Towards improving a national flood early warning system with global ensemble flood predictions and local knowledge.

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INTRO

This thesis is part of the MSc Hydrology at the Vrije Universiteit in Amsterdam. This research was carried out at 510, an initiative of the Netherlands Red Cross. The fieldwork in Malawi of this research was funded by the EU-ECHO II project, *Enhancing resilience in Malawi,* led by the Belgium Red Cross and is part of the Forecast-Based Financing project of the Danish Red Cross.

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Humanitarian Aid and Civil Protection

Summary

Flood risk is increasing globally and flood early warning systems (EWS) are required to decrease this risk and its impacts. However, in developing countries, existing EWSs are often insufficient and not effective. In this research 2 methods are found to improve an existing flood EWS, in a case study of the most flood-prone area of Malawi, i.e. the Lower Shire Valley.

Method 1: Assessment of GloFAS

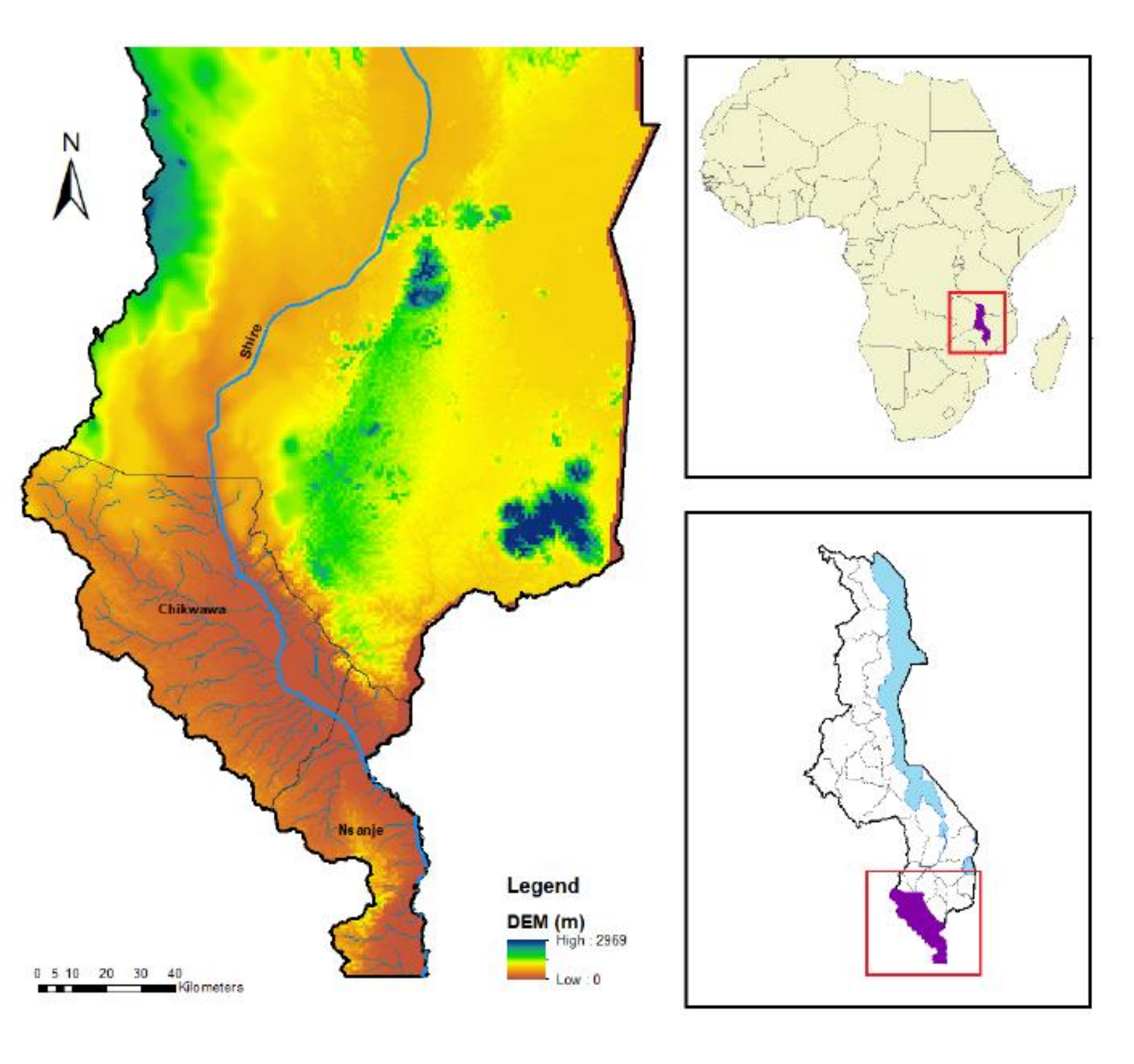
a medium-term forecast that can improve the EWS

Method 2: Assessment of the Integration of IK process

of flood forecasts to improve the EWS

Case study area: Lower Shire Valley in Malawi

- Chikwawa & Nsanje district
- Low lying area
- Most disaster- & flood prone area Malawi
- 80% of population below poverty line
- 90% of the households dependent on agriculture
- Area with an official Early Warning System (EWS)



Challenges in the current flood EWS in the Lower Shire Valley

- Many different **components** that are **not integrated**: various official forecasts, community based forecasts, indigenous knowledge forecasts → **complex decision making process**
- **Official forecast** not delivered in time to end-users.
- Rich **Indigenous Knowledge** is not taken into account in the current EWS
- The **official EWS** only operational in Lower Shire Valley

Research question

"How can the integration of indigenous and scientific knowledge on forecasting floods be used to improve the flood Early Warning System (EWS) in the Lower Shire Valley in Malawi?"

Methods used to answer this question:

Method 1:

Assessment of GloFAS (the Global Flood Awareness system), a medium-term forecast.

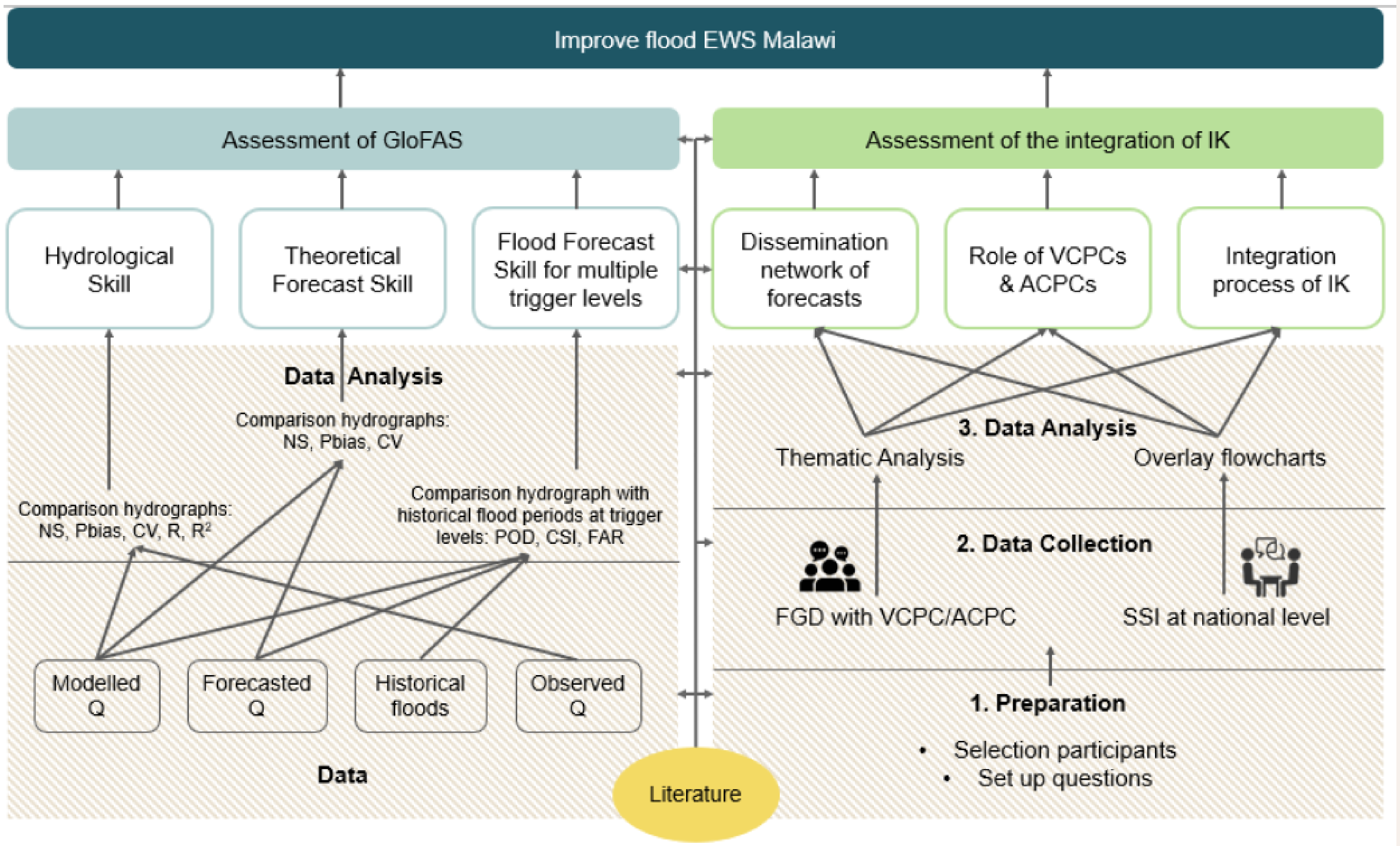
How well does GloFAS perform and can it be used to create an extended lead time for the EWS?

Method 2:
Assessment of the integrating process of flood forecasts in the EWS.

What forecast sources are available, how is the information disseminated, what is the role of the local people?

An overview of the complete method can be found in on the next slide.

Method of the research



Main advantages of both methods

Method 1:
Assessment of GloFAS

- **Medium-term forecast** model: up to 15-30 days → increased time to act
- Available for **whole of Malawi**
- **Free** to use

Method 2:
Assessment of the Integration of IK process

- The sources of knowledge will **complement each other's strengths**
- **Indigenous Knowledge (IK)** can help communities to **understand and communicate the official forecast** information.
- **IK** is **specific** for **every village**
- **IK** that is used might be **less reliable** due to climate change, so needs to be combined with other forecast information.

Method 1: Assessment of GloFAS

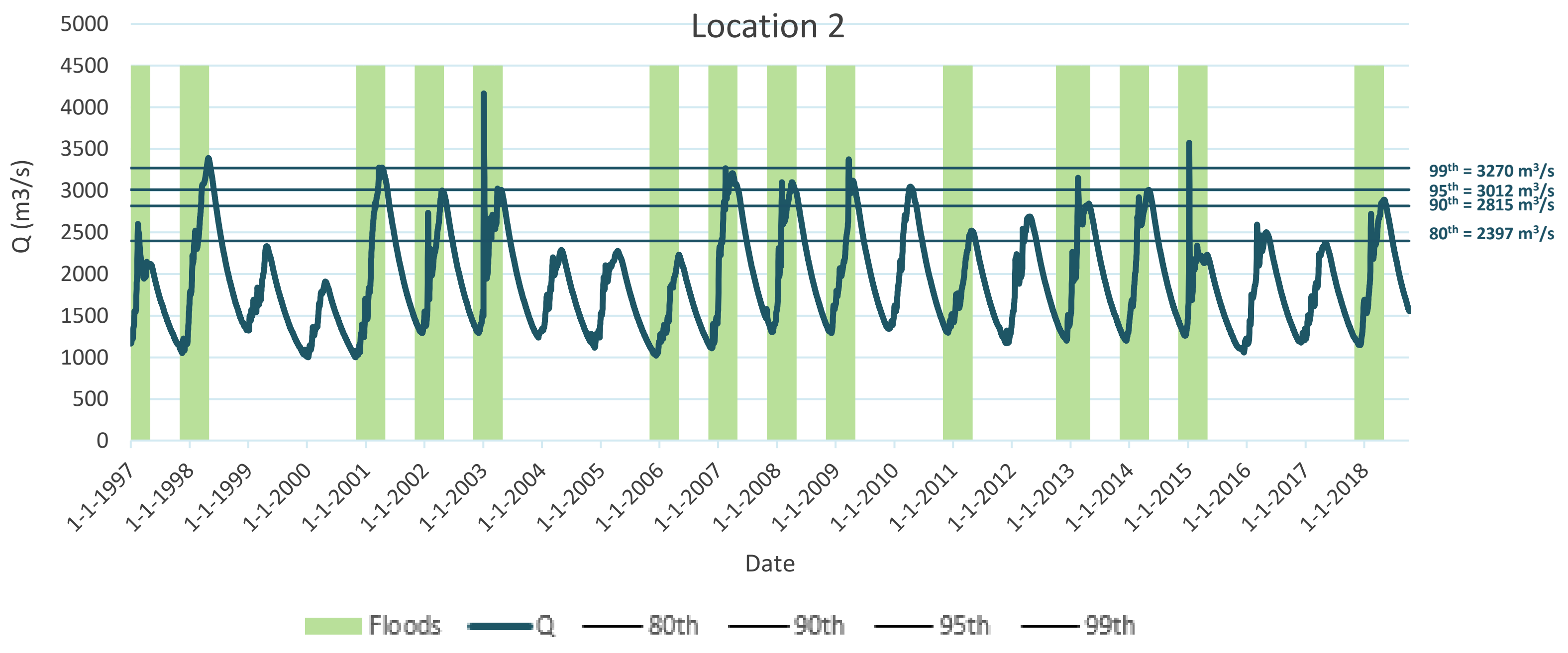
The forecast skill and trigger levels of the medium-term Global Flood Awareness System (GloFAS) model are determined for four gauge locations to assess how they can improve the national EWS. **The assessment of GloFAS** for the Lower Shire Valley shows:

- The hydrological skill has shown that **the modelled discharge is overestimating the overall observed discharge** or the peaks of the observed discharge.
- The theoretical forecast skill is showing that **the modelled and forecasted discharges are better in agreement**. However, the forecast skill is decreasing and getting more variable over the river cells with an increasing lead time.
- **GloFAS** does not predict absolute discharge values precisely, but **can be used to predict floods if the correct trigger levels are set per location**.
- The main **steps that need to be taken** to choose correct trigger levels **are, improving the historical flood database, and calibrating the system for Malawi.**

Method 1: Assessment of GloFAS

An example of determining the correct trigger level for location 2:

The **modelled discharge** at LT0 **and the forecasted discharge** at LT7 and LT15 **are compared with reported floods** using multiple thresholds. This is done to assess **if the modelled and forecasted discharge are able to detect reported floods and what trigger level gives the best result.** The figure below shows the different thresholds for location 2 and shows that a threshold of the 80th percentile gives the best result using the table next to the graph.



		Historical Floods	
		Yes	No
Modelled floods	Yes	Hit	False Alarm
	No	Miss	Correct Negative

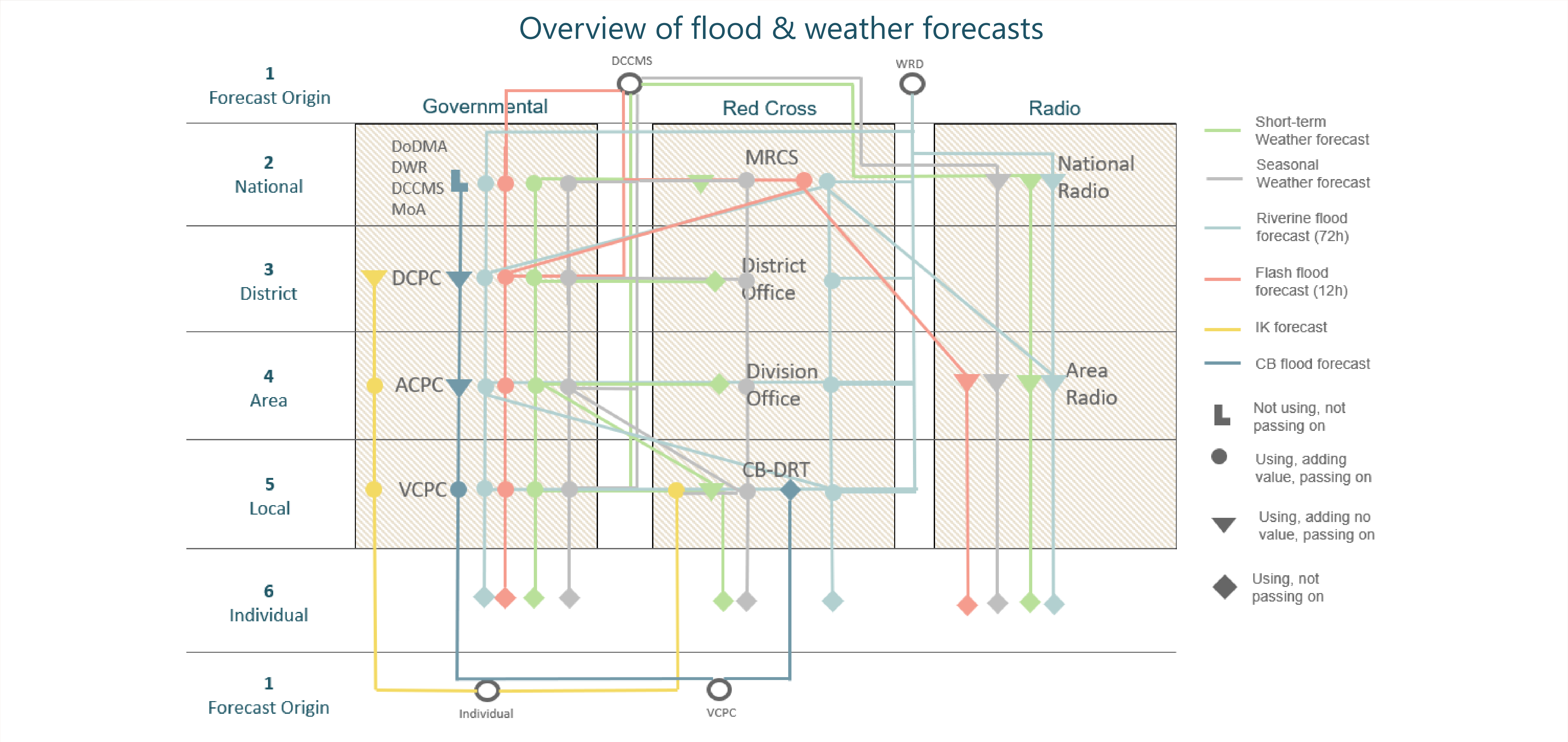
Method 2: Assessment of the integration process

An assessment is done on how the process of integrating flood forecasts based on local knowledge with official forecasts, can help to improve the EWS. The complete **flood and weather forecast dissemination network i**n the Lower Shire Valley showed that:

- **A very complex process is going on**, where all stakeholders receive information from different sources via different channels. This makes it **hard for the end-users of the forecasts to make a decision**, especially if not all sources are giving the same warning.
- **Every local committee** that was part of this research **uses, next to various official forecasts, community-based forecasts and forecasts based on indigenous knowledge.**
- **Local indicators** used most to predict floods are**:** observations of more **ants**, more fruits produced by **mango trees**, **hippo's** away from river.
- **Not all stakeholders receive the information** they are supposed to get and official warnings are not always received **in time**.
- **Indigenous knowledge might become less reliability** due to climate change, therefor the importance of integrating the different sources is increasing.
- **The integration** of multiple forecast sources **is found to be useful at both national and community levels**.
- An integration process is proposed where **village stakeholders should take the leading role** by using existing disaster management and civil protection coordination mechanisms.

An overview of the complete flood and weather forecast dissemination network can be found on the next slide.

Method 2: Assessment of the integration process



The way forward

Method 1: Assessment of GloFAS

GloFAS can be used as medium-term flood forecast model but a few steps must be taken first:

- The most **suitable trigger level to detect floods** differs per location and different lead times. So, if GloFAS would be used in the future, the trigger levels should be determined per location and per lead time.
- The **lack of observed discharge** locations, gaps in the data, and the short periods make it hard to state that the results on the hydrological skill are completely reliable. To use the method in this research, to calculate the trigger levels, the historical flood database must be completed and more detailed for specific locations.
- GloFAS must be **calibrated** for Malawi.
- The **current official EWS must be assessed** (data from the government is necessary).
- **Advice** on the use of **the current EWS or GloFAS:** either use one of both and expand it to the whole country or combine both systems by using ODSS for the first 72 hours and GloFAS for the longer lead times.

Method 2: Assessment of the integration process

A very complex process is going on in using the **different forecasts** which has multiple challenges, so it is important to **integrate the different sources**:

- **The Village Civil Protection Committees are the structures that are most adequate** to take a leading role in this integration process. However, VCPCs are not available in the whole of Malawi or are not always active. So, VCPCs have to be introduced in all areas and committees have to become active by giving the members allowances for their work, making sure all members are chosen democratically and by making sure each committee has enough resources to do their job.
- **The actual integration process should start.**

Conclusion

This research has shown a method to improve or establish a flood EWS, that can be valuable in various developing countries. Using the two methods can potentially maximize the benefits an EWS and decrease the flood risk in the Lower Shire Valley in Malawi.

The **Flood EWS** can potentially be **improved** by implementing **GloFAS** as (additional) medium-term model & by **integrating all sources** that are used by the local communities.

The complete thesis can be found from the next page on.

Assessing Two Methods to Potentially Improve the Flood Early Warning System in the Lower Shire Valley in Malawi

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Abstract

Flood risk, a function of hazard, exposure and vulnerability, is increasing globally. Mainly, the hazard and exposure components are increasing. However, decreasing the vulnerability of a country or community can decrease the flood risk and impacts of floods. In developing countries, where resources are often limited, the use of an effective flood early warning system (EWS) is very valuable to decrease this vulnerability. An example of such a vulnerable country to riverine floods is Malawi. This research presents an assessment of two methods to improve the flood EWS in the Lower Shire Valley, the most flood-prone area of Malawi. Firstly, an assessment is done on how the medium-term Global Flood Awareness System (GloFAS) can help to improve the EWS. This is done by assessing its forecast skill and determining trigger levels for 4 locations. Secondly, an assessment is done on how the process of integrating flood forecasts based on indigenous knowledge with official forecasts, can help to improve the EWS. This is done by doing semi-structured interviews at national level and focus group discussions at community level. The study shows that GloFAS is not a good predictor of absolute discharge values, but can be used to predict floods if the correct trigger levels are set per location. The integration of multiple forecasts sources is found to be useful at both national and community level. An integration process is proposed where stakeholders at village level should take the leading role. Overall, both methods can contribute in improving the flood EWS and decreasing the flood risk in the Lower Shire Valley in Malawi.

Acknowledgements

This thesis is part of the MSc Hydrology at the Vrije Universiteit in Amsterdam. This research was carried out at 510, an initiative of the Netherlands Red Cross. The fieldwork in Malawi of this research was funded by the EU-ECHO II project, *Enhancing resilience in Malawi*, led by the Belgium Red Cross and is part of the Forecast-Based Financing project of the Danish Red Cross.

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List of Abbreviations

ACPC	Area Civil Protection Committee
ADC	Area Development Committee
CB	Community Based
CB-DRT	Community Based – Disaster Response Team
CB-EWS	Community Based – Early Warning System
CB-FRM	Community Based- Flood Risk Management
CPC	Civil Protection Committee
CSI	Critical Success Index
CV	Coefficient of variation of the Root Mean Squared Error
DCCMS	Department of Climate Change & Meteorological Services
DCPC	District Civil Protection Committee
DoDMA	Department of Disaster Management Affairs
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
DSS	Decision Support System
DWR	Department of Water Resources
EM-DAT	Emergency Event – Database
ESP	Ensemble Streamflow Prediction
EWS	Early Warning System
EWT	Early Warning Team
FAR	False Alarm Ratio
FbF	Forecast Based Financing
FGD	Focus Group Discussion
FRM	Flood Risk Management
FRR	Flood Risk Reduction
GloFAS	Global Flood Awareness System
GVH	Group Village Head
IFCR	International Federation of Red Cross & Red Crescent Societies
IK	Indigenous Knowledge
ITCZ	Inter-Tropical Convergence Zone
LT	Lead Time
MoA	Ministry of Agriculture
MRCS	Malawi Red Cross Society
NDRM	National Disaster Risk Management
NGO	Non-Governmental Organization
NS	Nash-Sutcliffe
NWP	Numerical Weather Prediction
ODSS	Operational Decision Support System
PBias	Percentage Bias
POD	Probability of Detection

Q	Discharge
R	Pearson's Correlation Coefficient
R^2	Coefficient of Determination
RC	Red Cross
SK	Scientific Knowledge
SSI	Semi-Structured Interview
TA	Traditional Authority
VCPC	Village Civil Protection Committee

Introduction | 1

1.1 Global Flood Risk

Floods are the natural hazards with most impact worldwide. Floods have the highest frequency: they account for one-third of all natural hazards. In addition, they have the widest geographical distribution, annually leading to US$104 billion losses (UNDRR, 2015). Moreover, floods are leading to more than half of all victims caused by natural hazards (UNDRR, 2015). More than 95% of all fatalities, as a result of natural hazards, are in the lower-income countries (United Nations, 2002).

Flood risk is a combination of hazard, exposure, and vulnerability. This risk is expected to increase in most regions in the world as the flood hazard will increase due to climate change, and exposure will increase due to the growth of population and economic assets (Jongman et al., 2015). However, decreasing the vulnerability of a region can help to decrease the flood risk, even with an increasing hazard and exposure. Vulnerability is often higher in low-income countries and includes all efforts made to reduce the impact of flood hazard on the exposed elements (Jongman et al., 2015). This means that with increasing hazard and exposure, especially in developing countries, it is getting more and more important to take measures to decrease this vulnerability and therefore the flood risk.

1.2 Flood risk in Malawi

An example of such a vulnerable region is the South of Malawi, that experienced two flood events in early 2019, the floods claimed 56 lives and almost 900,000 people were affected (EM-DAT, 2019). Overall, from 1979 to 2010, natural disasters affected nearly 21.7 million people and led to about 2,596 deaths in Malawi (GoM, 2015). According to Trogrlić & Chawawa (2019), Malawi is the third poorest country in the world and about half of the population lives below the poverty line. More than 80 percent of the population relies on agriculture, depending on one rainy season a year, which makes them particularly vulnerable to floods. Other factors that increase community's vulnerabilities are poor quality of housing and infrastructure, lack of economic diversification, employment opportunities and access to social services. These factors combined create a high flood risk, leading to the displacement of hundreds of people and food insecurity (Trogrlić & Chawawa, 2019).

In Malawi, various efforts have been taken to decrease this risk. For example, a national disaster risk policy, government pushing for resettlement of people living in flood-prone areas, Non-Governmental Organizations (NGOs) implementing Community Based - Flood Risk Management (CB-FRM) and an attempt to create a national Early Warning System (EWS) (Trogrlić et al., 2017). Despite these efforts, the floods still significantly impact livelihoods due to damage to agriculture and infrastructure for example (Trogrlić et al., 2017). This is partly due to challenges in the EWS, the main problem with the current EWS is that different components, like various official forecasts, community-based forecasts and forecasts based on Indigenous Knowledge (IK) are not integrated, leading to a complex decision-making process for early action (Trogrlić & Van den Homberg, 2018). Other issues with the official EWS are that the forecast is sometimes not delivered in time to the end-users, it is only operational in the Lower Shire Valley and it does not take rich IK into account. Furthermore, individuals do not always act upon warnings (Trogrlić & Van den Homberg, 2018).

1.3 Flood Early Warning Systems

If resources are not available to take flood protection measures, flood risk can be managed through preparedness capacity and increased response time. Warnings before a flood create additional time to take action. The longer the lead time (LT), the time between issuing the forecast and the event itself, the more time is available to take action (Cools & Innocenti, 2015). The use of an EWS can improve the preparedness capacity and increase the response time and therefore decrease the vulnerability to flood risk (United Nations, 2002).

The four key elements of an effective EWS are (UNDRR, 2006):

1. Risk Knowledge
2. Monitoring and Warning Service
3. Dissemination and Communication
4. Response Capability

There is a range of overarching issues that also has to be accounted for, next to the four key elements to make an EWS effective. Communities at risk need to be actively involved, public education and awareness of risk must be facilitated, messages and warnings must be effectively disseminated, and a constant state of preparedness must be ensured. A local, "bottom-up" approach to early warning enables a multi-dimensional response to problem and needs (UNDRR, 2006).

In most EWSs, the elements "monitoring & warning service" and "dissemination & communication" can still be improved (UNDRR, 2006). In the "monitoring & warning service", a reliable forecast and warning system is needed, with continuous monitoring to generate accurate warnings in time (UNDRR, 2006). The major issue with this is that the LT provided by the hydraulic models is often insufficient to allow for the implementation of protection measures (Pappenberger, 2012). A solution can be the use of a medium-range forecast that can predict up to 30 days, instead of the use of a short-range forecast that can only predict up to a few days (Thiemig, Bisselink, Pappenberger & Thielen, 2015). An example of a medium-range forecast is the Global Flood Awareness System (GloFAS), a daily hydrological forecast for the next 30 days (Alfieri et al., 2013).

To create effective dissemination and communication of the warnings, clear messages containing simple and useful information are needed. A gap needs to be bridged between what is useful according to the producers of scientific knowledge (SK) and to the end-users of the forecast (Luke et al, 2018). For improved dissemination of the warnings, unofficial warnings should be considered. This directly addresses the importance of involving local communities in the EWS. Often unofficial warnings are still neglected, this includes IK and extensive personal networks (Parker & Handmer, 2002). This unofficial system can be used to add information or confirmation before action is taken and to generate a timely and effective response (Parker & Handmer, 2002). Besides the role of dissemination of early warnings, IK should be recognized as a part of the knowledge generation on flood forecasting (Amitangshu & Prakash, 2018). Even though the value of unofficial forecast systems and IK are recognized, the process of integrating IK and SK, specifically in flood EWS, has not received a lot of attention yet.

1.4 Improving the flood EWS in the Lower Shire Valley, Malawi

This research will focus on how the flood EWS in Malawi can be improved in the most flood-prone area of the country, the Lower Shire Valley. The method that is proposed to improve the EWS in this case study, has the potential to be used in other developing countries as well. An assessment will be done on using bottom-up and top-down methods to improve this system. The top-down aspect is covered by evaluating the forecast skill of the medium range forecast system, GloFAS, to potentially improve the "monitoring and warning service". The bottom-up aspect by looking at how different sources of forecasts can be integrated with the involvement of communities, to improve the "dissemination and communication" of the warnings. GloFAS can potentially be used as scientific forecast in this integration process. It has the advantage of a longer LT, it is freely available and has a long time series available. This research is assessing if and how these improvements can be made in the current EWS of Malawi, which leads to the main research question of the study, with a set of sub-questions:

"How can the integration of indigenous and scientific knowledge on forecasting floods be used to improve the flood Early Warning System (EWS) in the Lower Shire Valley in Malawi?"

1. How can GloFAS be used as forecast system to improve the flood EWS in the Lower Shire Valley in Malawi?
    a. What is the hydrological skill of GloFAS?
    b. What is the theoretical forecast skill of GloFAS?
    c. What trigger levels are most suitable to detect floods?
2. How can the integration of forecasts based on indigenous knowledge with scientific knowledge, be used to improve the flood EWS in the Lower Shire Valley in Malawi?
    a. How is the forecast information disseminated through the entire network?
    b. What is the role of VCPCs and ACPCs in this dissemination process?
    c. How can the different sources of forecast information be integrated?

To answer the main question two aspects will be assessed. Firstly, an assessment will be done on if and how GloFAS can be introduced to improve the EWS. This is done by evaluating the skill of GloFAS with a method proposed by Bischiniotis et al. (2019) for Peru. The method is using several statistical scores to determine the hydrological and forecast skill. A comparison is made between the modelled discharge with historical flood data, to determine trigger levels to detect floods in four locations in the South of Malawi. Secondly, an assessment is done on the current dissemination network of forecast information and on how the integration of forecasts based on IK with scientific forecasts can be done. This is done by a literature research, 7 semi-structured interviews (SSIs) at national level and 15 focus group discussions (FGDs) at community level.

1.5 Thesis outline

This report consists of eight chapters. The first two chapters (chapter 2 and 3) provide the reader with a theoretical framework with background information and describe the case-study area. Chapter 4 describes the methodology that is used in this research, followed by the results in chapter 5 and 6. Chapter 5 answers if and how GloFAS can be used in the EWS. Chapter 6 answers how forecasts based on IK can be integrated with the official forecast information. Chapter 7 discusses the results, addresses the limitations of the research and gives recommendations for further research. Finally, chapter 8 concludes the research by highlighting the key findings.

Theoretical Framework | 2

This chapter will describe the theory and research that has already been done on effective EWSs, medium-term forecast models and the use of IK in forecasting. This chapter will also show how the overall method of this research, as described in chapter 4, is established.

2.1 Effective Early Warning Systems

As discussed before, an EWS is an important element of flood risk reduction (FRR). EWSs give individuals and communities at risk more time to act and can reduce the possibility of personal injury, loss of life and damage to property and environment. As explained in the introduction, an effective EWS requires communities at risk to be actively involved, public education and awareness of risk. Warnings from EWS need to be effectively disseminated, and a constant state of preparedness is required. A local, “bottom-up” approach in early warning enables a multi-dimensional response to the problems and needs (UNDRR, 2006). According to the UNDRR (2006), an effective EWS exists of four key elements:

1. Risk Knowledge: risk assessments and maps help to motive people, prioritize EWS needs and guide preparation for disaster prevention and responses.
2. Monitoring & Warning Service: continuously predicting and forecasting hazards.
3. Dissemination & Communication: multiple communication channels are needed to ensure as many people as possible are warned.
4. Response Capability: disaster management plans are in place, well-practised and tested.

A complete and effective EWS compromises four inter-related elements and has strong inter-linkages and effective communication channels between all of the elements (UNDRR, 2006). According to the research of the Red Cross (RC) by Trogrlić & Van den Homberg (2018), the second, third and fourth element of the EWS in Malawi still experience challenges. However, this research will only focus on the second and third element to keep the research in the scope of a hydrological thesis.

For effective monitoring and warning, a reliable forecasting and warning system is needed, with continuous monitoring to generate accurate warnings in time (UNDRR, 2006). Pappenberger et al. (2012) identifies three issues that are often seen in this monitoring and warning aspect. The level of forecasting uncertainty is often not represented, which leads to an increasing number of false and missed alarms. The uncertainties have to be communicated in a simple and clear way so end-users can understand. In most situations, the LT provided by the hydraulic models is insufficient to allow for the implementation of protection measures.

For effective dissemination and communication of the warnings, clear messages containing simple and useful information are needed. The national, regional, and community level communication systems have to be identified. The use of multiple communication channels is necessary to ensure that as many people as possible are warned (UNDRR, 2006). An issue that often arises is a gap between what is useful according to the producers of SK and the end-users of the forecast (Luke et al, 2018). As explained in the introduction, the role of unofficial warnings should be considered as well. There is an increasing call for the integration of local and scientific information. This can help deal with, for example, inadequate dissemination and communication, lack of understanding, lack of timely action, issues that are also seen in the flood EWS in Malawi, as will be explained in the case study area description. Increased consideration of local communities’ capacities can also help to make NGO projects sustainable (Trogrlić, Wright, Adeloye, Duncan & Mwale, 2017).

The next sections will explain how several elements of the EWS potentially can be improved. In chapter 2.2, it is explained how a medium-term forecasting model can help to improve the key element: monitoring & warning service. In chapter 2.3, it is explained how the use of IK in EWSs can help to improve the key element: dissemination & communication and can help to improve the relation between the key elements.

2.2 GloFAS: Ensemble Streamflow Predictions

Most flood forecasting systems, like the official EWS in the Lower Shire Valley in Malawi, are based on a short-term model that use precipitation data to model the discharge. However, the use of a medium-term model could potentially give communities more time to receive the warnings and to take action. This is especially useful in less developed countries, where the dissemination network can be slower and communities do not have advanced techniques to protect themselves from floods.

Medium-range forecasts could potentially reduce flood-related losses as they provide more time for decision-making and preparation compared to short-range forecasts but produce also more accurate estimations than seasonal forecasts (Thiemig, Bisselink, Pappenberger & Thielen, 2015). However, often a larger the LT, means a larger uncertainty in the forecast. This would mean that a medium-term forecast would have a larger uncertainty than a short-term forecast and also a larger chance on false alarms or missing floods. A solution to minimize this problem is the use of Ensemble Streamflow Predictions (ESPs).

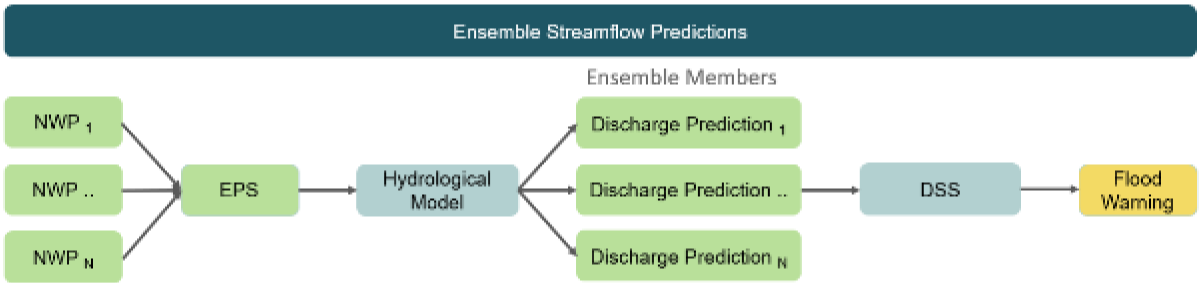


Figure 1: Ensemble Streamflow Predictions (Based on Cloke & Pappenberger, 2009)

Figure 1, shows the different components of an ESP and is based on the research of Cloke & Pappenberger (2009). First, multiple Numerical Weather Predictions build up the Ensemble Prediction System (EPS). Numerical Weather Prediction data is obtained by using current observations of weather as input and processing these data with numerical computer models to forecast the future state of the weather (NOAA, 2019). By using NWPs instead of actual precipitation data, lead times can be established that are longer than the catchment’s concentration time, the time of response of a catchment to a precipitation event. This ensemble of weather predictions can then be processed in a hydrological model. This hydrological model can produce the ensemble members of the ESP. The ensemble members are multiple river discharge predictions based the different NWPs. These ensemble members can then be used as input in a Decision Support System (DSS) to determine whether a flood warning needs to be issued or not. This can be done by looking at how many ensemble members predict a discharge above a certain threshold and a prediction can be made on the probability a flood will happen.

ESPs are more valuable than single forecasts as they can assess the probability of occurrence of extreme and rare events and not only identify whether an event is expected or not. There is a common assumption that authorities prefer deterministic forecasts rather than having probabilistic information. However, this is not always the case, as long as the communication of the resulting probabilistic information is clear (Pappenberger et al., 2012).

Cloke & Pappenberger (2009) mention that in the future, more evaluations have to be done on the forecast skills in a specific ESP context. They also mention that one major difficulty in the evaluation of the flood forecasts is that it is fundamentally flawed by the low frequency of extreme floods. Extreme floods are usually harder to predict than the average discharge, as data on extreme events is limited. There are still many challenges in the development of ESP, like improving the resolution, increasing the numbers of ensemble members, deal with biases and understand the total uncertainty in the system (Cloke & Pappenberger, 2009).

The Global Flood Awareness System (GloFAS) is an example of an ESP designed for flood early warning and the triggering of humanitarian action. The system compares ensemble streamflow forecasts to climatological distributions at a local scale. Ensemble NWPs are used as input for the hydrological simulation (Bischiniotis et al., 2019). This results in an ensemble of 51 streamflow forecasts produced over a LT of 30 days. The first 15 days are produced with rainfall forecasts, the last 15 days with river routing only (Coughlan de Perez et al., 2016). These ensemble members lead to probabilistic streamflow forecasts for grid cells of 0.1 x 0.1 degrees (~10 km resolution) and are compared with flood thresholds to estimate if unusual high or low river flow situations are expected (GloFAS, 2019).

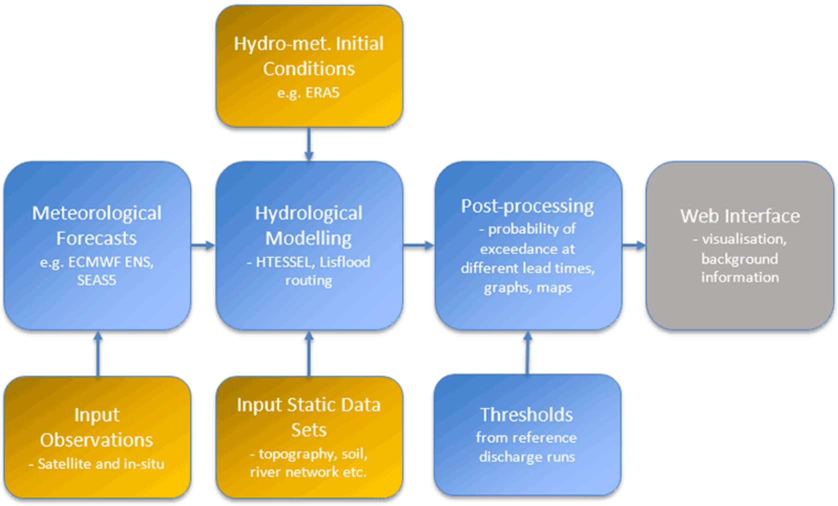


Figure 2: Overview of method GloFAS (GloFAS, 2019)

Figure 2 is showing an overview of the method used in GloFAS. The orange squares show the input data. Satellite and in-situ observations are used as input data for the meteorological forecasts. The meteorological forecasts are a set of NWP forecasts. Together with the initial conditions and other static datasets (like topography, river network etc.), the runoff is computed with hydrological modelling by the models HTESSEL and Lisflood. The results of the ensemble runoff outputs can then be post-processed by comparing it with thresholds and creating graphs and maps and resulting in the probability of floods in a certain region.

2.3 Use of Indigenous Knowledge in Early Warning Systems

2.3.1 Bottom-up & Top-down DRR

In Disaster Risk Reduction (DRR), a large amount of studies have been published on disaster-related issues. According to the research of Gaillard & Mercer (2012), two major paradigms have emerged. On the one side the hazard paradigm, saying that disasters result from extreme and rare natural hazards, and people are affected because they fail to adjust. On the other hand, the more recent vulnerability paradigm, saying that disasters primarily affect marginalized people who lack access to resources of protection. The research notes that most national policies on DRR still rely on these hazard, top-down frameworks, which emphasize SK and national government intervention at the expenses of local actions. The vulnerability paradigm is mostly considered on an international level and can be found in international policy frameworks, such as the Hyogo Framework for Action (2005-2015) and the Sendai Framework for DRR (2015-2030). However, such non-binding treaties are often too vague to get to concrete actions at national level (Gaillard & Mercer, 2012).

This is seen in FRR as well. The designers of official flood forecasts often neglect the potential of local unofficial warning systems to improve the overall EWS. The focus lies on the hazard paradigm, with top-down interventions (Parker & Handmer, 2002). However, NGOs have been arguing for increased involvement of the people affected by disaster risk, a bottom-up FRR approach. Local communities are not helpless in facing natural hazards and IK is a valuable source. Local communities have dealt with flooding for a long time before the development of modern science and technology. They often have developed effective adaptation measures and knowledge about their changing environment. However, this IK is often not taken seriously (Parker & Handmer, 2002). To be able to decrease disaster risk, a gap must be bridged between IK and SK, and between bottom-up and top-down actions (Gaillard & Mercer, 2012). This chapter will describe the two key elements of unofficial warning systems, IK and extensive personal networks (Parker & Handmer, 2002). Followed by a proposed framework to integrate official and unofficial warning systems.

2.3.2 Indigenous knowledge & Bottom-up approaches

As mentioned before, the use of unofficial EWSs can be very useful to decrease any disaster risk. IK is one of the two aspects of an unofficial EWS. According to UNESCO's program on Local and Indigenous Knowledge Systems, local and indigenous knowledge refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings (Hiwasaki, Luna, Syamsidik, & Shaw, 2014). Different terms for IK are found in literature, for example, local knowledge, traditional knowledge, traditional ecological knowledge, rural people's knowledge, indigenous technical knowledge, folk knowledge etc. (Trogrlić et al., 2019).

IK has long been seen as irrelevant compared to technology-based knowledge by non-locals, as well as by locals. Even if locals want to preserve their own knowledge, there often is a lack of respect for this knowledge and is not included in development work (Mercer, Kelman, Alfthan, & Kurvits, 2012). IK is often being seen as inferior to technical solutions, due to the lack of a real evidence base to demonstrate the utility of IK. So, there is an increasing call for identification and documentation of IK (Trogrlić et al. 2019).

Between the 1980s and 1990s, a paradigm shift was seen from top-down, technologic approaches to development and disaster risk research, to more bottom-up, people-centred, and participatory approaches (Trogrlić et al. 2019). Even though this led to an increased focus on IK, the topic was still not extensively covered in the disaster literature until the 2004 Indian Ocean Tsunami, when local responses of local communities were widely shared (Trogrlić et al. 2019). As there is an increasing acknowledgement of the relevance of IK nowadays, developing countries are given a powerful asset in natural disaster management. Successful development can only be achieved when local people are involved in the planning and implementation of development projects (Bongo, Dodo & Muzenda-Mudavanhu, 2017). There is evidence that countries that manage disasters successfully apply bottom-up approaches, with the use of IK (Dube & Munsaka, 2018). By applying this bottom-up approach, IK can empower community members to take leading roles in activities aimed at reducing disaster risk. Other advantages of using IK in FRM are that the warning messages are increasingly received by individuals, but also have better quality, leading to greater local credibility and can provide an alternative to the official system as this is perceived as unreliable (Parker & Handmer, 2002). Official EWSs are not always able to create and disseminate dependable data, therefore scholars argue for deeper engagement with IK systems (Amitangshu & Prakash, 2018).

These were all reasons for international organizations and governments to describe the importance of IK in their international policy frameworks. The UN Yokohama Strategy and Plan of Action for a Safer World asks for all countries to "Aim at the application of traditional knowledge, practices, and values of local communities for disaster reduction" (DHA, 1994, p. 9). In 2009, the United Nations stated that IK is an essential element in the development process and the livelihoods of many local communities (Bongo, Dodo & Muzenda-Mudavanhu, 2017). The Sendai Framework for Disaster Risk Reduction 2015-2030 (UNDRR, 2015) advocates for the use of local peoples’ knowledge and practices to complement SK in disaster risk assessment. In Malawi, a national framework on DRR was proposed in 2015 and includes several aspects from these international frameworks (GoM, 2015). However, as can be read in the case study description, the implementation of these goals is often challenging.

An example of a bottom-up approach is Community Based-Disaster Risk Reduction (CB-DRR). CB-DRR supports the participation of vulnerable communities in evaluating and reducing disaster risk. It empowers communities with locally developed measures to cope with natural hazards. However, for communities to reject all support from outside the community can have negative effects, because necessary resources to the most vulnerable are often dependent on outside help. The gap between both frameworks is wide, and attempts to integrate global top-down and local bottom-up strategies for DRR have so far been sparse (Trogrlić et al. 2019).

Even though IK has a lot of advantages, it is not perfect and should not be the only source of information in local decision-making (Mercer, Kelman, Alfthan, & Kurvits, 2012). Parker & Handmer (2002) mention that IK has multiple disadvantages as well. Unofficial warnings may not provide the credibility of official sources. Those who are not part of a local network might not be warned or networks may even be used to exclude people. Some crucial safety-related decisions may be delayed by networks and messages may be distorted. Unofficial warnings may compete with and undermine the official system. The warnings may promote rumours, which may create needless anxiety (Parker & Handmer, 2002). Trogrlić et al. (2019) also mentions that IK in resilience-building strategies might shift attention away from the broader socio-economic processes that determine vulnerabilities. IK might not apply to extreme events that are outside the lived experience of communities. According to Ton, Gaillard, Cadag & Naing (2016), some recent studies point out that local people view climate patterns as increasingly less predictable due to climate change. IK based on meteorological information alone is not always sufficient in reliability or confidence to make decisions on measures. Meanwhile, scientific meteorological forecasts are becoming increasingly credible as a result of the development of advanced technologies and are emerging as a valuable source of meteorological information to complement IK.

However, top-down policies have largely failed to prevent the occurrence of disasters, thus an alternative, bottom-up framework for reducing disaster risk is suggested (Trogrlić et al. 2019). As SK can no longer be seen as superior to IK, or vice versa, the two areas of knowledge need to be integrated to provide a sustainable assessment of and solutions to disaster risk. The combination of top-down and bottom-up approaches are essential for local communities to benefit from both scientific information, and from their own IK.

2.3.3 Stakeholder networks

As stated before, the dissemination and communication of flood forecasts and warning messages are a key element of the EWS. A warning message is only useful as it is communicated through diverse networks and is understandable to a variety of people. Especially in developing countries, personal networks are important in the transmission of those messages. Individuals who receive a warning want confirmation before responding. The higher the number of consistent warnings that are received the more likely an individual is to respond to a warning (Parker & Handmer, 2002).

Dissemination is only effective if stakeholders pass on forecast information and use it or add value to it before passing it on (Ziervogel & Downing, 2004). According to the research of Parker & Handmer (2002), an issue with local networks is that they can distort formal messages, especially when the official system is perceived to be less accurate than unofficial sources. They note that this can be solved by creating an environment where both systems can be combined and there is no competition between them. Another disadvantage of local networks for warning dissemination is that certain individuals may be missed. For example, people with no contact with neighbours, minorities or homeless people. A warden-type warning system may help to ensure their inclusion. This is an informal system of communication where information is passed on by different actors in society. Flood-wardens are often volunteers that pass on flood warnings to their surroundings. These flood-wardens exist in official and unofficial flood warning systems and are potentially important in the integration of both systems (Parker & Handmer, 2002)

2.3.4 Process of integration

To retrieve the most advantages from a disaster EWS and to deal with its disadvantages, it is useful to integrate official and unofficial EWSs. This can be done by integrating IK and SK on forecasting disasters. Combining SK with IK will lead to complementary actions that address the vulnerability of communities, next to the technical solutions (Hiwasaki, Luna, Syamsidik, & Shaw, 2014). The two types of knowledge will complement each other's strengths (Dube & Munsaka, 2018). The unofficial systems can interpret and communicate the scientific information and can add their own information before action is taken, this leads to many advantages as described earlier. For example, the dissemination network of the unofficial flood forecasts can be used for the dissemination of the official warnings. There is an increased quantity of messages that are being received, but the quality of the received information increases as well. Local communities get greater credibility (Parker & Handmer, 2002).

However, next to the many advantages, some disadvantages exist as well. Therefore, research is still needed on how IK and networks can be best combined with the official systems (Parker & Handmer, 2002). Aspects that must be accounted for when using unofficial warnings are: it must be ensured that the unofficial information must reach all people in a community, it must be taken into account that unofficial information can be unreliable and has uncertainties as well, and it may not undermine the official system. However, if the process of integration is done in the right way most of the drawbacks can be dealt with (Parker & Handmer, 2002).

There are some frameworks developed to integrate these two types of knowledge. However, these frameworks are not tested in an EWS case study yet. In this section, the most important and suitable elements of the frameworks will be described for this research.

A process to integrate the IK and SK is proposed by Hiwasaki, Luna, Syamsidik, & Shaw (2014). In their case study, the process was bottom-up and led by the community, with initial support from outside organizations. These organizations helped the community with orientation and training so they can identify, document and access and validate their own knowledge. The communities can categorize and choose which knowledge to integrate with science.

The five phases of the integration process of Hiwasaki, Luna, Syamsidik, & Shaw (2014) are explained below:

1. **Preparation:** People from the local community must be selected to become researchers and trained on the process, methodology, and key scientific terms. The currently used IK has to be assessed. Forms must be prepared to gather data for each type of IK.
2. **Data-gathering:** The IK must be observed and recorded with the forms. Records must be made on when the observation was done, what disaster event happened after the observation and when the impact occurred. Each local researcher can focus on a specific type of knowledge.
3. **Data analysis & validation:** each documented IK undergoes the following six steps:
    I. Analysis and confirmation that the expected impact took place.
    II. Data must be analysed by tabulating the frequencies of the observations, analysing trends and comparing and explaining the outcomes.
    III. The community has to validate which knowledge and practices are mostly used and are considered most effective, with a criteria list that can be checked during FGDs for example.
    IV. A scientific explanation of the indicators must be searched for by scientists and experts. They assess if science knowledge can explain the IK and can make suggestions on how to deal with the knowledge that could not be explained by science at this point. They also provide insights on how SK can be integrated with IK.
    V. The results are taken back to the community again.
    VI. The IK is categorized depending on the availability of scientific explanations and the relationship and relevance to DRR.
4. **Science integration:** IK with a scientific explanation is combined with empirical data from the field.
5. **Popularization & utilization:** The new information can be promoted through information, education and communication materials used by communities themselves, by scientists for further research and by practitioners and government entities for DRR plans.

This research will evaluate how each step in this process can be reached in practice in Malawi. Mercer, Kelman, Taranis & Suchet-Peason (2009) mention some important aspects to keep in mind when using this process. The process is not static after the integration strategy has been applied, the framework must allow for revision over time. Another important difference in their framework is that the first step is community engagement. In this step, it is determined if the community wants to start this integration process at all and if they want to participate in the project. The first step is not only to select a community, but also to engage the community. The researcher is only a facilitator to guide and listen, but not to direct. Another difference is the way the integration is done. In this situation, all strategies will be scored to identify the most beneficial strategy in reducing the vulnerability of the community. When the local and scientific strategies are not in conflict they can be integrated.

Mercer, Kelman, Alfthan, & Kurvits (2012) added to this that the IK and observations have to be documented, preferably in the local language, such that no information gets lost in translation. A methodology is needed to record, store and manage data and information so that all stakeholders are able to access the information. All identified knowledge must be assessed for its efficacy and validity. It must be kept in mind that IK does not fit all different communities, which is why it must be adjusted to be suitable.

Gaillard & Mercer (2012) propose a specific integration framework for DRR. Three of the main important aspects to make DRR inclusive instead of exclusive is to:

1. Recognize different forms of knowledge are valuable in addressing disaster risk.
2. Undertake actions at different scales, from the top down and from the bottom up, is necessary to reduce the risk of disaster in a sustainable manner.
3. Collaborate between a large array of stakeholders operating across different scales.

In this research, a framework will be used that follows the most important steps of the described frameworks. The framework is mainly based on the framework of Hiwasaki, Luna, Syamsidik, & Shaw (2014), but also added some components of the other frameworks. All of these aspects of the different researches and frameworks combined will optimize the integration process in Malawi. Some parts of the process have already been done in Malawi by NGOs and previous research (Trogrlić & Van den Homberg, 2018). NGOs have already established contacts with communities and potential local researchers could be members of the Village Civil Protection Committees (VCPCs) or the Area Civil Protection Committees (ACPCs) in Malawi. The research of Trogrlić & Van den Homberg (2018) already determined the IK used by communities. This research has to find out if the communities want such integration at all if the ACPCs or VCPCs are suitable as local researchers and how they think this integration should take place.

Case Study Description | 3

This chapter will give an introduction of the study area by discussing the country characteristics, the climatology & natural hazards and the EWS of Malawi and Lower Shire Valley.

3.1 Country Characteristics

Malawi, officially the Republic of Malawi, is a landlocked country in south-eastern Africa. Malawi shares its boundaries with Zambia, Mozambique and Tanzania and lies between 9° and 18° South and 32° and 36° East. The surface area of the country is 118,484 km^2, of which 20% is water (DoDMA, 2015).

Malawi has a population of around 18.6 million people. The country has an agro-based economy, with 35% of the country's Gross Domestic Product based on the agricultural sector and 80% of the population's livelihood depends on subsistence farming. (GoM, 2015)

The country is divided into three administrative regions, the Northern, Central and Southern Region, with the capital Lilongwe lying in the Central Region. The regions are further divided into 27 districts, these are again divided in constituencies and the constituencies are again sub-divided into Traditional Authorities (TAs). The Village Group Heads are the smallest administrative regions (DoDMA, 2015).

3.1.1 Lower Shire Valley

A case study will be done in the Lower Shire Valley in Malawi. The Lower Shire Valley lies in the south of Malawi and consists of the Chikwawa and Nsanje district, as can be seen in figure 3. Together, these districts form an area of approximately 6700 km^2 (Trogrlić et al., 2017). It is the most disaster-prone area in Malawi. Floods form a severe threat to the livelihoods of the population in this area. The Chikwawa and Nsanje districts are the poorest districts in the country. Around 80% of the population in these district lives below the poverty line, exceeding the national average of 50.7% (Trogrlić et al., 2017). 85-90% of the households are mainly dependent on agricultural activities. However, large parts of the population have experienced food shortages in previous years due to droughts and floods (Trogrlić & Van den Homberg, 2018).

This area is chosen as case study, as it is representative for other areas that are most in need of a well-working EWS, as it a poor and flood-prone area. The Lower Shire Valley is also the only area were the official flood EWS is working. It is also chosen because it is the focus area of the EU ECHO II project, and many contacts are already established with communities and other stakeholders in this area by the RC.

3.2 Climatology & Natural Hazards

3.2.1 Topography

The topography of Malawi is dominated by the Great Rift Valley, reaching from North to South across the country. The valley exists of Lake Malawi and is surrounded by high plateaus. The plateaus rise on average between 914 to 1219 m above sea level, and peaks in the Mulanje highlands at 3048 m. The Shire Highlands are located in the South, below Lake Malawi, at around 914 meters above sea level. (DoDMA, 2015). The lowest area can be found in the south in the Lower Shire Valley and has an average elevation of around 30 m above sea level, as can be seen in figure 3.

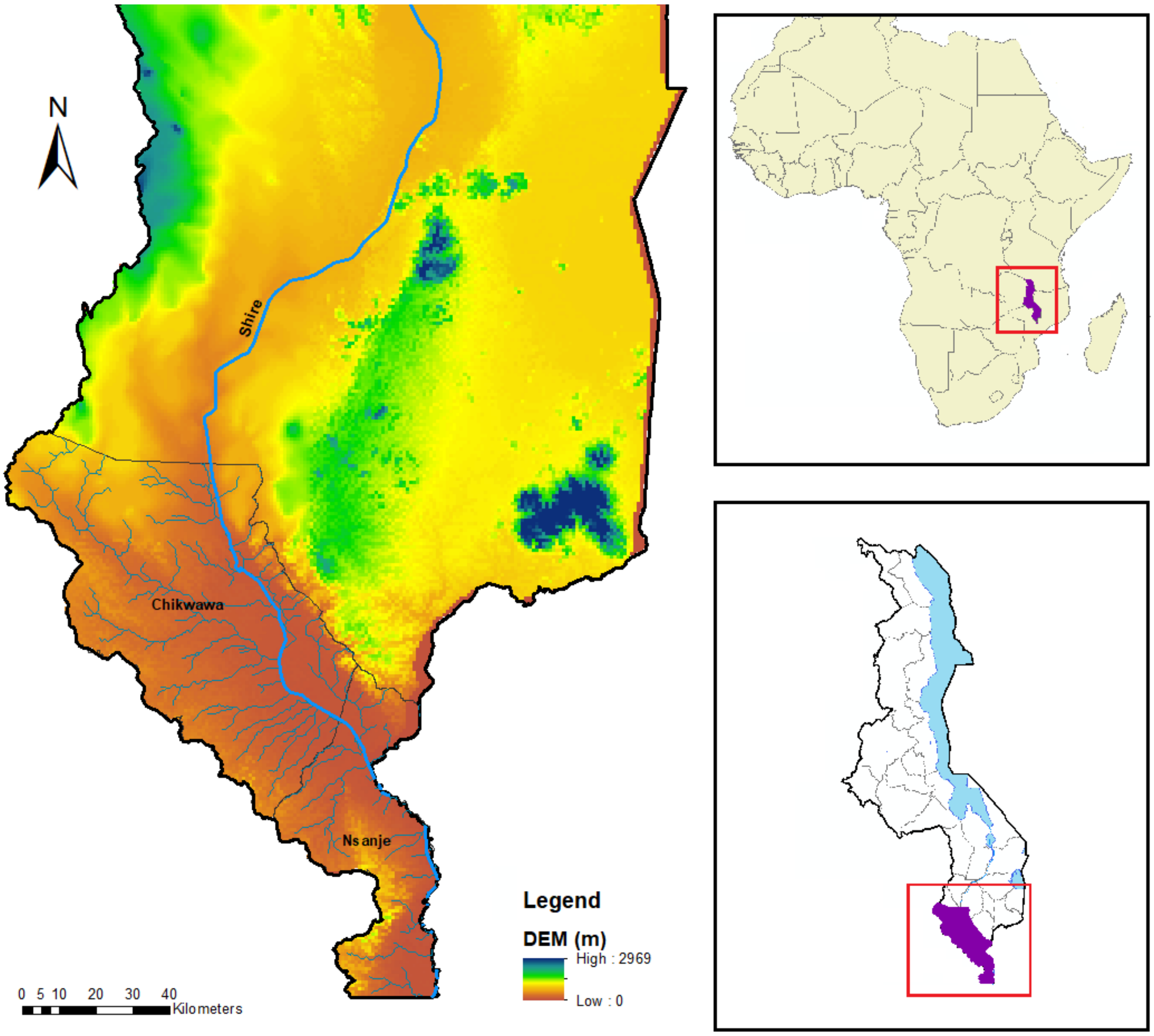


Figure 3: Digital Elevation Map South of Malawi (Source: USGS Earth explorer)

3.2.2 Climate

The country has a subtropical climate that is relatively dry but characterized by seasons. The climate is mainly determined by the oscillations of the Inter-Tropical Convergence Zones (ITCZ). The ITCZ moves over the country late October and goes south throughout November. The variations in altitude lead to large differences in climate over the seasons. From November to April there is a wet and warm season. Temperatures in this hot season range from 25°C to 37°C. The relatively dry and cooler winter season is in the period between May and August. Temperatures in this season range from 17°C to 27°C (DoDMA, 2015).

The annual average precipitation ranges between 750 and 1000 mm. The average precipitation is higher in certain regions along the Northern coast and in the Zomba and Blantyre district in the south (DoDMA, 2015). In general, high areas experience more precipitation than low lying areas (Kumambala & Ervine, 2010). The Lower Shire Valley receives the least amount of rainfall in the country of 400 to 700 mm annually. Almost all annual precipitation (95%) takes place in the wet season. Between April and May, there is a post-rainy season, rains sometimes continue longer in the northern and eastern mountains (DoDMA, 2015).

3.2.3 Hydrology

The Great Rift Valley runs through Malawi from north to south. East of the valley lies Lake Malawi, covering 75% of the eastern boundary of the country. Lake Malawi is 587 km long and 84 km wide. The Shire River is the only outlet of the lake, flowing out at the south-end of the lake. The Shire River is about 400 km long and joins the Zambezi River farther south in Mozambique (DodMA, 2015). The Shire River is flowing through the Shire Basin. The flow in the basin increases downstream, the average annual flow of the Shire River in the upper catchment at Matope is around 450 m^3/s and between the middle and low section of the river at Chikwawa this is around 550 m^3/s (Mwale, 2014). The Shire River Basin has an area of 19,248 km^2 in Malawi, including 303 km^2 of Lake Malombe. The hydrological system of the Shire River Basin is the most important water resource of Malawi for its development and economy.

3.2.4 Natural Hazards

Malawi is prone to multiple natural hazards like floods, droughts, strong winds, storms, landslides, heatwaves, and earthquakes. Floods and droughts are being most common, like in the rest of Sub-Saharan Africa (Trogrlić & Van den Homberg, 2018). Records indicate an increase in frequency, intensity and magnitude of these hazards over the years (DoDMA, 2015). Floods occur almost annually, as can be seen in figure 4, showing the occurrence of floods and droughts over the past 30 years. In the Lower Shire Valley, from 1997 on, there were at least 15 years of flooding.

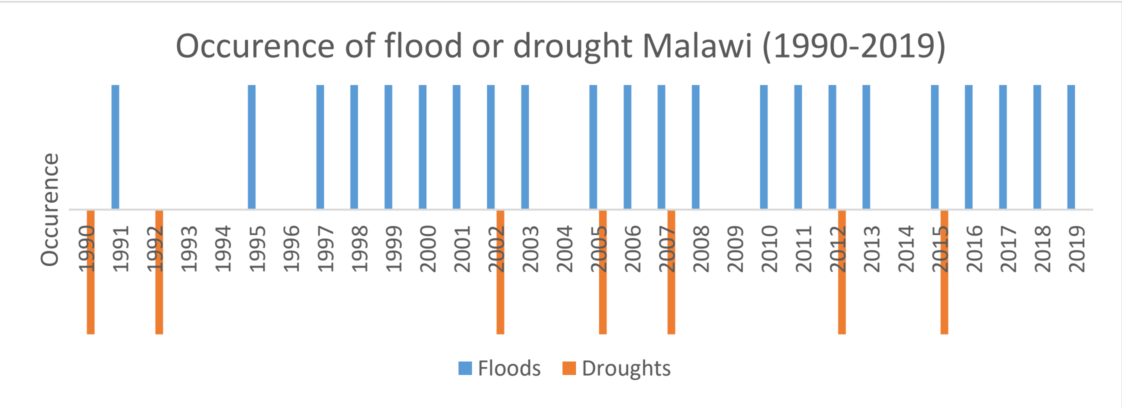


Figure 4: Occurrence floods & droughts in Malawi, 1990-2019 (EM-DAT, 2019)

Floods mainly occur in low-lying areas that are affected by large amounts of precipitation in higher areas. The large amounts of rain can lead to high water levels in Lake Malawi, which can lead to floods around the lake, but also to high discharge levels in the rivers (Kumambala & Ervine, 2010). The hydrology of the Lower Shire River is mainly dominated by the Shire River. Flooding in the Lower Shire Valley is mainly caused by flooding of the Shire River itself, flash flooding of the Ruo River and backwater effects from the Ruo River joining the Shire River (Trogrlić et al., 2017).

Many people are affected by the floods, leading to deaths, injuries and sickness due to water borne diseases for example. They experience loss of property, displacements, loss of crop harvest leading again to food insecurity or even loss of life. Because of these adverse effects of floods, many actions are already taken as can be read in the next section.

3.3 Early Warning System of Malawi

3.3.1 The National Disaster Risk Management Policy

To reduce the impacts of natural disasters, a National Disaster Risk Management Policy (NDRM policy) was established in 2015 by the government of Malawi (GoM, 2015). The goal of the policy is to achieve sustainable development by ensuring that Disaster Risk Management (DRM) is integrated into development planning by all sectors in the country. The policy is aligned to the Hyogo Framework for Action adopted by the United Nations in 2005. One of the objectives of the policy is to develop an integrated and effective people-centred EWS that is comprehensive and effective. The EWS of Malawi exists out of many components that are not integrated (GoM, 2015). Figure 5 shows a general overview of the EWS components that are active in Malawi. The EWS can be separated into three main sections (Trogrlić & Van den Homberg, 2018):

1. Official forecast: The Operational Decision Support System, ODSS.
2. Community-based forecast: Measuring discharge upstream & communicate to downstream areas.
3. Forecast based on IK: Local indicators are used to forecast floods.

Each stakeholder level plays a different role in the different EWSs. For example, the stakeholders at the national level (DCCMS, DoDMA), only play a role in the national EWS, whereas the community members play a role in all EWSs. In the paragraphs below each EWS will be described.

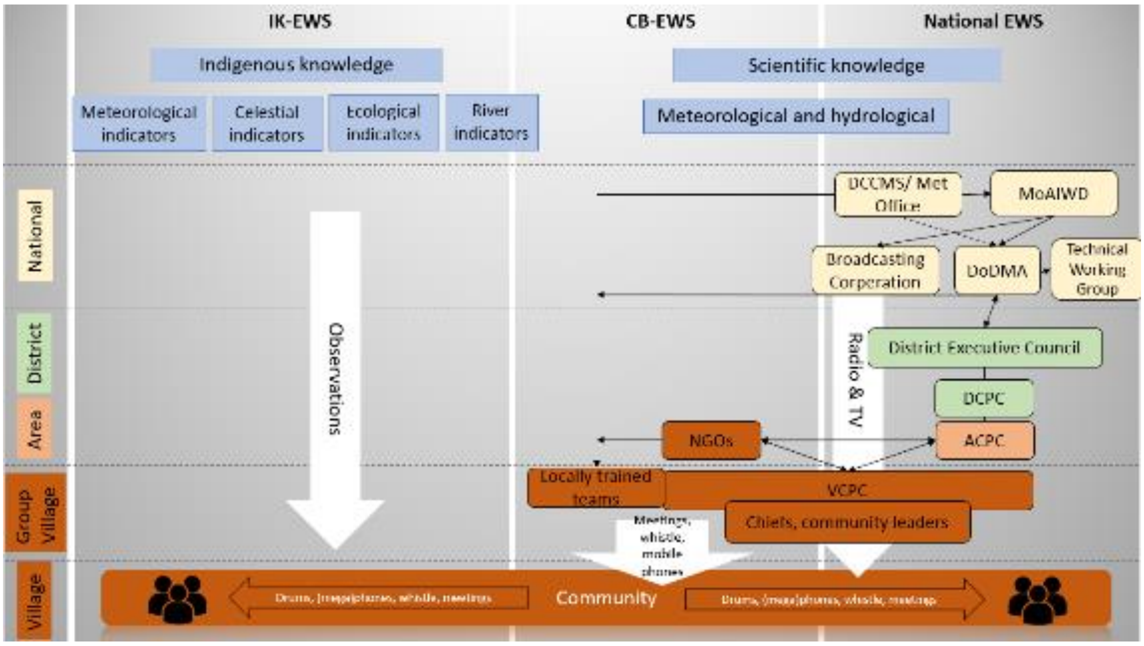


Figure 5: Structure of flood EWS Malawi (based on the research of Trogrlic & Van den Homberg, 2018)

3.3.2 ODSS: The National Flood Forecasting System

The official national EWS, developed in 2016 as part of the Shire River Basin Management Programme, is the Operational Decision Support System (ODSS) and is only operational yet in the Lower Shire Valley. The ODSS has several components (DHI, 2016):

- Weather forecast: short-term and seasonal rain forecast
- Flood and flow forecast: short-term flow and river levels forecast
- Seasonal forecast: long-term flow and lake water levels forecast
- Drought monitor: satellite-based drought indices
- Crop calendar: phenology and short-term forecast for key crops.

The focus of this research will only be on the flood and flow forecast. This is a short-term flood forecast that runs automatically every six hours. In these six hours the real-time data of rainfall and river water levels from a range of discharge gauges are imported, quantitative precipitation forecast is imported, a quality control of the real-time data is done, the rainfall for the sub-catchments is calculated in both the hindcast and forecast period, the models are ran, the model results are updated with real-time measurements to improve accuracy, and the analysis of the results and dissemination of information and warnings are done (SRBMP, 2016).

The hydrological model that is used is the NAM MIKE 11 and is set up for all sub-catchments. This model results in runoff components, evaporation, and recharge of groundwater. The runoff obtained from this model forms the input for the hydrodynamic model, MIKE 11, to simulate the water levels and discharge variations in the Shire River and its main tributaries, taking structures and other important features into account. The river flow is simulated over a period of five days, typically starting three days back and continuing two days into the future (SRBMP, 2016).

Warning and danger levels are determined by water level thresholds. If these thresholds are exceeded the operator needs to approve the forecast. Then the automatic dissemination of risk maps to relevant stakeholders starts (SRBMP, 2016). The forecasts are disseminated by radio and television and by communication through the different stakeholder levels.

3.3.3 Community-Based Flood Forecast

The CB-FRM projects are a result of the NDRM policy and are implemented at local government structures. The Civil Protection Committees (CPCs) oversee preparing and annually updating DRM Plans for the local levels. These plans give a detailed overview of the disasters in the area and guide different stakeholders in various projects. CB-FRM has a bottom-up approach. These CPCs have an active role in risk identification, selecting solutions, project implementation, monitoring, and operation. Leading to more sustainable solutions, strengthening of the local capacities, increased local resilience and cohesion, and empowered communities (Trogrlić et al., 2017).

The CPCs can be found on district, area and village level. The VCPCs are leading all disaster-related interventions at GVH level. The active VCPCs are supported by NGOs. The VCPCs have DRM, contingency and action plans, and write reports about their activities. The members of the VCPCs consist of representatives of Early Warning Teams (EWT), Community Based - Disaster Response Teams (CB-DRT), and of RC Volunteers (Trogrlić et al., 2017).

3.3.4 Forecasts based on Indigenous Knowledge

Community members have extensive experience in dealing with natural hazards for years. Local communities have various ways through which they can forecast floods and other hazards by using locally available signs and indicators. The communities in the case study area have many forecasting signs and indicators that are divided into five categories (Trogrlić et al., 2019):

- Ecological: behaviours, phenomena, and patterns that are not related to human behaviour
- Riverine: the behaviour of the waters in the river
- Meteorological: encompasses wind movements, rains pattern, temperature and clouds
- Celestial: related to the behaviour of celestial bodies (e.g. sun, moon, stars)
- Phenomenological: elderly community members feeling pain, villagers unable to sleep.

IK can be found across different stages of the FRM cycle: before, during and after the flood. Trogrlić et al. (2019) has shown that community members in flood-prone areas in Lower Shire Valley have a high level of understanding of flood dynamics. They are able to deviate between fluvial flooding from large rivers, and flash floods from smaller rivers, and between annual and extreme flooding. They are aware of the ways of how water is spreading and how severe a flood will be, based on rainfall intensity and duration.

The local indicators based on IK are primarily shared in informal ways. The indicators are shared during community gatherings or meetings set up by local chiefs or disaster committees. Women educate their children about the indicators. However, the reliability of local EW indicators is thought to be decreasing due to a number of factors, like climate change and (population-driven) environmental degradation. Cultural dynamics are also influencing the perceived reliability of IK, elderly community members were seen as key players in observing the indicators, with younger generations often thought not to be interested in such indicators. If the early warning is not well understood or perceived as unreliable, early action is not taken by individuals or households. (Trogrlić et al. 2019)

Several local institutions were identified as playing an active role in FRM at local level (Trogrlić et al. 2019):

- Village Civil Protection Committees (VCPCs) & Area Civil Protection Committees (ACPCs): are the forefront of flood-related activities, serve as a mediator between the community at large and the external stakeholders involved in DRR (NGOs, government).
- Religious institutions: raise awareness during ceremonies, churches as evacuation locations.
- Community-based organisations: youth clubs developing theatre dramas on flooding as a risk communication tool, assisting with temporary shelter construction, assisting with afforestation initiatives.
- Traditional leaders (i.e., chiefs): knowledge holders and communicators, warning dissemination through meetings, evacuation leaders, facilitation stakeholder collaboration, land provision, providing advisory services to the community.

Even though IK is important for communities, the dissemination of early warning information and decisions to take action are not solely based on local EW indicators, but on a complex triangulation process between local information and official warnings. (Trogrlić et al. 2019)

3.3.5 Challenges in the current EWS

There are various technical and social challenges found in the overall flood EWS in Malawi.

<u>Technical challenges</u>

- Equipment and processes for gathering early warning data are insufficient (NDRM, 2015).
- The flood EWS only covers the major rivers, leaving out the small rivers which also cause a lot of flooding (NDRM, 2015).
- National forecasts are often not delivered in time to the end-users. (Trogrlić & Van den Homberg, 2018).
- National forecasts do not come with a flood extent map, which makes it hard to identify which regions will be impacted (Trogrlić & Van den Homberg, 2018).

<u>Social challenges</u>

- The EWS exist of many components that are not integrated, leading to a complex decision-making process (NDRM policy, 2015) & (Trogrlić & Van den Homberg, 2018).
- The lack of practical capacity at community level on the use of early warning information (NDRM policy, 2015).
- The CB-EWS is often only done at community level rather than with the community, there is a lack of community participation (Trogrlić et al., 2017) & (Trogrlić et al. 2019).
- Rich IK of community members are not taken into account in the current EWS (Trogrlić et al., 2017).

- It is difficult to make CB projects sustainable and operational without the help of NGOs (Trogrlić et al., 2017). Community participation is limited to working with VCPCs, they are mainly established in areas where NGOs have an active role (Trogrlić et al. 2019).
- The government does not has the capacity to facilitate and deliver risk reduction at local scale (Trogrlic et al. 2019).

There are many challenges, however, also opportunities to create one well-functioning system where multiple sources are integrated. According to Trogrlić et al. (2019), multiple steps need to be taken to tackle these challenges. A first crucial step is to increase the role of IK in FRM and find new ways to involve communities. Integration is already happening informally on the ground, in an unstructured manner led by local people. A further understanding is needed of how this negotiation and knowledge production takes place in local communities and what the enabling and hindering factors are in this process.

This chapter describes the method to reach the aim of this research, improving the flood EWS of Malawi by assessing the use of GloFAS, as a medium-term flood forecast model, and assessing the use of IK on forecasting floods. An overview of the methods that are used to assess these two parts of the research are shown in figure 6. GloFAS is assessed by looking at the hydrological skill, theoretical forecast skill and flood forecast skill for multiple trigger levels. To calculate these skills comparisons are made between the hydrographs of the observed, modelled, forecasted discharge and historical floods. These methods are explained in more details in chapter 4.1. The assessment of the integration of IK is done by looking at the dissemination network of different types of forecasts, what the role of the VCPCs and ACPCs are in this and how the integration process should look like. Information for these sections are obtained from FGDs and SSIs. These methods are explained in more detail in chapter 4.2

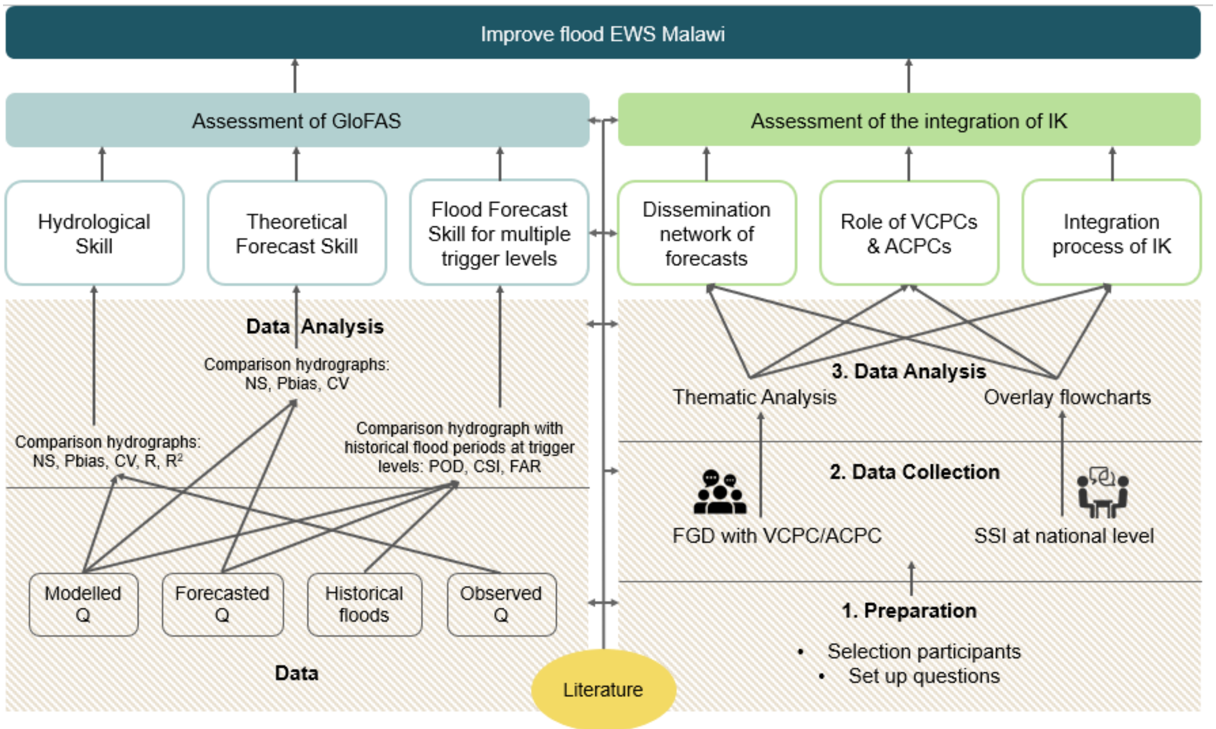


Figure 6: Method to improve the flood EWS

4.1 Assessing GloFAS on forecasting discharge & floods

To assess if GloFAS can be used in the EWS of Malawi, the hydrological- and the forecast skills are determined. First, the used datasets will be described. Second, the method used to assess the hydrological skill will be described. Third, the method used to assess the forecast skill. Lastly, the method used to assess how well GloFAS can depict historical floods at different trigger levels.

4.1.1 Datasets

This section gives a description of the datasets used for getting the observed discharge, modelled and forecasted discharge by GloFAS and of the historical reported floods.

Observed discharge

Table 1: Characteristics observed discharge South of Malawi

Location number	River	Gauge station	Coordinates station	Coordinates of GloFAS cell	Covered period	Days covered
1	Shire	Liwonde	-15.07, 35.21	-15.05, 35.25	01/01/1997 - 10/07/2018	72.59%
2	Shire	Chickwawa	-16.03, 34.80	-16.05, 34.85	01/01/1997 - 11/26/2009	74.88%
3	Ruo	M1 Road bridge	-16.09, 35.67	-16.05, 35.65	01/01/1997 - 10/30/2008	69.43%
4	Lichenya	Milonde	-16.10, 35.48	-16.15, 35.45	01/01/1997 - 10/30/2002	96.52%

The observed discharge data is limited in Malawi. Only four discharge measuring stations are usable for this research. These stations were the only ones that provide data in the right time range in Malawi and had information over their exact location. Information about this data can be found in table 1 and the locations are shown in figure 7. The GloFAS model provides discharge data from 1997 until 2018, so this is also the period that is usable for the observed data. All locations are in the southern part of Malawi. The measurements of the first two are from the Shire River, which is the largest in the country. The third measuring station is located along the Ruo River and the fourth along the Lichenya River, a smaller river along the eastern border. The first three locations cover around 70% of the days in the available period. The fourth location covers almost 97%, however, this data is only available up to 2002. The hydrological skill is only calculated for the available data, as it would be hard to create reliable data with interpolation because large parts are missing.

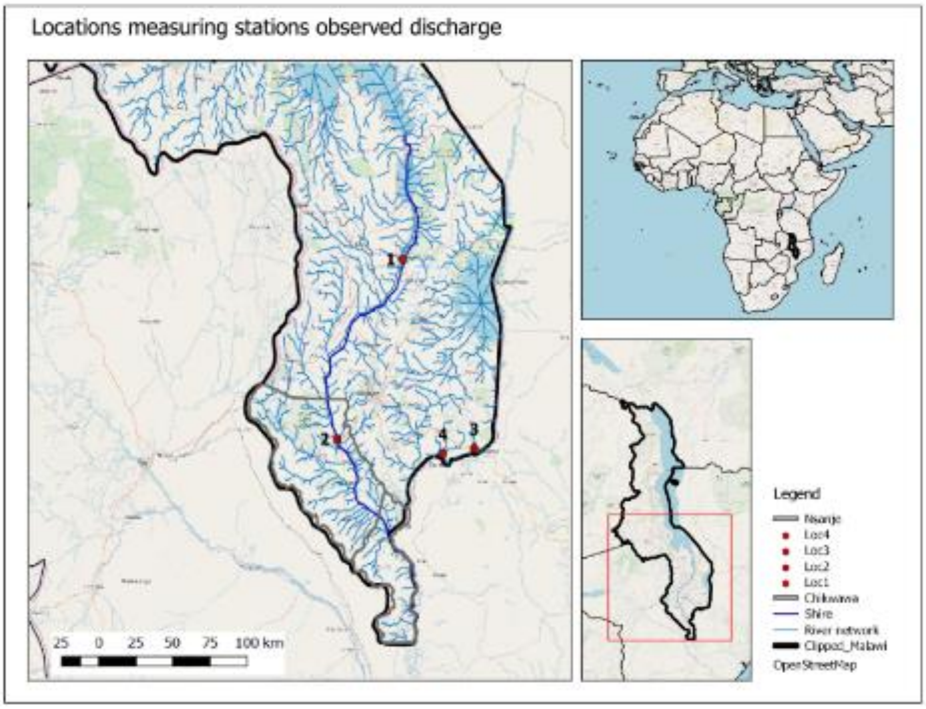


Figure 7: Locations observed discharge measurements

Modelled & forecasted discharge GloFAS

The modelled discharge of GloFAS is produced in hindcast for the period 1997 till 2018. The raster data is covering the whole of Malawi with grid cells of 0.1 ˚ by 0.1 ˚ (around 10km by 10km). The river network that is displayed by GloFAS can be seen in Appendix K. The discharge up to 2016, is determined by 11 ensemble members, forecasting the discharge for each river cell over a LT of 30 days. The discharge is produced every 3 to 4 days. For the days that the discharge was not available, the data is linearly interpolated. This interpolated data is also used in the calculations, to make sure enough data points were available in the comparison with the observed data. In 2017 and 2018, the discharge is determined by 51 ensemble members and is produced every day. The first 15 days are determined by meteorological forcing, the last 15 days is derived from water routing of the overland flow produced in the first 15 days (Alfieri et al., 2013). To calculate the hydrological scores, the hydrographs produced by GloFAS are used in the same four locations as the observed discharge. These coordinates can also be found in table 1. The data that is used to compare the observed discharge with is the discharge modelled for LT0.

In the calculation of the theoretical forecast skill, the modelled discharge is compared to the discharge at LT1 to LT15. The forecasted discharge is used up to LT15, because up to this LT the data is still determined by meteorological forcing. For the forecasted discharge, the average of all the ensemble members is used.

Historical flood dataset

The historical flood dataset that is used in this research is a combination of all different historical flood databases available of Malawi (from 1997 to 2018). The databases that are used in creating this list of floods are from the Emergency Event Database (EM-DAT), Dartmouth Flood Observatory, MunichRe (an insurance group) and documents from the International Federation of the Red Cross Societies (IFCR). Since the floods, described in the databases, are not always systematically recorded in all databases, a certain list of criteria is followed to select the floods used in this part of the research:

- Flood must have occurred between 1997 and 2018.
- Flood must have occurred in the southern region of the country.
- Flood must be described in at least 2 different sources.
- Flood must have had some sort of impact (e.g. fatalities, economic losses, displacement of people, injuries, etc.).

The FGDs, as described in the next part of the chapter, are used to validate these floods, by asking the participants in what years they experienced severe floods. This has created a list of 14 floods. This is probably not the total number of floods in this area in this period, as (small) floods happen so often and are not all documented. By setting the used criteria it is assumed that the floods in the list did actually happen. However, for the floods that are not reported, it is assumed that they did not happen. This list of floods and information per flood can be found in Appendix A. Instead of using the flood period that was indicated by the databases, the period of the whole rainy season of a certain flood is used. This is done because all datasets give various periods that a flood occurred and often multiple floods happen in different locations at different times. So, to cover all floods in the period, the whole rainy season is chosen.

4.1.2 Hydrological skill

The hydrological skill of GloFAS can be found by comparing the modelled discharge at LT0 with the observed discharge. The comparison is done by calculating different skill scores that all compare different aspects of the two hydrographs. The hydrological skill of GloFAS can be analysed looking at these skill scores. Skill scores are calculated for periods that both datasets are available. The skill scores that are explained below have been used in different flood risk researches like, Alfieri, Thielen, Pappenberger (2012), Alfieri et al. (2013), and Bischiniotis et al. (2019).

1) Nash-Sutcliffe efficiency (NS)

$$NS = 1 - \frac{\sum_{t=1}^{N}[Qobs(t) - Qmod(t)]^2}{\sum_{t=1}^{N}[Qobs(t) - \overline{Qobs}(t)]^2} \qquad (1)$$

N	=	The number of forecast in the period [-]
t	=	Time [days]
Q_{obs}	=	Observed discharge [m^3/s]
$\overline{Qobs}$	=	Average observed discharge [m^3/s]
Qmod	=	Modelled discharge (LT0) [m^3/s]

The NS score, proposed by Nash and Sutcliffe (1970), can be used to reflect the overall fit of a hydrograph. It indicates how well GloFAS modelled the observed temporal variability. The value of NS is between -Inf and 1 (a perfect fit). A negative value means that the mean value of the observed discharge is a better predictor than modelled discharge.

2) Percentage bias (PBias)

$$PBias = \frac{\frac{1}{N}\sum_{t=1}^{N}[Qobs(t) - Qmod(t)]}{\overline{Qobs}} \qquad (2)$$

The PBias score, proposed by Gupta et al. (1999), measures the average tendency of the GloFAS values to be smaller or larger than the observed values. It can indicate systematic deficiencies. The values are percentages, a PBias of 0 means a perfect fit, positive values indicate overestimation and negative values underestimation.

3) Coefficient of variation of the Root Mean Squared Error (CV)

$$CV = \frac{\sqrt{\frac{\sum_{t=1}^{N}[Qobs(t) - Qmod(t)]^2}{N}}}{\overline{Qobs}} \qquad (3)$$

The CV score measures the standard deviation between the GloFAS and the observed values, at the same time it allows comparison between river cells with large differences in discharge. It is the Root Mean Squared Error normalised by the average observed discharge. The scores can range from 0 (perfect fit), till Inf.

4) Pearson's correlation coefficient (R)

$$R = \frac{N(\sum(Qobs * Qmod)) - (\sum Qobs)(\sum Qmod)}{\sqrt{[N(\sum Qobs^2) - (\sum Qobs)^2]\,[N(\sum Qmod^2) - (\sum Qmod)^2]}} \qquad (4)$$

The Pearson's correlation coefficient measures the linear relationship between the GloFAS and the observed values. A value of -1 or 1 means that for every increase in one variable there is also a linear increase in the other. The datasets have a perfect negative or positive correlation. A value of 0 means for every increase, there is no positive or negative increase, there is no correlation between the data (SHT, 2019).

5) Coefficient of Determination (R^2)

$$R2 = \left(\frac{N(\sum(Qobs*Qmod))-(\sum Qobs)(\sum Qmod)}{\sqrt{[N(\sum Qobs^2)-(\sum Qobs)^2]\,[N(\sum Qmod^2)-(\sum Qmod)^2]}}\right)^\wedge 2 \qquad (5)$$

The coefficient of determination, called R-squared, is the square of the correlation coefficient. It represents to what extent the variance of the one variable explains the variance of the other variable. An R^2 of 1 shows that all the variation of the one variable is explained by the other.

4.1.3 Theoretical forecast skill

The forecast skill is calculated to determine how well the model can forecast discharges at different LTs. The evaluation of the forecast skill of GloFAS will be done by comparing the forecasted discharges at different LTs with the modelled discharge, with a LT of zero. The method to examine this is based on the research of Alfieri et al. (2013) and Bischiniotis et al. (2019). Because the observed discharge data is limited, the forecasted values will be compared to the modelled ones, this will compute the model's theoretical skill (Bischiniotis et al., 2019). The modelled discharge can significantly differ from the actual values, as will be determined by the hydrological skill explained in the previous part. However, by using the theoretical skill, the outcomes of the model can be assessed for each grid cell of the river, and not just for the observed data points. The theoretical forecast skill is not only showing how well the forecasted discharge is predicting the modelled discharge, but also the skill of the forecast precipitation model that is used as input in GloFAS (Bischiniotis et al., 2019). Even if the absolute values of the modelled discharge might not be very good, that does not directly mean that the forecast precipitation model is bad as well and the model cannot be used to forecast floods.

The theoretical forecast skill will again be determined by calculating different skill scores. The skill scores that are used in this part are Nash-Sutcliffe efficiency, Percent Bias and Coefficient of variation of the Root Mean Squared Error. The same formulas as above are used. The only difference is that the forecasted discharges of different LTs, will be compared with the modelled discharge at LT0 instead of with the observed discharges. The skill scores will be shown per LT in box plots to show the temporal aspect of the forecast skill and in maps for LT7 and LT15 to show the spatial distribution of the forecast skill. The values that are used for this are the average of the values of the ensembles members. LT7 and L15 are chosen, as LT7 is in the middle of the meteorological forcing period and LT15 at the end, similar to the research of Bischiniotis et al. (2019).

4.1.4 Skill to forecast floods for different trigger levels

To determine how well GloFAS can forecast floods, the modelled GloFAS discharge dataset is compared with a historical flood database. This is done by making a list of the flood periods based on historical datasets, as described below. The rainy seasons of these flood periods are plotted in the hydrographs at LT0 of the same four locations as described earlier. This will show if a peak in discharge is seen during the flood period. To set a standard for this, thresholds are set to determine if the peak is high enough and actually depicts a flood. The threshold levels are based on the 80th, 90th, 95th and 99th percentile of the discharge for each location. After doing this for the modelled discharge at LT0, the same is done for LT7 and LT15, to observe what happens if the actual forecasted data is used.

This is again done for the average of the values given by the ensemble members. This can also be used to assess what trigger level can be used best to forecast a flood for each location. However, in this research, the scores do not give a statistically significant outcome as the number of historical floods is too low, but it is giving an indication of which thresholds give the most reliable outcome.

In the discussion of this research, the observed discharge is also compared with the historical flood data in graphs for the four locations. This is done to determine if the observed discharge and historical flood database are in agreement and are therefore reliable.

Scores used in this research are:

- Probability of Detection (POD): This score shows the part of floods that are successfully forecasted of all the reported floods.
  $$POD = \frac{H}{H+M} \quad (6)$$

- Critical Success Index (CSI): This score shows the part of floods that are successfully forecasted of all the forecasted floods.
  $$CSI = \frac{H}{H+FA+M} \quad (7)$$

- False Alarm Rate (FAR): This score shows the part of false positives.
  $$FAR = \frac{FA}{H+FA} \quad (8)$$

To determine the variables in the equations, a contingency table is used:

Table 2: Contingency table (Bischiniotis et al., 2019)

		Observed	
		Yes	No
Forecasted	Yes	Hits (H)	False Alarms (FA)
	No	Misses (M)	Correct Negatives (CN)

Next, a comparison is done between the modelled floods at discharge at LT0 and forecasted floods at a discharge at LT7 and LT15 using multiple thresholds. The modelled floods are described as the modelled discharge is above a certain threshold. The forecasted floods are also determined by looking if the forecasted discharge is above a certain threshold. To calculate the POD, CSI and FAR, the modelled and forecasted floods are compared with each other. In total 22 rainy seasons are taken into account in these calculations. The results of this theoretical flood forecast skill assessment will not only show how well the forecasted floods predict the modelled floods for certain trigger levels, but also evaluates the skill of the precipitation forecast in the GloFAS model (Bischiniotis et al., 2019).

Overall, the hydrological skill, theoretical forecast skill and the skill to forecast floods all contribute to assessing if GloFAS is a suitable system in the EWS of Malawi and if it can potentially improve the EWS. The next part of this chapter will explain what method is used to assess the integration of IK for improving the EWS of Malawi.

4.2 Assessing the use of Indigenous Knowledge in the EWS

To provide an in-depth study on how IK is and can be used in the flood EWS, a qualitative research framework is used. This part of the research follows steps that are based on the work of Bryman (2012) and can be seen in figure 6 at the beginning of this chapter. The steps of the qualitative research are preparation, data collection, data analysis and presenting the results.

Figure 6 shows two methods that are used to collect data to assess how IK can be used and integrated in the flood EWS in Malawi, Semi-Structured Interviews (SSIs) and Focus Group Discussions (FGDs). The SSIs at national level are used to determine the network for disseminating the official forecast information from national level to community level. The FGDs at VCPC and ACPC level, are used to complement and validate the information obtained from the SSIs, but also to find answers to the question on how the VCPCs and ACPCs, at community and area level, are triangulating between different sources of early warning information. Together this information, combined with information from the theoretical framework, will show how IK can be integrated with the official forecast information. The next sections of this chapter describe both data collection methods.

4.2.1 Semi-Structured Interviews at national level

Interviews are done with stakeholders at the national level. The interview method that is chosen in this are SSIs. During an SSI a set of questions is available that will all be asked during the interview, however, the exact way the questions are outlined in this format do not have to be followed and questions that are not included in the format can be asked as well (Bryman, 2012). SSIs are chosen as method to make sure that there is no bias in the questions asked to different organizations, but it is still possible to get more specific information per stakeholder if needed. The format of questions used in these interviews can be found in Appendix I.

Table 3: Semi-Structured Interviews National level

#	Organization	Type of organization	Participants role in organization
1	Department of Climate Change & Meteorological Services	Government department	Chief Meteorologist
2	Department of Water Resources	Government department	Design Hydrologic Structures
3	Ministry of Agriculture	Ministry government	Deputy Director of Crop Development
4	Department of Disaster Management Affairs	Government department	Response & Recovery
5	Malawi Red Cross Society - 1	Humanitarian organization	Data Team member
6	Malawi Red Cross Society - 2	Humanitarian organization	Disaster Response & Recovery Specialist
7	Lilongwe University of Agriculture & Natural Resources	University	Agrometeorologist

For the SSIs at national level, all organizations are selected that have a role in receiving or providing forecast information or have a certain interest in it. In total, 7 SSIs at national level are done, an overview of the interviews at national level are shown in table 3. All of these interviews are done in English, at the office of the participants. The interviews are done together with Ileen Streefkerk, a MSc student Water Management at the TU Delft. A pilot interview is done with an employee from the Malawi Red Cross Society (MRCS). However, as the interview structure is only slightly adjusted after the pilot, the results of this interview are also used in this research. The interviews are audio-recorded and transcribed afterwards. Next to asking the interview questions, a sketch is drawn on how the organization is receiving and providing information. This is done to validate if the information explained by the participants is well understood. The sketches that are drawn during the SSI at national level are combined to create an overview of the network of how information is disseminated, resulting in figure 17 in the results. Information from the interviews is used to create additional information on this network.

4.2.2 FGDs at village and area level

FGDs are done at community level with the VCPCs and at area level with the ACPCs, to find out how IK is used in forecasting floods and to determine what is needed for integration of different forecast sources. The set of criteria for selecting the VCPCs is based on the research of Trogrlić et al. (2019). The criteria for selecting the villages and areas for the FGDs are:

(1) The committees must be located in the south of Malawi (Chikwawa or Nsanje district),
(2) The committees must be in a flood-prone area
(3) The FGDs must include active and some passive committees.

The format of the questions that are asked during the FGD can be found in Appendix J. Table 4 shows an overview of the FGDs and information about the committees that are part of the discussions. It shows the name of the district, the TA, the GVH and if the village itself is prone to flooding. It also describes the number of participants, females and males, and the age range of the participants. The number of participants is the total number of people that were able to attend the discussion. However, sometimes a few participants per group were not very active during the discussions. The table also describes if a committee is active or not, as described by the RC.

Table 4: Information on Focus Group Discussions with ACPCs/VCPCs

FGD #	VCPC/ACPC	District	Traditional Authority	Group Village Head	Prone to flooding	#P	#F	#M	Age range	Active
1	VCPC	Chikwawa	Makhuwila	Nyambalo	Yes	11	5	6	25-60	Yes
2	VCPC			Jana	Yes	15	7	8	30-65	Yes
3	VCPC			Nyangu	Yes	6	4	2	30-60	No
6	VCPC			Chikuse	Yes	9	2	7	25-60	No
4	VCPC		Chapananga	Tiyimbenawo	Yes	11	3	9	30-65	Yes
5	ACPC			-	Yes	2	1	1	30-65	Yes
7	VCPC		Lundu	Besitila	Yes	13	7	6	25-70	Yes
8	VCPC	Nsanje	Ndamera	Ndamera	Yes	8	4	4	25-60	Yes
9	VCPC			Thaundi	Yes	5	0	5	25-60	No
10	VCPC			Madani	Yes	9	4	5	20-50	Yes
11	VCPC			Chilema	Yes	8	4	4	30-50	Yes
12	ACPC			-	Yes	5	1	4	30-60	Yes
13	VCPC			Mphampha	No	7	2	5	25-60	No
14	VCPC			Mtema	No	7	2	5	25-60	No
15	ACPC		Chimombo	-	Yes	5	1	4	30-70	Yes

Figure 8 shows the locations of the VCPCs and ACPCs. The discussions with the committees are done in three different TA's in Chikwawa and in two TA in Nsanje. The FGDs at VCPC level are also used to obtain information on the periods when floods occurred as explained in the previous sections of the methods. The first FGD is used as a pilot, even though a couple of answers are missing, the answers that are given, are still used in this research.

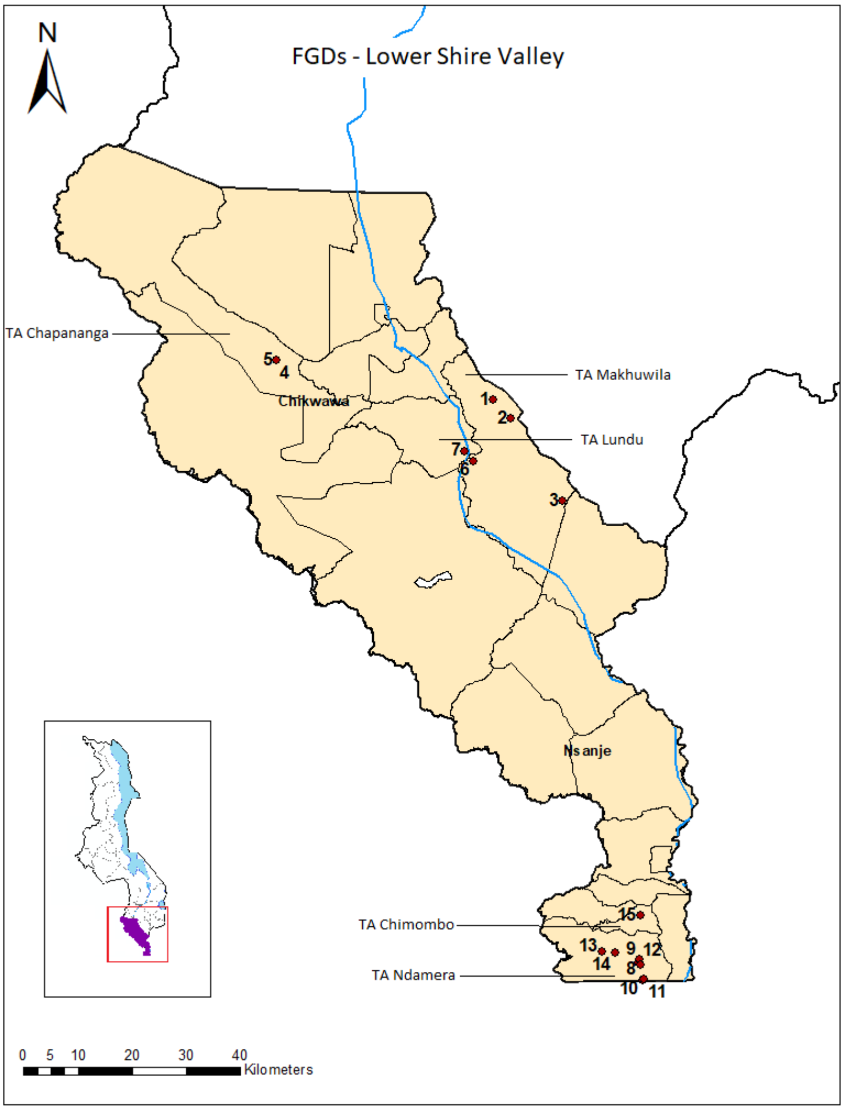


Figure 8: Locations FGDs Lower Shire Valley

The district officers from the RC arranged the FGDs. The discussions are moderated by the facilitator, Chris Sande, a radio journalist at Zodiak Radio in Malawi. The facilitator moderated FGDs for the RC before. Participants were free to answer in any of the local languages, like Chichewa or Sena, or in English. The FGDs are done by visiting the villages the committees were covering. The discussions took place outside under a tree sitting in chairs or benches, in school buildings or once in an evacuation tent. Figure 9 shows how the setting of a discussion looked like in general. The discussions started with an introduction of the topic of the research, an introduction of all the participants and the research team, and a prayer most of the time.

Figure 9: Set up FGDs

The FGDs are audio-recorded and transcribed into English. A thematic analysis is used to code and analyse the transcribed data (Bryman, 2012). All answers were divided in themes for the thematic analysis. These themes are again based on the questions asked during the discussions, then, conclusions can be drawn per theme.

Together the results from all the interviews and discussions help to find a way on how IK can be integrated in the official forecast information and potentially improve the EWS. The interviews and discussions create an overview of the current dissemination network of the forecasts and the role of the VCPCs and ACPCs. Various types of information are obtained, e.g. it is determined which stakeholders receive and disseminate all different sources of forecasts, what methods they use to spread the information, if the community itself feels it is useful to integrate etc. All of this information is than added to existing integration frameworks to make it fit for the case study and to determine what steps are already taken and still have to be taken in the future.

In this chapter the skill of GloFAS to model and predict discharge and floods will be assessed. First, the hydrological skill of GloFAS is determined by comparing observed discharge with discharge modelled by GloFAS. Second, the (theoretical) forecast skill is determined by comparing the discharge at LT0 with the forecasted discharges at different LTs. Lastly, the skill of GloFAS to predict floods, for different thresholds, is assessed.

5.1 Hydrological skill GloFAS

The hydrological skill of GloFAS is showing how well the GloFAS and observed discharge are in agreement with each other. Figure 10 shows the hydrographs of the observed discharge (green) and the discharge modelled by GloFAS (blue) for the four different locations as described in the method. To facilitate the readability, the hydrographs, with large differences in the first two locations, are also presented in detail in Appendix C. The hydrographs are plotted for the time periods in which the observed discharge was available. Especially in the first two locations, which are both located in the Shire River, the hydrographs are not well in agreement. The base flow, the discharge in the dry season, and peak flow, the discharge in the rainy season, are both much lower in the observed discharge than in the modelled discharge. These graphs are also presented in greater detail in Appendix B. In the first location, clear peaks during the rainy season (December to April) are missing. These peaks are found in the second location. Mostly, the timing of these peaks is not very good and the observed peaks are earlier than the modelled peaks. However, sometimes the peaks only differ a few days.

In the third and fourth location, (i.e. Ruo river and Lichenya river), the hydrographs are more in agreement. The base flow is corresponding better for these two datasets, compared to the first two locations. However, the absolute values of the peak flow are in general overestimated by the modelled discharge. In all four locations, the hydrographs of modelled discharge are showing a smoother peak in the wet season, while the observed discharge exhibits multiple smaller peaks in the same period.

Table 5: Hydrological skill scores 4 locations

	NS	PBias	CV	R	R^2
Location 1	-168.2	5.5	5.9	0.17	0.03
Location 2	-88.1	2.0	2.3	0.25	0.06
Location 3	-16.7	1.5	4.0	0.50	0.25
Location 4	-2.0	0.8	2.5	0.49	0.24

Looking at the hydrological skill scores in table 5, it is seen that the hydrographs are indeed not very well in agreement. The Nash-Sutcliffe efficiency shows that the hydrographs do not have a very good overall fit. Negative values indicate that the mean of the observed discharge is a better predictor for the observed values than GloFAS. The values are especially very low for the first two locations, which can be attributed to difference in base flow between the two hydrographs. The third and the fourth location, have a score of -16.7 and -2.0, indicating a much better the overall fit compared to the scores of -168.2 and -88.1 of the first two locations.

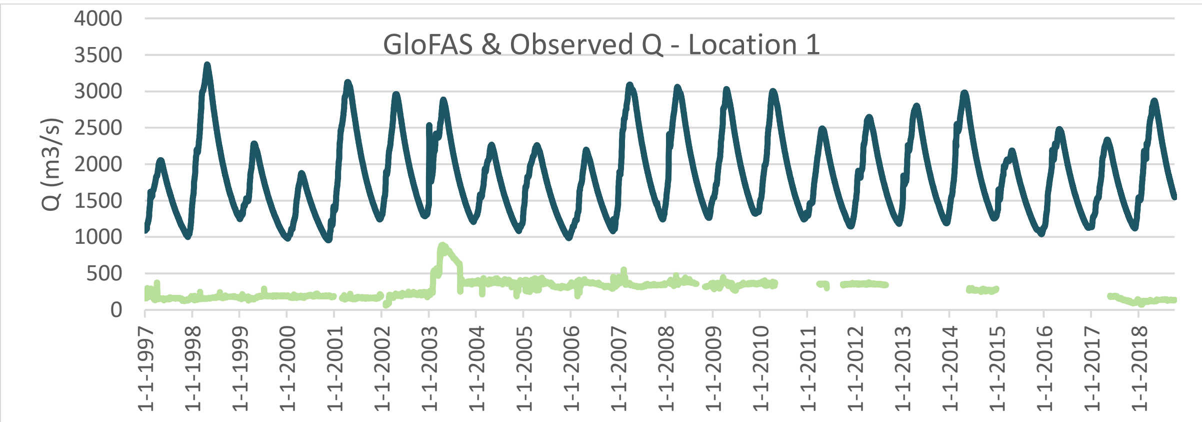
The Percentage bias shows that GloFAS values tend to be higher or lower than the observed values. What can already be seen from the graphs is that in all four locations GloFAS overestimates the discharge, which can also be seen in the positive values in the table. The scores show again that location

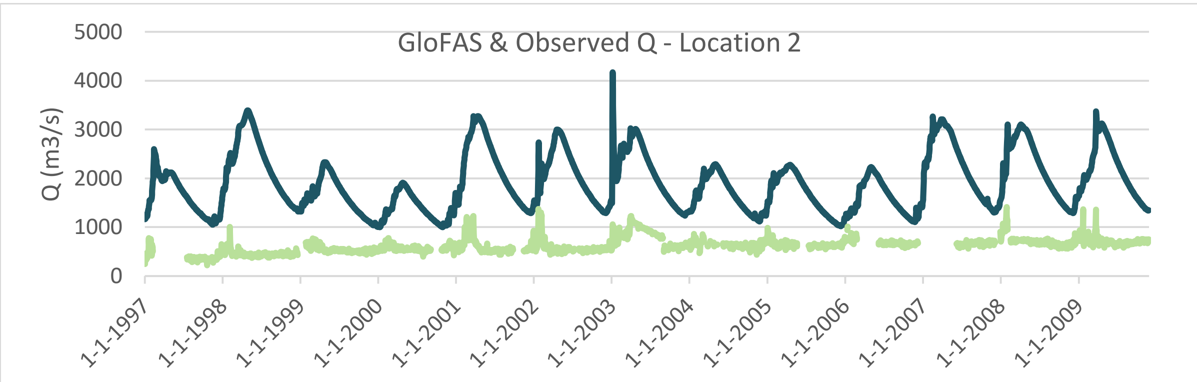
1 has the worst score of 5.5, indicating that in this location the modelled discharge is mostly tending to be higher than the observed values, which can also be seen in the hydrographs.

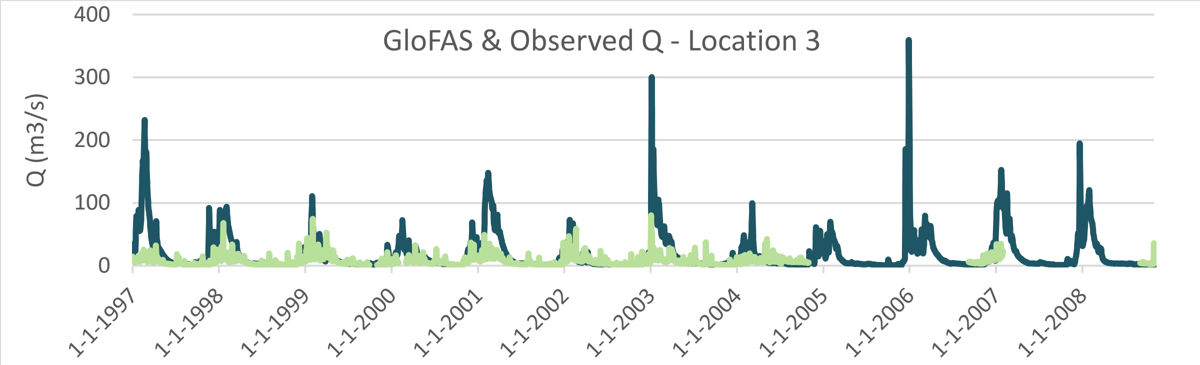
The Coefficient of Variation of the Root Mean Squared Error is showing the standard deviation between the two hydrographs. Location 2 and 4 score the best and 1 and 3 the worst. This might be caused by the observed hydrograph 1 and 3 showing smaller peaks, which is not seen in the modelled hydrographs. These peaks are also seen in 2 and 4 but seem to be more in agreement with the peaks of the modelled hydrograph looking at figure 10.

The Pearson's correlation coefficient and the coefficient of determination, show the correlation between both datasets, and to what extent the variance in the one hydrograph is explained by the variance in the other. The correlation coefficient is showing again that most correlation between the hydrographs can be found in the third and fourth location. This can be also seen in figure 10, in graph 1 and 2, except for the annual trend in discharge, there is less variance in the modelled hydrographs than in the observed discharge. Therefore the variance of the modelled discharge cannot be explained by the variance of the observed discharge. In the third and fourth graph, more variance is seen in modelled discharge, which might explain the increasing scores for those locations.

Looking at all the scores and hydrographs it has become clear that the hydrographs of location 1 and 2, which are both located in the Shire River, exhibit the least agreement. Looking at the hydrographs of location 3 and 4, they seem to be more in agreement than location 1 and 2. However, the hydrological performance based on the skill is poor. If it is assumed that the observed discharge values are the true values, it can be concluded that in these locations, GloFAS does not model discharge quantitatively correct and GloFAS is not suitable as model to forecast absolute discharge values.







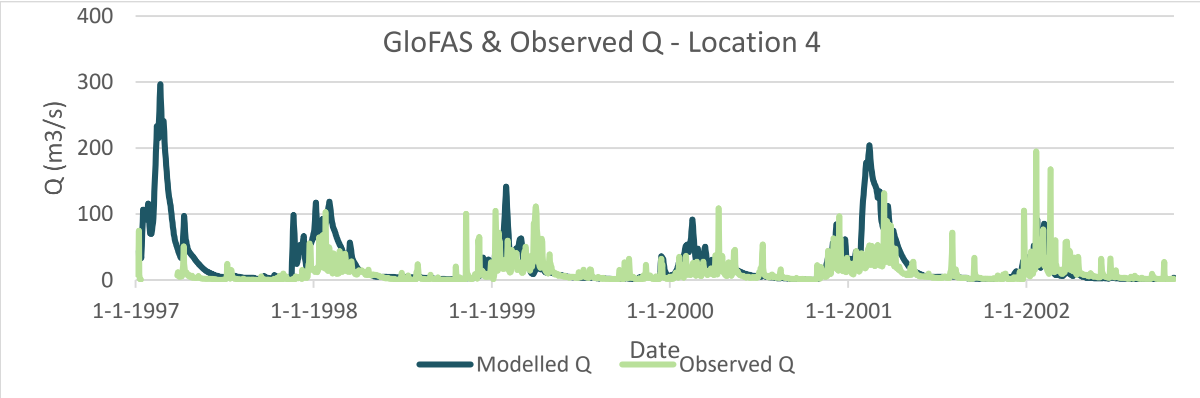


Figure 10: Hydrographs of GloFAS & observed discharge

5.2 Forecast skill GloFAS

The theoretical skill is showing how well GloFAS is able to forecast discharge. The discharge at LT0 is compared with discharges at LT1 to LT15. Figure 11, is showing three plots of the NS, PBias, and CV score, calculated for every LT. The plot of NS is given without whiskers to show more detail, the plot with whiskers can be found in Appendix M. Every LT is shown in a boxplot with scores aggregated over all river cells in Malawi. The boxplots show the median score, the boxes show the 25^{th} – 75^{th} percentile and the whiskers the 1^{st} -99^{th} percentile of the scores in all the river cells.

The NS score reflects the overall fit of the forecasted discharge compared to the modelled discharge. In figure 11, it can be seen that the longer the LT the lower the score and the larger the variability in the scores. Especially the values from the median till the 99^{th} percentile have a large variability. The negative values indicate that the mean value of the modelled discharge is a better predictor than the forecasted discharge.

The PBias score is showing the average tendency of the forecasted values to be lower or higher than the modelled values. The positive scores indicate that the forecasted discharge is on average higher than the modelled values. This indicates that the precipitation forecasts that are used as input of GloFAS have a tendency to forecast higher precipitation than the one produced at LT0. As a result, the model forecasts higher discharge at longer LTs than the modelled discharge LT0. The CV score measures the standard deviation between the modelled and forecasted discharge. Both CV and PBias show higher values with longer LTs. The variability of the scores per river cells is increasing with longer LTs as well. In both scores, the largest variability is seen in the higher scores, from the median up to the last percentile. This increasing variability indicates that with a longer LT there are more river cells that give extreme worse scores. However, the three scores are on average quite good, indicating that the skill of the precipitation model is good as well and that the forecasted discharge is on average a good predictor of the modelled discharge.

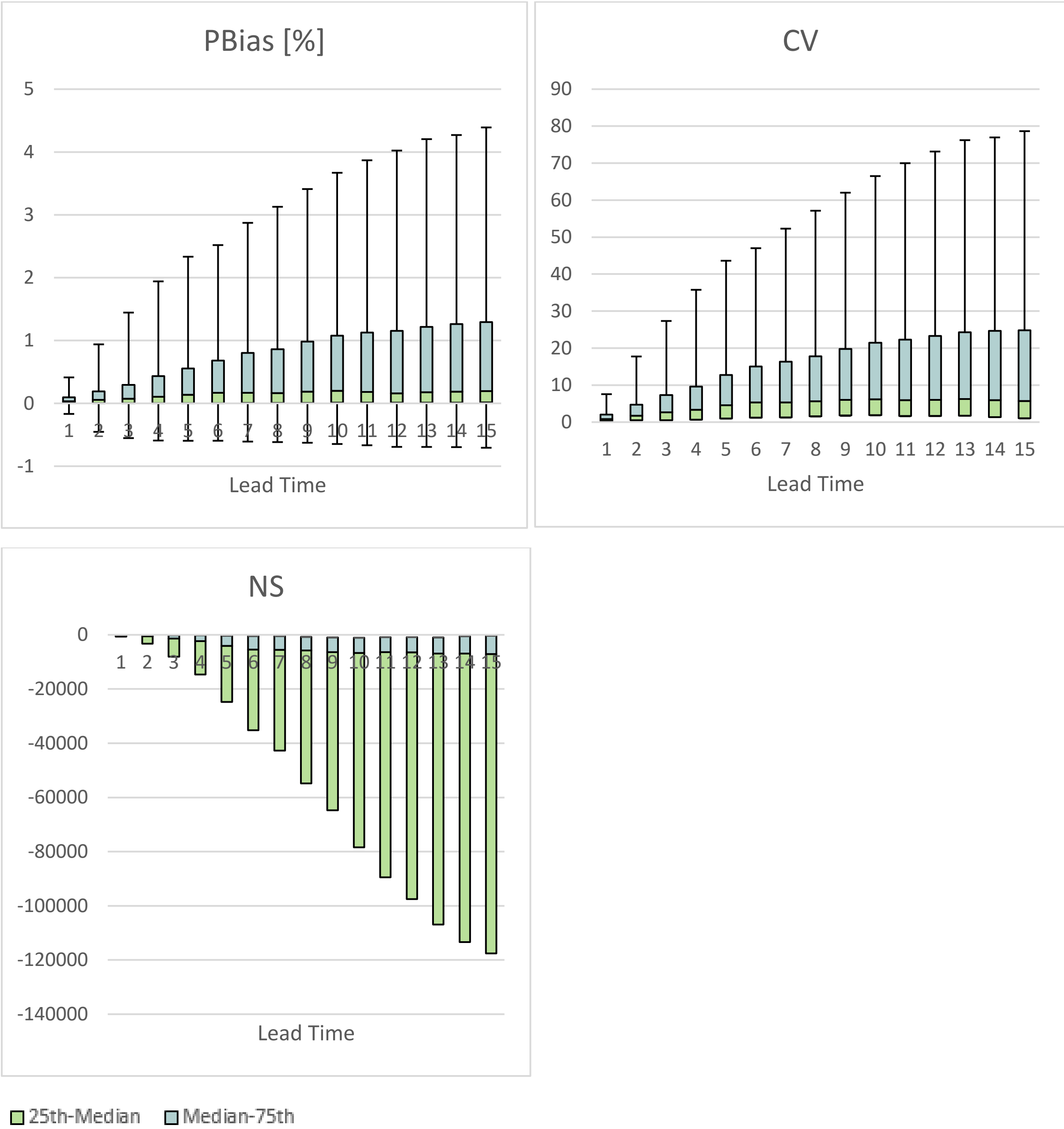


Figure 11: Forecast skill scores for various lead times

The changes in the median value for all three scores, show for the first six days in LT the largest increase. After the LT of 6 days, the scores are only slightly increasing or are even decreasing in the PBias. This is shown for the CV score in figure 12, the same figure for the other scores can be found in Appendix D. This indicates that up to LT6 the performance of the model to forecast the modelled discharge decreases, but after LT6 this performance does no longer decrease that much. So, forecasted discharges at LT6 and LT15 are on average predicting with the same performance. However, due to the large variability at larger LTs, there are some river cells that do perform much worse at LT15 compared to LT6 for example.

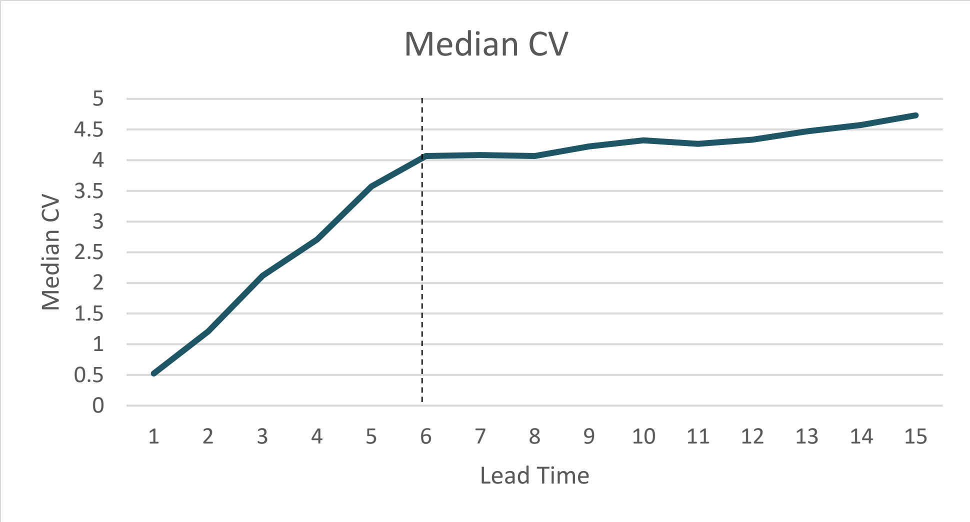


Figure 12: Median CV forecast skill scores

Figure 13 is showing maps of how the CV score differs spatially at LT7 and LT15, the numbers 1 to 4 are the locations of the previous results. Other maps for the other scores can be found in Appendix E. However, all maps show a similar spatial pattern in scores. For each river cell in figure 13, the skill scores are calculated over the period 1997 till 2018. If the value is closer to 0, the better the correspondence between the modelled discharge at LT0 and the forecasted discharge. The upper right "river cells" within the yellow colours are part of Lake Malawi. The difference in maps is that in general, the map for LT15 gives brighter colours, meaning lower results than at LT7. In both maps, it is seen that in general moving away from the main stream, the Shire River, the scores get higher, so give a worse result. What can also be seen from these figures is that the river network of GloFAS is very coarse and small rivers are not modelled, an overview of the river network modelled by GloFAS can be found in Appendix K.

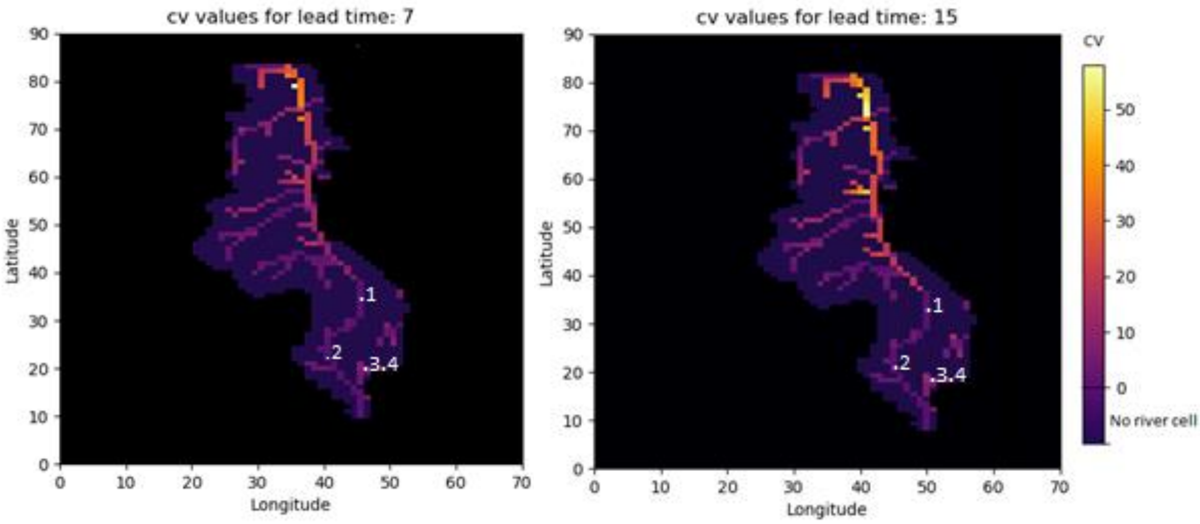
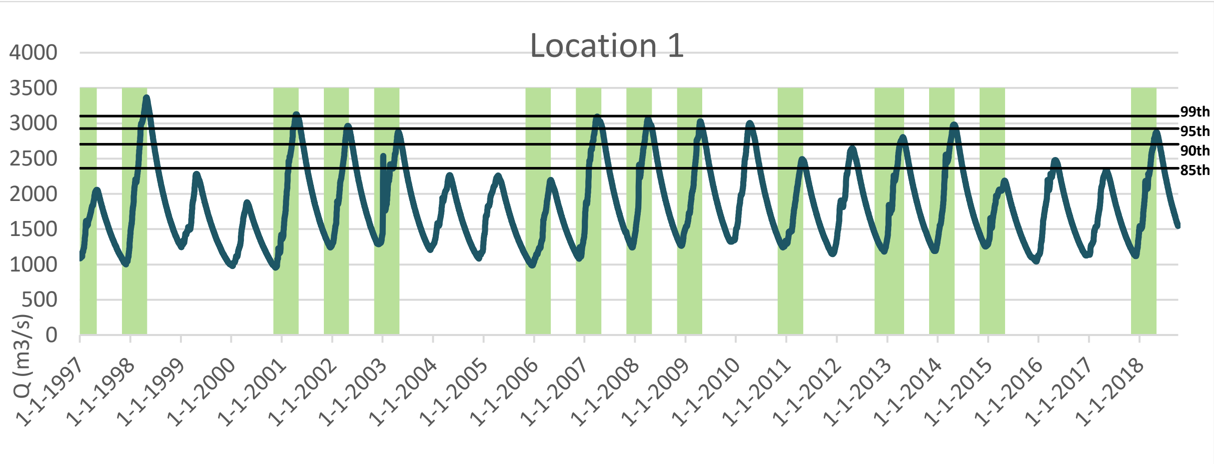


Figure 13: Spatial distribution CV LT7 & LT15

5.3 Flood forecast skill GloFAS

In this section two assessments have been done. First, the modelled discharge at LT0 and the forecasted discharge at LT7 and LT15 are compared with reported floods using multiple thresholds. This is done to assess if the modelled and forecasted discharge are able to detect reported floods and what trigger level gives the best result. Second, a comparison is done between the modelled discharge at LT0 and forecasted discharge at LT7 and LT15 using multiple thresholds. A discharge is described as a flood if the discharge is above a certain threshold. This is done to assess whether the forecasted "floods" are a good predictor of the modelled "floods". This is also evaluation the skill of the precipitation forecast, as the modelled streamflow can significantly differ from the actual values (Bischiniotis et al., 2019).

In figure 14, the hydrographs of the four locations modelled by GloFAS at LT0 are shown from 1997 to 2018. The green shades show the rainy season of the historical flood periods, as described in Appendix A. These databases described 14 floods in the South of Malawi in this period. The black lines are the 80th, 90th, 95th, 99th percentile of the overall discharge for each location. These percentiles can be used as thresholds for the trigger level. For example, during the period of the first flood in location 2, shown in the red box in figure 14, it can be seen that the discharge is above the threshold of the 80th percentile, but not above the others. This indicates that there was a "Hit" by the modelled discharge if a threshold of the 80th percentile is used, but a "Miss" if the other percentiles are used. Figure 14 shows that the flood periods are indeed mostly close to a peak in discharge. However, this peak is not always above certain thresholds. Also, floods are not always reported at high peaks.



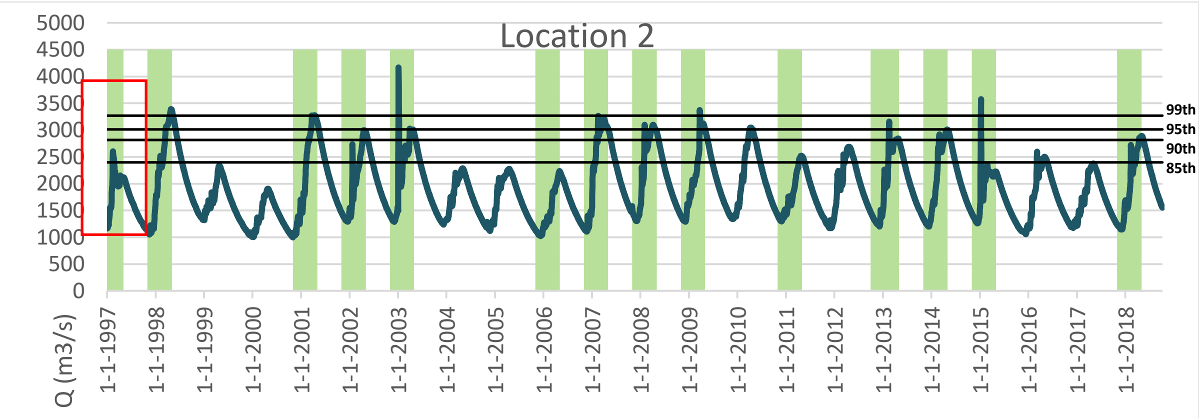


Figure 14: Flood periods, modelled discharge & possible trigger levels

As explained in the method three different scores are calculated to determine how well GloFAS models floods for the four different percentiles. Important to mention is that these scores do not give significant results as there are only 14 floods available, but give an indication of how thresholds can be determined and what thresholds might be best. The scores for location one can be found in figure 15, the graphs for the other locations can be found in Appendix H. For the Probability of Detection (POD) and the Critical Success Index (CSI), a value closer to one indicates a better score, for the False Alarm Ratio (FAR) closer to zero indicates a better score.

The first plot in figure 15 is showing that the POD for LT0 for the 80th percentile is 0.79, meaning that 79% of the reported floods are successfully shown by the modelled discharge data. This amount decreases as the threshold increases. For the CSI, the same trend is seen, but the scores are lower, for a threshold of the 80th percentile only around 70% of the floods are successfully modelled as part of all the forecasted floods. The FAR is showing the number of times a discharge peak is above the threshold, but a flood is not reported. The number of false alarms is increasing with lower thresholds. The same trends are seen for the other three locations. However, location three and four show on average a higher POD, but also a higher FAR. Different trigger levels give different values, the POD is often the best at a threshold of the 80th percentile, while the FAR is often best at the 99th percentile. This would mean that for the 80th percentile, the end-user would have received a flood signal for almost all reported floods, however, they would also have had a higher number of false alarms. Therefore, the best trigger level can only be chosen if it is known what is most important for the end-users, detecting all floods or having a low number of false alarms for example.

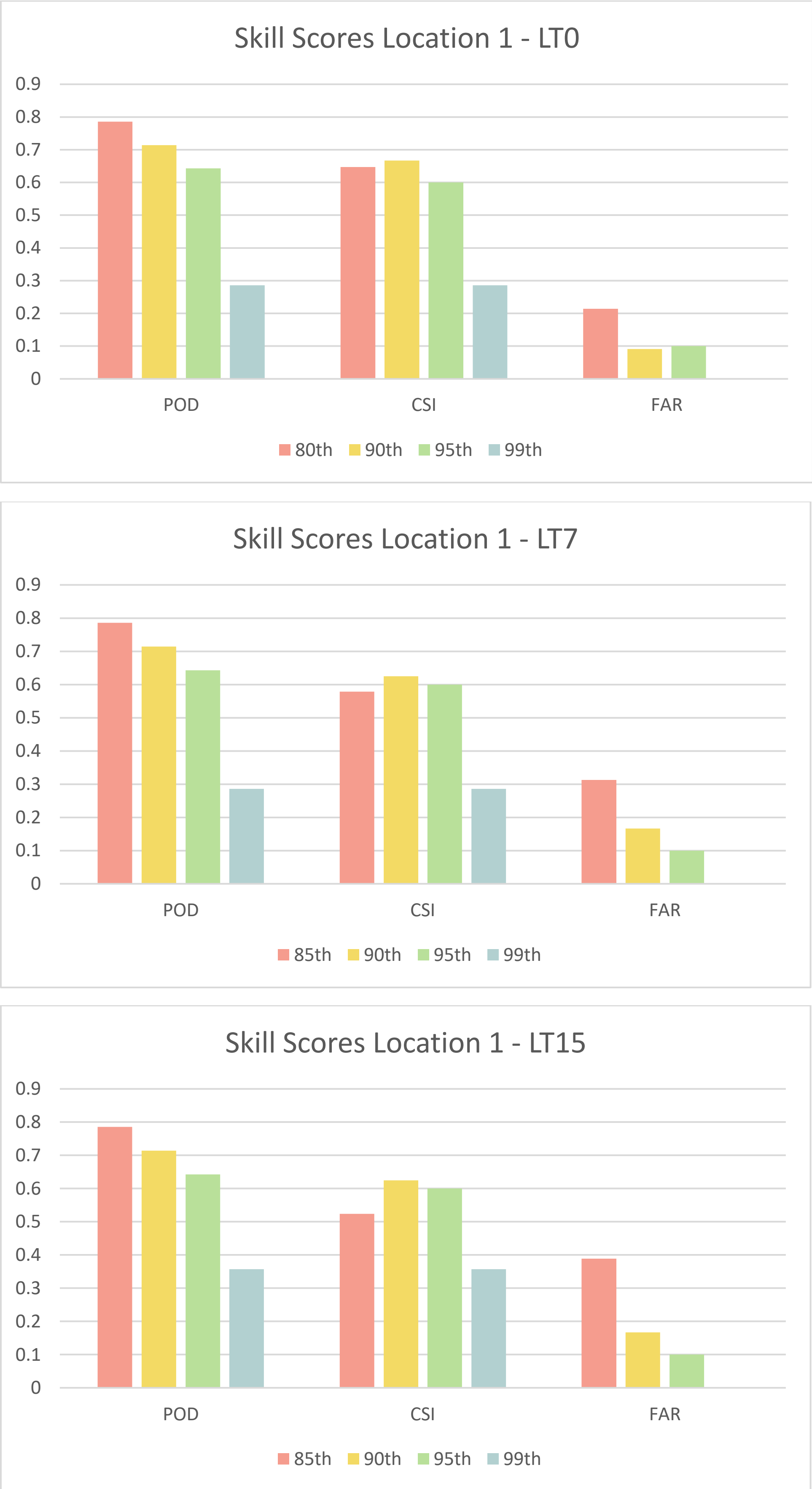


Figure 15: Forecast skill scores per trigger level

The second and third plot of figure 15, show the skill scores for the forecasted discharge at LT7 and LT15. The hydrographs of these forecasted discharges can be found in Appendix G. Both of these plots show the same trend as plot one, there only is a small difference in values in the three figures. The scores of LT7 are slightly better than the scores at LT15 and the scores of LT0 are again slightly better dan the scores of LT7 in this location. In the other three locations, Appendix H, it can be seen that sometimes LT15 gives better results than LT7 for certain thresholds. The best scoring trigger levels can differ depending on what location and LT is used, this must also be taken into account when choosing a trigger level.

As explained before, a comparison is also done between the modelled "floods" and forecasted "floods". The plots of these graphs can be found in Appendix M. The same skill scores, POD, CSI and FAR, are calculated again. The actual floods are assumed to be the periods when the modelled discharge is above a certain thresholds. These modelled floods are compared with if the forecasted discharge, at LT7 and LT15, is above that same threshold as well or not. The values of these scores are again plotted and can be found in Appendix N. The average of the four locations for LT7 and LT15 is given in figure 16. The scores in this figure show very good values, especially using the 85th percentile almost all modelled floods are predicted by the forecasted floods, and almost no false alarms are issued. The 85th percentile gives perfect scores for LT7, and almost perfect for LT15. This indicates that floods predicted by the forecasted discharge predict the floods described by the modelled discharge very well. This means that even though the absolute discharge values might not be correct, the skill of the precipitation forecast is very good and if the correct trigger levels are chosen GloFAS can be used to forecast floods.

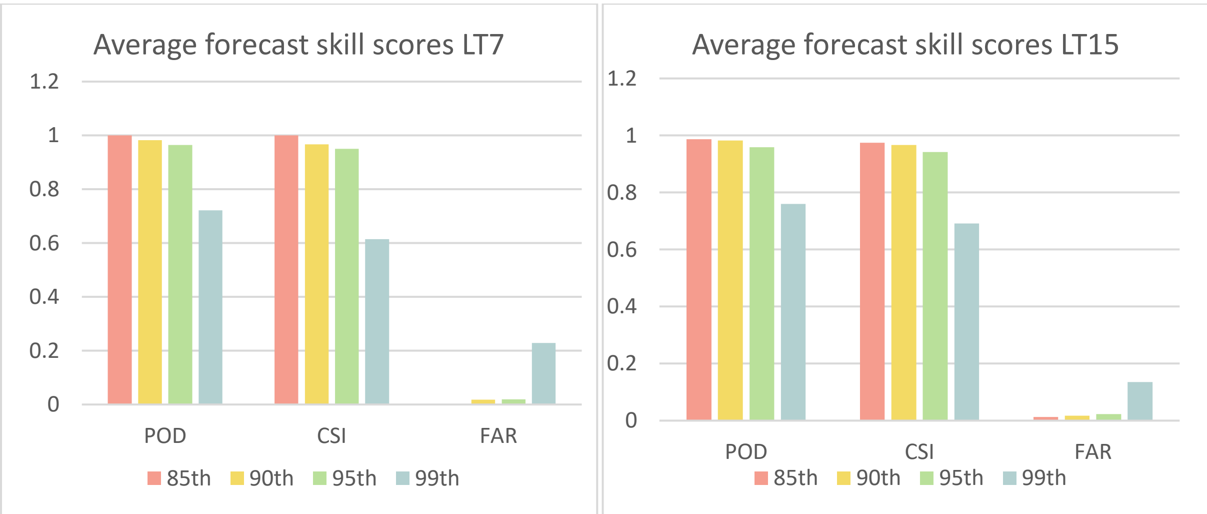


Figure 16: Average flood forecast skill scores per trigger level.

Assessment Integration Process of Forecasts | 6

In this chapter, an assessment will be done on the possibility of integrating IK forecast indicators and community-based forecasting with the official forecast. First, a description of the complete flood and weather forecast dissemination network will be given. Second, the role of the VCPC and ACPC will be described in this process and how they triangulate between different sources. Third, the steps are described that need to be taken to integrate the different forecast sources on VCPC level.

6.1 Flood & weather forecast dissemination

The analysis of the transcripts from the interviews and the notes from the FGDs offer various insights into the types and flows of forecast information. From the interviews, it became obvious that there are six types of forecast information that are discussed in this section. Additional information from the FGDs is combined with this. Figure 17 shows the six types and levels of forecast information that are part of the flood EWS. This figure is made by combining the different information flows from the different organizations, as were described in the transcripts of the interviews. The dissemination of each type of forecast through different levels is shown in a different colour.

The different levels are the forecast origin, national, district, area, local and individual level. In each level, different stakeholder structures can be found from the government, MRCS and the radio. The government has the different departments and ministries at national level, the District Civil Village Protection Committee (DCPC) at district level, the ACPC at area level (Traditional Authority level) and the VCPC at local level (Group Village Head level). The RC has the Malawi Red Cross Society (MRCS) at national level, district offices at district level, division offices at area level and Community Based – Disaster Response Teams (CB-DRTs) at village level. The CB-DRTs work hand in hand with the VCPCs, they often share members. The radio is the most important stakeholder in disseminating information, this is either done on national radio or on the so-called community radio, which takes place at area level. Different stakeholders that compose the forecasts are the Department of Climate Change and Meteorological Services (DCCMS) also called the Met Department, the Water Resources Department (WRD), the VCPCs and the individuals. The forecasts flow top-down or bottom-up, but also move horizontally and diagonally from governmental stakeholders to the RC and the Radio and vice versa. In the next sections, a description will be given on how each forecast type is disseminated in the whole network, according to the interviews and discussions.

6.1.1 Seasonal weather forecast

The interviews with the DCCMS (2019), DoDMA (2019), and MoA (2019), have given insights on how the seasonal weather forecast is produced. The forecast originator of the seasonal weather outlook is the DCCMS. Before the rainy season, in September or October, a seasonal outlook is issued on the expected rainfall patterns. They produce this information on regional continent level during a meeting with the Southern Africa Development Community. The DCCMS scales this seasonal outlook down to national level by including local features and conditions, this forecast is done for the southern and northern region of Malawi. Then these forecasts are downscaled to district level.

The national forecast is discussed with the so-called “technical committee” that includes responsible secretaries and heads of ministries and other relevant stakeholders like NGOs. The Department of Disaster Management Affairs (DoDMA) is responsible for the dissemination of this information that is discussed within the technical committee. Together with the DCCMS, the DoDMA presents the information with a district-specific poster to the DCPCs, who takes this down to the ACPCs and VCPCs (DoDMA, 2019). Another member of this technical committee is the Ministry of Agriculture (MoA), who is also dissemination the information to lower levels, but especially to agricultural stakeholders (MoA, 2019). Often humanitarian organizations like the MRCS and the World Food Program join the visits to the districts. During these district meetings more relevant stakeholders are invited like, extension officers, CB-DRTs, VCPCs and ACPCs. Next to the meetings, this information is also sent through the radio and emails (DCCMS, 2019).

6.1.2 Short-term weather forecast

Interviews with DCCMS (2019), MoA (2019) and WRD (2019) have shown that DCCMS also produces short-term weather forecasts (daily and 5-day forecasts). Also, a 10-day weather bulletin is shared during the rainy season for the specific districts on dry spells and floods. The MoA receives this directly and adjusts this information to make sure it is understandable for the end-users (MoA, 2019). These short-term weather forecasts are shared in various ways to all stakeholders. The main ways of disseminating the weather forecasts are by radio and internet, these sources reach most people and stakeholders. The messages are also sent in WhatsApp groups or emails. This information is discussed again between the different stakeholders. The DCCMS is sharing actual rainfall data with the WRD. If the actual rainfall is above a certain threshold the responsibility of providing flood warnings is transferred from DCCMS to the WRD (DCCMS, 2019).

6.1.3 Flash flood forecast

The interview with DCCMS (2019) and DoDMA (2019) have given insight that DCCMS also produces the flash flood forecasts. This forecast has a LT of 12 hours and is determined by the use of different models including the COSMO model. This information is officially supposed to be disseminated to the director of the DoDMA if the flash flood is of a significant magnitude. The DoDMA disseminates the information to the concerning district, who again shares it to lower levels like the ACPCs and VCPCs. However, in practice, the information is also shared directly with the DCPCs and the MRCS through WhatsApp groups (DCCMS, 2019).

6.1.4 Riverine flood forecast

The riverine flood forecasts are produced by the WRD, as was mentioned in the interview with the WRD (2019). This is done for the Shire River Basin with the ODSS that forecasts riverine floods with a LT of 72 hours. The ODSS sends out forecast information automatically by text messages and emails to many stakeholders. This information is showing the danger levels (green, yellow, red) of the water levels at certain stations. The messages are sent every day and during the rainy season twice a day (WRD, 2019). One of the receivers of these messages is the MRCS, who receives this message by email and in various WhatsApp groups. The MRCS translates warnings into local languages and sends it to DCPCs and community radio (MRCS-2, 2019). If the red level is reached, a warning is sent every hour. This warning is sent to DoDMA and they send it again to the lower structures. Warning letters are sent to the general public by newspaper, national radio and DCPC, which together disseminate the information to the community (WRD, 2019).

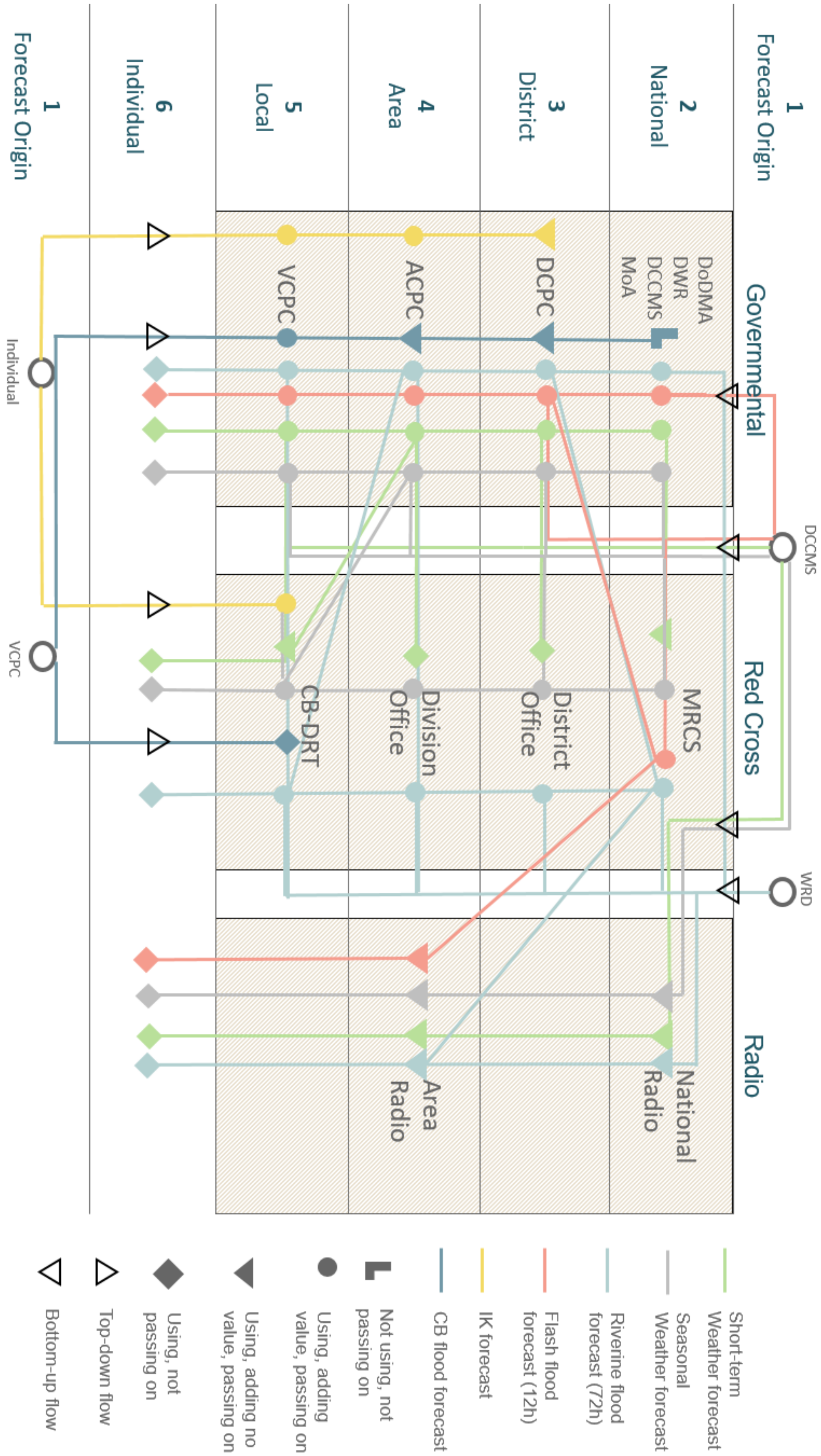


Figure 17: Dissemination network weather & flood forecast information

6.1.5 Community based flood forecast

Insights on the CB and IK-based flood forecasts are obtained from the FGDs but also from interviews with the WRD and DoDMA. The CB flood forecasts are produced as part of the CB-EWS. The CB flood forecasts are determined by reading water levels at river gauges in upstream areas by VCPCs. These VCPCs communicate the information to other VCPCs and their ACPC if a danger level is reached, by calling them. The VCPCs are also supposed to document the water levels only a daily basis and report this to the ACPC, who is supposed to report it to the DCPC. The WRD mentions that they are supposed to receive this information back from the VCPCs (WRD, 2019). However, it has not become clear if this actually happens and what the WRD does with the information.

6.1.6 Indigenous knowledge-based flood forecast

Flood forecasts based on IK are mainly produced at lower levels in the network. Individuals often observe certain indicators and discuss this within their community and village, this will be discussed in more detail in section 6.2. Members of the VCPCs receive this information back from the individual level, and the VCPC reports this again to the ACPCs. However, members of the VCPCs and ACPCs also observe the indicators themselves. The indicators are shared mouth to mouth between individuals and the committees. The VCPCs write reports, including these indicators, that are shared with the ACPC. The DCPC discusses with the ACPCs and VCPCs if they have observed any local indicators during the meetings on the seasonal forecast information, to let the communities confirm the official information. However, DCPC itself does nothing with the information.

6.1.7 Challenges & improvements in the EWS according to the national level

The different stakeholders at national level have mentioned various challenges and improvements that can be made in the dissemination of flood forecasts. First of all, the interpretation and understanding of the official forecasts can be difficult for the communities. The interview with DCCMS (2019) indicates there is a need for journalists to know how to interpret the information before disseminating it. He also mentions that a translation is needed into the local language in the seasonal outlook. During the interview with WRD (2019), it was also mentions that from all flood warnings, text must be made with information because graphs are sometimes hard to understand for the end-user.

Another major challenge is the lack of resources in the overall flood EWS. There are not enough resources for fast dissemination of the seasonal outlook from district level to the community. There is also need for more resources and capacity for producing the forecasts (DCCMS, 2019). The ODSS only covers the Lower Shire Basin and needs to be expanded to the whole county. However, there is not even enough budget to keep the current ODSS operational as the funding of the project ended (WRD, 2019). People who are monitoring the river gauges are volunteers and need to use their own credit to call people downstream, but if people do not have credit, people downstream are not warned (DoDMA, 2019). VCPCs and ACPCs are introduced by the government in some districts and are promoted by NGOs and projects. However, if the ACPC or VPCP is not there or not active, they fail to disseminate and act on information. If projects regarding EW end, it is a challenge to keep the project sustainable without funding (MRCS-2, 2019). It is not exactly clear how much of the committees are active or not, but the MRCS indicated that of the 15 committees that participated in this research 10 were active and 5 were less active.

Improvements also can be made on the technical aspects of the EWS. Manual hydrological stations have to become automatic. Rating curves of the automatic stations have to be updated (WRD, 2019). Another model with a longer LT, GloFAS for example, has to be integrated with the current ODSS to increase the LT and give people time to prepare (MRCS-2, 2019). During the interview with LUANAR (2019) it was mentioned that data in Malawi is lacking in general. The quality of rainfall and discharge data is very bad; there are a lot of gaps in the data. Also, manual stations are not well kept and automated data stations create other problems, like stolen solar panels and different accuracies. There are only a very few weather stations (LUANAR, 2019). Awareness has to be created so more automatic stations can be installed and communities can feel ownership of it (DCCMS, 2019).

Also, a holistic approach is needed in the EWS. The occurrence of floods in a certain district is also affected by upstream areas, so more communication is needed between upstream and downstream areas (MRCS-2, 2019). Other dissemination methods have to be obtained as the network is not always working so people do not receive the WhatsApp messages or emails (MoA, 2019).

6.1.8 Views from national level on integration of IK forecasts with official

Stakeholders at national level have different views on the use of IK in forecasting floods. DoDMA (2019) describes, for example, the importance for DCPCs to match the official forecast with IK to see if they are complementary to each other, to make the official forecast more understandable, she gives an example:

> "For example in Chikwawa, they have all the indigenous warning systems that are used. We don't ask them to disregard them, because sometimes the forecast is used to understand the scientific one."
>
> – DoDMA

During the interview with MoA (2019) it was mentions that IK is used often at lower levels, but needs to be backed up by scientific data especially because IK is less reliable because of climate change. During the first interview with the MRCS (2019) it was mentions that IK is not always taken seriously at national level.

This overview of forecast information flow through the whole network is showing that there are many different actors involved that are again interrelated with each other. What can also be seen is that the official forecasts, coming from the national level are flowing through all the levels. However, the forecasts that are community based or based on IK are not used in all levels of the network and are mainly used at the area and village level. In the next section, the role of the ACPCs and VCPCs are described in more detail, together with an assessment of the opportunity to integrate all the sources of forecasts at these levels.

6.2 Triangulation between different sources of forecasts in VCPC & ACPC

6.2.1 VCPCs and ACPCs

VCPCs and ACPCs are structures introduced by the government in a couple of the districts in Malawi, including Chikwawa and Nsanje. These committees are introduced to provide response capacity to disasters and are equipped and trained in this (Trogrlić & Van den Homberg, 2019). The VCPCs are on the level of the Group Village Heads and the ACPC on the level of the Traditional Authorities. On district level, the DCPC is active covering the ACPCs again. The committees receive various resources from government and NGOs. RC has given the committees several trainings for example.

The FGDs with the committees have shown that the VCPCs, that are part of this research, were mostly established around 2015, after the implementation of the National Disaster Risk Management policy. The VCPCs have on average 15 members, with an exception of 10 members in Chilema and 17 members in Nyambalo. On average, 44 percent of the VCPC members are female and 56 percent are male. In most of the VCPCs, the members are chosen every five years by elections. Members of the current VCPC can be re-elected. During one discussion it was mentioned that members can serve a maximum of two terms. Two VCPCs mentioned that they have elections every three years instead of every five years. Members in the VCPCs are often members drawn from different sectors or other local structures. Members are drawn from educational, health, agricultural, religious sectors and youth clubs. Examples of local structures that members are often also part of are the Community Based – Disaster Response Team, led by RC volunteers or Village- or Area Development Committees (ADCs). Most VCPCs in Chikwawa & Nsanje work together with RC volunteers from the CB-DRTs.

From the three FGDs with the ACPCs, two of the committees were established in 2014, and one in 2018. The three committees have respectively 17, 15 and 10 members. The ACPCs are supposed to have elections every five years like the VCPCs, however, only one ACPC is doing this. The other two are not because they say that there are no resources to train new members. The Chimombo ACPC also mentions that some of their members, mostly agricultural extension officers, had to be replaced because they transferred for their job. So, the new members have not received any trainings. Members of the ACPC are drawn from different VCPCs or are extension officers.

Discussions with VCPCs were done with seven active and five less active committees. A less active committee is described by the MRCS as a committee that is less adequate in carrying out their responsibilities, even though they received the proper resources and trainings from government and/or NGOs to operate. The two VCPCs that are more upstream, with a village that is not prone to flooding, are both part of the five less active VCPCs. However, from the discussions itself it was not clear what committees are active or not, as all committees described themselves as active. The reasons they gave for this is that they received training by government or NGOs; they functioned well during the 2019 floods; they meet and write reports structurally; they feel that they work hard and do their job.

Most committees meet twice a month, and a few meet only once a month. Most VCPCs report to the ACPC after they meet on the current situation in their village. Some of them report to other higher levels like, the ADC, Agricultural officials, and to the RC. Some mention that they report extra if local indicators are seen that forecast floods. The Nyangu VCPC, less active, mentioned they do not report anything from their meetings. The ACPC in its turn reports to the DCPC once a month after their meetings, so action can be taken and feedback can be taken back to the VCPCs.

6.2.2 Forecast information used by VCPCs and ACPCs

To be able to take early action as a VCPC and ACPC, the committees triangulate between different sources of forecast information before disseminating it to the communities. The next sections describe the process of receiving and disseminating, improvements and trust in the official forecast information, the CB EW information and the forecasts based on IK.

Official forecast information

In general VCPCs and ACPCs receive three types of official forecast information. This can be daily weather updates, monthly or seasonal weather updates, and specific flood forecast information. The information is received from different sources, as described in table 6. However, the one source every committee receives information from is the radio. They receive the daily forecast on it, but also if the seasonal weather forecast is out or if floods are predicted.

Table 6: Method to disseminate each type of official forecast information

Type of information	Communication channels for VCPCs	Communication channels for ACPC
Daily weather forecast	Radio	Radio
	DCCMS: text messages	**MRCS**: meetings
	Extension officers: text messages	Extension officers: WhatsApp groups
Monthly or seasonal weather forecast	Radio	Radio
	MRCS: WhatsApp messages, phone calls, meetings, meeting with poster together with **DCCMS**	**MRCS:** meeting with poster together with **DCCMS**
	ACPC: meeting showing poster	
	Extension officers: text messages or meetings	
Flood forecast information	**R**adio	Radio
	MRCS: phone or meeting	**MRCS**: meetings
	ACPC: phone call or meeting	**Extension officers**: WhatsApp groups
	Extension officers: text messages	
	DoDMA: phone calling or text messages	
	Various WhatsApp groups	
	Social media	

When the ACPC receives the official forecast information, they share it with the VCPCs, so they can share it with the community again. The dissemination of the information to VCPCs is done by awareness meetings or by calling on the phone. In case of an urgent warning, they come by to visit them. The warning calls are done with personal phones because they do not have any phones from the ACPC, so an improvement that can be made in the EW process according to them is having phones. They also mention that having bicycles will improve the dissemination of information.

Overall, all VCPCs trust and use the official weather and flood forecast information. Reasons for them to trust it are because the forecasts are mostly correct and they are set up by experts. However, false alarms sometimes confuse them and make trust in the forecast less, especially within the community. Communities feel that the official forecasts are second-hand information, not observed by themselves. VCPC members indicate that the trust in the official forecast depends on whether the forecasts in the past were correct or not. One VCPC member gave an example of how in 2016 heavy rains and floods were forecasted, so lots of measures were taken, but the floods never came. Another example:

"I remember in July last year, we experienced floods which damaged crops in our gardens yet we have never received heavy rains in July. This happened after the meteorological department warned us but we did not believe them until we saw the rains and floods. So, we cannot say let us not believe in the scientific or the local knowledge, we believe in both because they are useful to us."

– Female, Nyambalo VCPC

The ACPCs trust the official forecast information as well because the information is often confirmed by their own observations, like clouds for example.

When VCPCs receive any type of weather or flood forecast information it is shared with the community in various ways. Methods that are used to disseminate the information are determined by the expected LT of the warning, as can be seen in table 7. There is a distinction between forecasts with a longer LT, this can either be a seasonal weather forecast or a flood forecast a few days before the event is forecasted, and for a short LT, a few hours to the event up to the moment the flood is actually seen.

Table 7: Method to disseminate official forecasts within community

Longer lead time	Short lead time
Community awareness meetings	Go door by door
Meetings with chiefs and traditional leads	Warn people by making noise with: whistles, megaphones, locally made drums.
Drama/traditional dance performances	
Go door by door	
Spread messages at secondary schools → children can take message home to community	

For the longer LTs they often have enough time to disseminate the forecasts to all the members in the community and potentially for the community to evacuate. However, with short LTs they have more difficulty to reach every community member in time. This is due to the fact that most VCPCs only have limited materials to warn on short notice, for example only whistles. They mentioned that every VCPC should receive a few (smart) phones because even if they have their own phones there is sometimes not enough credit or service to reach other people. VCPCs that do not have megaphones also ask for this. According to the VCPCs, another important material that is needed to spread the information in time for a short LT is having bicycles to disseminate the information.

Forecast based on indigenous knowledge

In all VCPCs and ACPCs flood forecast indicators based on IK, are used. As can be seen in figure 18, the indicator that is most used by all committees is the observation of more ants (in their houses) to forecast heavy rains or floods. Two other indicators that were both mentioned by nine committees in the discussions are the observations that hippos move away from the river and that mango trees produce more bumper fruits. These two indicators were mainly seen in Nsanje, both seven times and only twice in Chikwawa. The other indicators are more specific per village. The indicators ants and hippos are observed a few weeks up to a week before a flood event is coming. The increased production of fruits in a mango tree is seen a few months before the rainy season starts, in October or November. Even though these indicators have different LTs in forecasting heavy rains or floods, they are all seen before the announcement of an official forecast.

"An example, this year in January a hippo moved from Shire River and it reached at one of our gardens where floods have never reached. But in this year's floods in March, floods went as far as my garden, so this tells us that the hippo's movement from the water really predicts floods."

- Female, Ndamera VCPC

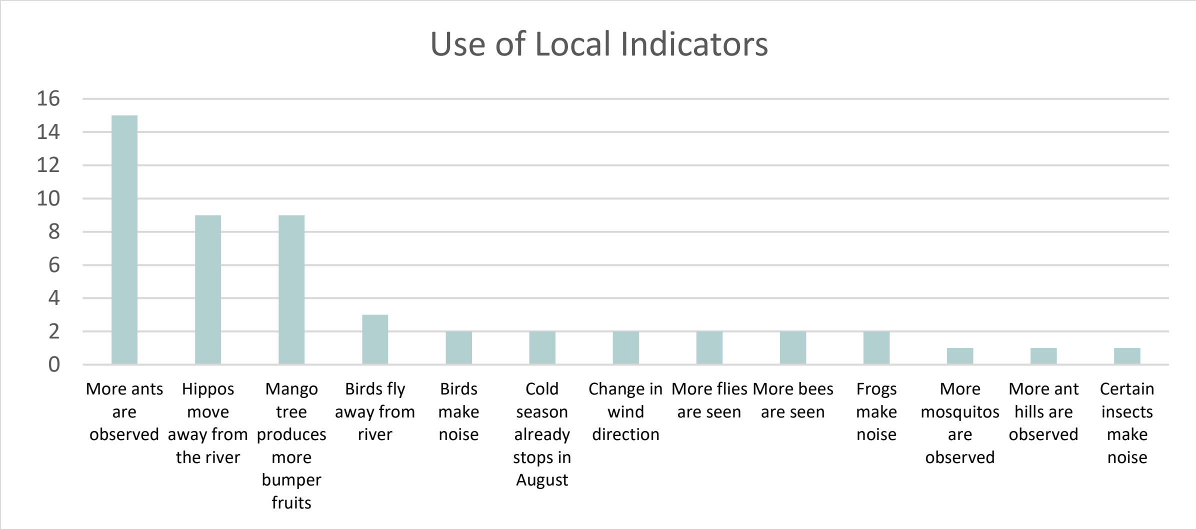


Figure 18: Use of local indicators in CPCs

In all VCPCs, the local indicators that are observed are discussed within the VCPC. In some situations, the VCPCs receive the information on the local indicators from the elderly people in the community. The information is also always disseminated and discussed with other people in the community, by community awareness meetings or by meetings with chiefs or traditional leaders.

One VCPC mentioned that they did not report to higher levels, this committee was described as less active. All of the VCPCs that do report information of their meetings to the ACPCs, also report the local indicators except for one committee. Sometimes they also report these indicators to other committees like the ADC, VDC, DCPC or the RC. Normally, they report local indicators to the ACPC after the meeting, however, a few VCPCs also report additionally when they observe certain indicators. The one VCPC that does not report any of the indicators to higher levels mentions that the indicators are their own local indicators and therefore they do not share it. The ACPCs also observe local indicators themselves. They discuss this information with the VCPCs and also receive information back from them. If they discussed it within their committee, they also report it to the DCPC.

Community Based Early Warning

Next to the official forecast and forecast based on IK, in some areas, there is an EWS that is community based, set up by the MRCS. From all the committees, two of the VCPCs were in upstream areas and had this CB-EWS. Four downstream committees mentioned they received information from this CB-EWS. The EWS consists of one or two manual river gauges upstream, that indicate the water level and danger levels, green, yellow and red. If the water level upstream reaches the yellow indicator, the upstream communities have to inform the people downstream. The measurements and dissemination are done by VCPC and CB-DRT members. At the time the yellow warning is observed, the downstream community has a few hours to minutes to evacuate depending on the area. The villages in the upstream areas do not experience floods, so the river gauges are only used to warn the people downstream. In the discussions, four of the VCPCs mentioned they received information from communities in upper areas. The warnings are disseminated by phone, however, sometimes the phones do not have service or credit to reach the people downstream. The ACPCs mentioned that they received information from the river gauge measured by the VCPCs. The upstream VCPCs are also supposed to write down the water levels daily and to share this with ACPCs.

6.2.3 Triangulation between the different sources of forecast information

The committees all combine the official forecasts with the forecasts based on IK. Some of the committees even triangulate between three sources, also using the community-based forecast. Figure 19 is showing that different types of forecasts are received in different time ranges. The committees mentioned they first observe the local indicators and then receive the official flood forecast information. Only the seasonal outlook is received simultaneously with the local indicators. The community-based forecast, the observations from the river gauge, are only a few hours up to minutes observed before the flood event. If the official forecast is received, the local indicators are used to confirm if the official forecast is correct. The community-based forecasts are only used to evacuate people if they are sure a flood is coming.

"When we see such (local) indicators and hear or receive the official forecast, we try to compare them and make a conclusion that we will have heavy rains, for example in 2019, when there were a lot of ants and the meteorological department predicting the heavy rains also."

– Male, Timbeneo VCPC

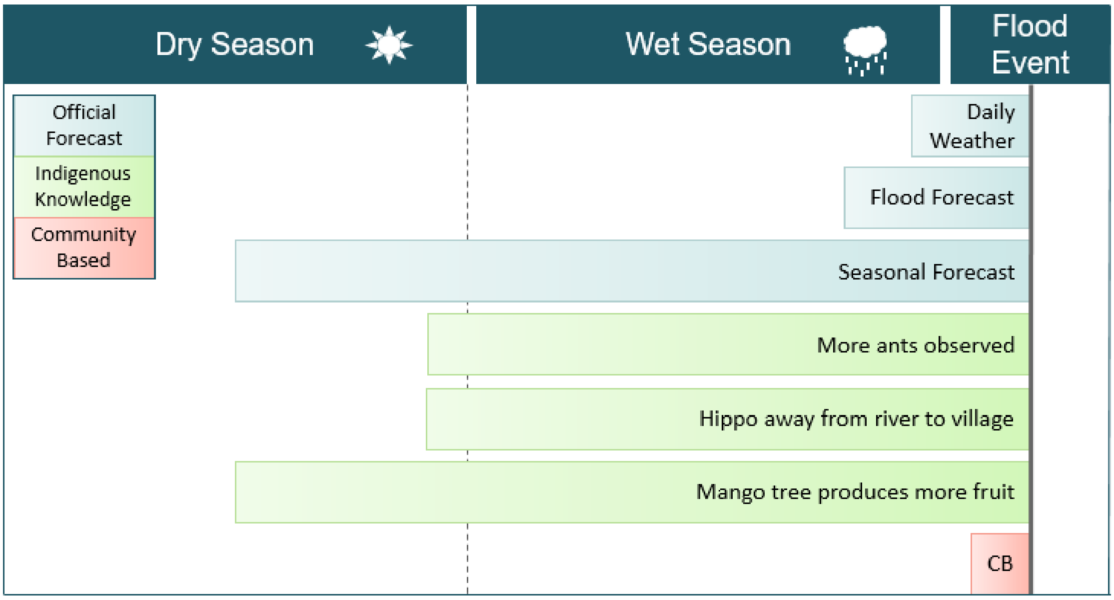


Figure 19: Lead time of different types of forecasts

In all of the VCPCs in this research, all available forecast sources are used and are trusted most of the time. However, if the question is asked on which source they trust the most, 9 of the 15 committees, trust the official forecast more than their local indicators, as can be seen in figure 20. The main reason that was given for this is that the information is coming from technology and experts. A smaller part of the VCPCs, 3, trust the local indicators more than the official forecast. This is because they are received first, the official forecast is sometimes wrong and the official forecast is second-hand information. The 3 VCPCs that trust the local indicators more are all described as less active committees.

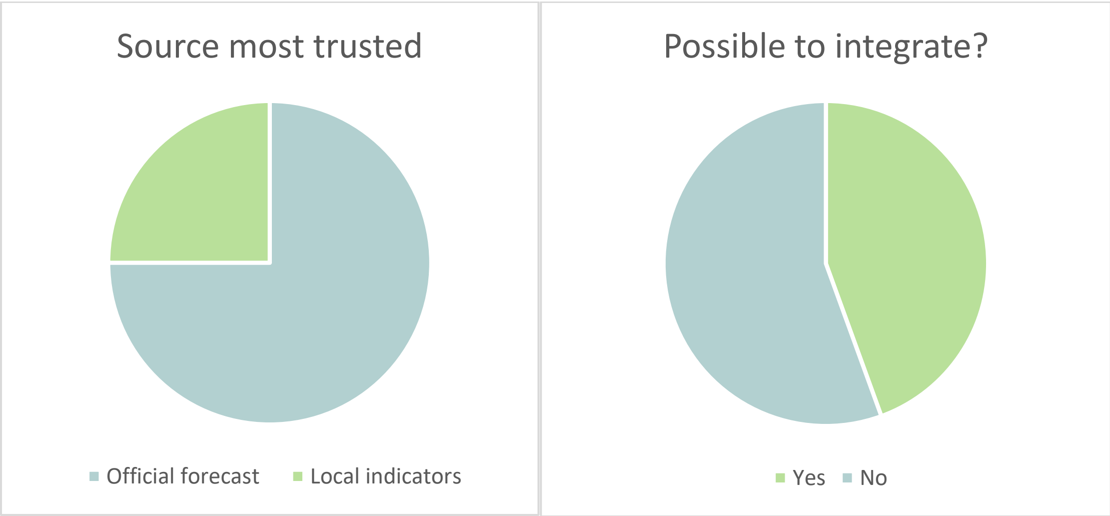


Figure 20: Information on official forecast & local indicators

The ACPC also trusts the IK because they got if from their ancestors and when they observe the indicators floods or heavy rains actually occur. However, trust in IK is getting less because of climate change. Another reason for them to rely more on the official forecast is because the ACPC covers a whole area and the observation of local indicators can differ per village.

Overall, all of the committees use different sources in their decision-making process. They also all described that integrating the different sources would be useful. Reasons given for this are:

- People can benefit from both sources.
- People can understand the value of local indicators by comparing to the official forecast.
- Sources are already being combined.
- It can help to make better decisions.
- It can improve the dissemination of information.

"Although we believe more in the local indicators, we think scientific indicators also have a big role in our survival. So, if they can be integrated, they can aid smooth dissemination or easy flow of information."

– Male, Mtema VCPC

The committees were also asked if they believed it is possible to integrate the official forecast and IK. As can be seen in figure 20, the opinions are more dispersed about this. A larger part of the committees feels that it is difficult or impossible to do the integration, because:

- Local indicators vary from area to area.
- IK is only understood by the communities at local level.
- They believe more in SK.
- Because of climate change, the reliability of local indicators is getting less.

The part that believes integration is possible mentions that:

- Local indicators and the official forecast always give the same results.
- The government understands IK.

However, it is mentioned that integration should take place at a local level and not at national level, because indicators can vary. This section has made clear that a triangulation is going on between multiple sources and decisions are being made on different types of information. However, these sources are not integrated, the next section will show how this combination of sources can be integrated.

6.3 Integration of official, CB & IK based forecasts

As can be read in the previous sections of this chapter, the VCPCs are all combining different sources of forecast information. Again, all of the committees feel that it would be useful to integrate the different sources, even though they are not sure how this can be done. In the next sections it will be described, according to the discussions and interviews, what the benefits of integration are according to the stakeholders, why this should happen at village level, and therefore by the VCPCs, and what steps need to be taken in this integration process.

6.3.1 Integration beneficial for improving the EWS

The main benefit of integrating different sources of forecasts is to improve the flood EWS and the decision-making process in taking action after a warning is issued. The discussions have shown that VCPCs believe that integration will lead to more benefits from all available sources. IK can be validated and might be more valued; if the IK is documented it can also be used and valued by younger generations; it will be easier for them to make decisions especially because sources are already being combined and it can help to improve the dissemination of information.

As described before, the potential of integration is also seen by stakeholders at national level. However, some are not taking IK seriously. Yet, the integration can also help to cover some of the challenges in the EWS that are mentioned by actors at the national level. It can help in interpretation and understanding the official forecast. It can also contribute to keeping governmental or NGO projects sustainable, even after funding is stopped. Especially, if not all national stakeholders take IK seriously, it is important to integrate it with the official forecast because communities will use it anyway, and by integrating it, it can be scientifically validated.

6.3.2 Integrating at village level

The discussions and interviews have shown that the integration process should take place at village level by the VCPCs. The first important criteria for this are that the integration should happen at a level that receives all different sources. As can be seen in figure 17, this can either be at village or area level. The ACPCs and VCPCs are the most adequate structures to potentially do this integration because they are already established and involved in the whole EW process. The case study areas in Chikwawa & Nsanje showed a diverse range of local indicators, but also have three indicators in common. However, the discussions have shown that the observations of these indicators can vary in each village. For example, one village might observe a hippo coming to the village, while another village does not. The advantage of this is that even if official forecasts are not specific per area or village, including the local indicators can help to make the forecasts more area-specific, which can help communities to make better decisions for themselves. So, even as some common indicators can all be used in the integration, and the integration process can be the same, still every VCPC has to do their own integration.

6.3.3 Integration process

The proposed steps of this integration process are based on the research of Hiwasaki, Luna, Syamsidik, & Shaw (2014) as described in the theoretical framework. However, before the integration process can start, Mercer, Kelman, Taranis & Suchet-Peason (2010) mention that it is important to engage the community that will take part in the integration. In this step, research has to be done on if communities feel that such integration would be useful and if they want to be part of the integration process at all. This step has already been undertaken by this research, the discussions have shown that the ACPCs and VCPCs feel that integration would be useful and that the integration should take on village level. The next steps will describe how the integration process can be done by each VCPC:

1. **Preparation**

In preparing the process, researchers have to be selected and training in gathering the data. All people in and outside the VCPC can observe local indicators, but some members should be selected and trained to document the observations. The other part of this step, an assessment of the currently used IK has already been done for the Lower Shire Valley by Trogrlić & Van den Homberg (2018).

2. **Data gathering**

After preparations are taken, the data gathering process starts. After the determination of what indicators are used, now observations have to be made on how often and when these indicators are seen and if an event occurs after the observations. The VCPCs are already documenting some of the indicators they observed to higher levels. However, the documentation has to be done in a structured manner with forms for example. Recordings have to be made on when an indicator was observed if the event happened after the observation, when the impact occurred and with what magnitude. Mercer, Kelman, Alfthan, & Kurvits (2012) added that the IK and local indicator observations have to be documented in the local language, so nothing is lost in translation. They also mention that all stakeholders should be able to access the information, so their recordings have to be shared with the ACPC, so they can disseminate it to higher levels again if necessary.

3. **Data Analysis & Validation**

After all data is gathered, an analysis of this data has to be done on what indicators are good forecasters. Then, scientific explanations have to be found for the selected indicators. To make this easier and more cost-effective, it would be useful for all VCPCs in the same area, to find some indicators that are common in the whole area (like ants, hippos and mango trees for example), so it is easier to validate the indicators scientifically. Then, the results should be taken back to the community.

4. **Science Integration**

In this step the actual integration takes place. Local indicators that are analysed and validated can be integrated with scientific forecasts. A system has to be developed on when a warning is issued. A choice has to be made on what the trigger is to issue a warning. This can be if any of the forecasts predict a flood, if both forecasts predict a flood, or if one specific indicator predicts a flood and is valued more for example.

5. **Popularization & Utilization**

The last step for the VCPCs is to promote the new information to the community, this can be done by methods that VCPCs are already using to reach the community, for example by community awareness meeting or drama performances. The information must also be promoted to higher levels, like the government and various NGOs and can be shared with scientists for further research.

If each VCPC follows this process, integration can take place on village level. As described before, the process can be the same for each VCPC, but the integrated forecast will be specific for a certain area.

Discussion | 7

This study was initialized with the overall aim to assess methods to improve the flood EWS in the Lower Shire Valley in Malawi. After a literature search, two main methods were proposed to reach this aim. The first is the use of a medium-term forecast model, GloFAS, that is able to provide flood warning with longer lead times than the existing models. The second, is the integration of forecasts based on IK with scientific forecasts, with the main advantage to ease the complex decision-making process for the end-users. Both methods have the potential to decrease the flood risk and impacts of floods in the Lower Shire Valley. This chapter will describe if both methods can lead to this goal, what the strengths and limitations of this research are and what future steps need to be taken on this topic.

7.1 Use of GloFAS

In the assessment of the hydrological skill of GloFAS, the comparison between the observed discharge and the modelled discharge by GloFAS showed that the data is not very well in agreement with each other. The overall fit of the hydrographs is not good, the GloFAS data is either showing a constant overestimation or an overestimation in the peaks, differing per location. This might be due to the fact the GloFAS is not calibrated for Malawi. Especially, for the Shire River locations the hydrographs are not corresponding very well. These large quantitative differences between the modelled and observed discharge can be explained by the fact that the model is not calibrated in Malawi. If a larger number of gauging stations was available the comparison between the two datasets could have given further insights about the model's performance and nature of errors and biases (Bischiniotis et al., 2019). However, the purpose of GloFAS is not to model or forecast the correct absolute discharge values, but to forecast floods.

The theoretical skill shows better values in skill scores than the hydrological skill. This can indicate that the hydrological model itself needs to be calibrated for the area, but the precipitation forecast data as input for the model is performing quite good. An increase in LT means on average a decrease in the forecast skill. However, it can also be seen that the median of the scores is staying around the same level from LT6 onwards. Meaning that after LT6 the average theoretical forecast skill is not decreasing a lot anymore. However, the variability in scores is still increasing after LT6. This indicates that on average the river cells between LT6 and LT15 will give the same results, however, in some cells the forecast skill does get much worse after LT6. To be able to know in what locations LT15 can be used and still give an acceptable result and in which not, the spatial distribution of the skill scores can be used. This is showing that the values in the main streams are on average a bit better than in the smaller side streams. This might be due to the fact that these locations have a larger upstream area. The larger upstream areas might filter out the short-term variable of meteorological forcing due to water attenuation compared to shorter river systems that have a rapid response time (Bischiniotis et al., 2019). To improve the overall forecast skill and make the skill sufficient enough, even for the worst scoring river cells, the system can be calibrated specifically for Malawi. This means that more observed discharge station points need to be available.

In this research, the most suitable threshold as trigger level was assessed at different LTs. The results have shown that different locations and different LTs give different results on what the best trigger level is. So, if the GloFAS would be used in the future, the trigger levels should be determined per location and per LT. In setting these trigger levels, it is also important to remember what the purpose of the trigger levels is. If the trigger level is used to trigger evacuation, the FAR cannot be too high, because the impact of evacuations are very large, as was noted in the FGDs. However, if the trigger is used for the distribution of food, the costs of a false alarm might be not that high. So, together with a decision maker it has to be determined what the trigger level is used for and what actions need to be taken after the threshold is exceeded, to choose the most suitable level.

7.1.2 Limitations & Further research

In the assessment of the skill of GloFAS, the main limitation is the lack of (reliable) data. The lack of observed discharge locations, gaps in the data, and the short periods make it hard to state that the results on the hydrological skill are completely reliable. To be able to determine if the observed discharge and the historical flood data are reliable, both datasets are compared. Appendix F is showing the observed data with the flood periods plotted in the hydrograph. What can be seen is that the flood periods mostly show a peak in discharge as well, if data is available. However, peaks are also seen in times no flood period is plotted. This can indicate that the reported floods probably did actually happened, but that the database might not be complete.

Because the historical floods in the database might not be complete and also do not give specific locations of the flood, it is not advised to use the calculated trigger level in practice. However, the method can be easily repeated if a reliable flood database is established. This can be done by using different methods. The database can be filled with information from a media analysis, as is done by Coughlan de Perez et al. (2016). If for some floods the geographical information is not clear, flood extent maps can be used to determine the exact locations of the historical floods. By analysing the flood extent maps that are available of the historical floods from the databases, it can also be assessed what the return period of the flood is and link trigger levels with floods of various return periods.

Even though, using GloFAS can give a lot of benefits, first more research has to be done before an advice can be given on what flood forecast system is most suitable for the Lower Shire Valley and in the end for whole of Malawi. To decide on continuing the use of the current ODSS, first an assessment needs to be done on the forecast skill of the ODSS and therefore the data from the government of Malawi is necessary. If a choice is made to keep using the ODSS, the system has to be expanded for the whole country. To decide on the introduction of GloFAS, first steps have to be taken to make it a suitable system for Malawi, as described in the previous section. Also, the forecast skill analysis has to be done for the whole country. Another option is combining both systems by using ODSS for the first 72 hours and GloFAS for the longer LTs. Only if both systems are assessed, an advice can be given to get the optimal forecasting system as EWS.

7.2 Process of integration

In the assessment of integrating different forecast sources as a method to improve the overall flood EWS, an overview is given of all the stakeholders and weather and flood forecast information flows. What stands out is that a very complex process is going on, where all stakeholders receive information from different sources via different channels. This makes it hard for the end-users of the forecasts to make a decision, especially if not all sources are giving the same warning. Additionally, not all stakeholders receive the information they are supposed to get and official warnings are not always received in time. Together with the problem of IK that might become less reliability due to climate change, the importance of integrating the different sources is increasing.

The VCPCs are the structures that are most adequate to take a leading role in this integration process. However, VCPCs are not available in the whole of Malawi, and most VCPCs are only active if they are involved in NGO projects. If a committee is not active, their role in the integration process cannot be fulfilled. For example, the VCPC that did not report anything to higher levels and also the VCPC that did not report anything about the observed local indicators were both described as less active committees. The reasons for a committee to be less active could be that the members are working voluntarily and the lack of resources within a committee. So, before the integration process can start, VCPCs have to be introduced in all areas and committees have to become active. Potential solutions to make a committee more active, according to the discussions and interviews, is by giving the members allowances for their work, making sure all members are chosen democratically and by making sure each committee has enough resources to do their job. This should be arranged by the government, as the committees are government structures, or with the help of NGOs.

This research has shown the value of combining bottom-up and top-down methods to improve the flood EWS. The research of Mercer, Kelman, Taranis & Suchet-Pearson (2010) proposed a framework on integrating IK and SK for DRR in general. This paper already showed the value of IK and the use of a participatory approach. In 2012, Gaillard & Mercer highlighted the importance of integrating bottom-up and top-down actions to bridge gaps in DRR. The proposed process in this research has taken some important lessons from these two studies but is mainly based on the research of Hiwasaki, Luna, Syamsidik & Shaw (2014). However, research specifically on integrating IK and SK in a flood EWS situation has not been done before. That is why this research proposed steps, adjusted for a specific flood EWS situation, that can work in different developing countries. This can be very useful in this field because every participant of the FGDs showed that both IK and SK are used and valued in the decision-making process.

7.3 Implications of the study

Both methods used in this study focus on different aspects of the EWS. The assessment of GloFAS is based on the method of the research of Alfieri et al. (2013) and Bischiniotis et al. (2019), focussing on forecasting of the flood. The assessment of the possibility of integrating IK and SK builds on the research of Trogrlić & Van den Homberg (2018) and Trogrlić et al. (2019), focussing on the communication and dissemination of the forecasts as well. By combining these two different methods, challenges in the forecast itself, the communication & use of the forecast, and social aspects around the EWS are accounted for. The research is showing that improvements in FRM, like in the EWS, are most efficient if both a top-down and bottom-up method is combined, maintaining the strengths of both methods and dealing with the weaknesses of both.

Another important aspect of the methods that are being used in this research is that both can be used in areas where resources are limited. GloFAS is a system that is free to use and is globally available, which makes it especially attractive for developing countries. This is also the case for the integration process. Developing countries, often countries that are not completely impacted by globalization, have rich IK that is used in forecasting different types of natural hazards. So, even if a country does not have an EWS yet, with the use of GloFAS and integration with forecasts based on IK, a valuable EWS can be set up, even if resources are minimal. The integration process in a different country can follow the same steps that are proposed in this research. However, research has to be done on which stakeholders can take a leading role in this process and on what local indicators are being used in that specific country.

Another application of the use of the trigger levels of GloFAS is by humanitarian organizations, like the RC, in Forecast Based Financing (FbF). FbF is a method used to release humanitarian funding when a warning is issued before an event. This is done to reduce risk, enhance preparedness and response, and make disaster risk management overall more effective (510, 2018). Using a medium-term system like GloFAS is giving organizations more time to take an early action such as to distribute money if a warning is issued. This is useful because the distribution of cash can be a slow process in developing countries. It can take more than three days from the moment of a warning for the end-users to receive the money, so using the current EWS gives the organizations not enough time.

Overall, both methods can have multiple benefits and combining the two has the potential to improve the EWS in Malawi, as well as in other developing countries, as long as the correct steps are taken.

Conclusion | 8

This research has assessed two methods to potentially improve the flood EWS in the Lower Shire Valley in Malawi. An assessment has been done to determine if the forecast skill of GloFAS is sufficient to be implemented in the flood EWS and how trigger levels could be determined for detecting floods in four locations in southern Malawi. The hydrological skill has shown that the modelled discharge is overestimating the overall observed discharge or the peaks of the observed discharge, depending on the location of the measurements. The theoretical forecast skill is showing that the modelled and forecasted discharges are better in agreement. However, the forecast skill is decreasing and getting more variable over the river cells with an increasing LT. Still, if the correct trigger levels are determined per location and LT, GloFAS can be used for forecasting floods in the case study area. The main steps that need to be taken to choose correct trigger levels are, improving the historical flood database, and calibrating the system for Malawi.

An assessment has also been done on how the process of integrating SK and IK on forecasting floods can be done to improve the EWS. This research has shown that the process of using all different types of forecasts at local and individual level is very complex and making it hard for communities to make the right decisions on whether to take action or not after a warning is issued. This process is discussed in more detail for the governmental structures at village and area level, the VCPCs and ACPCs. Every committee that was part of this research uses, next to various official forecasts, community-based forecasts and forecasts based on IK. The analysis of the interviews and discussions has also shown that the VCPC should take a leading role in the integration process. The proposed integration process can be the same for every committee, however, every village should do their own integration as observed indicators might vary from village to village. To be able to start the integration process, all areas need active VCPCs.

This research has shown a method to improve or establish a flood EWS, that can be valuable in various developing countries. Using the two methods can potentially maximize the benefits an EWS and decrease the flood risk in the Lower Shire Valley in Malawi.

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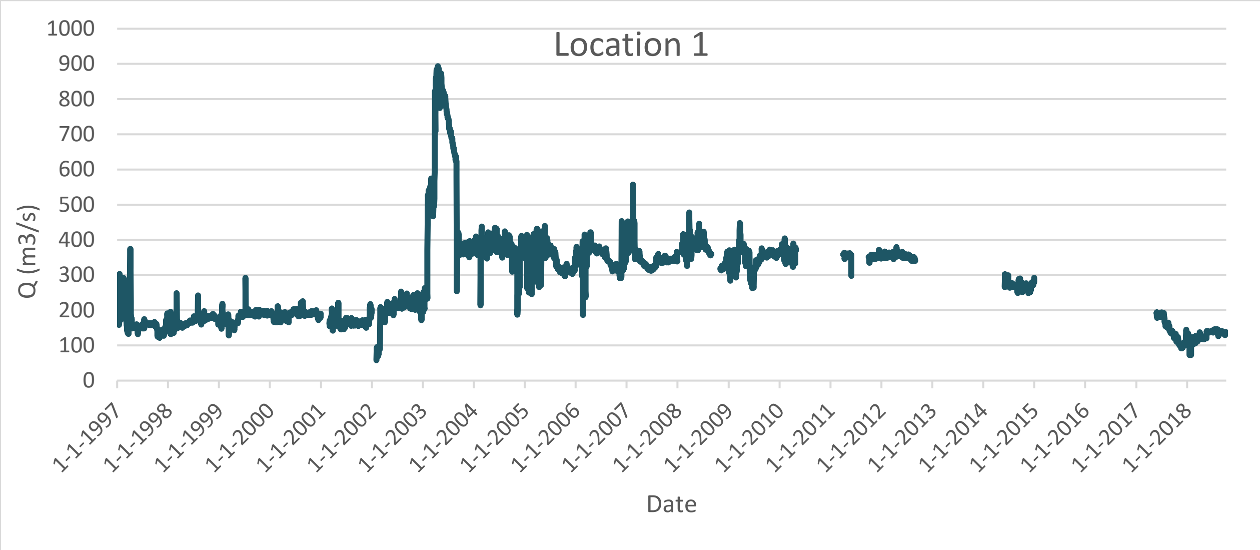
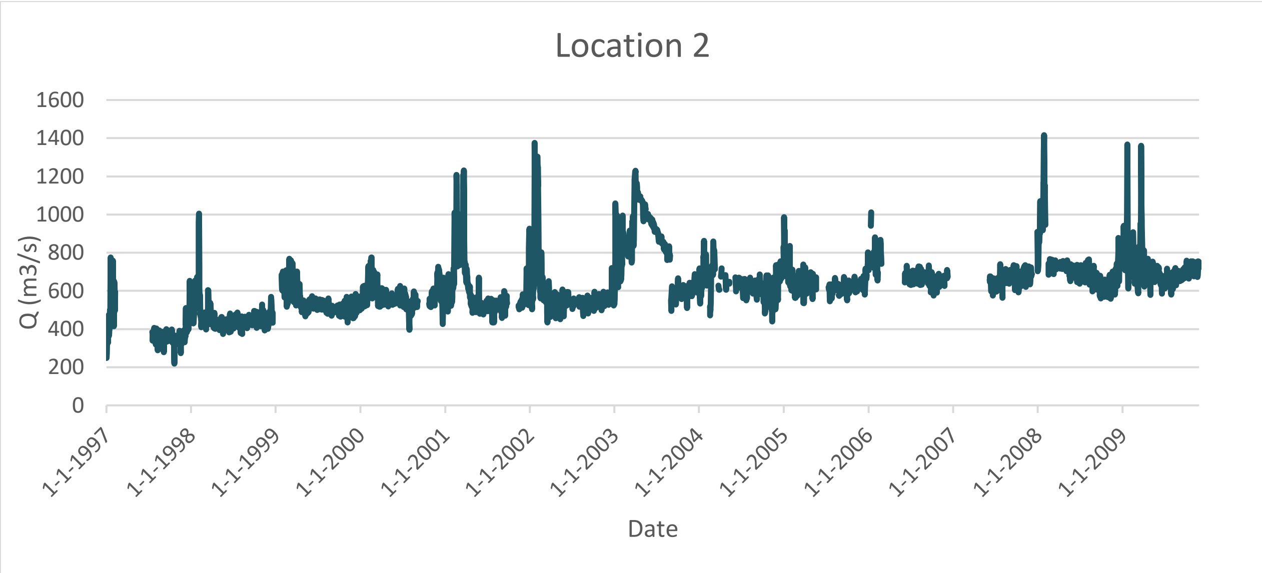
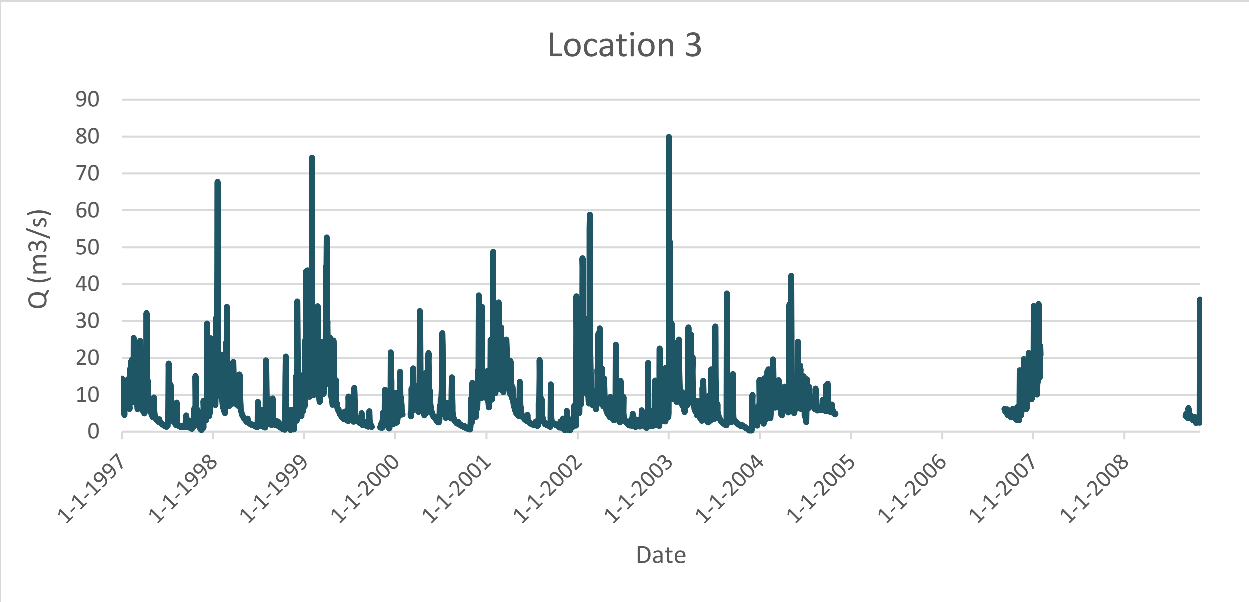
Appendix A: Historical Flood Database

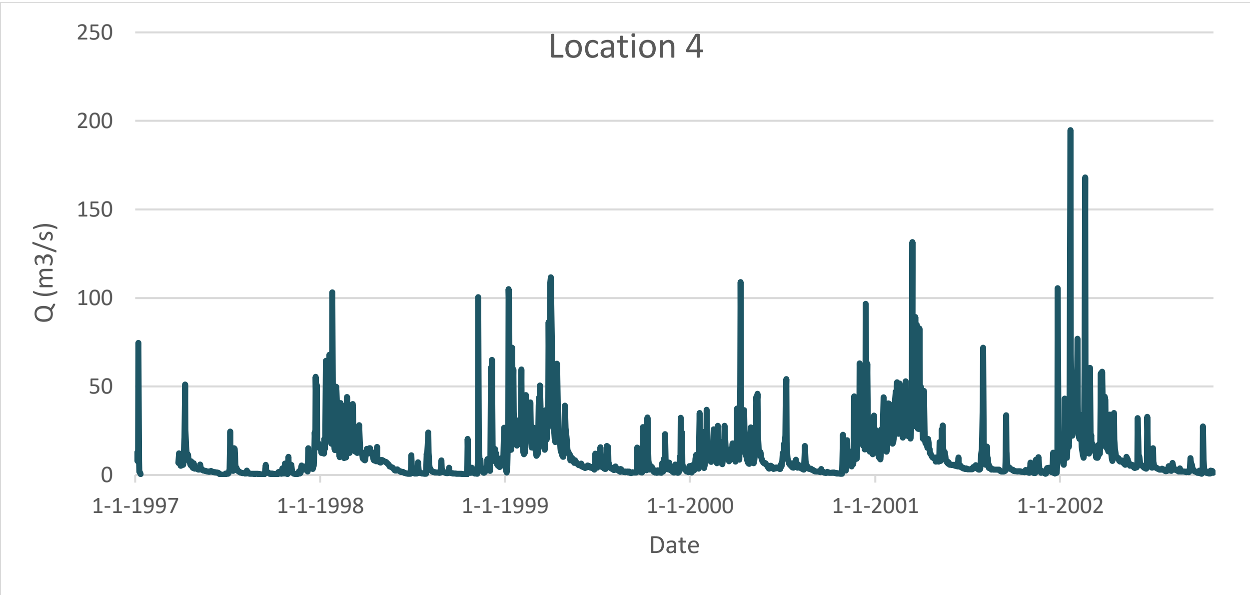
Year	Onset date	End date	Type	Districts	Rivers	Coordinates	Fatalities	Displaced	Source
1997	15-1-1997	28-2-1997	gf	Caia, Nsanje, Chikwawa, Makhanga	Zambezi, Pungue,	-15.8;35	78	300000	MunichRe, Dartmouth,EM-DAT
1998	19-1-1998	4-2-1998	gf	Karonga, Nkhotakota, Phalombe, Zomba	Phalombe river	-12.9;34.3	4	15000	MunichRe, Dartmouth,EM-DAT
2000	28-2-2000	30-3-2000	gf	Blantyre, Nsanje, Chikwawa, Karonga	Lalanje, Thangadz	-15.8;35	35	20000	MunichRe, Dartmouth,EM-DAT,ifrc emergency appeal 2000
2001	4-1-2001	25-1-2001	gf	Chikwawa, Nsanje, Rumphi, Phalombe, Blantyre	Shire, Lungazi rive	-13.5; 34	1	508750	MunichRe, Dartmouth,EM-DAT,ifrc emergency appeal 2001
2002	29-12-2001	5-3-2002	gf/ff	Blantyre, Chikwawa, Dedza, Karonga, Kasungu, Machinga, Mangochi, Nkhotakota, Nsanje, Salima and Zomba.	Mwanza, Lower Sl	-15.8; 35	4	100000	MunichRe, Dartmouth,EM-DAT
2003	2-1-2003	16-4-2003	gf	Salima, Balaka, Dedza, Machinga, Ntcheu, Dowa, Phalombe, Lilongwe, Mwanza, Rumphi, Nsanje, Shire, Chikwawa, Nyungwe-Wovwe in Karonga District. Bwanje Valley.	Shire	-15.8; 35	23	400000	MunichRe, Dartmouth,EM-DAT
2006	28-12-2005	15-4-2006	gf/ff	Chikwawa, Nsanje, Mangochi, Machinga, Ntcheu, Salima	Linthipe	-16;34.8	3	400000	MunichRe, EM-DAT, ifrc appeal 2006-2007
2007	26-11-2006	24-1-2007	gf/ff	Chikwawa, Nsanje, Ngabu, Ngowe, Mbenje,Phalombe	Mwanza river	-15.8; 35	7	8000	MunichRe, EM-DAT, ifrc, DREF bulletin 2007
2008	18-11-2007	28-1-2008	gf/ff	Chikwawa, Nsanje, Mangochi	Lower Shire Valley	-15;35	13	70000	MunichRe, EM-DAT, ifrc, emergency appael 2008
2010	15-3-2010	23-3-2010	gf	Central District, Dedza		-14.4;34.3		21200	MunichRe, EM-DAT
2011	11-3-2011	20-4-2011	gf	Nsanje District, Mzimba District		-13.6;33.9		3200	MunichRe, EM-DAT
2013	1-10-2012	27-3-2013	gf	Phalombe, Zomba, Mangochi, Nsanje		-15.5;35.5	3	33000	MunichRe, EM-DAT, ifrc, dref final report 2013
2014	1-1-2014	28-2-2014	gf/ff	Mangochi, Mzimba		-14.5;35.3	11	54200	MunichRe, EM-DAT
2015	28-12-2014	31-3-2015	gf/ff	Chikwawa, Nsanje, Central, Namakala, Mpunga, Chikanda, Mpondabwino, Mangoche, Blantyre, Lilongwe; Zomab; Phalombe	Likangala River	-14; 34	106	>1000000	MunichRe, EM-DAT,ifrc, emergency appeal 2015
2018	1-11-2017	1-4-2018		Chikwawa					EM-DAT

Appendix B: Observed discharge for four locations

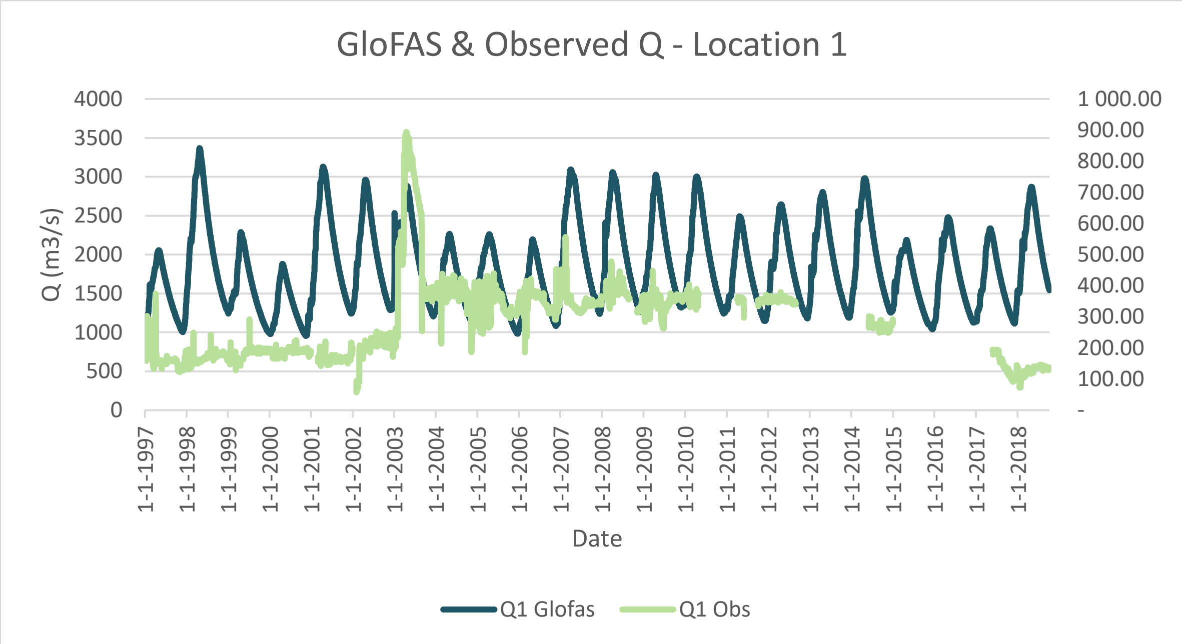


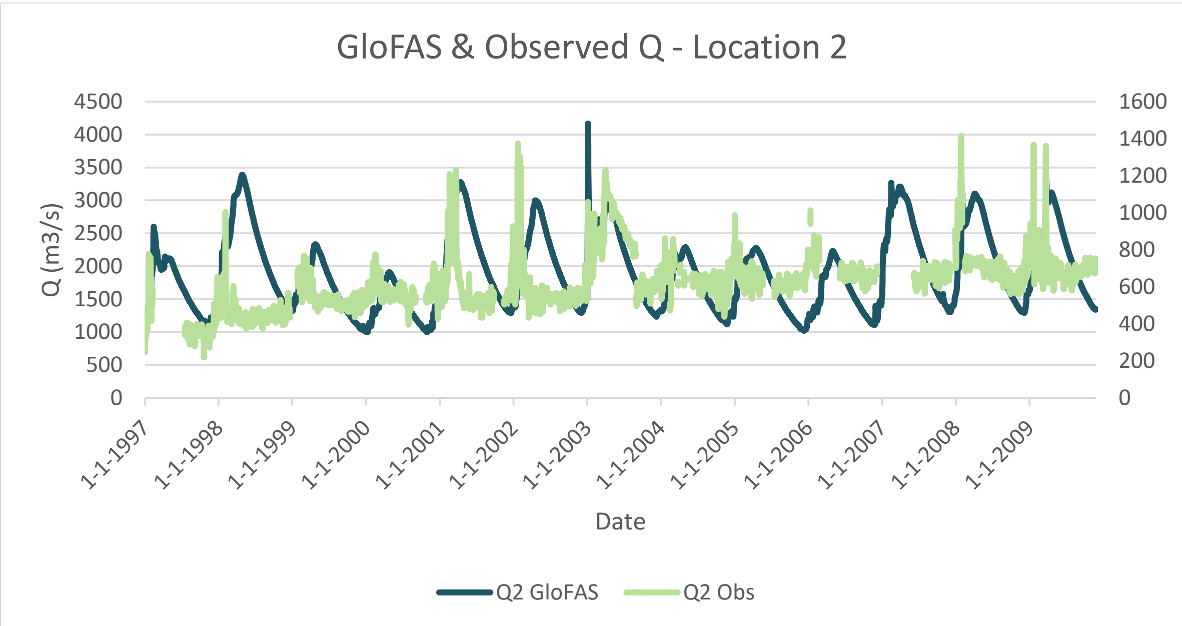



Location 3
90
80
70
60
50
40
30
20
10
0
Q (m3/s)
1-1-1997
1-1-1998
1-1-1999
1-1-2000
1-1-2001
1-1-2002
1-1-2003
1-1-2004
1-1-2005
1-1-2006
1-1-2007
1-1-2008
Date

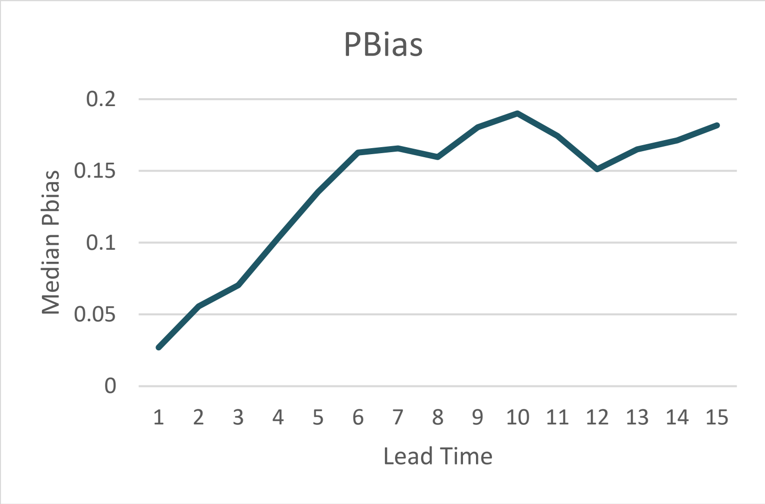

Location 4
250
200
150
100
50
0
Q (m3/s)
1-1-1997
1-1-1998
1-1-1999
1-1-2000
1-1-2001
1-1-2002
Date

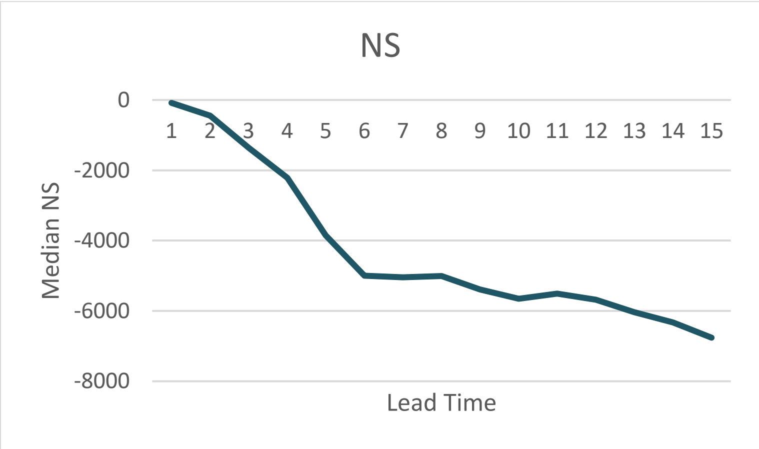
Appendix C: Observed & modelled discharge

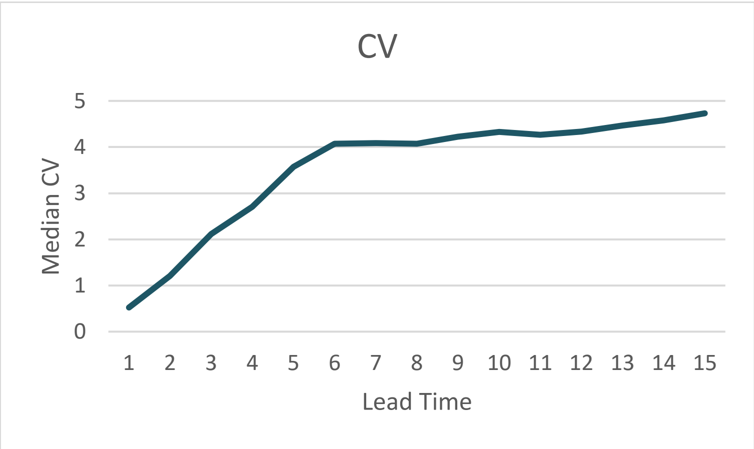




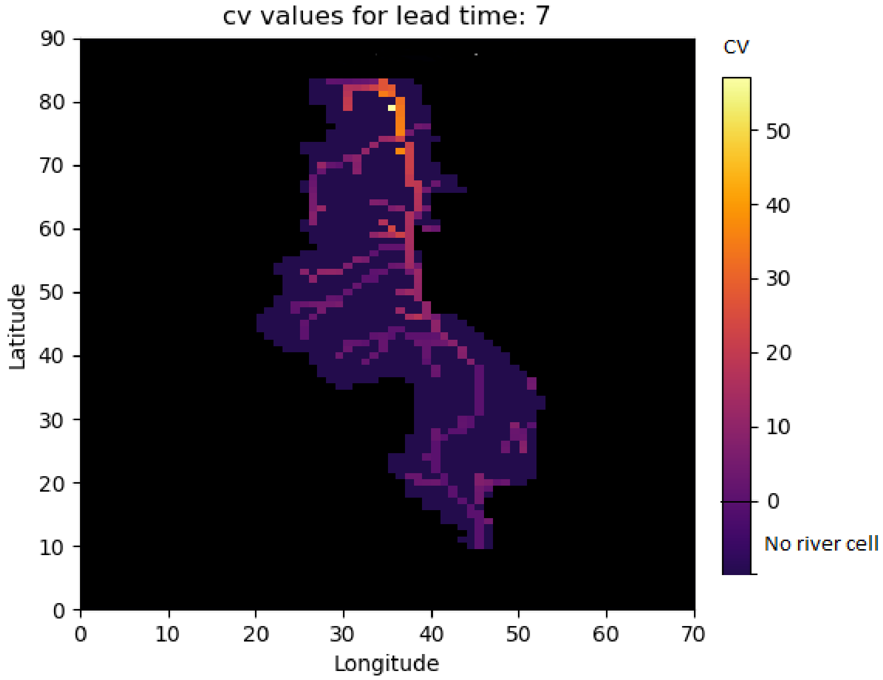
Appendix D: Forecast Skill GloFAS

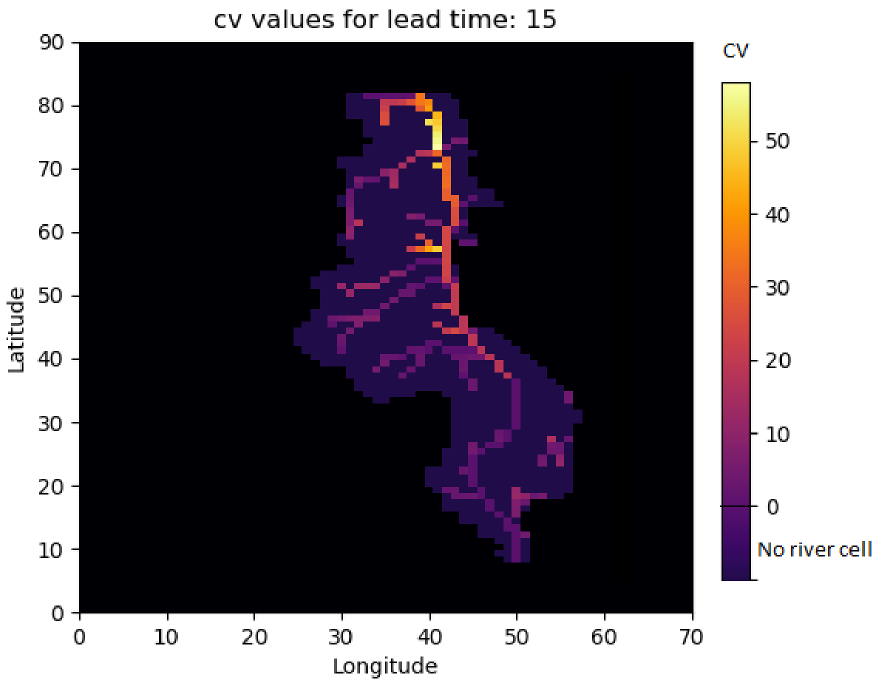


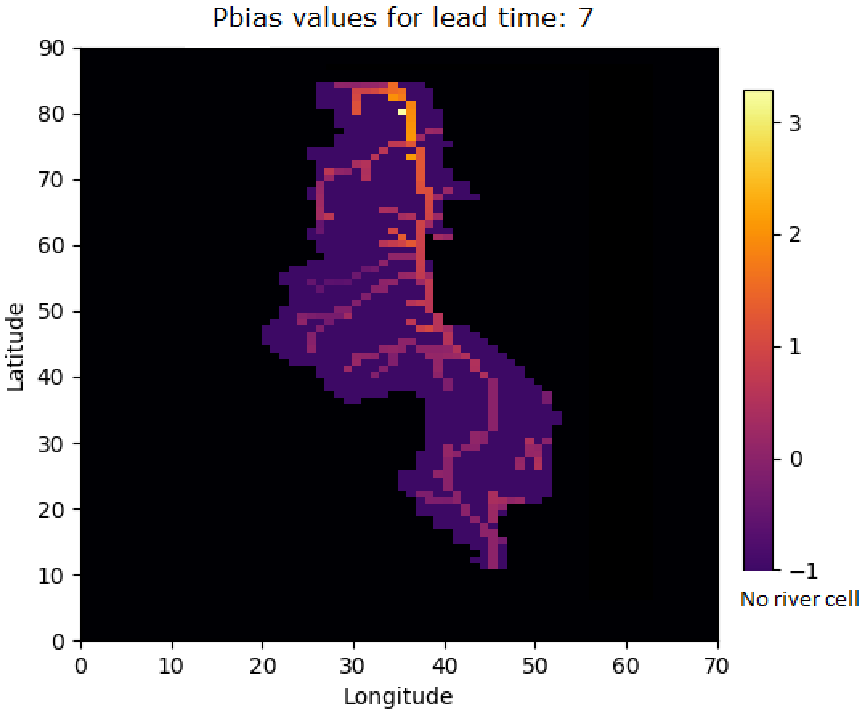


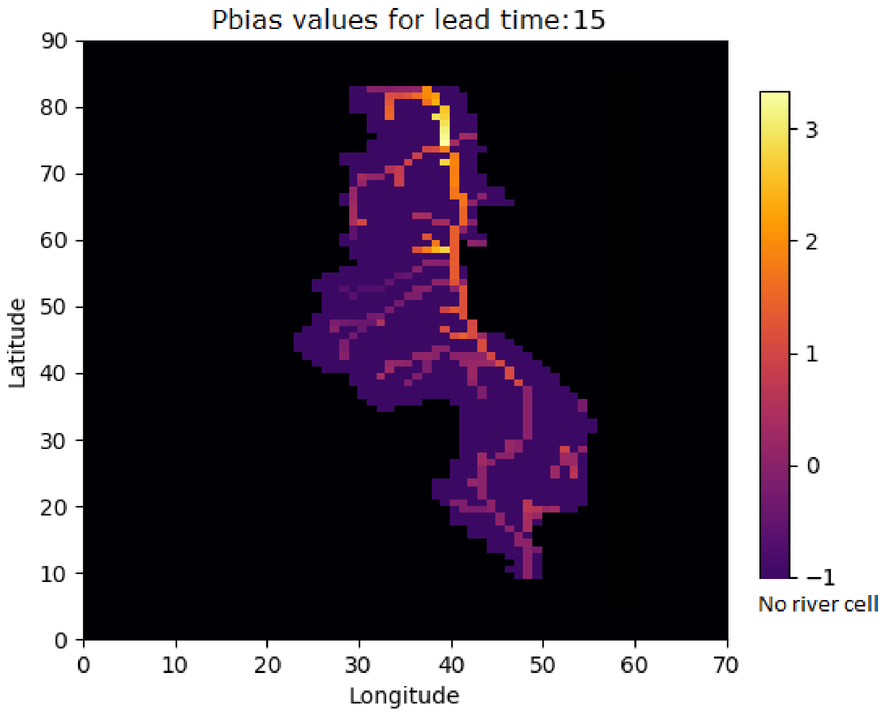


Appendix E: Forecast skill scores spatially

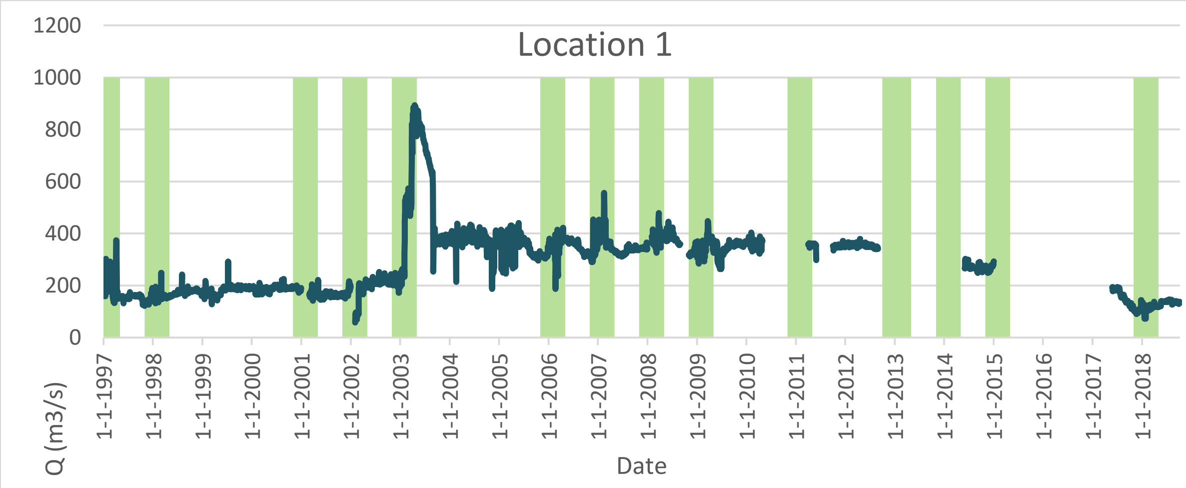


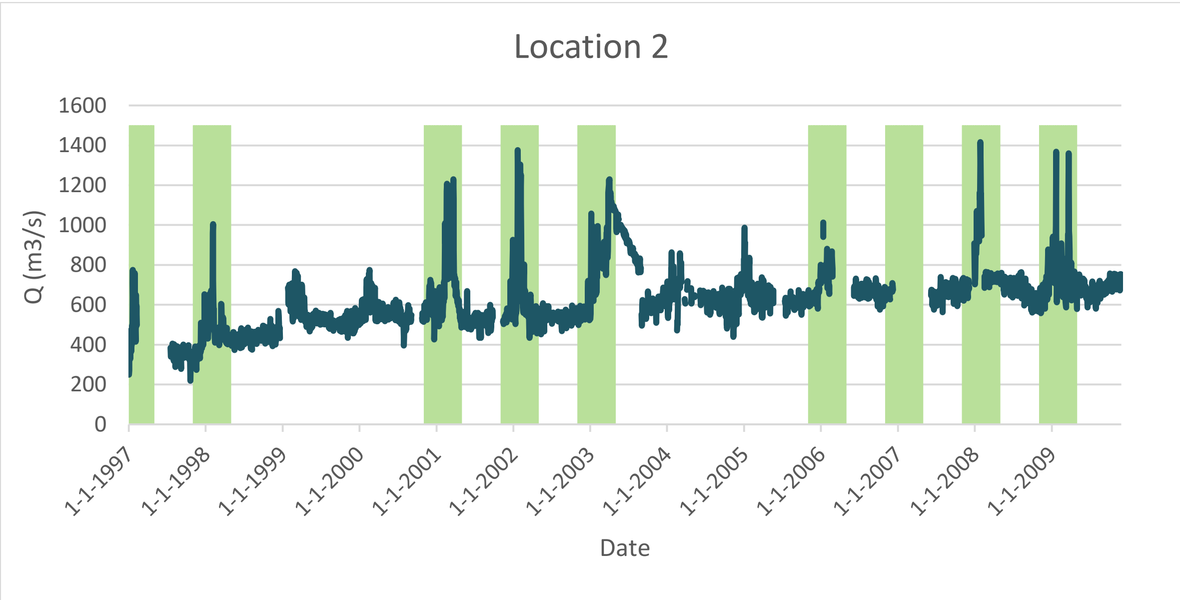


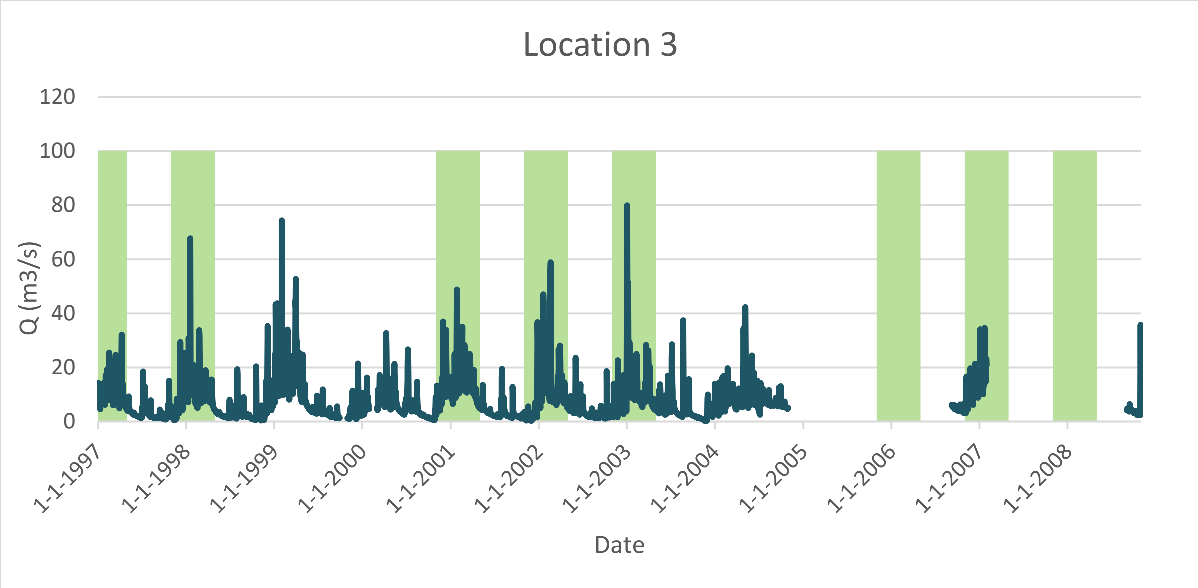

Pbias values for lead time: 7
Latitude
Longitude
No river cell

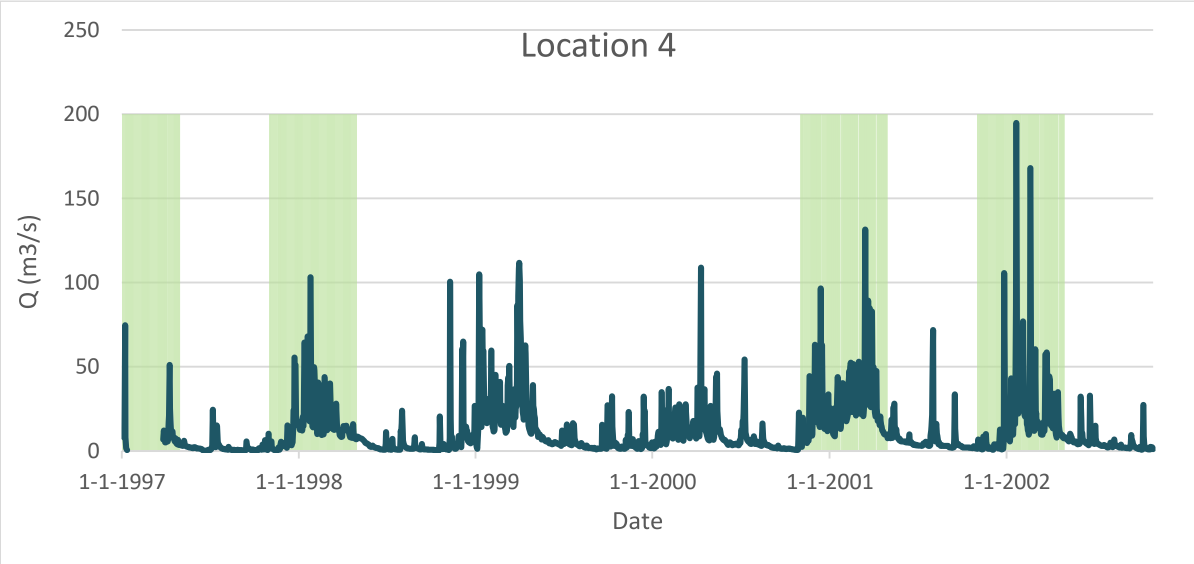

Pbias values for lead time:15
Latitude
Longitude
No river cell

Appendix F: Observed discharge and floods

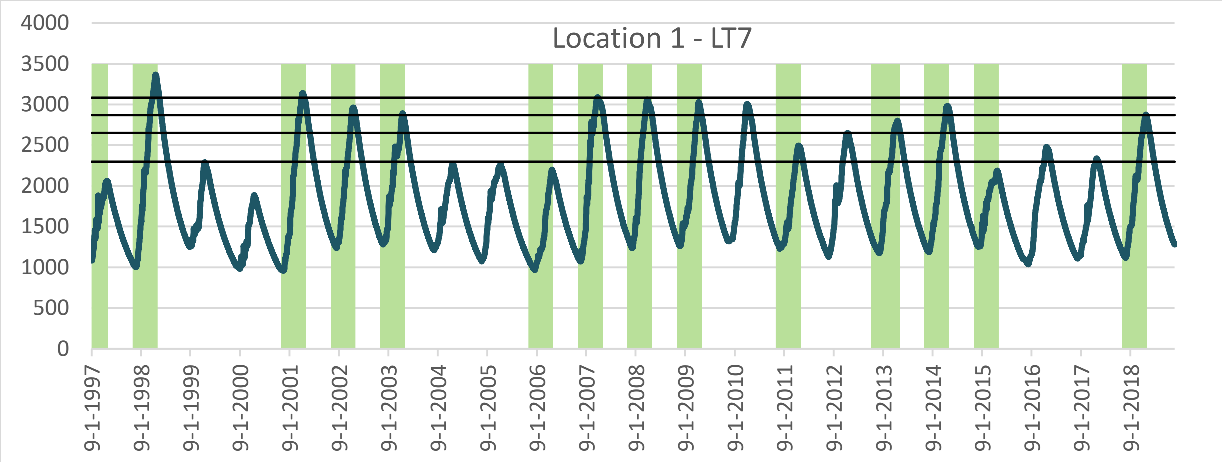


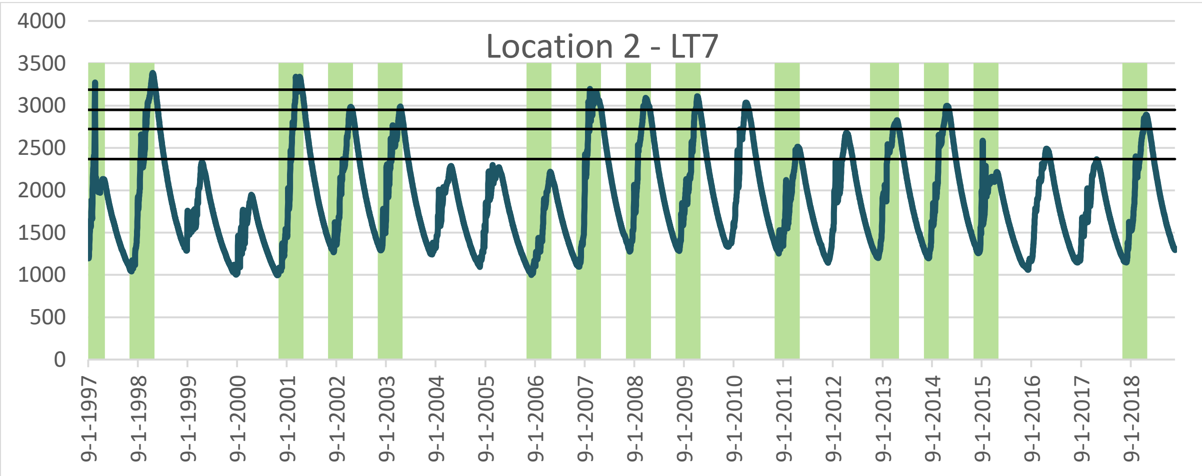


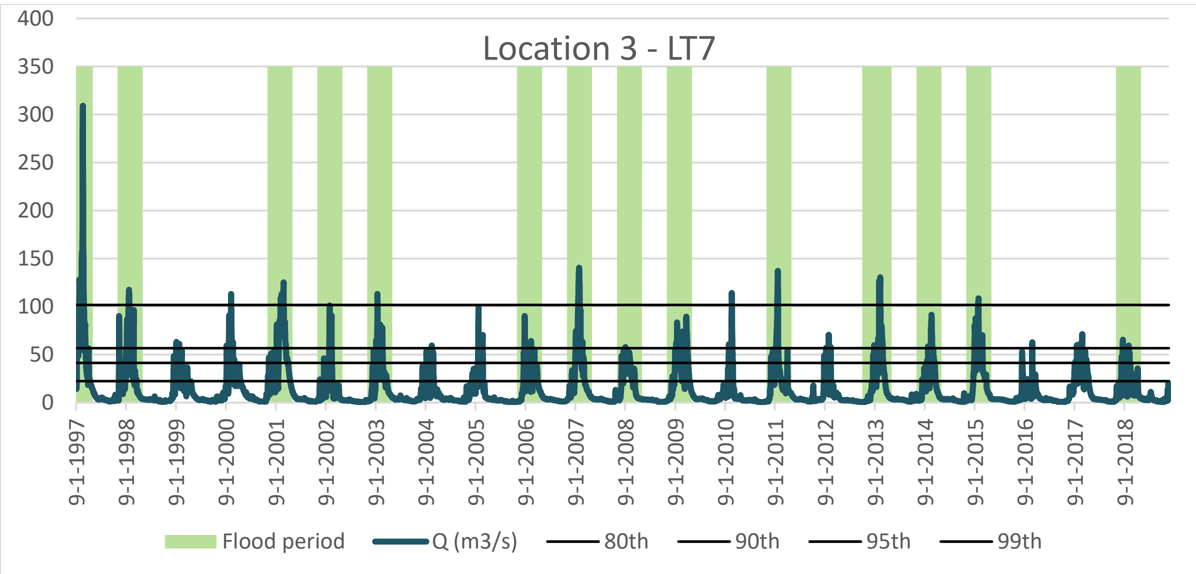

Location 3
120
100
80
60
40
20
0
Q (m3/s)
1-1-1997
1-1-1998
1-1-1999
1-1-2000
1-1-2001
1-1-2002
1-1-2003
1-1-2004
1-1-2005
1-1-2006
1-1-2007
1-1-2008
Date

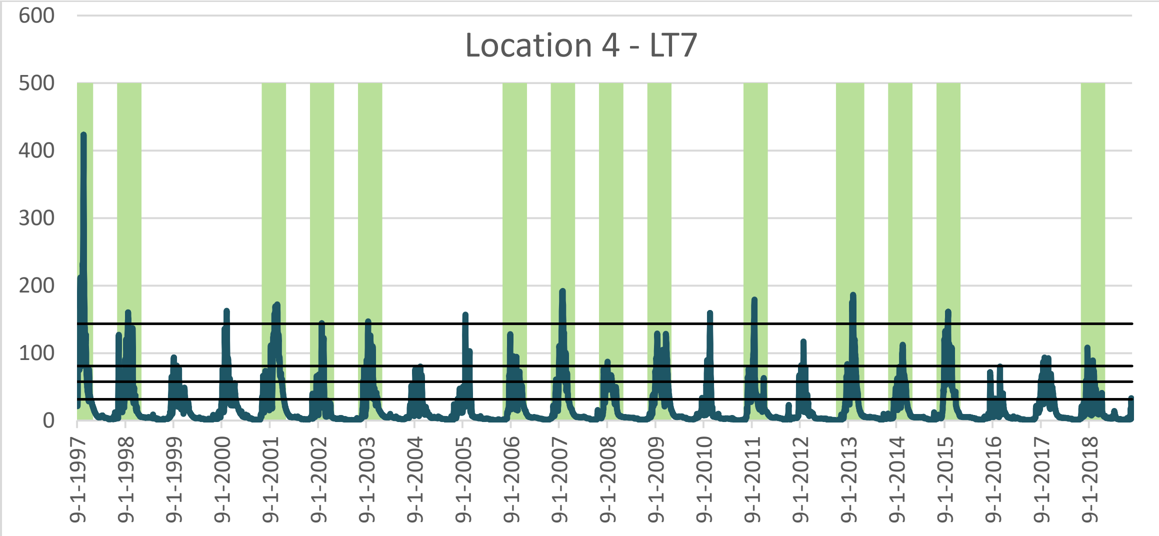

Location 4
250
200
150
100
50
0
Q (m3/s)
1-1-1997
1-1-1998
1-1-1999
1-1-2000
1-1-2001
1-1-2002
Date

Appendix G: Forecast skill GloFAS LT7 & LT15








Location 4 - LT7
600
500
400
300
200
100
0
9-1-1997
9-1-1998
9-1-1999
9-1-2000
9-1-2001
9-1-2002
9-1-2003
9-1-2004
9-1-2005
9-1-2006
9-1-2007
9-1-2008
9-1-2009
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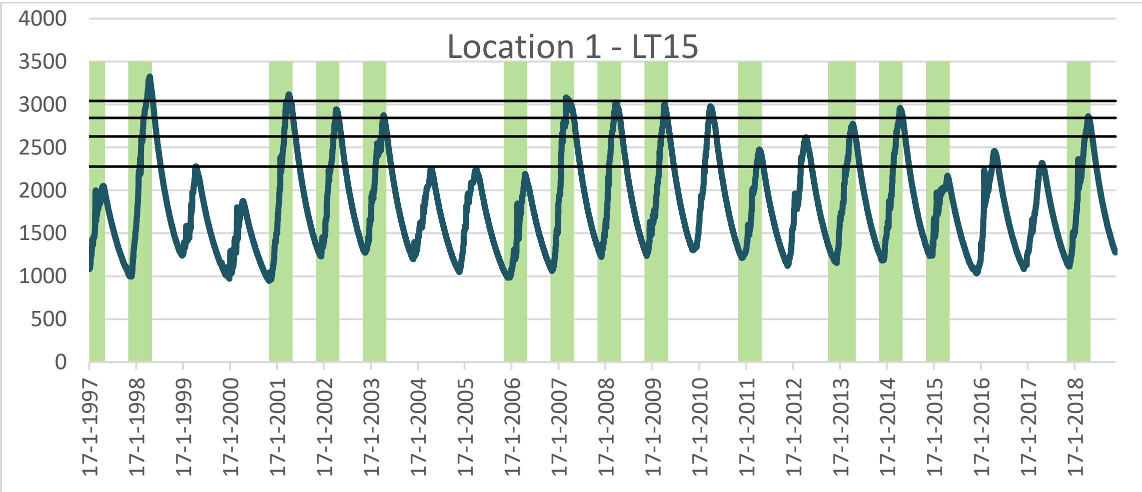
9-1-2016
9-1-2017
9-1-2018


Location 1 - LT15
4000
3500
3000
2500
2000
1500
1000
500
0
17-1-1997
17-1-1998
17-1-1999
17-1-2000
17-1-2001
17-1-2002
17-1-2003
17-1-2004
17-1-2005
17-1-2006
17-1-2007
17-1-2008
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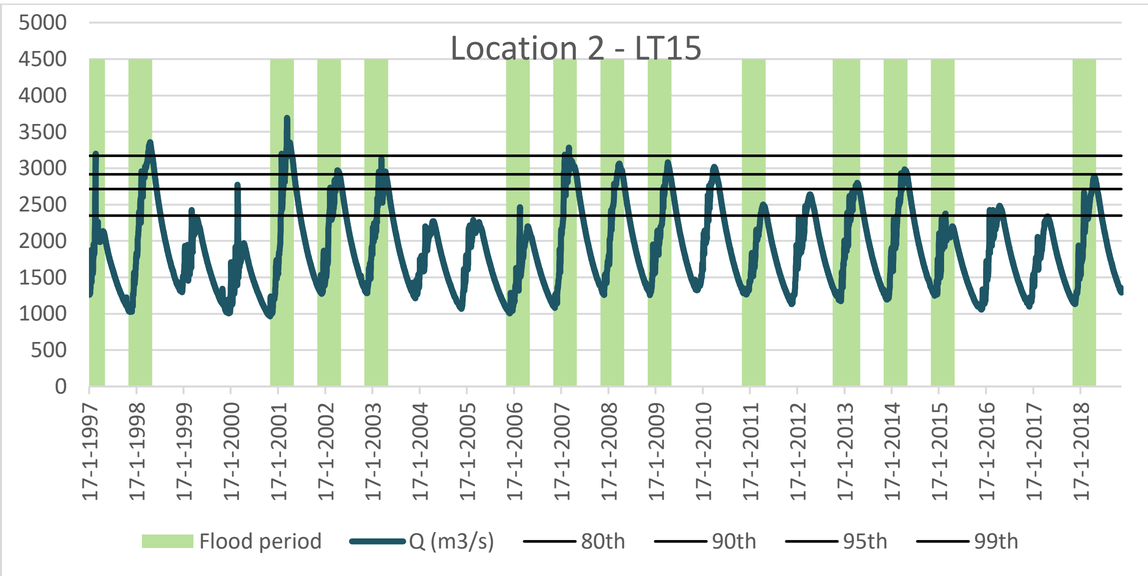
17-1-2017
17-1-2018


Location 2 - LT15
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
17-1-1997
17-1-1998
17-1-1999
17-1-2000
17-1-2001
17-1-2002
17-1-2003
17-1-2004
17-1-2005
17-1-2006
17-1-2007
17-1-2008
17-1-2009
17-1-2010
17-1-2011
17-1-2012
17-1-2013
17-1-2014
17-1-2015
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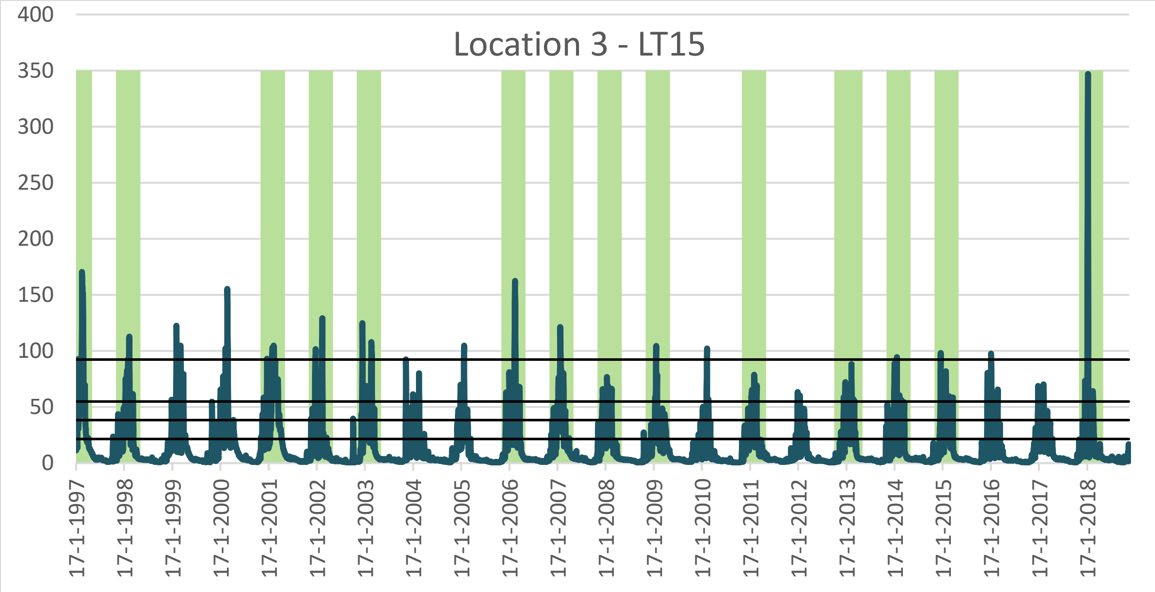
17-1-2018
Flood period
Q (m3/s)
80th
90th
95th
99th


Location 3 - LT15
400
350
300
250
200
150
100
50
0
17-1-1997
17-1-1998
17-1-1999
17-1-2000
17-1-2001
17-1-2002
17-1-2003
17-1-2004
17-1-2005
17-1-2006
17-1-2007
17-1-2008
17-1-2009
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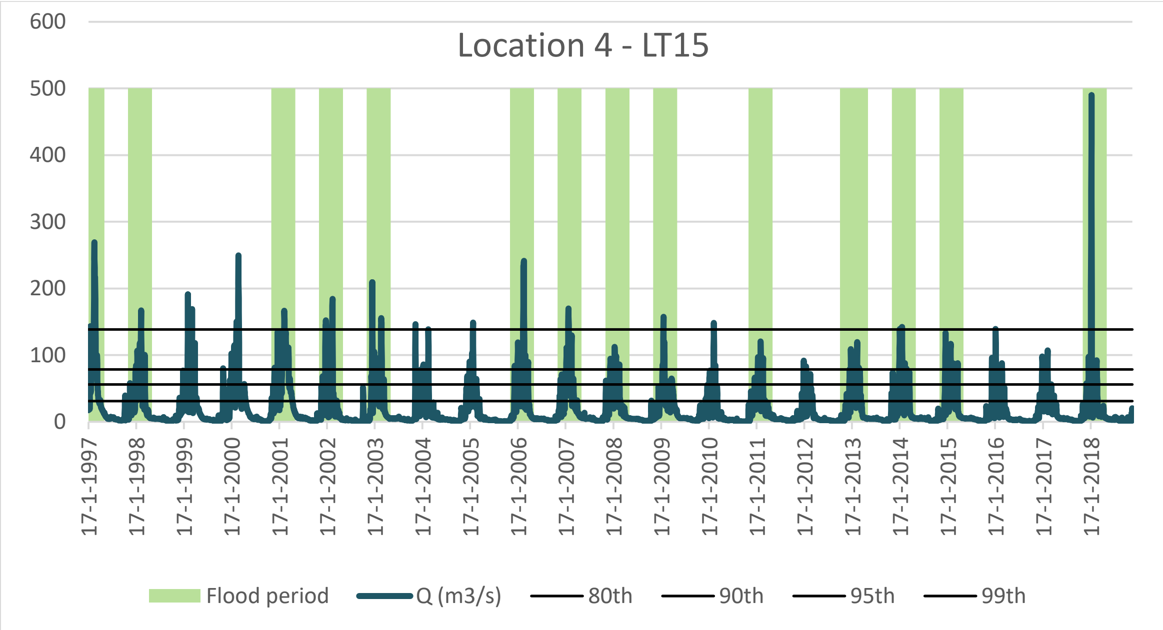
17-1-2017
17-1-2018


Location 4 - LT15
600
500
400
300
200
100
0
17-1-1997
17-1-1998
17-1-1999
17-1-2000
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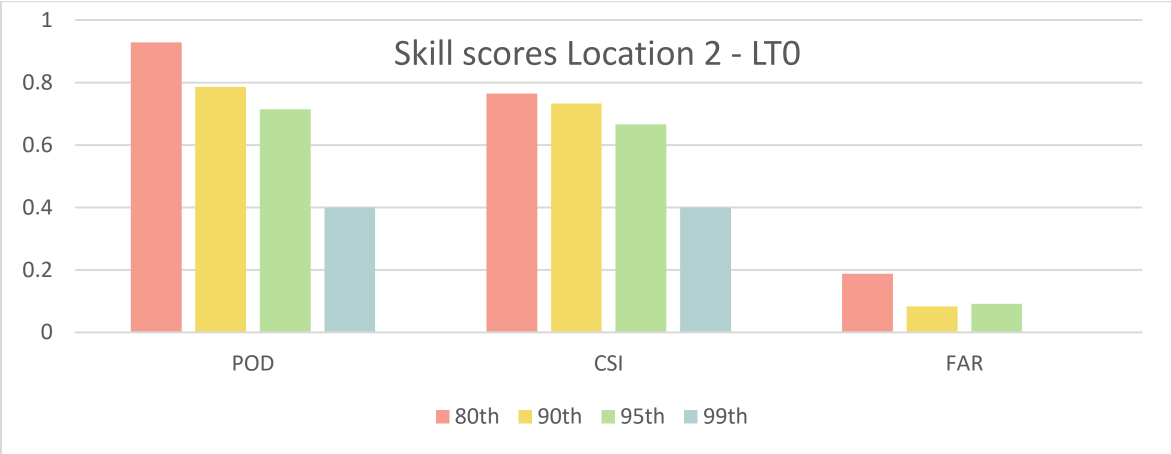
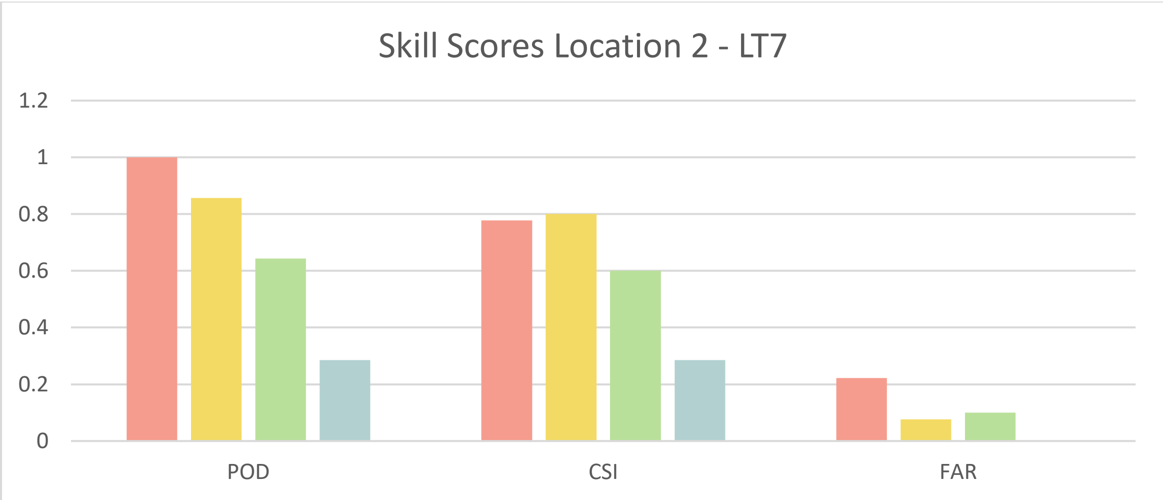
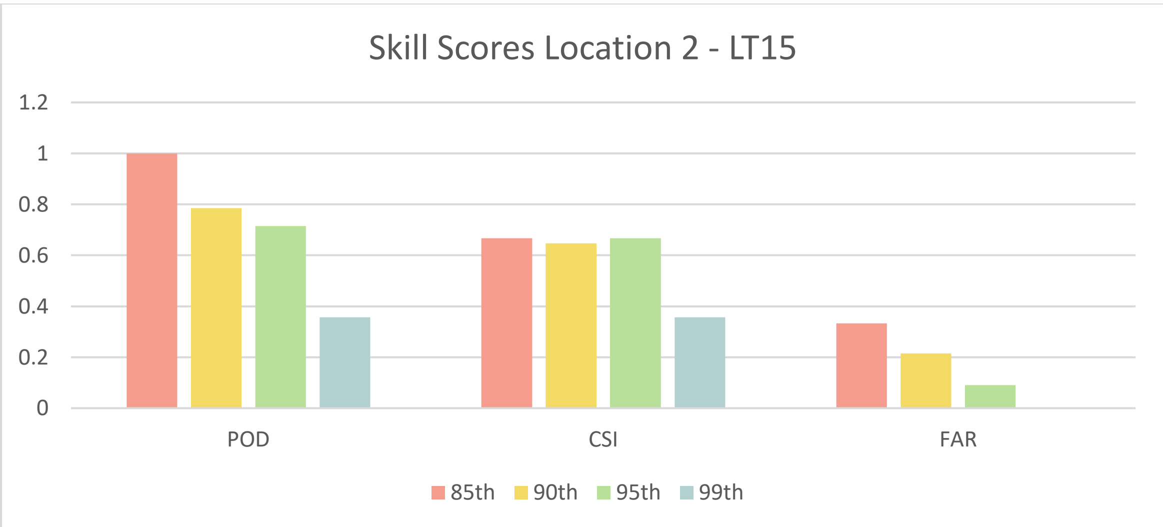
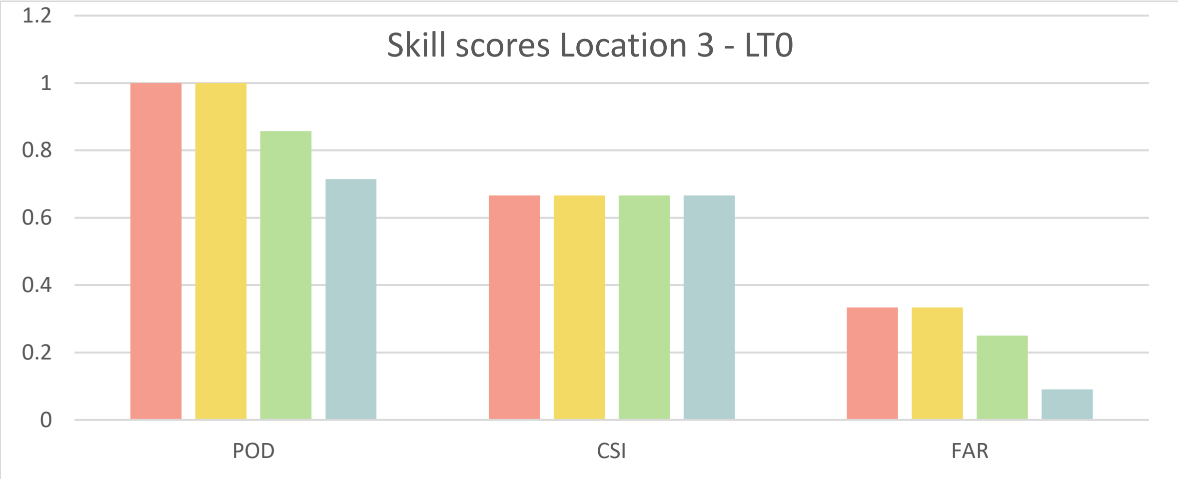
17-1-2002
17-1-2003
17-1-2004
17-1-2005
17-1-2006
17-1-2007
17-1-2008
17-1-2009
17-1-2010
17-1-2011
17-1-2012
17-1-2013
17-1-2014
17-1-2015
17-1-2016
17-1-2017
17-1-2018
Flood period
Q (m3/s)
80th
90th
95th
99th

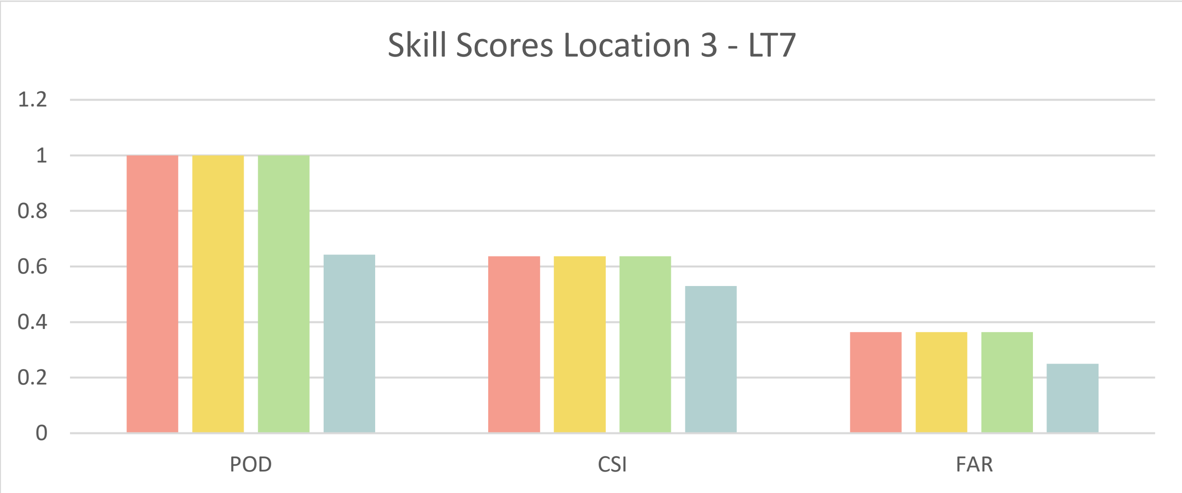
Appendix H: Skill scores detecting reported floods

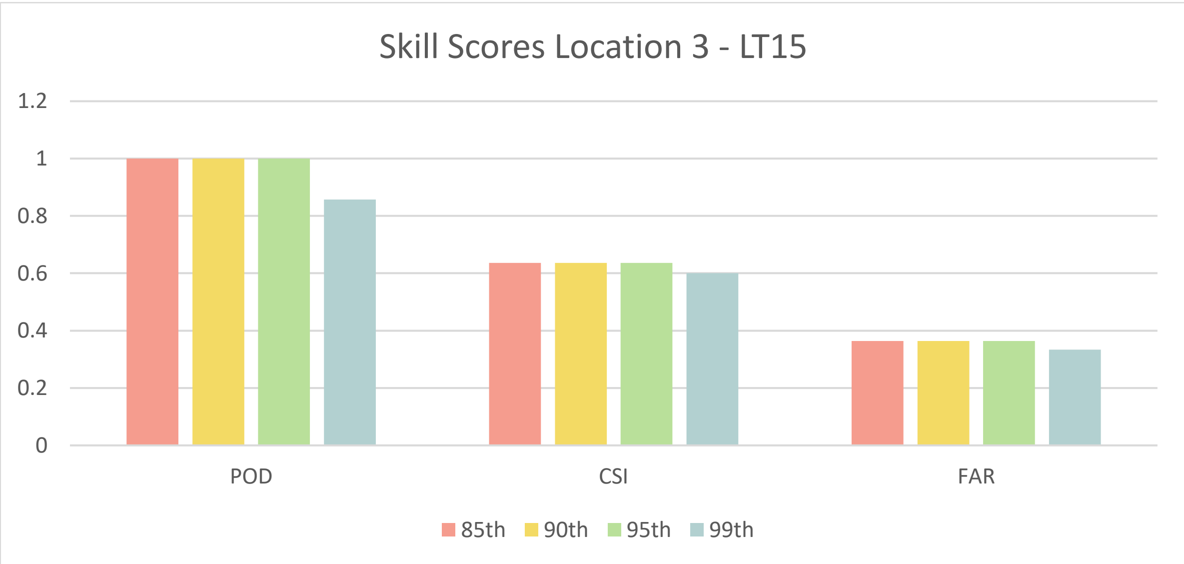


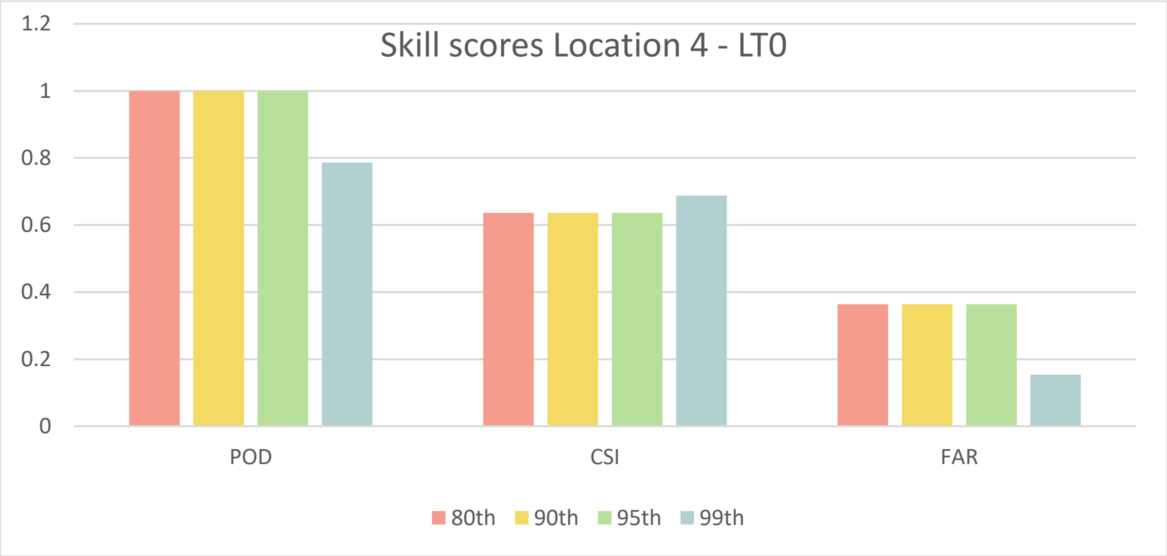


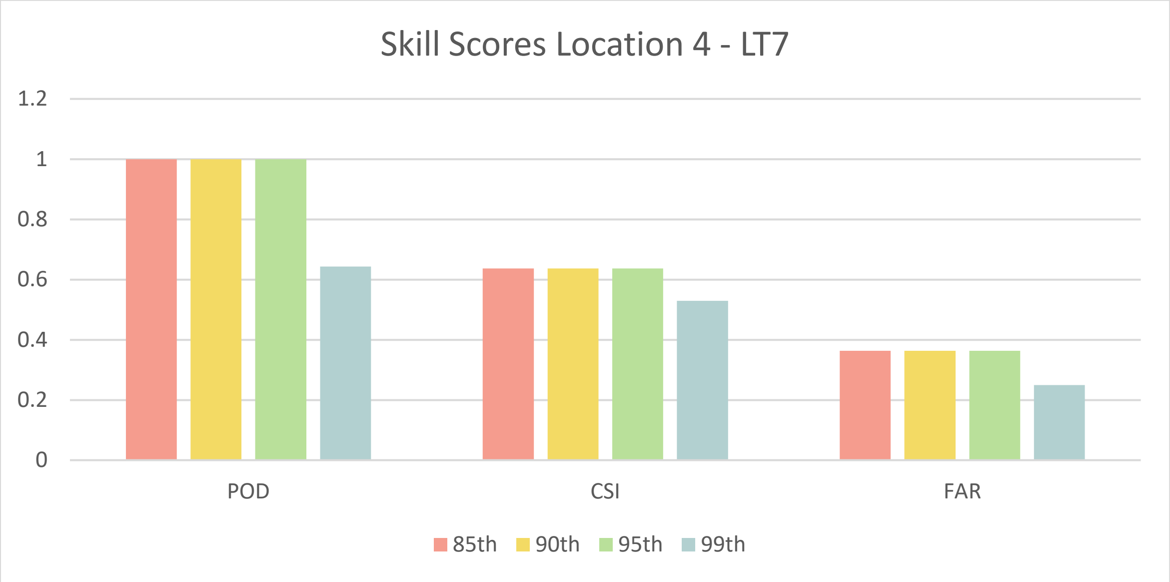


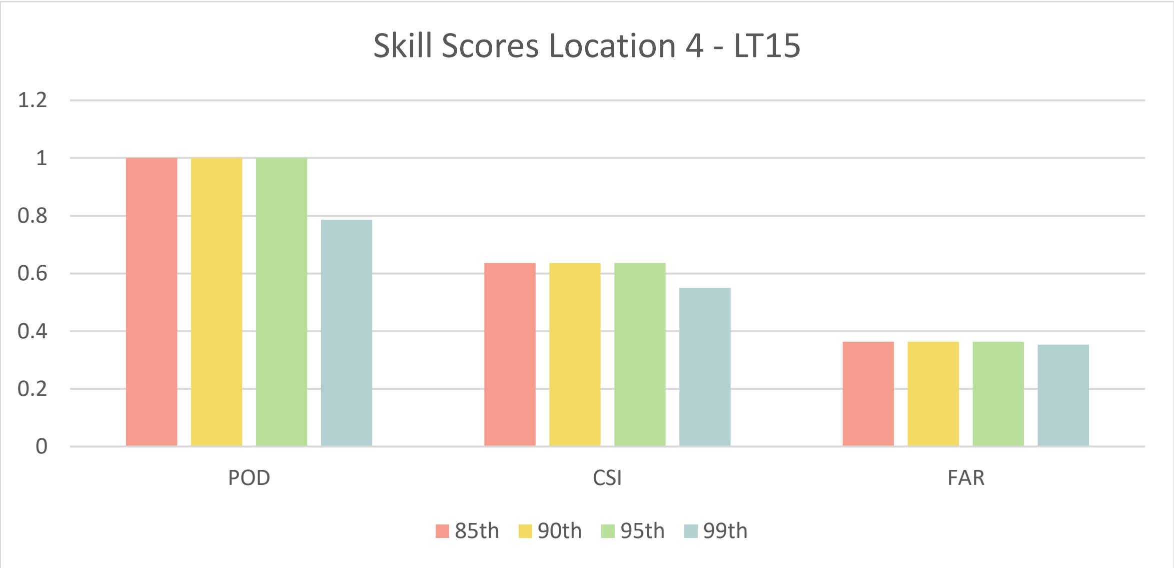

Skill scores Location 3 - LT0
1.2
1
0.8
0.6
0.4
0.2
0
POD
CSI
FAR


Skill Scores Location 3 - LT7
1.2
1
0.8
0.6
0.4
0.2
0
POD
CSI
FAR


Skill Scores Location 3 - LT15
1.2
1
0.8
0.6
0.4
0.2
0
POD
CSI
FAR
85th
90th
95th
99th


Skill scores Location 4 - LT0
1.2
1
0.8
0.6
0.4
0.2
0
POD
CSI
FAR
80th
90th
95th
99th


Skill Scores Location 4 - LT7
1.2
1
0.8
0.6
0.4
0.2
0
POD
CSI
FAR
85th
90th
95th
99th


Skill Scores Location 4 - LT15
1.2
1
0.8
0.6
0.4
0.2
0
POD
CSI
FAR
85th
90th
95th
99th

Appendix I: Format SSI at national level

Protocol for interviews on national level on the extreme climate/weather information flow

Organisations to interview: DCCMS, MRCS, MoAIWD, DODMA

Initiation

Let everybody introduce themselves: name, organisation, role. Thank the interviewer for their time. Ask for permission to record the interview.

We are doing this interview for our master thesis research at the Netherlands Red Cross. I'm a MSc Hydrology student at the VU University in Amsterdam (Thirza). My thesis research is on assessing the flood early warning system of Malawi, as part of the ECHO-II project of the Netherlands Red Cross in cooperation with the Malawi Red Cross Society.

My name is Ileen and I am a MSc Water management at the TU Delft in the Netherlands. My research is on drought early warning systems targeted on agricultural practises and decisions, linked to the NERC SHEAR IPACE project of the University of Leeds in cooperation of the Netherlands and Malawi Red Cross. I am currently based at Malawi Red Cross as an intern, also doing other activities concerning Early Warning Systems in the ECHO-III project.

Brief introduce research and purpose of this interview

We are aiming to find out how the weather forecast information flows; from the forecast that has been given by DCCMS or another source eventually to the communities. We are focusing especially on the years when drought or flood event occurred.

Interview Questions

The interview should be recorded and fully transcribed into English.

- What is your role in the organisation? Could you briefly describe your responsibilities?
- Are you involved in any projects/programmes linked to early warning systems?
- What type of climate/weather information are you working with (E.g. droughts, flash floods, riverine floods etc.)
- Do you receive or provide climate information / warnings? Or both?

It might be that they are both a receiver of information and a provider of information. Then ask both columns

<u>Receiving</u> extreme weather/climate information	<u>Providing</u> extreme weather/climate information
From where do you receive this information (please describe the whole chain from whoever produces the information down to getting to you)?	To who do you provide that information (please describe the whole chain from who you deliver next and thereafter)?
What type of information do you receive? (e.g. forecasts for the next 5 days, seasonal forecast, spatial scale etc)	What type of information do you provide? (e.g. forecasts for the next 5 days, seasonal forecast, spatial scale etc)

	Do you produce this information? If so, how do you produce the information?
	Do you tailor the information before distributing it to other stakeholders? If so, what do you add or change?
How do you receive this information? E.g. text message, radio, email etc	How do you send out/communicate this information? E.g. text message, radio, email etc
Who else is involved when you receive information? (in the WhatsApp group, meeting, workshop etc)	Who else is involved when you provide information? (in the WhatsApp group, meeting, workshop etc)
In what format do you receive that information? (e.g. a text/graphs/charts describing the weather/climate conditions for that period)?	In what format do you provide that information? (e.g. a text/graphs/charts describing the weather/climate conditions for that period)?
How frequently / when do you receive this information? (How many days/weeks/months before the extreme event do you receive this information?)	How frequently / when do you provide this information? (How many days/months before the extreme event do you provide this information?)
In your opinion, how could this process of receiving weather/climate information be improved?	In your opinion, how could this process of delivering weather/climate information be improved?
Communities have also developed a lot of local knowledge over the years on forecasting floods and droughts. They are able to see signs in the environment that indicate an upcoming extreme event.	
Do you receive this type of information from local communities? If so, do you combine this information with "official forecast information" and how? If not, do you think it is useful and possible to combine this information?	
Do you know if any other efforts are taken to involve the local knowledge of communities in early warning systems for extreme weather events? If so, how?	

Appendix J: Format FGD for VCPCs & ACPCs

Protocol for Focus Group Discussions with Village Civil Protection Committees (VCPCs) and Area Civil Protection Committees (ACPCs)

Initiation

Let everybody introduce themselves: gender, age, occupation in daily life, role in VCPC/ACPC, time they have been active in VCPC/ACPC. Thank the participators for their time. Ask for permission to record the interview.

Brief introduce research and purpose of this interview

We are doing these interviews for my thesis research at the Netherlands Red Cross. I'm a MSc Hydrology student at the VU University in Amsterdam. My thesis research is on assessing the flood early warning system of Malawi, as part of the ECHO-II project of the Netherlands Red Cross in cooperation with the Malawi Red Cross Society.

This aim of this discussion is to provide knowledge on what flood forecast information you as a community receive, produce, use, disseminate and document. There are no wrong or right answers and all your answers will be treated confidential.

Interview Questions

General questions about the VCPC/ACPC (can be answered by one person)

- How long ago was this VCPC/ACPC established?
- Would you describe this VCPC/ACPC as an active VCPC/ACPC?
- Did an organization (like the Red Cross) started this VCPC/ACPC and is it still supporting the VCPC/ACPC in any way?
- Do you experience a lot of floods in this area?

The following questions can be answered by everyone in the group. When answering the questions, please keep the situation of the floods of this year (2019) in mind.

1. Do you receive the official flood forecast information & do you disseminate it again? (forecast that is received from the government) If yes:

a. How do you receive the information?
b. How frequent and how long before a flood do you receive the information?
d. In what form do you receive the information (what is the content) and is this useful and understandable?
e. How much you trust this forecast information and do you act on it?
g. Was there any time that a forecast was that was smaller in the end?
Do you remember any false alarm cases (what kind of false alarm ratio)? If yes, did they affect your choices in the subsequent forecasts? If no, would you evacuate the next time you get a forecast
h. Do you warn others if you receive the forecast information? If yes, who do you disseminate the warning to?
i. Do you think that everyone in the community receives the warning?

2a. <u>VCPC</u>: Do you make use of flood forecasts based on local knowledge from your community? (local knowledge indicators can be for example: looking at weather patterns or at different behaviour of animals or plants to predict floods) **If not: Why not? If yes:**

a. Do you produce your own forecast information?
b. Do you receive forecasts based on local knowledge indicators, if yes how?
c. How long before a flood event do you receive this information?
d. How much you trust this forecast information and do you act on it?
e. What is the main indicator you use to predict a flood?

f. Do you discuss this information during (VCPC) meetings? If yes, how do you discuss this?
g. Do you share this information again with other community members? If yes, how and when do you share it?
h. Did you used local knowledge for forecasting the last flood? If yes, how long before the flood were you able to predict it?

2b. <u>ACPC</u>: Do you make use of forecasts based on local knowledge from communities? (local knowledge indicators can be for example: looking at weather patterns or at different behaviour of animals or plants to predict floods) **If not: Why not? If yes:**

a. From who do you receive this local knowledge and how do you receive it?
b. Which indicators do you trust and use?
c. How long before a flood event do you receive this information?
d. Do you discuss this information during (ACPC) meetings?
e. Do you share this local based information again with other communities?

3 Do you combine different sources of the forecast, like the official forecast and locally produced forecasts? If not: Why not? If yes:

a. Which sources do you combine?
b. Which source is received first?
c. Which source do you trust the most?
d. How do you combine multiple sources?
e. Do you notice a difference in the use of forecast sources between community members of different ages?
f. Did you combine different forecast sources before and during the last flood? If yes, how?

4 How are the ACPCs/VCPCs structured?

a. Who are the members of the VCPCs/ACPCs?
b. How and by whom are they chosen?
c. How often do you meet and what topics do you discuss?
d. Do you communicate with your community, other VCPCs/ACPCs and other higher-level organizations (governmental levels for example)? If yes, what information do you communicate with them?
e. What is documented from the meetings, is any local flood forecast information documented?
f. Is anything digitized?
g. Was any information about the last flood documented or digitized?

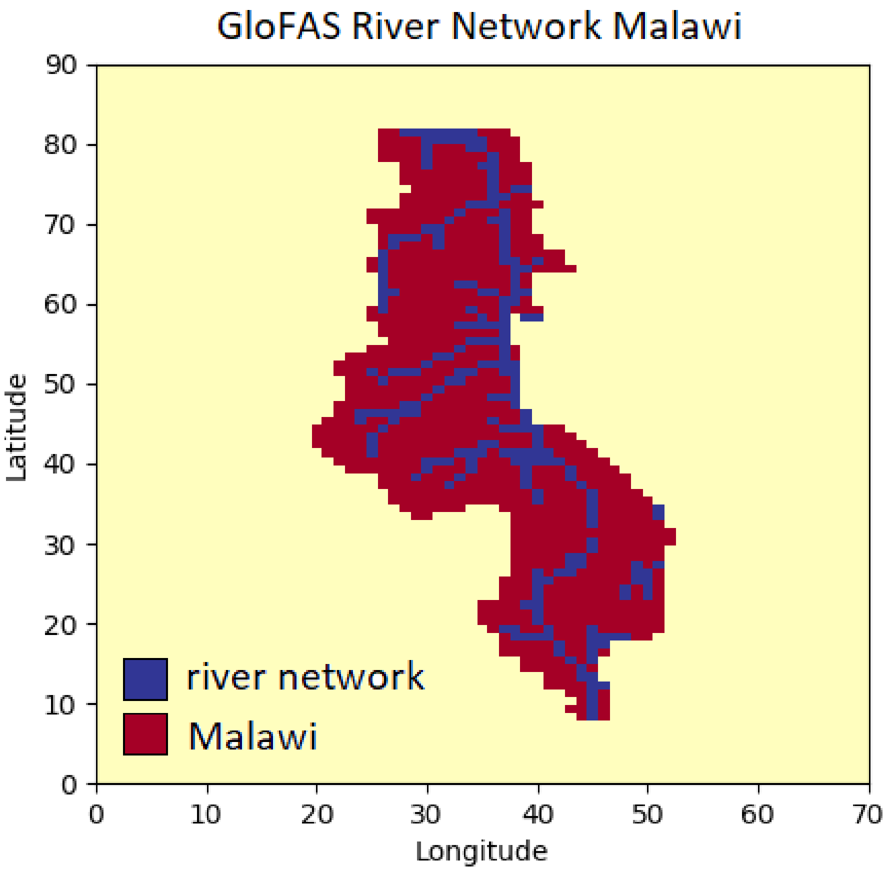
5 Do you think flood forecasts produced by local communities should be integrated into the official forecasts? If not: Why not? If yes: How should this be integrated?

6 Do you have any further comments to improve the overall flood early warning system?

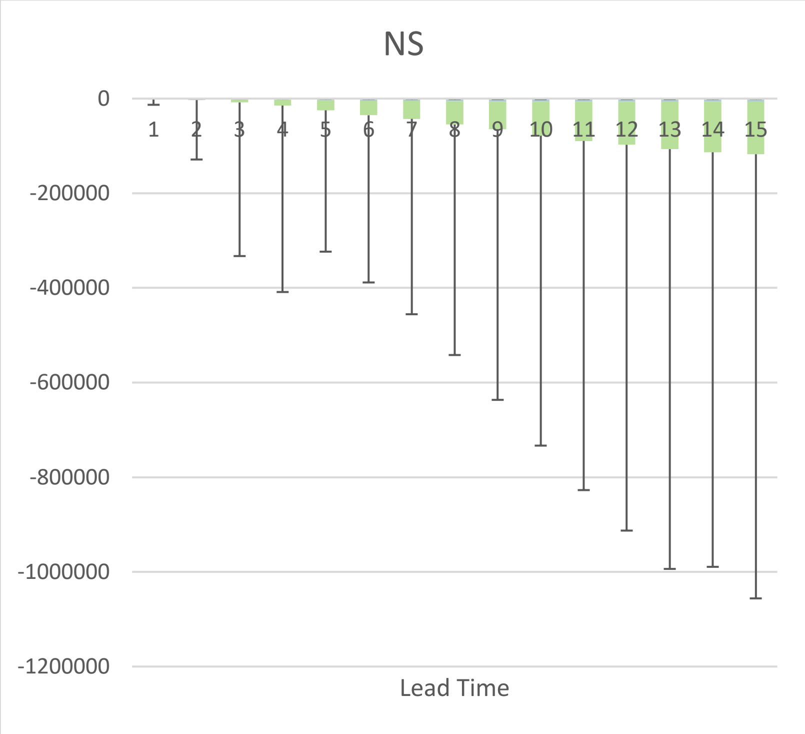
7 Measures against floods

a. How afraid are you of floods?
b. Which measures do you take against floods?
c. Would you take any different actions (compared to the actions you took), if you knew a flood like the flood of this year was coming? If yes, what other actions would you take?
d. If you could advice the government, what measures you would you implement to take action against floods?
e. Question only for **ACPCs**: What are the impacts of floods?

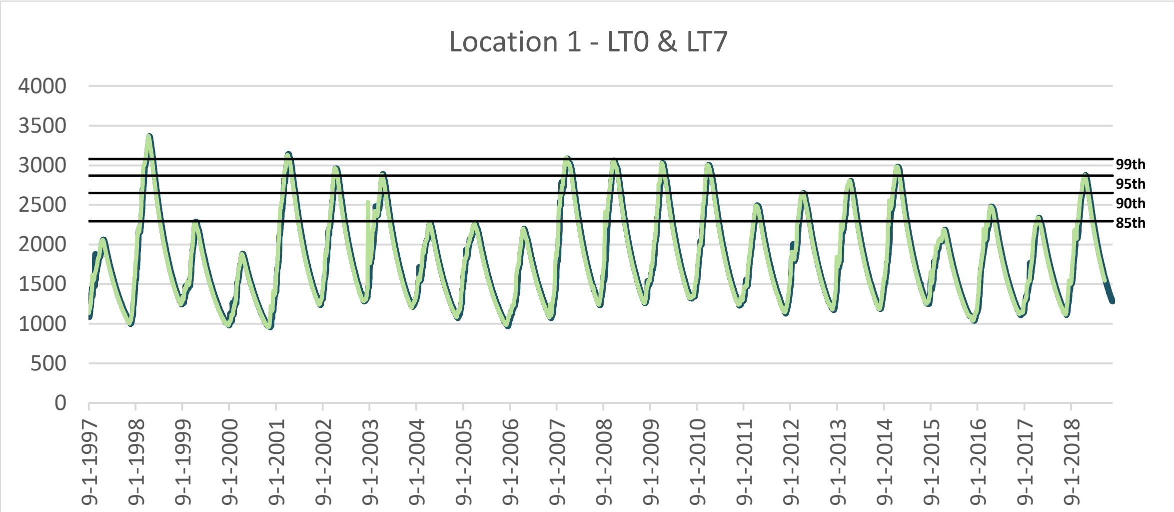
Appendix K: River network modelled by GloFAS

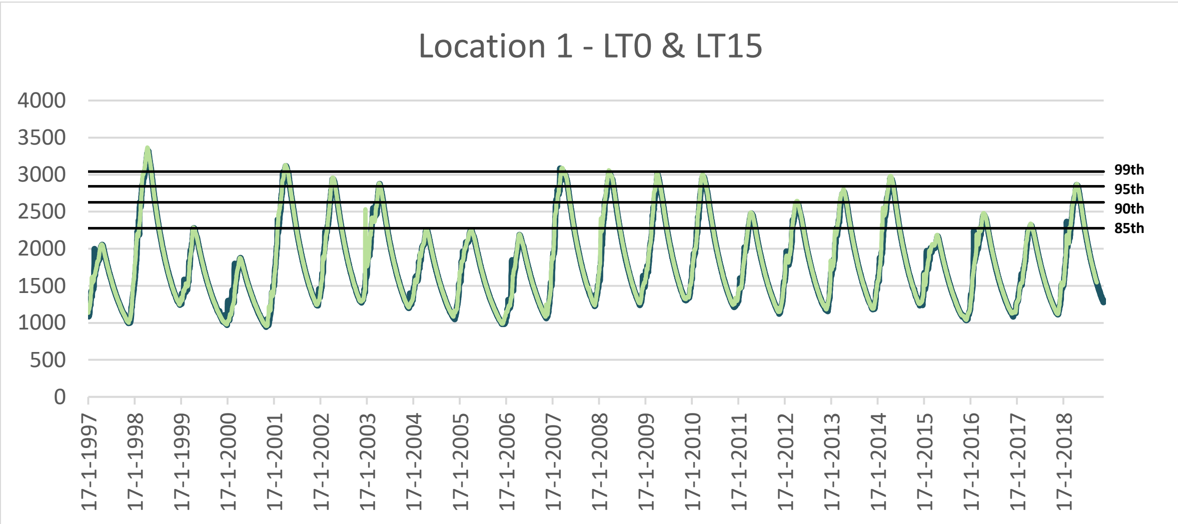


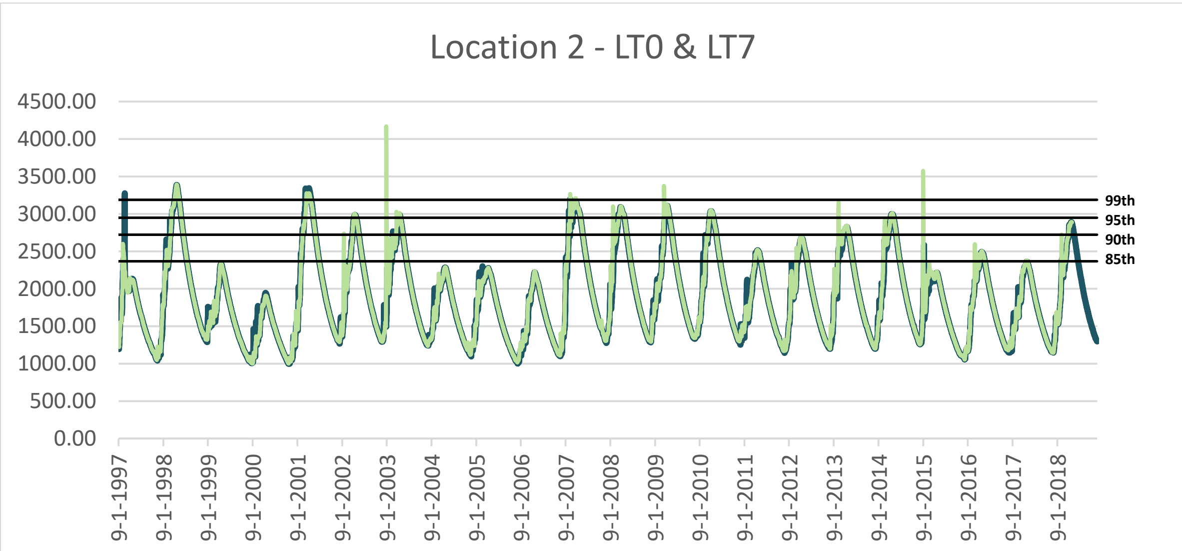
Appendix L: NS skill for different LTs

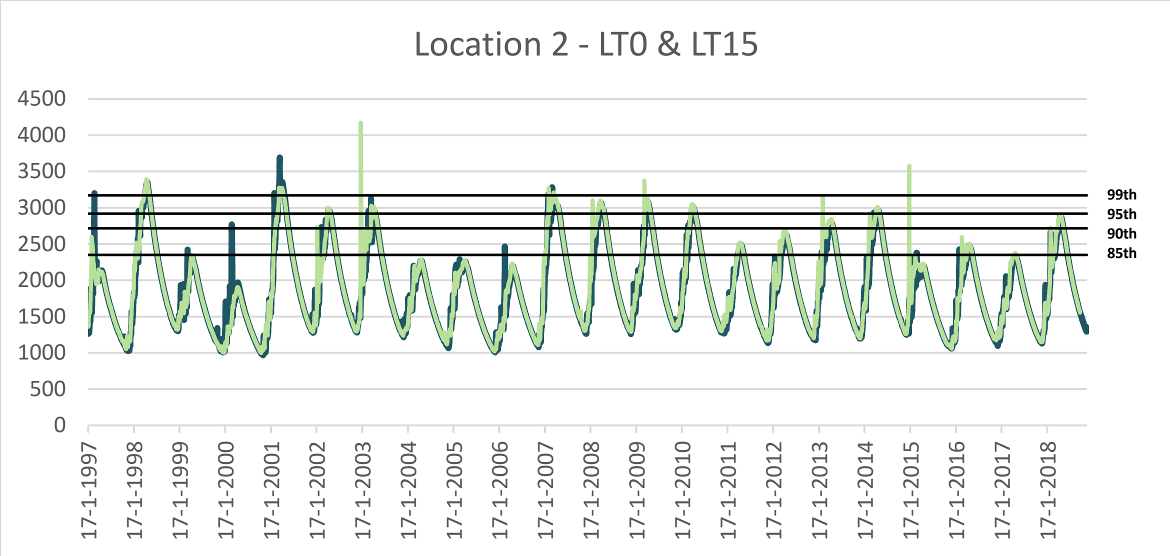


Appendix M: Hydrographs modelled & forecasted (LT7 & LT15) discharge against thresholds.








Location 2 - LT0 & LT15
4500
4000
3500
3000
2500
2000
1500
1000
500
0
99th
95th
90th
85th
17-1-1997
17-1-1998
17-1-1999
17-1-2000
17-1-2001
17-1-2002
17-1-2003
17-1-2004
17-1-2005
17-1-2006
17-1-2007
17-1-2008
17-1-2009
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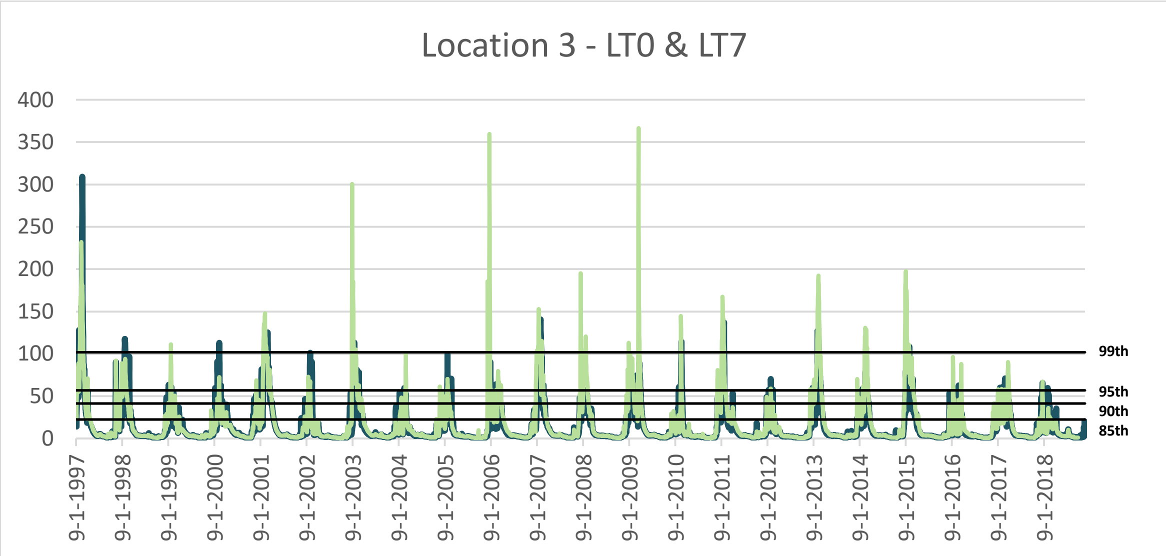
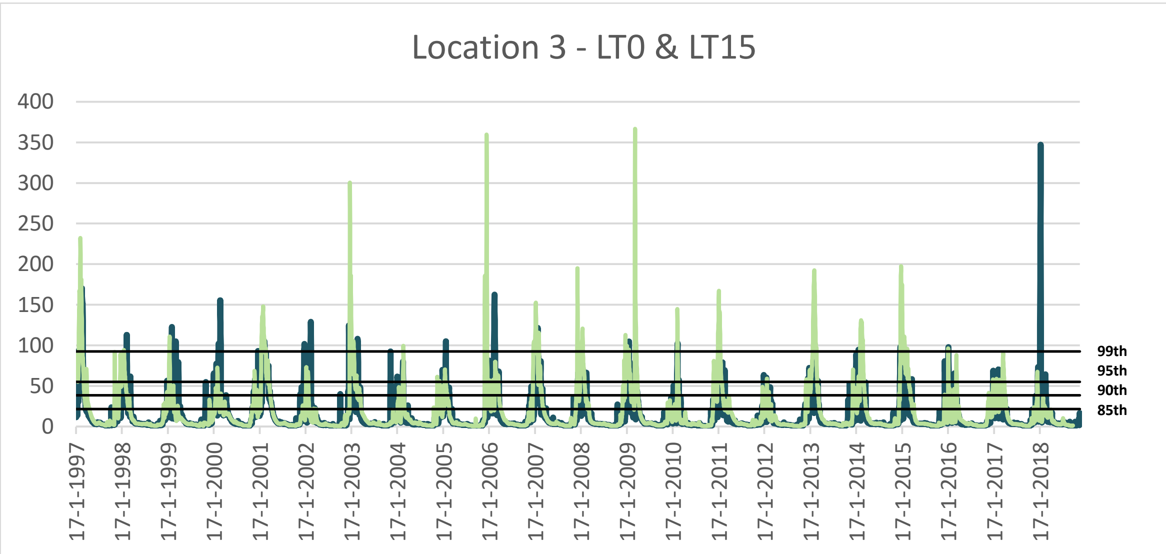
17-1-2014
17-1-2015
17-1-2016
17-1-2017
17-1-2018


Location 3 - LT0 & LT7
400
350
300
250
200
150
100
50
0
99th
95th
90th
85th
9-1-1997
9-1-1998
9-1-1999
9-1-2000
9-1-2001
9-1-2002
9-1-2003
9-1-2004
9-1-2005
9-1-2006
9-1-2007
9-1-2008
9-1-2009
9-1-2010
9-1-2011
9-1-2012
9-1-2013
9-1-2014
9-1-2015
9-1-2016
9-1-2017
9-1-2018


Location 3 - LT0 & LT15
400
350
300
250
200
150
100
50
0
99th
95th
90th
85th
17-1-1997
17-1-1998
17-1-1999
17-1-2000
17-1-2001
17-1-2002
17-1-2003
17-1-2004
17-1-2005
17-1-2006
17-1-2007
17-1-2008
17-1-2009
17-1-2010
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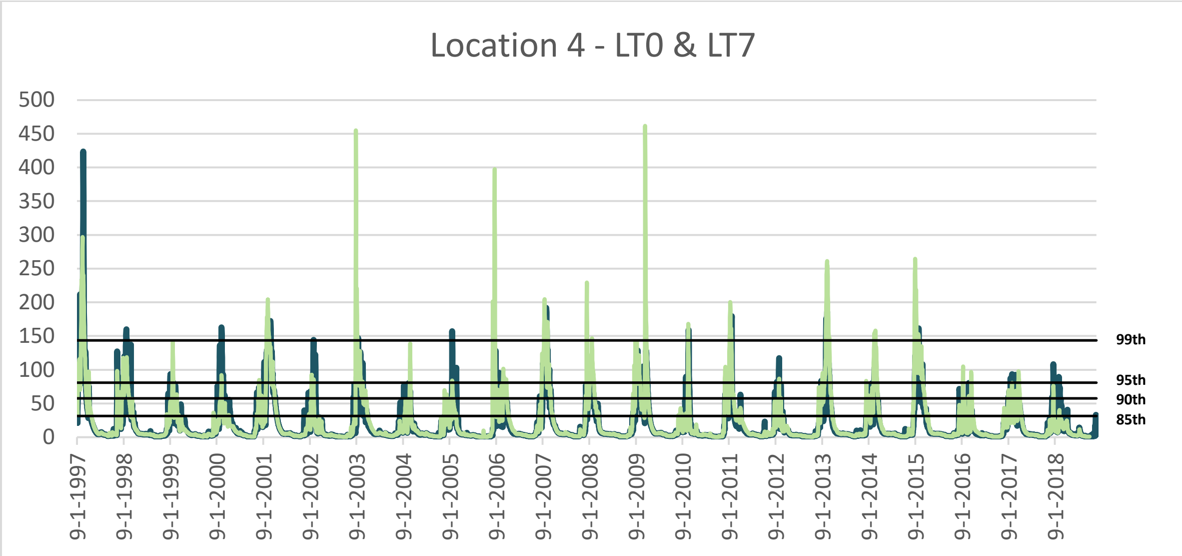
17-1-2014
17-1-2015
17-1-2016
17-1-2017
17-1-2018


Location 4 - LT0 & LT7
500
450
400
350
300
250
200
150
100
50
0
99th
95th
90th
85th
9-1-1997
9-1-1998
9-1-1999
9-1-2000
9-1-2001
9-1-2002
9-1-2003
9-1-2004
9-1-2005
9-1-2006
9-1-2007
9-1-2008
9-1-2009
9-1-2010
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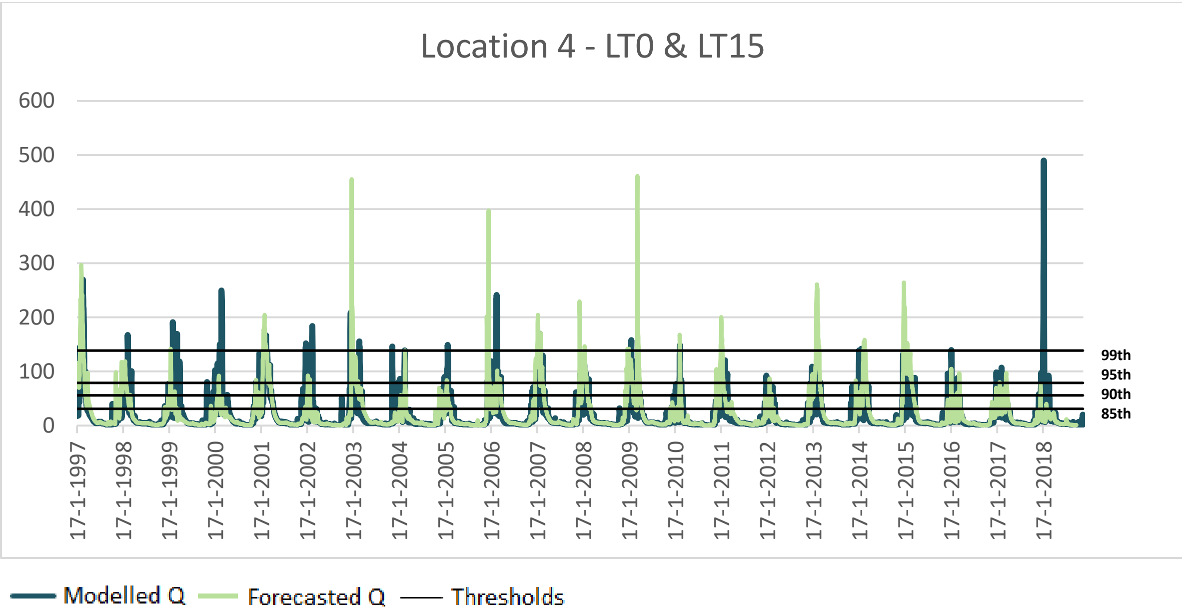
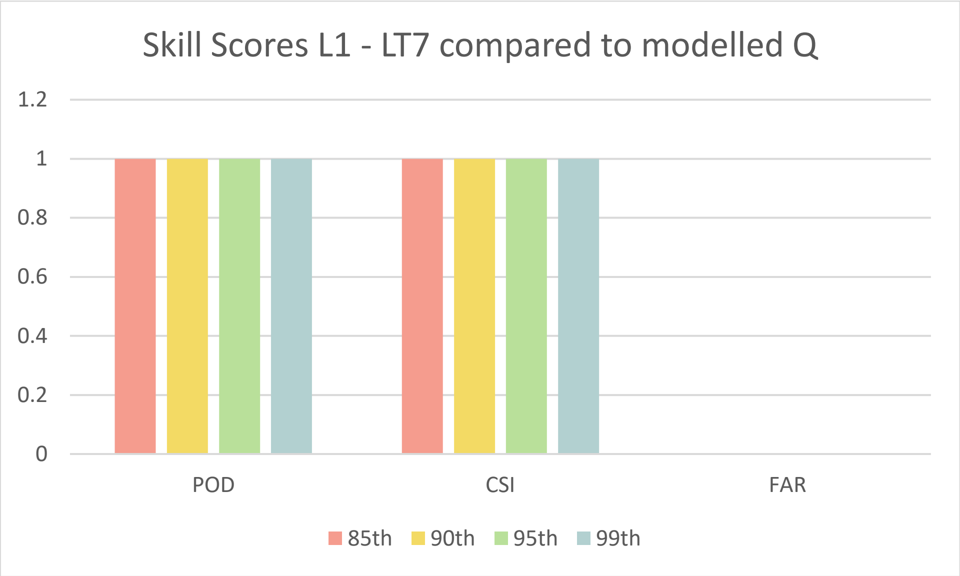
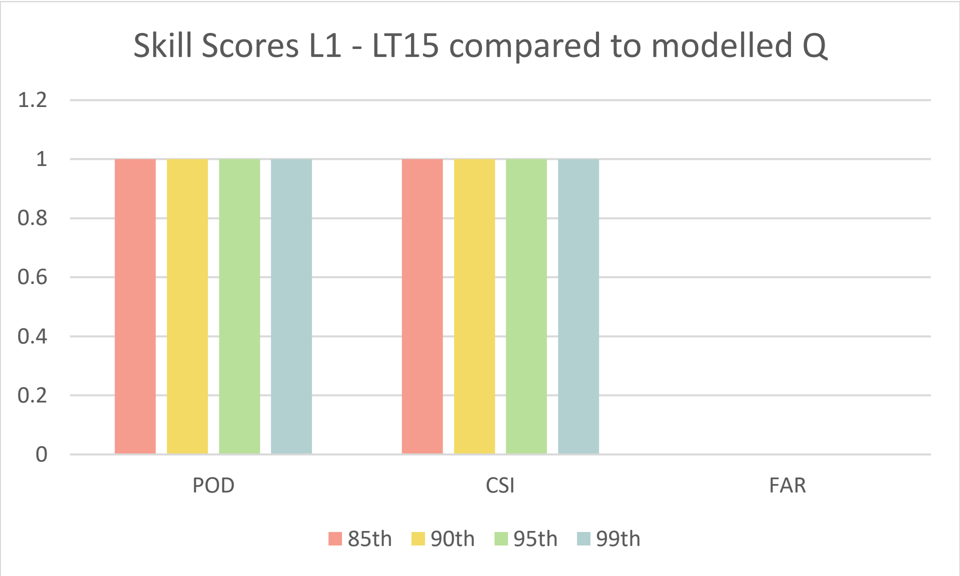
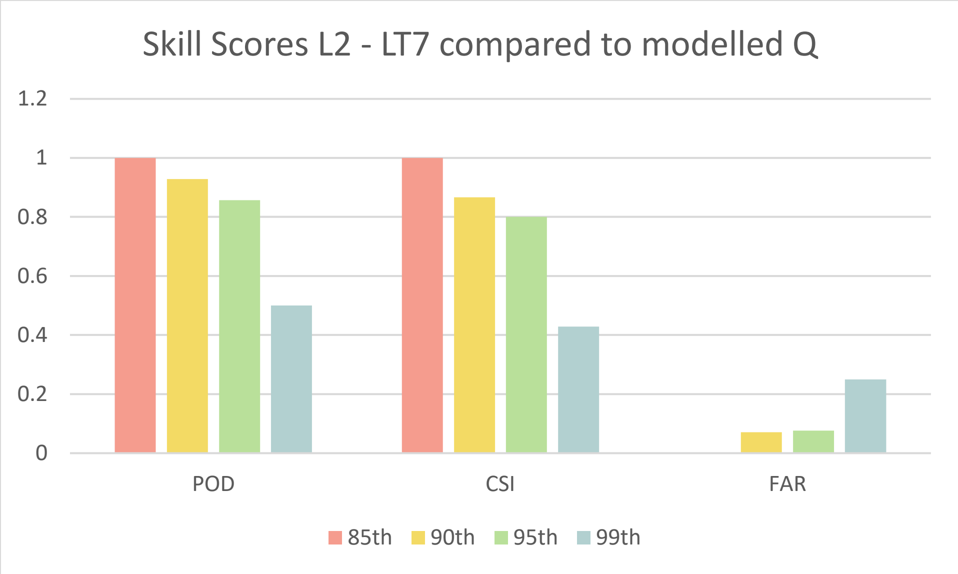
9-1-2014
9-1-2015
9-1-2016
9-1-2017
9-1-2018


Location 4 - LT0 & LT15
600
500
400
300
200
100
0
99th
95th
90th
85th
17-1-1997
17-1-1998
17-1-1999
17-1-2000
17-1-2001
17-1-2002
17-1-2003
17-1-2004
17-1-2005
17-1-2006
17-1-2007
17-1-2008
17-1-2009
17-1-2010
17-1-2011
17-1-2012
17-1-2013
17-1-2014
17-1-2015
17-1-2016
17-1-2017
17-1-2018
Modelled Q
Forecasted Q
Thresholds

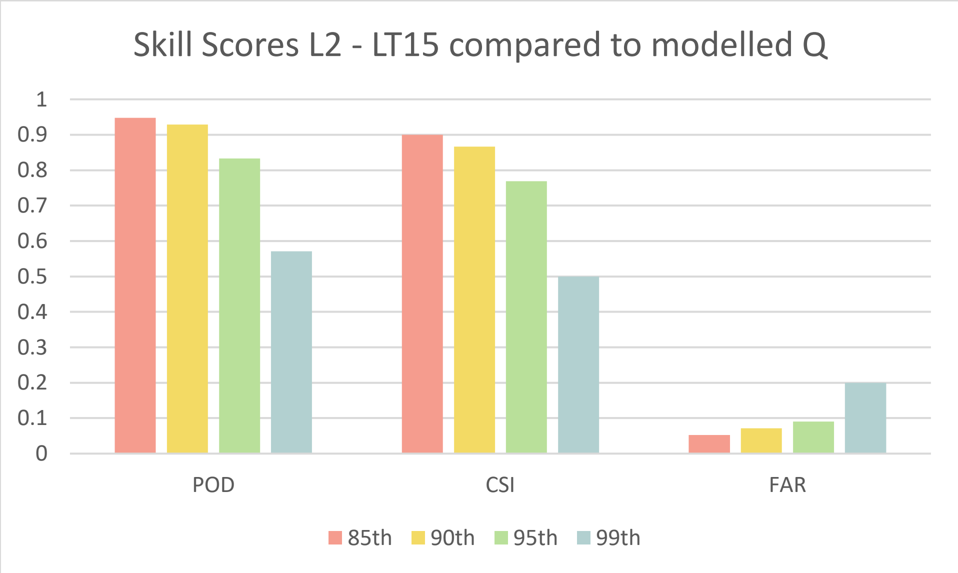
Appendix N: Skill scores detecting floods forecasted discharge vs modelled discharge



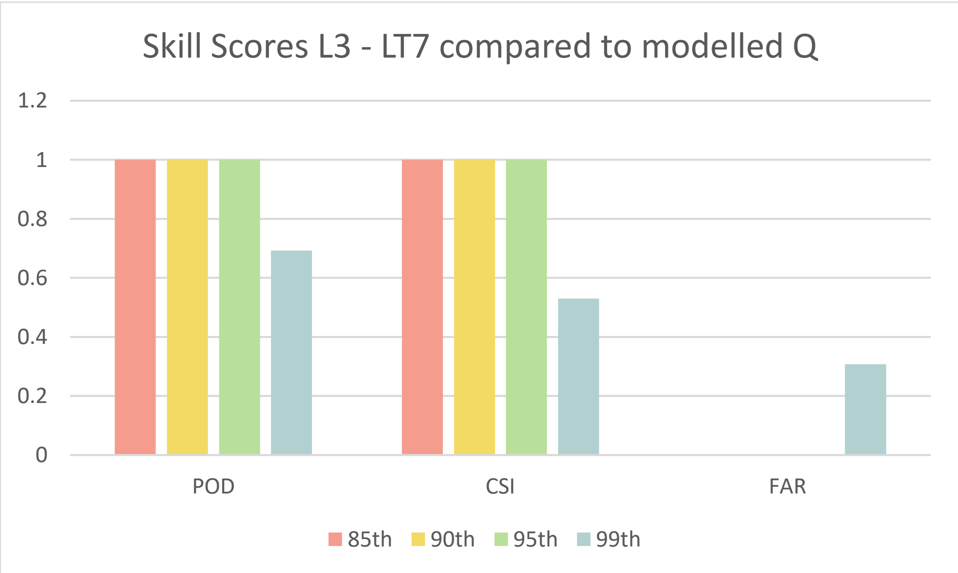




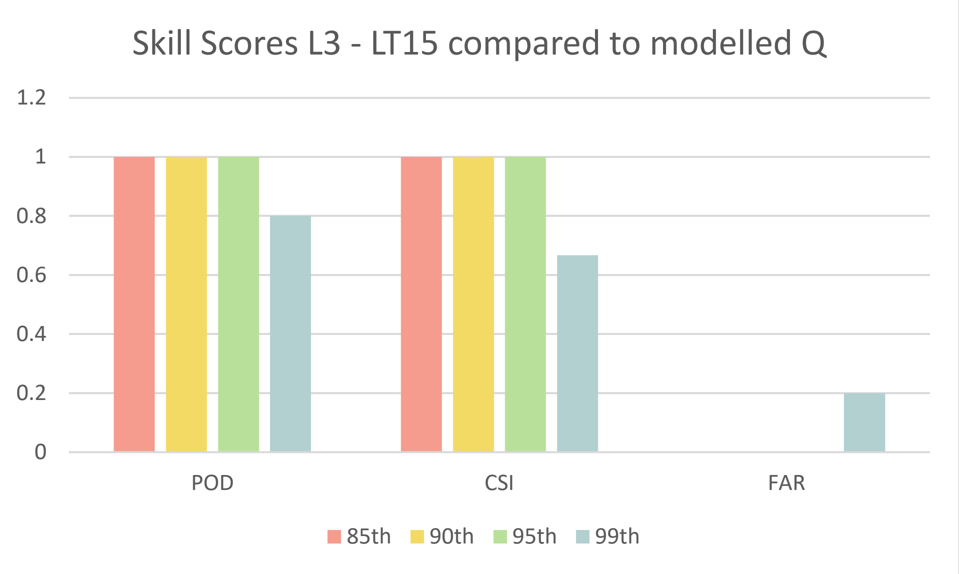
Skill Scores L2 - LT7 compared to modelled Q
1.2
1
0.8
0.6
0.4
0.2
0
POD
CSI
FAR
85th
90th
95th
99th

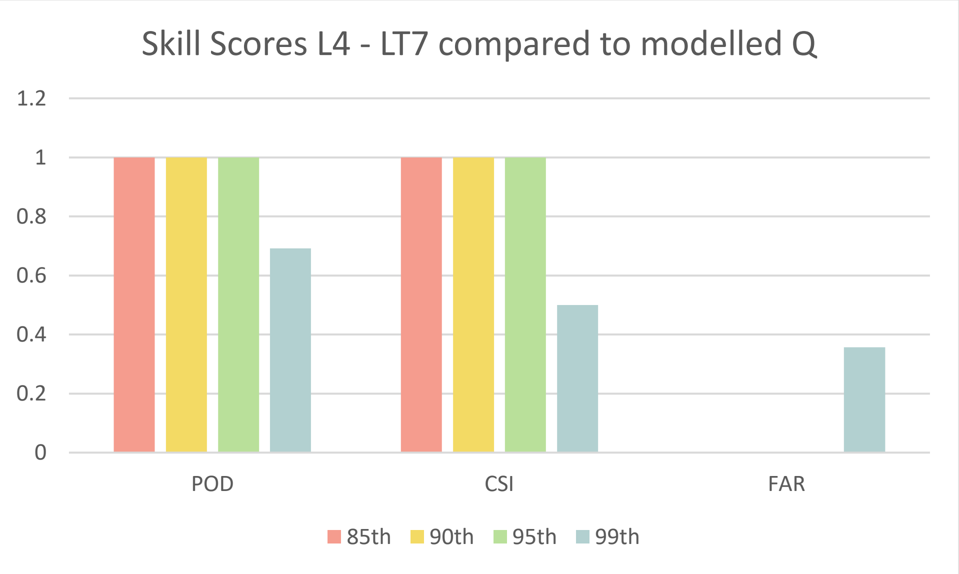


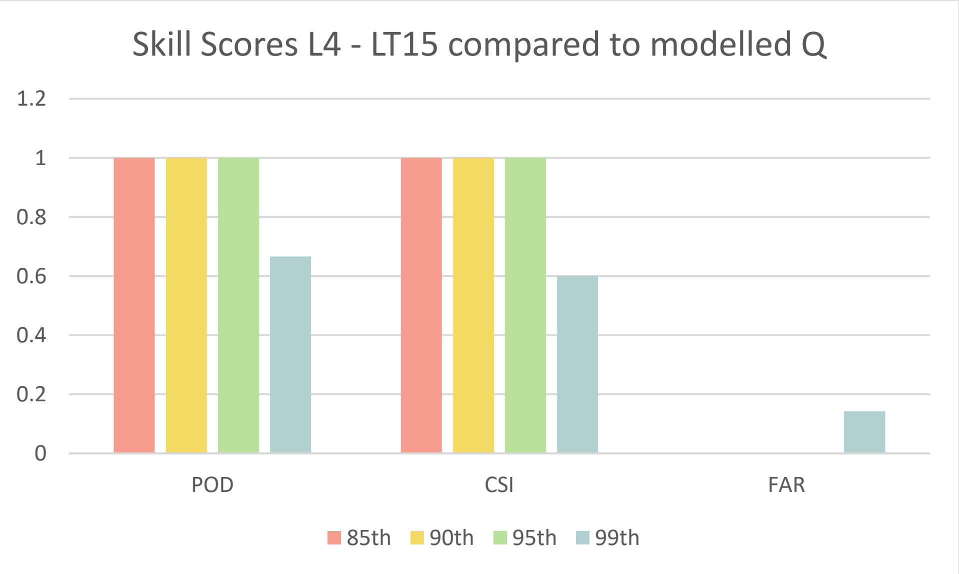
Skill Scores L2 - LT15 compared to modelled Q
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
POD
CSI
FAR
85th
90th
95th
99th



Skill Scores L3 - LT7 compared to modelled Q
1.2
1
0.8
0.6
0.4
0.2
0
POD
CSI
FAR
85th
90th
95th
99th


Skill Scores L3 - LT15 compared to modelled Q
1.2
1
0.8
0.6
0.4
0.2
0
POD
CSI
FAR
85th
90th
95th
99th


Skill Scores L4 - LT7 compared to modelled Q
1.2
1
0.8
0.6
0.4
0.2
0
POD
CSI
FAR
85th
90th
95th
99th


Skill Scores L4 - LT15 compared to modelled Q
1.2
1
0.8
0.6
0.4
0.2
0
POD
CSI
FAR
85th
90th
95th
99th