom]} + b \times PC[hypsom] + c \times PC[drain] + d \times PC[surf] \tag{1}$$

Table 1. Identified geomorphological and surface indicators related to flash flood susceptibility

	Index	Description	Source
Catchment geometry	Area [km^2]	The area of a catchment is correlated with its discharge. Bigger catchments have lower flash flood potential.	*Gray (1961)*
	Length to width LtoW [-]	Length to Width ratio is a shape indicator of a catchment, inversely proportional to the flash flood potential of a catchment.	*Schumm (1956)*
	Basin circularity Bc [-]	The circularity ratio 4*Π*A /P^2 is related to flow peak and debris flow occurrence. The more circular the basin, the more flash flood prone it is considered to be.	*Miller (1953)*
	Time of concentration. Tc [min]	Flash flood potential increases in basins with lower time of concentration. Computed using Kirpich's formula, where L is the longest flow path to the remotest point altitude H from the outlet at elevation h. $$tc = 0.01947 \times L^{0.77} \times \left(\frac{H-h}{L}\right)^{-0.385}$$	*Kirpich (1940)*
Hypsometry	Average slope [deg]	The average slope is an indication of the flashiness of a watershed, proportional to flood susceptibility. The slope is computed in degrees from the DEM using 2nd degree Polynomial Adjustment algorithm (Zevenbergen & Thorne, 1987)	*Lindsey et al. (1982),*
	Rel_Relief [-]	The Relief (H) is the difference between the highest and the lowest elevation point of the catchment. The Relative Relief is the Relief (H) divided with the basin perimeter (P). It is related to the event magnitude.	*Melton (1957)*
	Elv_RR [-]	The Elevation Relief Ratio definition using the Relief (H) divided by the Length of the catchment has been used.	*Oruonye (2016)*
Drainage network	Drainage relief ratio D_RR [-]	The Drainage Relief ratio corresponds to the drainage relief (maximum elevation of the drainage system minus the outlet elevation) divided by the longest stream length.	*Schumm (1956)*
	Drainage density Dd [Km^{-1}]	The cumulative river length over the area. This has a direct correlation with flood potential.	*Patton and Baker (1976)*
	Bifurcation ratio Rb [-]	The bifurcation ratio of a basin is inversely linked to the flash flood risk: Rb = ∑ Nu/Nu + 1, where Nu is the total no. of stream segments of order "u", and Nu +1 the no. of segments of the next higher order.	*Strahler (1957); Schumm (1956)*
Surface properties	Soil type	Soil types data are ranked according to the clay content, and reclassified from 0 to 10. The infiltration rate decreases with the clay content, increasing runoff and flash flood susceptibility.	*Smith (2003); Tincu et al. (2018)*
	LULC	Land Use Land Cover data are reclassified into classes from 0 to 10 depending on their susceptibility to increased flash flood risk.	*Smith (2003); Tincu et al. (2018)*
	NDVI	The Normalized Difference Vegetation Index is used as an indicator of the greenness of the vegetation. Data are extracted for two periods, at the beginning (21 to 31 Dec 2017), and at the end (21 to 31 March 2018) of the wet season. High NDVI values represent dense vegetation while low NDVI values indicate bare soils and increasing flash flood risk.	*Smith (2003); Tincu et al. (2018)*

210   Validating a map of flash flood susceptibility is a challenge where there is little historical data (Alam et al., 2020). For data rich catchments, machine learning techniques use historical flash flood data to calibrate the flash flood susceptibility map (integrating morphometric and precipitation indicators) and have been tested on specific catchment scale study (Arabameri et al., 2020; Pham et al., 2020). Here we estimate the weight (a, b, c, d) of each class by calibrating against the estimated relative flash flood frequency for each catchment as indicated by the communities interviewed. The best fit is defined

215 minimizing the Root Mean Square Error (RMSE) between the modelled susceptibility ($FF_{Suscept}$) and the normalised observations of flash flood frequency.

3.2 Identifying hydro-meteorological conditions associated with flash flooding.

Precipitation and large-scale hydro-meteorological indicator datasets are selected, guided by the knowledge gained from communities on the signs and triggers they consider as precursors to flash floods. The spatial and seasonal distribution of

220 indicators derived from the datasets are analysed to understand if these corroborate with the reported signs, and particularly if these reflect conditions associated with flash floods during and prior to the catalogued historical flash flood events.

Precipitation is derived from the GSMaP satellite-based precipitation products (Aonashi, 2009, Okamoto, 2005, Kubota, 2007), and extracted for the 15 wet seasons of the 2002-2018 period. We limit the extraction of these data to the wet season for computational reasons, as well as due to flash flood events occurring in the wet season. GSMaP was selected given the

225 high spatial (0.05 degrees) and temporal (hourly) resolution, as well as relatively low latency. Historical extreme rainfall patterns are explored spatially and temporally over the district. In addition, maximum daily 1-hour and 3-hour rainfall totals are extracted to characterise precipitation intensity associated with the 18 catalogued flash flood events affecting the six communities for the 2004-2018 period. Moving windows of 6h, 1-day and 3-day cumulative rainfall are extracted as indicators of antecedent cumulative precipitation. These precipitation indicators and associate statistics are extracted from

230 the GSMaP data at locations corresponding to the centroids of the catchments of interest. Time series are analysed visually for each flash flood event.

Large-scale hydro-meteorological conditions are derived from the ECMWF ERA5 climate reanalysis dataset (Hersbach et al., 2020) provided through the Copernicus Climate Change Service (C3S, 2017). This dataset is selected given its availability and as it provides the same parameters and at similar temporal and spatial scale as the forcing data used in global

235 hydro-meteorological forecast models such as GLOFAS (Alfieri et al., 2013). Daily data is extracted for the 2000-2018 period from ERA5 over a geographical box that encompasses the study area (longitude 32 to 36, latitude -8 to -12). Variables considered include the 2m surface air temperature; the 2m dew point temperature; the volumetric soil water content of the first 7cm of the land-surface; the relative humidity of the deep troposphere; the CAPE indicator (surface-based convective available potential energy), and the surface u and v wind vectors.

240 These variables are extracted from the ERA5 data at three locations (see Fig. 2), one in the northern part of the district (N), one in the southern part (S) and one in Lake Malawi (L). Daily averages of the selected ERA5 variables are extracted for the period 2000-2018 to analyse seasonal variations. To study the larger scale hydro-meteorological patterns and conditions associated with historical flash flood events, the same ERA5 hydro-meteorological variables are extracted and averaged over four regions (see Fig. 2), for up to 3 days before each of the catalogued flash flood events. These regions are selected based

245 on the precursor signs reported by communities interviewed, and include Karonga (Region W), Lake Malawi (Region S), and the areas to the north-west and north-east of Karonga (Region NW and NE, respectively).
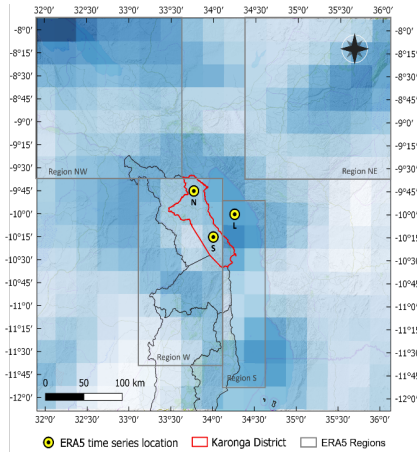
Figure 2: ERA-5 grid resolution, x,y point locations (yellow dots) and four regions (NW = North West, NE = North East, W =
250 **West, S = South) used for large-scale hydro-meteorological pattern analysis.**

4 Results

4.1 Building knowledge on Flash flooding.

Local knowledge on flash flooding in Karonga district has been compiled from all KII, FGD, transect walks and community
drawings, through the extraction of quotes from interview transcripts. We reported the knowledge extracted here, structured
255 along the five themes identified in the collection and analysis of the data. Additionally, the risk knowledge established in the
themes ii) Occurrence of flash flood events and *iii) Impact of flash floods* is based on the integration and corroboration of the
FGD and KII (primary data) with the flash flood occurrence and impact analysis derived from the secondary data.

(i) Flash flood description

260 Communities report that they experience sudden floods, induced by intense and short rainfall events, and that these form the
main type of weather induced disasters in Northern Malawi. All communities describe these flood events as unexpected
occurring "*without notice*", associated with intense power of flows, erosion of river banks and rivers bursting their banks.
Participants identified that the topography to govern the occurrence of flash floods in Karonga, and that the most affected
areas are on the flat rift valley floor close to the escarpment. In addition, fast onset floods are known sometimes to coincide

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280 with slow onset riverine floods in communities in the North of Karonga; a scenario described as resulting in larger scale, longer duration, and more severe disasters.

(ii) Occurrence of flash flood events

The analysis of the data from the KII and FGD, supported by the analysis of the secondary data on the spatial and temporal
285 occurrence of flash floods, reveals that flash floods happen between one and eight times per year in Karonga district, mostly in January and in March/April, and generally overnight. In addition, shorter duration and more localised flash flood events are reported to occur in January, while longer duration floods affecting larger areas are observed in April (Table 2). The frequency of flash floods is found to be higher in the northern part of the District, in Kyungu and Kilipula TA (see Fig. 3). In addition, April events affect mainly catchments in the northern TAs while January events may affect any of the catchments
290 in the entire district.

Table 2: Monthly flood event frequency based on 2000-2018 secondary data collection (43 recorded events), and associated proportion of short duration (<=3days) and local (affecting only 1 TA) recorded flood events.

	December	January	February	March	April
No. of recorded events	6	15	4	7	11
% short duration flood (<=3days)	83	80	100	86	55
% local event (affecting only 1 TA)	66.6	61.5	50	28.5	33.3

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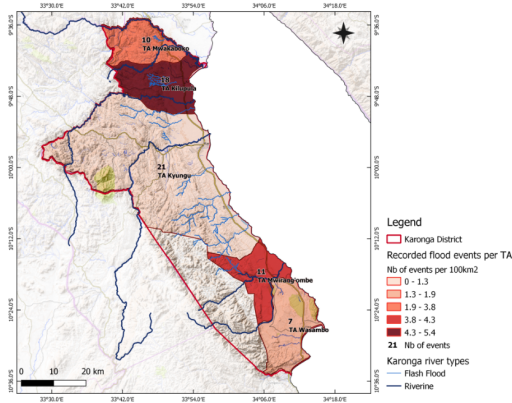


Figure 3: Number of recorded flood events per 100 km² for every TA (collected for the period 2000-2018), with the total numbers of events recorded for each TA indicated as labels.

(iii) Impacts of flash floods

300 Information about the impact of flash floods in Karonga is extracted from the interviews and the analysis of historical impact datasets. The main impact of flash floods experienced by Karonga's communities is on agriculture, as flash flood events are reported to systematically sweep away several hectares (ha) of crops (either recently planted or fully grown), and sometimes livestock. In addition, communities mentioned that flash floods can destroy parts of villages, irrespective of the type of buildings. Communities report an increase in flood impact since 2007. Based on our historical data, we estimate that when a

305 flood occurs in the district it has a 50% chance to affect at least 300 households, 200 ha of crops and kill at least one person. The communities also indicated that the impact of floods is higher in April, and also higher in the North of Karonga. This is attributed to the combination of flash floods with riverine floods in the Songwe, Kyungu, Lufira and North Rukuru rivers, as well as the higher population density in the North. These prolonged and larger-scale flood events are reported to trigger cholera outbreaks in the region. Flash flood events occurring in January can, however, affect the entire district. Their impacts

310 on communities are more spatially contained, but maybe more severe at that small scale.

(iv)Perceived drivers of flash flood risk

Extracted from the KII and FGD interview transcripts, a summary of six factors perceived to increase flash flood risks in Karonga District is presented below. Quotes made by different community members are provided, where relevant.

315 **River sediments**: Karonga has mostly ephemeral rivers with heavily silted river beds, which are dry from the months of August to December. Increasing sedimentation of the river beds and changes in river behaviour are reported by elderly

people. High sedimentation in rivers is recognised to have increased flood occurrence, and the exposure of people living along these rivers. *"Before, water would swell within its course and go back to normal without any damage. Today, rivers are full of sand, blocking culverts, and preventing water from flowing in its original course"*. River profiles where these cross the lake-shore plain are very flat, and their channels were observed during our transect walks to not be deep enough to accommodate peak discharges.

Land use: The sedimentation in the river courses is identified by all communities to be the result of deforestation in the upstream catchments, which started in the 1970's, after the independence of Malawi. Charcoal production, and the use of wood to build stronger burnt brick structures have risen; *"Bushfires and overgrazing animals are leaving the soil bare and prone to flood"*. In addition, the intensification of agriculture along the river banks is reported to reduce the natural control of the water velocity, increasing the spread of water on farmland.

Climate change: A shift toward shorter and more intense rainy seasons (December to March instead of November to April) is observed by communities, leading to more frequent and devastating events. An intensification of rain events and a change in meteorological patterns is described by elderly people, making the indigenous prediction more difficult than before.

Geomorphology: Fast running water is experienced to come from the steep slopes of the mountains of the escarpment, and affects villages in the low land areas, making the proximity to the hills a factor of increasing risk.

Soil type: The relation between flash floods and soil type is expressed in terms of erodibility of the soil; *"The soil, easily swept away during flood, is dispersed in agricultural fields and lowers soil fertility"*. In the Northern communities, a relation between the flood duration and the clay content in the soil, lowering the infiltration capacity in the lake margin plains, is observed.

Socio-economic vulnerability: The rapid increase of population and poverty, associated with poor settlement and farming practices, is perceived to have exacerbated the vulnerability of communities in the district.

(v) the signs leading to flash floods.

The local knowledge of the signs experienced prior to flash floods are categorised into two types of observations.

Meteorological signs: Community knowledge revealed that flash floods are associated with strong south-easterly winds at the end of the wet season. In addition, communities in the South of Karonga District described flash floods to be associated with highly localised storm events and thunder, black and slow-moving convective clouds, and changeable wind direction. In addition, a rise in temperature before flash floods was reported by all communities.

Hydrological signs: When water velocity and volume increase in the rivers, the amount of debris carried as well as the colour of the water changes (turning brown, black, milky or red), announcing that a major flood is coming. In addition, at the lake margin, the soil moisture and water table are known to be high at the end of the wet season, increasing the duration of floods and consequent impacts. When the soil is dry, water from the flash floods will infiltrate faster in the farmlands.

4.2 Geomorphological analysis of flash-flood susceptibility in Karonga District

360 All catchments that drain the escarpment are reported to be susceptible to flash flooding in Karonga district although the level of susceptibility may vary between catchments. The results from the flash flood frequency estimation from each community was fundamental to understanding the spatial difference in flash flood susceptibility from the geomorphology and surface characteristics of the upstream catchments upstream. The normalised indicator values and PCA composite results calculated for each catchment are presented in supplementary material section 4.2; the PCA component loadings are found in

365 Appendix A.

The relative catchment susceptibility results for the four geomorphological classes; geometry, hypsometry, drainage system and surface characteristics; reveals differences from North to South, as shown in Fig. 4. The dashed coloured lines show the results from the PCA analysis for each of the four categories of catchment characteristics. Black triangles show the normalised frequency of flash floods as reported by the communities visited, which were used to estimate the weights (a,b, c

370 and d) for the final flash flood susceptibility ranking of the selected catchments. The thick solid line shows the normalised flash flood susceptibility indicators, found from the weighted contributing factors; geometry (0.5), hypsometry (0.1), drainage (0.2), and surface (0.2), where the values in brackets are the weights in Equation 1 with the best fit (RMSE of 0.31). The resulting indices are mapped in Fig. 5.

The increased flash flood susceptibility of catchments appears to be mostly driven by catchment geometry and is inversely

375 proportional to the area and the time of concentration (Tc) of the catchment, together explaining 63% of the variance of the geometric class. While the high frequency of flash floods experienced by the community of Iponga and Nkhomi are explained mainly by their small upstream catchments size (lower than 10 km2) and Tc of about 40 minutes, the lowest flash flood frequency observed in Sabi community can be explained by the largest contributing Area (335 km2) and associated Tc (~4 hours).

380 The derived weights attribute an equally important influence to both the drainage characteristics (controlled essentially by the drainage relief ratio) and the surface characteristics. While the higher flash flood susceptibility of Iponga and Nkhomi catchments is also explained by the high drainage relief ratio, spatial variation of the susceptibility related to surface characteristics is mainly driven by the soil types and the vegetation cover. A strong variability in the NDVI is observed between the North and the South, particularly at the beginning of the wet season, exposing the South (with more bare soils)

385 to higher susceptibility to flash floods. The high susceptibility of Iponga catchment is additionally explained by the presence of clayey soils in the North, decreasing the infiltration capacity. Finally, catchment hypsometry results do not correlate well with field observations. The resulting low relative flash flood susceptibility of the Kyungu, Kibwe and Kasantha catchments in the North of Karonga, which were not visited, confirms these being ranked as less dangerous by Karonga experts through the KII.

390

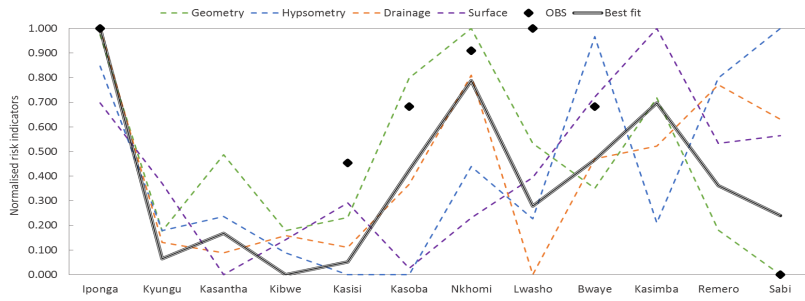



Figure 4: Results from the PCA analysis of the four catchment characteristic categories and weighted flash flood catchment susceptibility. The black dots correspond to the normalised estimation of flash flood frequency of communities visited (OBS=observed). Catchments are ordered from North to South (left to right).

395

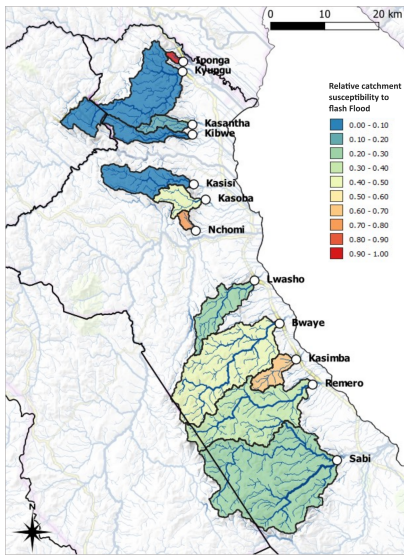



Figure 5. Relative flash flood susceptibility of the catchments in Karonga district.

4.3 Hydro-meteorological conditions associated to flash flooding

Guided by local knowledge on the hydro-meteorological signs associated with flash flood events, and the temporal distribution of flash flood events through the wet season, we analysed the characteristics of extreme rainfall and large-scale spatial and intra-seasonal hydro-meteorological patterns that could lead to flash floods in Karonga.

The analysis of historical precipitation indicates that heavy rainfall events are not homogeneously distributed spatially, and are distinctly different at the beginning and at the end of the wet season.

Figure 6 shows the maximum daily precipitation found with the GSMaP data, averaged over the time period 2002-2018 for the months of January and April, the months in which flash floods are reported by communities to occur. This reveals that extreme rainfall rates are constrained to the Northern part of Karonga at the end of the wet season in April, while these are distributed more homogeneously in January. A more detailed analysis of the hourly rainfall rate reveals that extreme rainfall events are more frequent in January than in April, though the maximum hourly precipitation rates are comparable in both months (see supplementary material section 4.3.1). All rainfall events associated with the 18 historical flash flood events were detected by GSMaP. It confirms that extreme rainfall peaks of at least 30 mm/h are associated with events localised in the North of Karonga, either at the beginning or at the end of the wet season. In addition, flash flood events that correspond to low GSMaP rainfall signals (peak rain below 10mm/h) are observed mainly in the South of Karonga, in January and February (see supplementary material section 4.3.2).

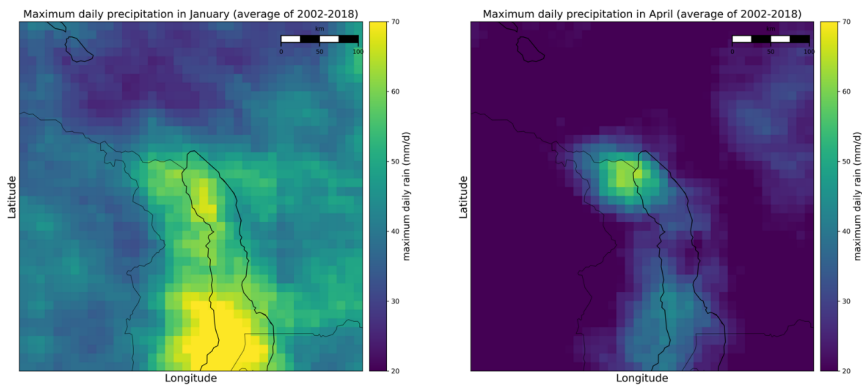



Figure 6: Maximum daily rainfall over two different months of the wet season (January and April), averaged for 15 wet seasons (2002/2003 to 2017/2018). Yellow colours indicate areas with higher maximum daily rainfall (mm/d) recorded on average for the month. The maps are centred on North Malawi, black lines represent the boundaries between countries and Lake Malawi.

420 The large-scale hydro-meteorological analysis on seasonal patterns and conditions associated with flash floods in Northern Malawi help to understand the extreme rainfall patterns in Northern Karonga.

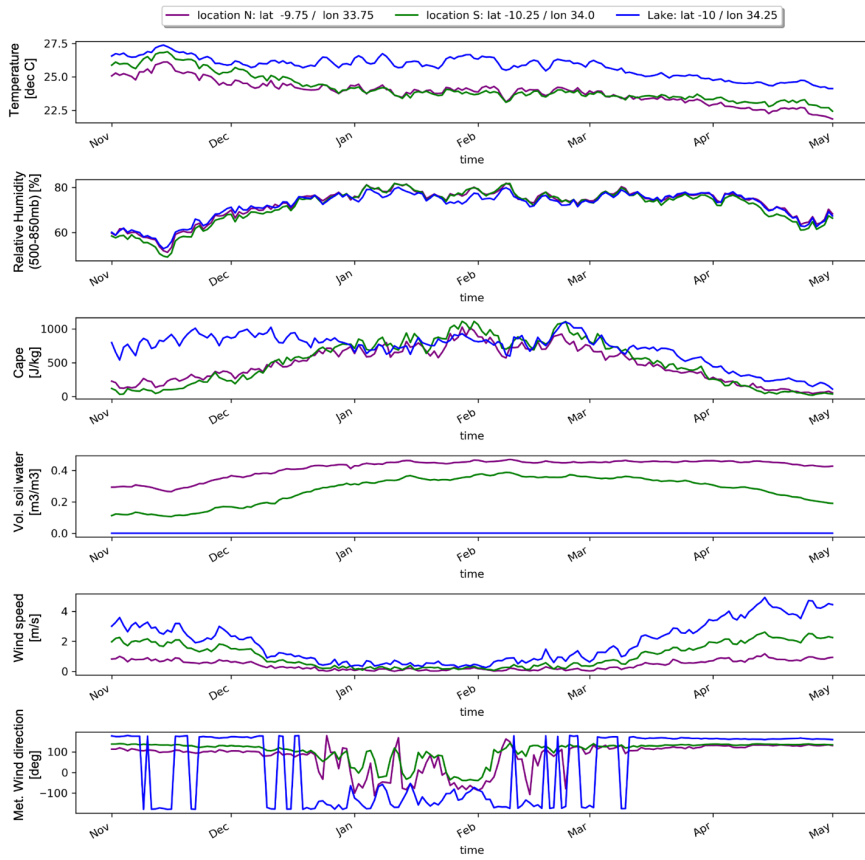
Figure 7 presents the standard daily averages for the selected variables spanning the 2000-2018 period, derived from ERA5 hourly re-analysis and sampled at three locations (Fig. 2).

The Relative humidity, which provides an indication of the water saturation of the deep troposphere, strongly increases
425 during the first part of the wet season, from mid-November to end of December. The average relative humidity is at its maximum from January to mid-February, approaching 80%, and is slightly lower from mid-February to the end of March. The relative humidity of the troposphere then drops significantly in April.

The Soil Moisture is generally lower in the South than in the North of Karonga. It gradually rises from November to February, then drops at the end of the wet season in the South while remaining high in the North. These results confirm the
430 precipitation observations, showing a prolonged rain season in April in the North of Karonga, but could also be attributed to differences in soil characteristics and vegetation.

The convective available potential energy (CAPE) is highly variable within the wet season. It shows a rising trend at the beginning of the wet season and a falling trend at the end of the wet season, with averaged maximum standard values of 1000 J/km at the end of January revealing a maximum atmospheric instability. In addition, the daily variability of CAPE is
435 higher in January.

The wind is generally stronger before December, becoming weaker at the beginning of the wet season. It reaches its minimum intensity in January and February, and increases again towards the end of the wet season. We observe that winds are stronger over the lake and in the South than in the North of Karonga at the end of the wet season.

During November-December and March-April, the wind is uniformly South-Easterly over land, and Southerly over the lake.
440 During the months of January and February, wind direction is more erratic, characterised by an alternation between North-westerly and North-easterly winds over Karonga and respectively North-westerlies and Southerlies over Lake Malawi.

445 **Figure 7: ERA5 standard daily averaged variables over the period 2000-2018 for the three locations as introduced in Figure 3 representing the North and the South of Karonga, and Lake Malawi. Six hydro-meteorological variables are shown: the surface**

temperature, the relative humidity of the troposphere, the CAPE factor, the volumetric soil water, the wind speed and the meteorological wind direction.

Our analysis of these variables confirms our hypothesis of two large-scale hydro-meteorological patterns in northern Malawi,
450 characteristic of the early and late wet season respectively.

The early wet season is characterized by a maximum atmospheric instability in January, with high temperatures and relative humidity. This is when the Inter-Tropical Convergence Zone (ITCZ) is positioned over Malawi. This suggests that the convective storm risk associated with the tropical climate regime is higher at the beginning of the wet season. During this period, extreme rainfall events are more frequent, more localised, and of shorter duration. Such convective events occur
455 evenly distributed over the district. The wind, alternating between two different regimes, can lead to either orographically enhanced rainfall in the North, or more scattered convective conditions in the South.

The late wet season is driven by an extra-tropical climate regime associated with Mozambique currents coming from the Indian Ocean. This is consistent with the strong winds from the South observed along Lake Malawi. When this pattern forms, clouds converge toward the northern part of Karonga, where rainfall is orographically enhanced. The North of
460 Karonga experiences a longer rainy season as a consequence, with frequent, intense and continuous rainfall until the end of April, while flash flood risk is considerably reduced in April in the South of Karonga.

While orographic effects in Karonga have been documented (Nicholson, et al., 2014), the differences between the orographic events of the late wet season and the predominantly convective events of the early wet season as a trigger for flash floods have not been previously studied. These distinct patterns do, however, corroborate the differences observed by local
465 communities as reported in the FGD held.

4.5 Linking Local and Scientific Knowledge on Flash Flooding in Karonga District

The local knowledge of the communities in Karonga district on the conditions that lead to flash floods, which we obtained through the FGD and supported by the KII, was used to guide the diagnosis of scientific data in the exploration of the factors contributing to flash-flood risk in Northern Malawi. In this section we synthesize this local knowledge, and explain how the
470 scientific diagnosis corroborates local knowledge. Table 3 shows the results for the three main themes of analysis (left column), linking the local to scientific knowledge (middle and right columns respectively).

475   **Table 3: Synthesis of the local and scientific knowledge on flash flooding in northern Malawi**

	Local Knowledge	Scientific Knowledge
Spatial-temporal occurrence of flash floods		
Spatial occurrence and annual frequency	Communities experience differences in FF frequency in the different catchments in Karonga, from one event every 3 years to 3 events per year.	Geomorphological features, surface characteristics and precipitation patterns explain spatial differences in FF susceptibility and impacts.
Seasonal trend	FF are experienced mostly in March/April, the months receiving the most rain, and sometimes January, related to the first precipitation events of the wet season.	The intra-seasonal hydro-meteorological analysis reveals different hydro-meteorological conditions between the start (January) and the end of the wet season (April), potentially leading to two types of flash flood conditions.
Diurnal trend	FF are observed mostly at night	Historical GSMaP precipitation events associated with flash flood events mainly occur during the evenings from 6-9 pm until the early morning 2-4 am in Malawi local time. In addition, a diurnal hydro-meteorological cycle is observed between the land and the lake.
Geomorphology and surface characteristics		
Soils	Communities describe clayey soils as an aggravating factor, increasing flood duration, while they experience that sandy erodible soils have negative impacts when transported on crops and grass fields.	Karonga soil type analysis reveals a large fraction of sandy soils in the district. More clayey soils are present in the North, potentially linking up with the longer flood durations reported in the North.
Vegetation	All communities see vegetation degradation in the Upstream catchment forest as a factor that increases flash flood risk.	NDVI analysis shows a lower vegetation greenness in the South of Karonga at the beginning of the wet season, exposing the South of Karonga to higher flash flood risks. This is either due to a more intense deforestation rate in the South, more visible during the dry season, or reflecting the natural variability of vegetation between the North and the South of Karonga.
Catchment geometry	Communities relate the proximity of the escarpment and hills from their village with increased flash flood risk.	The analysis of catchment time of concentration (40 min for small catchment to 4 hours for bigger catchments), an indicator of catchment geometry, shows the highest correlation with local spatial observation on flash flood frequency.
Hydro-meteorological Knowledge		
Precipitation	Short and intense precipitation events are indicated as the main trigger of flash floods for all communities.	The analysis of high-resolution GSMaP precipitation during flash flood events confirms that daily maximum hourly rainfall rates are the most important indicator explaining historical flash flood events.
Temperature	An increase in temperature is experienced before flash flood events	Daily Temperatures from ERA5 do not reveal any specific increase before FF events. However, a rise in humidity is observed in ERA5 data before flash flood events, potentially linked to an increase in ambient temperature.
Soil Moisture	The higher soil water saturation in the flat plain along Lake Malawi in April is responsible for an increased flood duration.	ERA5 volumetric soil water data confirm higher values during the late wet season and in the North.
Wind	Change in wind direction and strength associated with flash flooding. Some communities reported strong winds from the lake as a precondition to flash floods.	ERA5 wind data reveals two different regimes at the beginning and at the end of the wet season, with higher instability during the early wet season potentially linked to LK observation.
Storms	Localised storms, with rotating black clouds and thunder are described as conditions associated with flash floods.	ERA5 CAPE and Relative Humidity are good indicators of the susceptibility of convective events developing. These show promising signals of FF potential during the early wet season.

5 Discussion

5.1. Validating local knowledge in prediction of flash floods

480 Karonga district, and more generally most countries in Southern Africa, lacks the availability of high-resolution quantitative precipitation forecasts and high-resolution hydrological models that provide plausible prediction of flash floods (Hapuarachchi, 2011; Braud, 2018). Global and continental scale flood forecasting systems (Emerton et al. 2016, Alfieri et al., 2018) potentially fill this gap, but the current meteorological and hydrological models these use are too coarse to provide reliable hydrological predictions of flash floods at the scale of catchments susceptible to flash flooding (Emerton et al. 2016,

485 Gründemann et al., 2018), or there is insufficient in situ data to correct bias in forecasts derived from such global systems (Bischiniotis et al., 2018, Lavers et al. 2019). Despite this, our results show that larger scale patterns that are identified to be linked to the occurrence of flash floods in Karonga district based on local knowledge, can be discerned in the coarser global scale models and remote sensing datasets. This highlights the opportunity of local knowledge in helping bridge the temporal and spatial scale gap (Plotz et al., 2017) and in deriving flash flood warnings by interpreting forecasts of larger scales

490 patterns associated with flash floods in the district using indicators that reflect local knowledge. Plotz et al (2017) propose two approaches to combining local and scientific knowledge in forecasts; a consensus forecast approach and a science integration approach that validates the accuracy of forecasts based on local knowledge using scientific data. Following the second approach, we extract the identified indicators of the critical hydro-meteorological conditions associated with the 18 flash flood events recorded in Karonga and use a simple model to test the predictability of the binary occurrence of flash

495 floods in the Karonga district. The two indicators derived from ERA5 found to be the best predictors of conditions that may lead to a flash flood are the maximum hourly peak in the CAPE in the three days before an event, and the maximum hourly relative humidity of the troposphere one day before the flash flood. The latter indicator was found to be a good predictor in the early wet season only, confirming that in this period flash floods are primarily induced by convective storms. Conversely, antecedent rainfall conditions are found to have more predictive potential during the late wet season, particularly

500 for the catchments in the North. We explore the predictability of the binary occurrence of the observed flash flood events with these simple indicators at three spatial scales; i) at the scale of predicting the flash flood events in each catchment; ii) at the scale of predicting a flash occurring in the North and or in the South of Karonga district; and iii) at the scale of predicting the occurrence of flash flood events in the district as a whole. Clearly the sample size is small, particularly for predictions of flash floods occurring in individual catchments. Our results show there is little skill in the prediction of flash floods at the

505 scale of the individual catchments, as the reasonably high probability of detection (POD) is complemented with high probabilities of false detection (POFD). However, skill improved markedly in predicting the binary occurrence of flash floods when pooling warnings for either the northern or southern catchments, and further still at the scale of the district as a whole (see supplementary material section 5.1). These results underscore the complexity of predicting the occurrence of flash floods to trigger warnings at the local scale, particularly using coarser global datasets in absence of the availability of

510 high-resolution observational data and numerical weather predictions. Despite this difficulty of providing predictions at the

very local scale, the results do highlight the potential these datasets have in providing guidance on the occurrence of flash floods in the district. Predictions of the likely occurrence of a flash flood event, either differentiated to the North or South of the district, or in the district as a whole, could be translated to flash flood guidance in the individual catchments based on the knowledge of the communities of the relative susceptibility of each of the catchments in the district, and predicted large-scale meteorological conditions. This approach is in principle similar to differentiated rainfall thresholds derived to support flash flood guidance statements such as used in the Southern Africa Region Flash Flood Guidance System (SARFFG) developed in collaboration with the Malawi Department of Climate Change and Meteorological Services (DCCMS) (Jubach and Tokar, 2016), but differs as it differentiates catchments based on local knowledge, corroborated by the scientific assessment of catchment flash-flood susceptibility. We argue that this contributes to more effective dissemination of guidance on the potential occurrence of flash floods as it considers the knowledge and perceptions of the recipients.

Although our sample size of 14 KIIs and 6 guided FGDs with 7 to 11 persons allowed us to capture the diversity of local knowledge in the area, we cannot say data saturation was fully reached. Most likely a larger sample size of FGDs would have allowed for a further in-depth spatial characterization of local knowledge, and shed light on minor discrepancies such as why communities considered the Kasisi catchment to be more susceptible than the Sabi catchment, despite the contrary being suggested by the geomorphological characteristics. Nevertheless, the validation of the local knowledge obtained through the FGDs and KIIs evidences the complementarity of local and scientific knowledge, even with the coarse scale global datasets explored here, implying the potential of blending these to provide effective early warning of flash floods.

5.2 Combining local and scientific knowledge toward People-Centred early warning systems

None of the communities we interviewed in Karonga district had access to a formal warning before recent events, neither based on their knowledge of the hydro-meteorological conditions they recognise as possible precursors to flash floods, nor guidance from SARFFG issued through the DCCMS. Given the knowledge of the communities of the catchments most susceptible to flash floods and the hydro-meteorological conditions that may lead to flash flood events, and that these conditions can be identified in large-scale hydro meteorological datasets such as ERA5, there is clear potential in combining this information into a form of a consensus warning (Plotz et al, 2017) of elevated flash flood risk in the district. Developing warning messages that visualise the indicators that are understood by the recipients of the warnings can contribute to the credibility of these warnings, helping close the "usability" gap (Vincent et al, 2020), and foster two-way communication between observations of the communities and warning provision (O'Sullivan et al. 2012, Basher 2006). The taking of protective action by recipients of warning messages, if indeed these are received, depends on several factors, including understanding, trust in the provider of warnings, ownership, and personal and contextual relevance (Parker 2009, Moinari and Handmer, 2011, Salit et al 2013). Shah et al, 2012 found that confirmation of warning content through observation of visual cues in their environment that confirmed the warning content, contributes to the taking of protective actions by recipients. Additional research is needed on how to combine local knowledge and community observations with the

scientific forecast information in the provision of warnings to communities such as in Karonga, as careful design warning content and the dissemination and communication methods is required. This design should also acknowledge other signs communities recognise as precursors to flash flood events which were reported in the FGDs, such as in animal and plant behaviour. In Karonga, groups of big black Phanga birds flying fast towards the mountains, ant movements and the presence of butterflies are indigenous signs associated with imminent heavy rains, while frog noises are often heard the night before a flood. The community of Mwenelupembe village also said they perceived a change in vegetation colour, turning deep green before the flood. Such careful design is also relevant to avoid diminishing response and trust due to a high false alarm rate as a result of forecast over-confidence (Morss et al 2016). Though not extensively explored in the FGD we held with communities, elderly people described an intensification of rain events and a change in meteorological patterns, making the forecasts based on local knowledge more difficult. This reflects observations made by participants in the research of Sakic Trogrlic et al. (2019) in the Lower Shire river basin in Malawi, who saw the manifestation of climate change through a change in rainfall patterns, which negatively influenced the reliability of local indicators. Rising temperatures in Southern Africa as a consequence of climate change are consistently projected, as are changes to precipitation patterns, though the projections how precipitation will change is less certain (Engelbrecht, 2015). Further research will be needed to understand if and how local knowledge will adapt under climate change. Improved forecast information provided by global forecasting systems, including through integration of local hydro-meteorological observations (Lavers et al, 2019), as well as improved interpretation of these forecasts at regional level (Jubach and Tokar, 2016) could contribute to reducing false alarm rates.

Conclusion.

Using social science-based methods and secondary data sources, we document the knowledge that communities have on the occurrence and impacts of flash floods in Karonga District in northern Malawi. Thematic analysis of the transcriptions from focus group discussions with communities, and key informant interviews with local and national experts, revealed which catchments communities identify as susceptible to flash flooding, as well as the hydro-meteorological signs they recognise as precursors to flash flood events. This local knowledge was used to guide scientific analysis of the susceptibility of flash floods in catchments identified as flash flood prone by the communities, as well as the hydro-meteorological conditions prior to and during documented flash flood events extracted from coarse-scale globally available models and datasets.

The local knowledge of the communities, documented through the focus group discussion and key informant interviews shows that there is a well-developed knowledge of the occurrence of flash floods in the district, including which catchments are more susceptible to flash flooding and the factors that may aggravate susceptibility. There is also well-developed knowledge of the hydro-meteorological conditions they consider as precursors to flash flood events. Interestingly, the communities identified differences in flash flood events and the impacts these have across the district, including the different characteristics of flash flood events occurring in the early wet season and in the late wet season. Integrating this local knowledge with secondary data of flash floods and their impacts in the district contributed to developing a common baseline

of the knowledge and perspectives of the spatial and temporal occurrence of flash floods and their triggers in Northern Malawi.

580   Our geo-morphological analysis of the catchments, based on the geometric attributes and indicators extracted from SRTM DEM data, Normalized Difference Vegetation Index (NDVI) from the Copernicus Global Land Service, and national soil and land-cover datasets corroborates the variability of flash flood susceptibility of the catchments in the district described by the communities. Similarly, indicators of the hydro-meteorological conditions and patterns extracted from GSMaP satellite precipitation estimates and ERA5 global reanalysis datasets, validate the precursor signs communities report, including the

585   different characteristics of events across the district and across the wet season. This demonstrates that flash floods happen the way people say, as well as how local knowledge can be used to guide and validate scientific analysis.

Through combining the local knowledge and the scientific analysis of hydro-meteorological conditions and geomorphological patterns, we developed a common understanding of flash floods in Northern Malawi. We identified that the occurrence of flash floods and their impacts differ both spatially and temporally. The analysis suggests that flash floods

590   in the South of Karonga District are mostly triggered by localised convective storms, aggravated by lower vegetation cover, while flash floods in the North of the district are triggered by longer duration orographic rainfall, also extending later in the wet season, with events lasting longer due to the lower infiltration rate.

This common understanding of flash flooding is developed through a bottom-up approach that starts from the risk knowledge and interpretation of communities affected by flash floods and using this to guide the analysis of

595   geomorphological and hydro-meteorological conditions. This holds significant potential in developing a more people-centred early warning of flash floods in those areas of the world where high-resolution forecast data may not be available. Though warnings triggered by indicators extracted from the global datasets used here result in over-confident forecasts, our results highlight the potential these datasets have, even at the local scale. Combining the local and scientific knowledge and understanding, and using commonly understood cues, will lead to better efficiency in triggering action prior to flash flood

600   events, which is crucial to reduce flash flood impacts in vulnerable communities.

Appendices.

Appendix A:

605 **Table A1: List of indicators included in the Principal Component Analysis per categories, resulted indicator loading factors, and category weights (a, b, c and d).**

a) PC[geom]: Catchment geometry characteristics

Variable	Symbol	Loading Factor
Area	Area	0.29
Length to width	LtoW	0.24
Basin Circularity	Cb	0.13
Time of Concentration	Tc	0.34
Weight a	*0.50*	

b) PC[hypsom]: Catchment hypsometry characteristics

Variable	Symbol	Loading Factor
Relative Elavation Ratio	Rel_Relief	0.38
Elevation Relief Ratio	Elev_RR	0.24
Mean Slope	Slope	0.38
Weight b	*0.10*	

c) PC[drain]: Catchment drainage network characteristics

Variable	Symbol	Loading Factor
Drainage density	Dd	0.25
Drainage relief ratio	D_RR	0.50
Basin bifurcation ratio	Rb	0.25
Weight c	*0.20*	

d) PC[Surface]: Catchment surface chacacteristics

Variable	Symbol	Loading Factor
Soil Index	Soil	0.43
NDVI_december	NDVI_Dec	0.57
Weight d	*0.20*	

Data availability. The historical flood impact database of Karonga built for the current research is available on demand. The dataset is restricted to analysis only, and cannot yet be published openly, as it contains data entries that are property of the
610 Department of Disaster Management Affair (DODMA). Dataset reference: Bucherie, A.: Karonga historical flood occurrences and impacts dataset (2000-2018) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.4661438, 2021.

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620

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References

Alam, A., Ahmed, B. and Sammonds, P.: Flash flood susceptibility assessment using the parameters of drainage basin morphometry in SE Bangladesh, Quat. Int., (April), 1–13, doi:10.1016/j.quaint.2020.04.047, 2020.

Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J. and Pappenberger, F.: GloFAS - global ensemble
640 streamflow forecasting and flood early warning, Hydrol. Earth Syst. Sci., 17(3), 1161–1175, doi:10.5194/hess-17-1161-2013, 2013.

Alfieri, L., Berenguer, M., Knechtl, V., Liechti, K., Sempere-Torres, D. and Zappa, M.: Flash Flood Forecasting Based on Rainfall Thresholds, in Handbook of Hydrometeorological Ensemble Forecasting, pp. 1–38., 2015.

Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., Roo, A., Salamon, P., Wyser, K. and Feyen, L.: Global projections of
645 river flood risk in a warmer world, 5,171–182, doi:10.1002/2016EF000485, 2017.

Alfieri, L., Cohen, S., Galantowicz, J., Schumann, G. J. P., Trigg, M. A., Zsoter, E., Prudhomme, C., Kruczkiewicz, A., Coughlan de Perez, E., Flamig, Z., Rudari, R., Wu, H., Adler, R. F., Brakenridge, R. G., Kettner, A., Weerts, A., Matgen, P.,

Islam, S. A. K. M., de Groeve, T. and Salamon, P.: A global network for operational flood risk reduction, Environ. Sci. Policy, 84, 149–158, doi:10.1016/j.envsci.2018.03.014, 2018.

650 Aonashi, K., Awaka, J., Hirose, M., Hozu, T. and Kubota, T.: GSMaP passive, microwave precipitation retrieval algorithm: Algorithm description and validation, J. Meteor. Soc. Japan, 87A, 119-136., 2009.

Arabameri, A., Saha, S., Chen, W., Roy, J., Pradhan, B. and Bui, D. T.: Flash flood susceptibility modelling using functional tree and hybrid ensemble techniques, J. Hydrol., 587, 125007, doi:https://doi.org/10.1016/j.jhydrol.2020.125007, 2020.

Azmeri, Hadihardaja, I. K. and Vadiya, R.: Identification of flash flood hazard zones in mountainous small watershed of
655 Aceh Besar Regency, Aceh Province, Indonesia, Egypt. J. Remote Sens. Sp. Sci., 19(1), 143–160, doi:https://doi.org/10.1016/j.ejrs.2015.11.001, 2016.

Bajabaa, S., Masoud, D. M. and Alamri, N.: Flash flood hazard mapping based on quantitative hydrology, geomorphology and GIS techniques (case study of Wadi Al Lith, Saudi Arabia), Arab. J. Geosci., 7, doi:10.1007/s12517-013-0941-2, 2013.

Basher, R.: Global early warning systems for natural hazards: systematic and people-centred, Philos Trans A Math Phys Eng
660 Sci, 364(1845), 2167–2182, doi:10.1098/rsta.2006.1819, 2006.

Bischiniotis, K., Van Den Hurk, B., Jongman, B., Coughlan De Perez, E., Veldkamp, T., De Moel, H. and Aerts, J.: The influence of antecedent conditions on flood risk in sub-Saharan Africa, Nat. Hazards Earth Syst. Sci., 18(1), 271–285, doi:10.5194/nhess-18-271-2018, 2018.

Braud, I., Vincendon, B., Anquetin, S., Ducrocq, V. and Creutin, J. D.: The challenges of flash flood forecasting, Mobil.
665 Face Extrem. Hydrometeorol. Events 1 Defin. Relev. Scales Anal., 63–88, doi:10.1016/B978-1-78548-289-2.50003-3, 2018.

Bucherie, A.: Karonga historical flood occurrences and impacts dataset (2000-2018) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.4661438, 2021.

C3S: ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate . Copernicus Climate Change Service Climate Data Store (CDS), [online] Available from: https://cds.climate.copernicus.eu/cdsapp#!/home, 2017.

670 Calvel, A., Werner, M., van den Homberg, M., Cabrera Flamini, A., Streefkerk, I., Mittal, N., Whitfield, S., Langton Vanya, C. and Boyce, C.: Communication Structures and Decision Making Cues and Criteria to Support Effective Drought Warning in Central Malawi, Front. Clim., 2(November), doi:10.3389/fclim.2020.578327, 2020.

Chao, Y. S. and Wu, C. J.: Principal component-based weighted indices and a framework to evaluate indices: Results from the Medical Expenditure Panel Survey 1996 to 2011, PLoS One, 12(9), doi:10.1371/journal.pone.0183997, 2017.

675 Creutin, J. D. and Borga, M.: Radar hydrology modifies the monitoring of flash-flood hazard, Hydrol. Process., 17(7), 1453–1456, doi:10.1002/hyp.5122, 2003.

Drobot, S. and Parker, D. J.: Advances and challenges in flash flood warnings, Environ. Hazards, 7, 173–178, doi:10.1016/j.envhaz.2007.09.001, 2007.

EM-DAT: The CRED/OFDA International Disaster Database., [online] Available from: www.emdat.be, n.d.

680 Emerton, R. E., Stephens, E. M., Pappenberger, F., Pagano, T. C., Weerts, A. H., Wood, A. W., Salamon, P., Brown, J. D., Hjerdt, N., Donnelly, C., Baugh, C. A. and Cloke, H. L.: Continental and global scale flood forecasting systems, WIREs Water, 3(3), 391–418, doi:http//doi.org/10.1002/wat2.1137, 2016.

Engelbrecht, F., Adegoke, J., Bopape, M. J., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C. and Gatebe, C.: Projections of rapidly rising surface temperatures over Africa under low mitigation, Environ. Res. 685 Lett., 10(8), doi:10.1088/1748-9326/10/8/085004, 2015.

Farhan, Y., Anaba, O. and Salim, A.: Morphometric Analysis and Flash Floods Assessment for Drainage Basins of the Ras En Naqb Area, South Jordan Using GIS, J. Geosci. Environ. Prot., 04(06), 9–33, doi:10.4236/gep.2016.46002, 2016.

FloodList: Reporting floods and flooding news since 2008. Funded by Copernicus, the European System for Earth Monitoring, [online] Available from: https://floodlist.com/, n.d.

690 Georgakakos, K. P.: A generalized stochastic hydrometeorological model for flood and flash-flood forecasting: 1. Formulation, 22(13), 2083–2095, doi:10.1029/WR022i013p02083, 1986.

Georgakakos, K. P.: Analytical results for operational flash flood guidance, J. Hydrol., 317(1–2), 81–103, doi:10.1016/j.jhydrol.2005.05.009, 2005.

Gray, D. M.: Interrelationships of watershed characteristics, J. Geophys. Res., 66(4), 1215–1223, 695 doi:https://doi.org/10.1029/JZ066i004p01215, 1961.

Gründemann, G. J., Werner, M. and Veldkamp, T. I. E.: The potential of global reanalysis datasets in identifying flood events in Southern Africa, Hydrol. Earth Syst. Sci., 22(9), 4667–4683, doi:10.5194/hess-22-4667-2018, 2018.

Hapuarachchi, H. A. P., Wang, Q. J. and Pagano, T. C.: A review of advances in flash flood forecasting, Hydrol. Process., 25(18), 2771–2784, doi:10.1002/hyp.8040, 2011.

700 Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. and Thépaut, J.-N.: The ERA5 global reanalysis, Q. J. R. Meteorol. 705 Soc., 146(730), 1999–2049, doi:10.1002/qj.3803, 2020.

Hill, C. and Verjee, F.: Flash Flood Early Warning System Reference Guide - COMET - NOAA Report. [online], 2010.

Hoeppe, P.: Trends in weather related disasters – Consequences for insurers and society, Weather Clim. Extrem., 11, 70–79, doi:10.1016/j.wace.2015.10.002, 2015.

Horton, B. Y. R. E.: Erosional development of streams and their drainage basins; Hydrophysical approach to quantitative 710 morphology, Bull. Geol. Soc. Am., 56(March), 275–370, 1945.

ICA: Malawi Integrated Context Analysis, Word Food Program, 2014

IFPRI: IFPRI Key Facts Series: Poverty May 2019 Background to the Integrated Household Surveys (IHS), 2019.

IFRC-GO: Disaster Response and Preparedness Operation Database. International Federation of the Red Cross., [online] Available from: https://go.ifrc.org/, n.d.Jarvis, A., Reuter, H., Nelson, A. and Guevara, E.: Hole-filled SRTM for the globe

715   version 3, from the CGIAR-CSI SRTM 90m database, See http//srtm. csi. cgiar. org, 2008.

Javelle, P., Fouchier, C., Arnaud, P. and Lavabre, J.: Flash flood warning at ungauged locations using radar rainfall and antecedent soil moisture estimations, J. Hydrol., 394(1–2), 267–274, doi:10.1016/j.jhydrol.2010.03.032, 2010.

Jonkman, S. N.: Global Perspectives on Loss of Human Life Caused by Floods, Nat. Hazards, 34,151–175, doi:10.1007/s11069-004-8891-3, 2005.

720   Jubach, R. and Sezin Tokar, A.: International severe weather and flash flood hazard early warning systems-leveraging coordination, cooperation, and partnerships through a hydrometeorological project in Southern Africa, Water (Switzerland), 8(6), 1–11, doi:10.3390/W8060258, 2016.

Karmokar, S. and De, M.: Flash flood risk assessment for drainage basins in the Himalayan foreland of Jalpaiguri and Darjeeling Districts, West Bengal, Model. Earth Syst. Environ., 6(4), 2263–2289, doi:10.1007/s40808-020-00807-9, 2020.

725   Kauffeldt, A., Wetterhall, F., Pappenberger, F., Salamon, P. and Thielen, J.: Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level, Environ. Model. Softw., 75, 68–76, doi:10.1016/j.envsoft.2015.09.009, 2015.

Kirpich, Z. P.: Time of concentration of small agricultural watersheds., Civ. Eng 10362–368, 1940.

Kubota, T., Shige, S., Hashizume, H., Aonashi, K., Takahashi, N., Ushio, T. and Kachi, M.: Global Precipitation Map using

730   Satelliteborne Microwave Radiometers by the GSMaP Project : Production and Validation, IEEE Trans. Geosci. Remote Sens., Vol. 45, N, pp.2259-2275, 2007.

Lavers, D. A., Harrigan, S., Andersson, E., Richardson, D. S., Prudhomme, C. and Pappenberger, F.: A vision for improving global flood forecasting, Environ. Res. Lett., 14(12), doi:10.1088/1748-9326/ab52b2, 2019.

Lefale, P. F.: Ua 'afa le Aso Stormy weather today: Traditional ecological knowledge of weather and climate. The Samoa

735   experience, Clim. Change, 100(2), 317–335, doi:10.1007/s10584-009-9722-z, 2010.

Linsey, R. K., Kohler, M. A. and Pauhlus, J. L. H.: Hydrology for engineers (3rd ed.), New York: McGraw-Hill., 1982.

Luther, J., Hainsworth, A., Tang, X., Harding, J., Torres, J. and Fanchiotti, M.: Advancing Culture of Living with Landslides, Adv. Cult. Living with Landslides, doi:10.1007/978-3-319-59469-9, 2017.

Martin, N. and Rice, J.: Emergency communications and warning systems, Disaster Prev. Manag., Vol. 21 No, 529–540, doi:

740   10.1108/09653561211278671, 2012.

McSweeney, C., New, M. and Lizcano, G.: UNDP Climate Change Country Profiles, Malawi., 2010.

Meléndez-Landaverde, E. R., Werner, M. and Verkade, J.: Exploring protective decision-making in the context of impact-based flood warnings, J. Flood Risk Manag., 13(1), 1–11, doi:10.1111/jfr3.12587, 2020.

Melton, M. A.: An analysis of the relations among elements of climate, surface properties, and geomorphology, Department

745   of Geology, Columbia University, New York., 1957.

Miller, V. C.: A quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain area, Virginia and Tennessee, Dept. of Geology, Columbia University, New York., 1953.

Molinari, D. and Handmer, J.: A behavioural model for quantifying flood warning effectiveness, J. Flood Risk Manag., 4(1), 23–32, doi:10.1111/j.1753-318X.2010.01086.x, 2011.

750 Morss, R. E., Demuth, J. L., Lazo, J. K., Dickinson, K., Lazrus, H. and Morrow, B. H.: Understanding public hurricane evacuation decisions and responses to forecast and warning messages, Weather Forecast., 31(2), 395–417, doi:10.1175/WAF-D-15-0066.1, 2016.

Munich RE: Munich Re's NatCatSERVICE, [online] Available from: https://www.munichre.com/en/solutions/for-industry-clients/natcatservice.html, 2004.

755 Nicholson, S. E., Klotter, D. and Chavula, G.: A detailed rainfall climatology for Malawi, Southern Africa, Int. J. Climatol., Int. J. Cl [online] Available from: internal-pdf://235.205.73.189/Nicholson_et_al-2014-International_Journal_of_.pdf, 2014.

Nyasa Times: Malawi breaking online news source., [online] Available from: https://www.nyasatimes.com/, n.d.O'Sullivan, J. J., Bradford, R. A., Bonaiuto, M., De Dominicis, S., Rotko, P., Aaltonen, J., Waylen, K. and Langan, S. J.: Enhancing flood resilience through improved risk communications, Nat. Hazards Earth Syst. Sci., 12(7), 2271–2282,
760 doi:10.5194/nhess-12-2271-2012, 2012.

Okamoto, K., Ushio, T. and Iguchi, T.: The Global Satellite Mapping of Precipitation (GSMaP) project, 25th IGARSS Proc., 3414-3416., 2005.

Orlove, B., Roncoli, C., Kabugo, M. and Majugu, A.: Indigenous climate knowledge in southern Uganda: The multiple components of a dynamic regional system, Clim. Change, 100(2), 243–265, doi:10.1007/s10584-009-9586-2, 2010.

765 Oruonye, E.: Morphometry and Flood in Small Drainage Basin: Case Study of Mayogwoi River Basin in Jalingo, Taraba State Nigeria, J. Geogr. Environ. Earth Sci. Int., 5(1), 1–12, doi:10.9734/jgeesi/2016/23379, 2016.

Parker, D. J., Priest, S. J. and Tapsell, S. M.: Understanding and enhancing the public's behavioural response to flood warning information, Meteorol. Appl., 16(1), 103–114, doi:https://doi.org/10.1002/met.119, 2009.

Patton, P. C. and Baker, V. R.: Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic
770 controls, Water Resour. Res., 12(5), 941–952, doi:10.1029/WR012i005p00941, 1976.

Perera, D., Seidou, O., Agnihotri, J., Mehmood, H. and Mohamed Rasmy, A. W.: Challenges and Technical Advances in Flood Early Warning Systems (FEWSs), pp. 1–18., 2020.

Pham, B. T., Avand, M., Janizadeh, S., Phong, T. Van, Al-Ansari, N., Ho, L. S., Das, S., Le, H. Van, Amini, A., Bozchaloei, S. K., Jafari, F. and Prakash, I.: GIS based hybrid computational approaches for flash flood susceptibility assessment, Water
775 (Switzerland), 12(3), 1–30, doi:10.3390/w12030683, 2020.

Plotz, R. D., Chambers, L. E. and Finn, C. K.: The best of both worlds: A decision-making framework for combining traditional and contemporary forecast systems, J. Appl. Meteorol. Climatol., 56(8), 2377–2392, doi:10.1175/JAMC-D-17-0012.1, 2017.

Poolman, E., Rautenbach, H. and Vogel, C.: Application of probabilistic precipitation forecasts from a deterministic model towards increasing the lead-time of flash flood forecasts in South Africa, Water SA, 40(4), 729, doi:10.4314/wsa.v40i4.18, 2014.

ReliefWeb: Humanitarian information service. Provided by the United Nations Office for the Coordination of Humanitarian Affairs (OCHA)., n.d.

Rogelis, M. C. and Werner, M.: Regional debris flow susceptibility analysis in mountainous peri-urban areas through morphometric and land cover indicators, Nat. Hazards Earth Syst. Sci., 14(11), 3043–3064, doi:10.5194/nhess-14-3043-2014, 2014.

Roujean, J. L., Leon-Tavares, J., Smets, B., Claes, P., Camacho De Coca, F. and Sanchez-Zapero, J.: Surface albedo and toc-r 300 m products from PROBA-V instrument in the framework of Copernicus Global Land Service, Remote Sens. Environ., 215(May), 57–73, doi:10.1016/j.rse.2018.05.015, 2018.

Sai, F., Cumiskey, L., Weerts, A., Bhattacharya, B. and Haque Khan, R.: Towards impact-based flood forecasting and warning in Bangladesh: a case study at the local level in Sirajganj district, Nat. Hazards Earth Syst. Sci. Discuss., 1–20, doi:10.5194/nhess-2018-26, 2018.

Šakić Trogrlić, R., Wright, G., Duncan, M., van den Homberg, M., Adeloye, A., Mwale, F. and Mwafulirwa, J.: Characterising Local Knowledge across the Flood Risk Management Cycle: A Case Study of Southern Malawi, Sustainability, 11(6), doi:10.3390/su11061681, 2019.

Salit, F., Zaharia, L. and Beltrando, G.: Assessment of the warning system against floods on a rural area: the case of the lower Siret River (Romania), Nat. Hazards Earth Syst. Sci., 13(2), 409–416, doi:10.5194/nhess-13-409-2013, 2013.

Schumm, S. A.: Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey, GSA Bull., 67(5), 597–646, doi:10.1130/0016-7606(1956)67[597:EODSAS]2.0.CO;2, 1956.

Shah, M. A. R., Douven, W. J. A. M., Werner, M. and Leentvaar, J.: Flood warning responses of farmer households: a case study in Uria Union in the Brahmaputra flood plain, Bangladesh, 5, 258–269, doi:10.1111/j.1753-318X.2012.01147.x, 2012.

Smith, G.: Flash Flood potential: determining the hydrologic response of FFMP basins to heavy rain by analysing their physiographic characteristics., A white Pap. available from NWS Color. Basin River Forecast Cent. web site http//www.cbrfc.noaa.gov/papers/ffp_wpap.pdf, 11 pp [online], 2003.

Strahler, A. N.: Quantitative analysis of watershed geomorphology, Eos, Trans. Am. Geophys. Union, 38(6), 913–920, doi:https://doi.org/10.1029/TR038i006p00913, 1957.

The Nation: Nation Publications Limited (NPL) Newspaper, [online] Available from: https://www.mwnation.com/, n.d.

Tincu, R., Lazar, G. and Lazar, I.: Modified flash flood potential index in order to estimate areas with predisposition to water accumulation, Open Geosci., 10(1), 593–606, doi:10.1515/geo-2018-0047, 2018.

Tong, A., Sainsbury, P., Craig, J.: Consolidated Criteria for Reporting Qualitative Research (COREQ): A 32-Item Checklist for Interviews and Focus Groups, International Journal for Quality in Health Care, 19 (6): 349–57, https://doi.org/10.1093/intqhc/mzm042, 2007.

UNICEF: UNICEF Malawi blog, [online] Available from: https://unicefmalawi.blog/, n.d.

USAID: Conducting Key Informant Interviews Performance Monitoring & Evaluation TIPS., Washington DC., 1996.

815 Vincent, K., Conway, D., Dougill, A. J., Pardoe, J., Archer, E., Bhave, A. G., Henriksson, R., Mittal, N., Mkwambisi, D., Rouhaud, E. and Tembo-Nhlema, D.: Re-balancing climate services to inform climate-resilient planning – A conceptual framework and illustrations from sub-Saharan Africa, Clim. Risk Manag., 29(February), 100242, doi:10.1016/j.crm.2020.100242, 2020.

Werner, M. and Cranston, M.: Understanding the Value of Radar Rainfall Nowcasts in Flood Forecasting and Warning in 820 Flashy Catchments, Meteorol. Appl., 16(1), 41–55, doi:https://doi.org/10.1002/met.125, 2009.

WMO: Multi-hazard Early Warning Systems: A Checklist., 20 [online] Available from: https://library.wmo.int/doc_num.php?explnum_id=4463, 2018.

WMO: WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services. [online] Available from: internal-pdf://235.108.188.120/WMOGuidelinesonMulti-hazardImpact-basedForecas.pdf, 2015.

825 Zevenbergen, L. W. and Thorne, C. R.: Quantitative analysis of land surface topography, Earth Surf. Process. Landforms, 12(1), 47–56, doi:10.1002/esp.3290120107, 1987.

Zogg, J. and Deitsch, K.: The Flash Flood Potential Index at WFO Des Moines, Iowa - NOAA - NWS. [online], 2013.