A probabilistic impact-focussed early warning system for flash floods in support of disaster management in South Africa

by

Eugene René Poolman

Submitted in partial fulfilment of the requirement for the degree of

Doctor of Philosophy (Meteorology)

In the Faculty of Natural & Agricultural Sciences

University of Pretoria

Pretoria

June 2014

A probabilistic impact-focussed early warning system for flash floods in support of disaster management in South Africa

Student:	**Eugene René Poolman**
Supervisor:	**Prof C. J. de W. Rautenbach**
Co-supervisor:	**Prof C. Vogel**
Department:	**Geography, Geoinformatics and Meteorology**
Degree:	**Doctor of Philosophy (Meteorology)**

ABSTRACT

The development of the Severe Weather Impact Forecasting System (SWIFS) for flash flood hazards in South Africa is described in this thesis. Impact forecasting addresses the need to move from forecasting weather conditions to forecasting the consequential impact of these conditions on people and their livelihoods. SWIFS aims to guide disaster managers to take early action to minimise the adverse effects of flash floods focussing on hotspots where the largest impact is expected. The first component of SWIFS produced an 18-hour probabilistic outlook of potential occurrence of flash floods. This required the development of an ensemble forecast system of rainfall for small river basins (the forecasting model component), based on the rainfall forecast of a deterministic numerical weather prediction model, to provide an 18-hour lead-time, taking into account forecast uncertainty. The second component of SWIFS covered the event specific societal and structural impacts of these potential flash floods, based on the interaction of the potential occurrence of flash floods with the generalised vulnerability to flash floods of the affected region (the impact model component). The impact model required an investigation into the concepts of regional vulnerability to flash floods, and the development of relevant descriptive and mathematical definitions in the context of impact forecasting. The definition developed in the study links impact forecasting to the likelihood and magnitude of adverse impacts to communities under threat, based on their vulnerability and due to an imminent severe weather hazard. Case studies provided evidence that the concept of SWIFS can produce useful information to disaster managers to identify areas most likely to be adversely affected in advance of a hazardous event and to decide on appropriate distribution of their resources between the various hotspots where the largest impacts would be. SWIFS contributes to the current international research on short-term impact forecasting by focussing on forecasting the impacts of flash floods in a developing country with its limited spatial vulnerability information. It provides user-oriented information in support of disaster manager decision-making through additional lead-time of the potential of flash floods, and the likely impact of the flooding. The study provides a firm basis for future enhancement of SWIFS to other severe weather hazards in South Africa.

ACKNOWLEDGEMENTS

I am deeply grateful to the Almighty God for providing me with the health and strength during difficult times to complete this study.

I wish to express my sincerest gratitude to Professor Hannes Rautenbach and Professor Coleen Vogel for their encouragement, advice and support during the course of the study.

I also express my deepest appreciation to:

- The South African Weather Service for providing me with the technology and time to develop the impact forecasting system;
- The Water Research Commission for supporting the research into improving flash flood warnings;
- The University of Pretoria for providing me with the opportunity to complete this thesis;
- The National Disaster Management Centre for their general support to the implementation of the original South African Flash Flood Guidance system, and providing the vulnerability information used in this study;
- All my local and international friends and colleagues for their valuable advice on topics related to this study.

Finally, to my wife, Amelia, and my daughters, Marissa and Mariaan, who supported and encouraged me during the years I spent on writing this thesis: thank you, I love you.

DECLARATION

I, E. R. Poolman declare that the thesis, which I hereby submit for the degree PhD in Meteorology at the University of Pretoria, is my own work and has not been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE: …………………………………………………………………………..

DATE: ……………………………

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

BCF	– Bias Correction Factor
CRED	– Centre for the Research on the Epidemiology of Disasters
CSI	– Critical Success Index
EPS	– Ensemble Prediction System
EWS	– Early Warning Systems
FFG	– Flash Flood Guidance for a small basin determined by the SAFFG system
FFT	– Flash Flood Threat for a small basin determined by the SAFFG system
FFGS	– WMO program on regional Flash Flood Guidance Systems
FFP	– Flash Flood Potential determined from ensembles over a SAFFG basin
GIS	– Geographical Information System
HSS	– Heidke Skill Score
HyEPS	– Hybrid Ensemble Prediction System from a single UM model
ISDR	– International Strategy for Disaster Reduction
KSS	– Hanssen-Kuipers Score
NDMC	– National Disaster Management Centre in South Africa
LM	– Local Municipality
LM-FFH	– LM-based Flash Flood Hazard risk
MAP	– Mean Areal Precipitation over a SAFFG basin

NMS	– National Meteorological Service
NWP	– Numerical Weather Prediction
SADC	– Southern African Development Community (15 countries)
SAFFG	– South African Flash Flood Guidance system
SARFFG	– Southern Africa Regional Flash Flood Guidance system (in SADC)
SAWS	– South African Weather Service
SWFDP	– Severe Weather Forecasting Demonstration Project
SWIFS	– Severe Weather Impact Forecasting System
WMO	– World Meteorological Organization
UTC	– Coordinated Universal Time, 2 hours earlier than South African Standard Time
UM	– Unified Model of the UK Met Office
UM-SA12	– UM as run by SAWS on a southern Africa domain at 12 km resolution

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 THE NEED FOR IMPACT FORECASTING

The impact of weather on human livelihood is undisputed (Auld, 2008; ISDR, 2005a; ISDR, 2005b; Parry *et al*., 2008; Pelling, 2011). Earth's atmosphere is for the most part relatively calm and kind on mankind living in it. But, it can become extremely hostile and violent in the form of hazards such as heavy rain, gales, thunderstorms or tropical cyclones. These phenomena are part of the natural cycles of the atmosphere, exacerbated by the rotation of the earth around its own axis and around the sun. The incessant exchange of energy in the ocean-atmosphere system, as it tries to get rid of the excessive heat received from the sun in the tropical regions and the deficit of heat in the polar areas, leads to the development of severe weather systems (Holton, 1992). Hardly a day goes by without heavy rain or another hazardous phenomenon occurring somewhere on earth. It is when these severe natural events impact negatively on humans and their livelihood that it becomes disastrous. As population numbers grow and more and more people settle in flood-prone areas or try to make a living in marginal regions, the risk of natural hazards turning into disasters increases. Disaster risk is heightened if the ability of communities to cope can be impacted by enhanced dependence on their immediate natural surroundings, such as rural communities in poor and developing regions in the world (ISDR, 2005a).

Projected climate change and variability scenarios are expected to adversely influence weather-related disasters in the future (Auld, 2008; Berz, 2005; Boko *et al.,* 2007; IPCC, 2007a; IPCC, 2007b; Parry *et al.,* 2008; Pelling, 2011; IPCC, 2013; IPCC, 2014). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Managing the Risks of Extreme Events and Disasters issued in 2012 projected that climate change could lead to changes in the frequency, intensity, spatial extent, duration and timing of extreme weather and climate events (IPCC, 2012). South Africa will not be spared these changes and though the total precipitation is expected to decrease, heavy precipitation is expected to increase which could lead to an increase in flood events (IPCC, 2007a, Engelbrecht *et al.*, 2009; IPCC, 2012). Socioeconomic development and demographic changes are bound to exacerbate the vulnerability and ensuing impact of these changes in extreme events on the population, infrastructure, economy and the environment. This is why the call for more and improved Early Warning Systems (EWS) as a low-regrets measure (IPCC, 2012) is quite relevant to South Africa. As the IPCC (2012, p365) points out, however, "*early warnings systems are most effective when their users can identify and interpret the general warning messages into simple and relevant local impacts and actions, prioritize the most dangerous hazards*".

The International Strategy on Disaster Reduction (ISDR) of the United Nations (UN) listed a number of future challenges and priorities for early warning systems (ISDR, 2005a). These include communication requirements, application of scientific forecasts, public knowledge and participation, and coordination of early warning activities. Again, the weak link identified by them is the communication of forecasts in an understandable way to users to ensure effective decision-making and response. In their discussion on the topic of application of scientific forecasts, the need for improving the interface between warning producers and intermediaries to better interpret scientific predictions and translate it into effective actions was emphasized by the ISDR: "*Then more attention should be devoted to developing user-friendly products for decision-makers",* and *"Attention needs to be given to the consequence of uncertainty in forecasts on decision-making*" (ISDR, 2005a, p382).

From the above it is clear that users of early warnings (e.g. disaster managers or the public) find it difficult to translate complex scientific information into practical understandable disaster-related information they could base decisions on. For these reasons Auld (2008, p122) stated that research and development is needed to "… *move from weather prediction to risk prediction*" that can *"… identify general impacts, prioritize the most dangerous hazards, assess potential contributions from cumulative and sequential events to risks and identify thresholds linked to escalating risks for infrastructure, communities and disaster response*."

These statements call for the development of an **impact forecasting** methodology, a step beyond basic forecasting of weather conditions, to forecasting the consequential impact of these conditions. The WMO recognized the growing requirement for impact information by users, stating that "*in the case of hazardous weather, impact forecasting identifies areas and assets which are most vulnerable to the hazard, and allows prioritization of areas where responder services need to be deployed*" (WMO, 2012, p7). Impact forecasting is a mechanism to transform forecasts of weather variables (e.g. rainfall, wind, etc.) into social, economic or environmental variables (number of people affected, cost of infrastructure damage, etc.) that support more focused decision making by users. For example, disruptive snowfalls can lead to road closures. Instead of only forecasting heavy snow, forecasts of which roads and mountain passes could be closed or which communities could be cut off due to snow would add value for better decision making by authorities and the general public. Thus, impact forecasting is a blend between natural sciences (weather forecasting) and the social sciences (social and economic impacts) to produce more inclusive societal information related to expected natural hazards.

Essentially, impact forecasting attempts to enhance the application of the four main elements of effective EWS identified by the ISDR Platform for the Promotion of Early Warning (ISDR, 2012) are (1) risk knowledge, (2) monitoring and warning, (3) dissemination and (4) response. These four elements are inter-related and span the cycle of an early warning process up to the response of emergency services and communities. An EWS is just as effective as the weakest element, and failure in any of these four elements, imply failure of the EWS. In this process, impact forecasting combines detailed hazard-related *risk knowledge* with *monitoring and warning* of the expected hazard to *disseminate* enhanced user-oriented products to users that can lead to more effective user decision making and *response*.

1.2 PRESENT INTERNATIONAL STATUS OF IMPACT FORECASTING

Impact forecasting is a relatively new and growing development in weather forecasting internationally (WMO, 2012) and there are currently very few references to it in journals. De Groeve *et al.*, (2009) described the Global Disaster Alert and Coordination System (GDACS) mechanism under the United Nations umbrella that provides impact information on large scales in the first phase after major disasters when planning of assistance is done. Even though GDACS is not an impact forecasting system, but rather focus on impact assessment at the time an adverse event (flooding, earthquake or tropical cyclone) occurs, the methodology used to determine the impacts is of interest.

Very few national meteorological services have ventured into the development of sophisticated impact forecasting systems. The UK Met Office is on the forefront of research and development of the impact forecasting methodology. Starting in 2002 with the Severe Weather Impact Model (UK Met Office, 2002) they are now exploring through the Hazard Impact Model to forecast the number vehicles overturning on roads due to strong wind, depending on traffic density on various sections of the roads (Robbins, 2012). Operationally, however, they provide impact-based warnings using a high-level indication of severity of impact without detailed information on the type of impact and its spatial and temporal distribution (Neal *et al.,* 2013). Other national meteorological services (United States, China, and France) also follow this same route of providing high-level impact information with their warnings (WMO, 2012).

WMO (2012) is strongly advocating the development of impact forecasting systems by national meteorological services, recognizing that it is a new area for most services and that significant research is still required to optimally develop the methodology utilized.

1.3 PROBLEM DEFINITION

Consider the following two scenarios:

- On 26 February, 2009 a severe thunderstorm caused flash flooding in Soweto near Johannesburg resulting in the death of four people. According to a report in Newstoday (*www.newstoday.co.za*, accessed on 26/02/2009) a spokesperson of the Johannesburg Emergency Services said "*This was one of the worst thunderstorms in a few years, Sowetans have not seen something like this in a while*". On the same day a thunderstorm with similar size and intensity occurred in the Mpumalanga Province over a remote farmland area. No reports of damage or lives lost were received. Although both events were equally hazardous, the Mpumalanga Province event was far lower in priority for responsive action by disaster management services than the Soweto event due to the increased social and structural vulnerability in Soweto compared to the area in Mpumalanga Province.
- Almost exactly a year later, on the 23 February 2010 a cut-off low caused flash flooding in the remote Karoo nearby a town called Merweville. Confirmation was received from a local source (Personal communication: Riaan Cilliers, George Weather Office, 4 March 2010) of flash flooding in streams, but with minimal impact: a district road was breached with the unfortunate death of the driver of a small truck that drove into it at night, and some sheep were reported to have drowned on a nearby farm. An event such as this would have led to far more serious consequences if it occurred over a built-up area such as Soweto, or Port Elizabeth, or Cape Town. On the 20 October 2012 another cut-off low system in the Eastern Cape resulted in the road breach on the N2, but also caused severe flood impacts in the coastal town of Port Alfred. Houses of 57 residents in the nearby informal settlement were damaged and hundreds of residents were without water or electricity (SAWS, 2012b). Cars were submerged and some houses were flooded with up to 2m of water. A bridge was washed away and the damage to infrastructure and cars was estimated to be more than R1 billion.

These are only two examples of flash flood-related events illustrating where a better description of the expected impacts associated with flash floods could make a difference to disaster management decision making. Disaster managers need to be able to distinguish between low impact and high impact events, identify hotspot areas, or areas of most significant flood-related impacts, and thereby encourage the proper response to warnings issued based on the situational urgency.

Early warnings issued by the South African Weather Service (SAWS) provide weather information about the expected weather hazard based on radar and numerical weather prediction products with limited generalized descriptive information concerning typical impacts usually associated with these hazards. No detailed information on how the particular severe weather hazard will influence a specific community is, however, usually provided. This is typical to severe weather warnings issued by most weather services, and particularly those in developing countries. It is usually expected of users to do their own interpretation how they will be affected by the expected severe weather hazard (WMO, 2012).

There are various developments and improvements of forecasting systems of weather-related hazards (Georgakakos, 2005; Theis *et al*., 2005; NRC, 2006; Tennant *et al*., 2007; Toth *et al.,* 2007; Collier, 2007; He *et al*., 2009; Lean *et al*., 2008; De Coning and Poolman, 2011; Georgakakos, 2011; Warner, 2011; Landman *et al*., 2012). Similarly, various efforts attempt to identify the hazard-related vulnerability in disaster risk reduction systems (Pyle, 2006; IPCC, 2007a; IPCC, 2014; Peduzzi *et al*., 2009; Midgley *et al*., 2011; Scheuer *et al*., 2011; Fuchs *et al*., 2012; Kienberger, 2012; NDMC, 2013). No operational forecasting system, however, exists in South Africa that directly links the severe weather forecasts with socio-economic information in real-time to bridge the gap between weather-related scientific terminology and user-oriented socio-economic interpretation. Disaster managers are not provided with additional information such as intensity of storms or uncertainty of the forecast, or the likely impacts of that particular hazard on people and their livelihoods, infrastructure, ecology or economy to support them in deciding where intervention is necessary, and what the scale and urgency of the intervention should be. Still, disaster managers require information on what is going to happen, where and when, and what the impact will be (Poolman, 2013). These factors form the rationale behind this study for developing an impact forecasting methodology for South Africa.

Flash floods were chosen to be the hazard in the focus of this study since they are the most prominent severe weather-related hazard in South Africa (Caelum, 2010; CRED, 2014). Floods resulted in the most deaths and significantly impacted on people, their livelihoods and infrastructure. Compared to a riverine flood, which builds up and causes flooding over many days, a flash flood occurs in small streams and is defined as "A *flood that rises and falls quite rapidly with little or no advance warning, usually as the result of intense rainfall over a relatively small area.*" (AMS, 2012). The South African Flash Flood Guidance system (SAFFG[1]) used by SAWS provides hydro-meteorological diagnostic information of flash floods with a nowcast of flash floods up to at most a 6-hour lead time using persistence of rainfall estimates. Extended early warning of the potential of flash floods and the resultant socio-economic impact is consequently an appropriate study problem.

1.4 PURPOSE, GOALS AND SPECIFIC OBJECTIVES OF THE STUDY

1.4.1 Purpose of the study

To develop an **impact forecasting** system (beyond a purely hazard focussed system) for flash floods in South Africa that provides extended early warning of the likely occurrence and the resultant socio-economic impact of the flash flood hazards on people and their livelihoods.

---

[1] The South African Flash Flood Guidance System (SAFFG) is the intellectual property of the Hydrologic Research Center (HRC), a non-profit public-benefit corporation based in San Diego, USA. SAFFG and SARFFG were developed and implemented by HRC.

1.4.2 Main goals

The main goals of the impact forecasting system for flash flood hazards are to:

- Enhance the existing capability of nowcasting of potential flash floods through the combination of future uncertainty information from numerical weather forecasts with hydrologic information of the existing SAFFG imminent flash flood diagnostic system;
- Integrate the flash flood potential forecasts with hazard-specific vulnerability information to predict not only the potential of flash floods, but also the likely socio-economic impact of flash floods in river basins;
- Determine the risk level and magnitude of the predicted adverse impacts due to potential flash floods expected within the next few hours;
- Provide information to disaster management that will encourage more effective decision making and the appropriate response during critical hours (e.g. the first few hours after a warning is issued) regarding the level and location of intervention to areas under threat, depending on the situational urgency.

1.4.3 Specific objectives

The specific objectives of the impact forecasting system for flash flood hazards as presented in this thesis is to:

- Provide an overview of flash flood early warning systems including a description of the SAFFG system;
- Acquire an understanding of the origin of forecast uncertainty and its accumulation through the early warning chain, the impact of forecast uncertainty on users, and what their requirements are to effectively use forecast uncertainty in their decision-making processes;
- Develop a basin specific rainfall forecasting system with a lead-time of up to 18 hours addressing forecast uncertainty based on the SAWS operational numerical weather prediction system;

- Combining the basin specific rainfall forecast with hydrologic information of the existing SAFFG system to forecast the potential of flash floods in the SAFFG river basins with an 18-hour lead time;
- Develop the vulnerability and impact concepts for the impact model relevant to the impact forecasting model;
- Design a systematic methodology, or model, that can translate the forecast of weather hazards into relevant impact variables applicable to small river basins and local municipalities, and able to distinguish between low impact and high impact events, and identify hotspot areas, or areas of most significant flood-related impact;
- Develop products on the potential level and magnitude of impacts to support disaster managers and forecasters with more effective decision making and the appropriate response regarding the level and location of intervention to areas under threat, depending on the situational urgency;
- Provide a basis for the development of impact forecasting systems for the remainder of South Africa, and for other developing countries in southern Africa and elsewhere;
- Provide a basis for the enhancement of the severe weather impact forecasting system to include other hazards and more detailed impact information;

1.5 SCOPE OF THE STUDY AND CONTRIBUTION TO SCIENCE

The particular focus of the study is on hazards associated with heavy rain and flash floods, and their related social and infrastructural impact in South Africa within the area covered by the SAFFG. The target recipient audience is disaster managers in South Africa and weather forecasters of SAWS.

This study contributes new insight to the current international research on short-term impact forecasting through the development of an impact forecasting methodology in a developing country with its limited spatial vulnerability information. Furthermore, it contributes to the growing international application of the flash flood guidance technology similar to SARFFG by adding user-oriented components to it in terms of additional lead-time of potential flash floods, and the likely impact of flash flooding to support disaster manager decision-making. Lastly, the impact forecasting system developed through this study is the first operational impact forecasting system in South Africa, and provides the platform for future extension of the concept to other hazards than flash floods.

1.6 STRUCTURE OF THE STUDY

In Chapter 2 an overview of flash flood warning systems is provided and the SAFFG system described.

Chapter 3 present a discussion of forecast uncertainty and decision making of disaster managers related to forecast uncertainty.

Chapter 4 describes the development of the forecast system aimed at increasing the lead-time of the likelihood of flash flood disasters through the integration of forecast uncertainty using a numerical weather prediction (NWP) system.

In Chapter 5 the development of the impact model that determines the potential impacts of flash floods through the combination of hazard risk and vulnerability information of small areas is described.

Chapter 6 provides a summary of the study, with conclusions and recommendations.

CHAPTER 2

EARLY WARNING SYSTEMS AND FLASH FLOOD DISASTERS

2.1 INTRODUCTION

In South Africa flash flood warnings falls under the national multi-hazard early warning system under the jurisdiction of the NDMC. Due to the short response time of flash floods to heavy rain, issuing of a flash flood warning is a hydro-meteorological problem that can occur any time during a day or night, requiring 24 hours, 7 days a week monitoring. For this reason, it resides with the operational forecasters in SAWS. The SAFFG, implemented in SAWS, forms a central pillar of the Severe Weather Impact Forecasting System (SWIFS) developed in this study for flash flood hazards. Against this background, the starting point for describing the SWIFS system requires an overview of early warning systems followed by an introduction of the SAFFG modelling system.

2.2 WEATHER-RELATED DISASTERS

Disasters caused by natural phenomena such as floods, droughts, storms, earthquakes, fires and other hazardous events have serious and often tragic effects on humans and the economy of vulnerable communities and countries. In 2002 alone, globally, more than 500 disasters resulted in 10,000 deaths, brought misery to another 600 million people while damages of more than USD55 billion were caused of which only USD13 billion were insured losses (ISDR, 2005a). Natural hazards will always affect communities simply because humans are living in the volatile natural world which is dynamic and can be extremely hostile and violent at times. When these natural hazards disrupt human activity beyond the ability of the community to cope using their own resources, and the hazards cause loss of lives and livelihoods, then these natural hazards turn into disasters (ISDR, 2005a). Although these disasters are strictly speaking not “natural” since the community’s vulnerability is not natural (ISDR, 2005a), disasters caused by natural hazards will be referred to as natural disasters in this thesis in contrast to disasters caused by man-made technological hazards such as oil spills, etc..

The Sumatra tsunami disaster of 26 December 2004 tragically produced one of the strongest calls yet for effective early warning systems for natural disasters (Parker, 2005; WMO, 2005). Nine countries were affected and more than 300,000 lives were lost when the tsunami unexpectedly struck Indonesia and other countries on the Indian Ocean rim. In August 2005, the category 5 hurricane Katrina struck the Gulf coast of the United States of America (USA) resulting in many deaths and economic losses estimated to be more than US$100 billion (WMO, 2005). This was the largest loss on record for a single disaster in history. Closer to home, tropical cyclones Eline and Favio (comparable to a category 4 hurricane on the Sapphir-Simpson scale) struck Mozambique in 2000 and 2007 respectively, causing widespread disruption (Poolman *et al*., 2008). Contrary to the case of Eline, warnings were issued 5 days in advance of the landfall and movement of Favio, resulting in the death of only 9 people. More recently numerous severe weather events have caused flash flooding and other weather-related disasters in South Africa, resulting in damage of hundreds of millions of Rand and the loss of several lives (Holloway, 2007; Caelum, 2010).

In recent years many countries have reduced the impact of natural disasters through implementing effective early warning systems. Although the number of disasters and their financial impact has increased over the last few decades (ISDR, 2006b), the number of deaths has decreased. This is attributed (ISDR, 2006b) in part to the effect of improved early warning systems implemented in various parts of the world. Since 300,000 lives were lost during tropical cyclone Bhola in 1970 in Bangladesh, a 48-hour early warning system was installed to evacuate people to safe shelters using megaphones hours before a cyclone struck. Subsequently, the death toll from tropical cyclones decreased dramatically to 3,000 in November 2007 following the impact of tropical cyclone Sidr (ISDR 2008).

Less than a month after the December 2004 Sumatra tsunami the World Conference on Disaster Reduction was held in Kobe, Hyogo, Japan where the Hyogo Framework for Action

2005 – 2015 (HFA) was adopted as a guideline to reduce vulnerabilities to natural hazards (ISDR, 2005b). The HFA put strong emphasis on the development and enhancement of EWS. It stressed that EWS are essential to save lives and property, and that they are far more cost-effective than relying on post-disaster response and recovery measures. Participants at the Third International Conference on Early Warning organized by the ISDR in 2006 in Bonn, Germany echoed these sentiments. Several high ranking officials and early warning specialists from around the world attended the conference (ISDR 2006a).

Figure 2.1 depicts a graphical comparison of disasters that occurred in South Africa between 1920 and 2008 as registered in the international Belgium-based Centre for Research on the Epidemiology of Disasters (CRED) disaster database (CRED, 2014). Disasters are listed on the CRED database by country when a disaster is either declared in the country, or more than 10 people died, or more than 100 people have been affected, or international assistance was requested (CRED, 2014). An analysis of the total hazard list in the CRED database revealed that weather-related disasters amounted to 90% in South Africa compared to 85% in the entire Southern Hemisphere and 80% globally. This is mainly due to the low occurrence of geological-related disasters (earthquakes, volcanoes, landslides) in the country. Floods, drought, wind storms and wildfires were identified as the major hazards for South Africa. Even though drought affected more people, floods were more numerous, caused the most deaths and resulted in the most significant impact to people, their livelihoods and infrastructure.

The previous results are supported by an analysis of newspaper reports collected since the early 1900s and captured by SAWS in the Caelum document (Caelum, 2010). Any significant weather-related events reported in the newspapers are listed in Caelum. By nature, since disastrous events are newsworthy, the vast majority of events reported lead to adverse impacts on communities, even though they were not of the scale reported in the CRED database. According to the Caelum (Figure 2.2) floods resulted in 39% (or 777 out of 2014) of reported hazardous events between 1961 and 2005, followed by severe storms (severe thunderstorms including tornadoes or hail), wind, snow and wildfires in that order. The majority of the 777 flood events reported between 1961 and 2005 in the Caelum (2010) occurred as flash floods in minor streams. Of the nine provinces, the four mostly affected by these hazards, according to the Caelum analysis (Figure 2.2), are the Western Cape, KwaZulu-Natal, Eastern Cape and Gauteng. These four provinces have densely populated urban and rural areas, and, apart from Gauteng, they are affected by maritime weather phenomena. Despite being the smallest province, Gauteng with its dense population around the large cities is still fourth on the list of provinces affected by weather-related disasters.

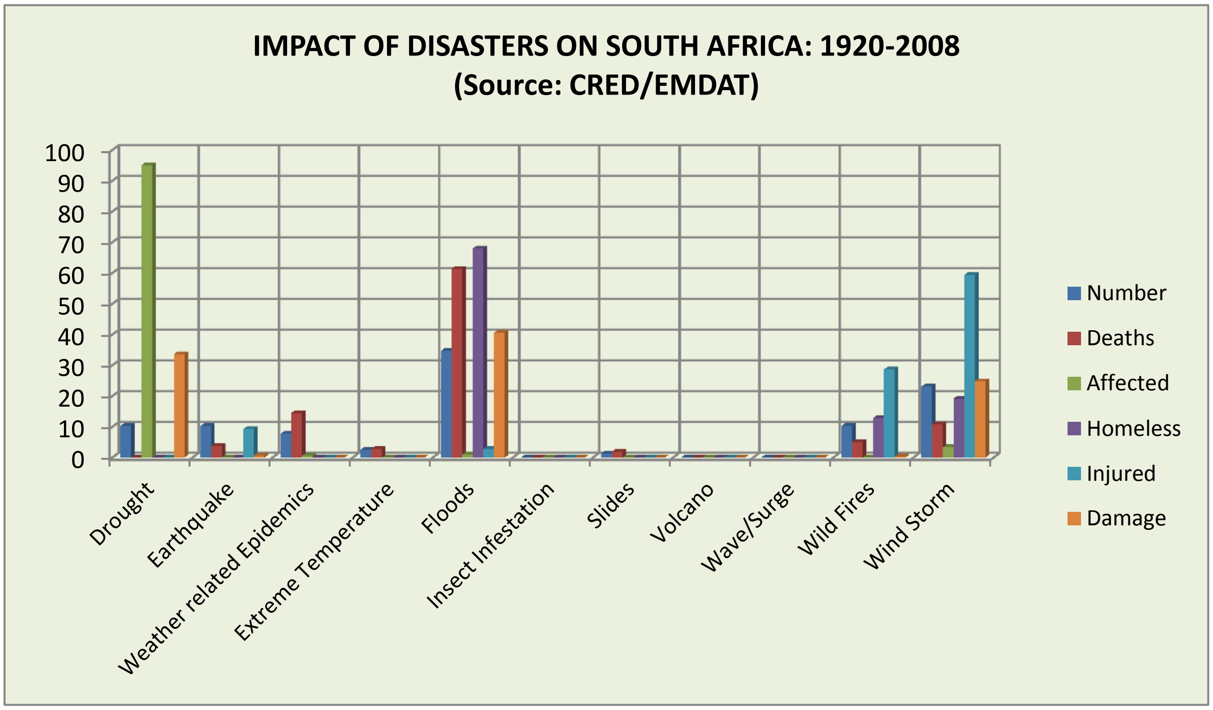
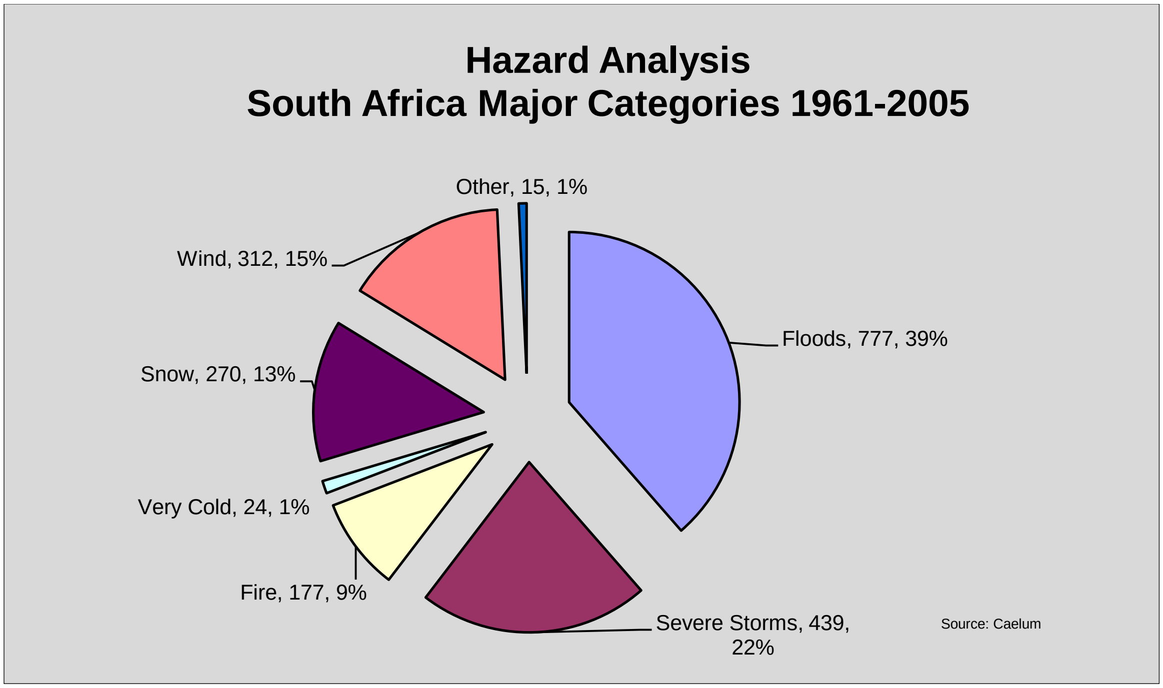
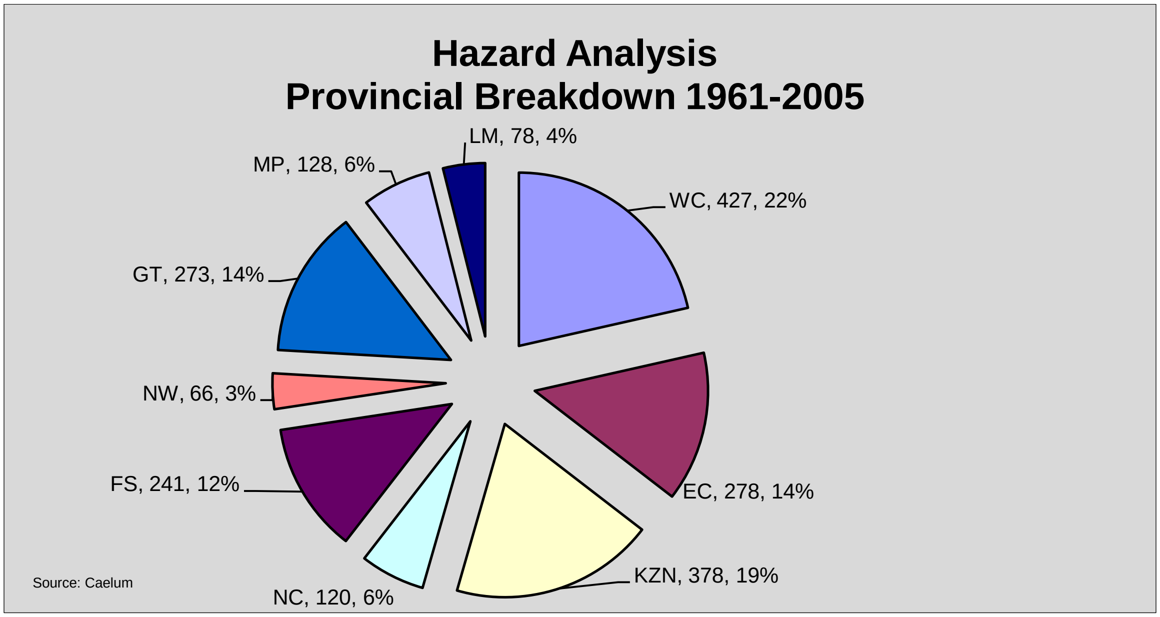


Figure 2.1: Comparison of the impact (as a percentage of the total impact per category) of different natural disasters that occurred in South Africa between 1920 and 2008 on human livelihood, according to the CRED/EMDAT disaster database.



(a)



(b)

Figure 2.2: Occurrence of severe weather hazards by major category in South Africa (a), and breakdown of per province according to SAWS Caelum newspaper record between 1961 and 2005 (b). The provinces are: LM = Limpopo, WC=Western Cape, EC=Eastern Cape, KZN=KwaZulu-Natal, NC=Northern Cape, FS=Free State, MW=North West, GT=Gauteng. Note: Caelum only reflects quick onset short-lived hazards, hence drought is not represented in these figures.

In a detailed investigation by Holloway *et al.* (2010) on the impact of six disaster events in the Western Cape Province between 2003 and 2008 they found flood and storm damage amounting to more than R2.5 billion (adjusted to 2005 values) in property and infrastructure damage. They concluded that weather systems causing floods and windstorms had significant impact on cities, coastal settlements and rural communities. Flooding caused by tropical cyclone Eline in 2000 caused extreme damage to roads, infrastructure, agriculture and property over Mpumalanga, South Africa, amounting to more than R3,000 million (Du Plessis, 2002).

2.3 EWS AS A COMPONENT OF DISASTER RISK REDUCTION

2.3.1 Definition of EWS

According to the ISDR (2010, http://www.unisdr.org/eng/library/lib-terminology-eng%20home.htm) disaster risk reduction is "*… the conceptual framework of elements considered with the possibilities to minimize vulnerabilities and disaster risks throughout society to avoid or to limit the adverse impacts of hazards, within the broad context of sustainable development*". This includes risk assessment, knowledge development, public commitment and early warning systems (ISDR 2005a, ISDR 2006a). A *hydrometeorological hazard* is a potentially damaging event or phenomenon of meteorological, hydrological or oceanographic nature that may lead to the loss of life or property (ISDR, 2010). *Vulnerability* of communities can increase as people settle and develop in risky areas such as flood plains or earthquake zones making them more susceptible to natural hazards such as floods.

Vulnerability of communities can also be exacerbated by the looming impact of climate change on weather-related hazards, and social and demographic changes (IPCC, 2012). To put it into some perspective: the total population of South Africa has grown from 17.4 million in 1960 to 47.8 million in 2008 (World Bank, 2010): a growth of 30.4 million people, or an increase from 14 people per square kilometre to 39 people per square kilometre. This population growth alone can dramatically increase the number of people living in areas vulnerable to natural hazards, particularly flood plains and river banks, thereby escalating the pressure on disaster risk reduction activities in these regions (Davis, 2001; Pegram, 2007). Increasing vulnerability and risk of disasters drive the need for enhanced early warnings systems to provide timely and useful information from recognized sources to aid vulnerable people to take action to avoid or reduce the negative impact of a hazard.

The ultimate aim of Early Warning Systems (EWS) is to "*empower individuals and communities threatened by hazards to act in sufficient time and appropriate manner so as to reduce possibility of personal injury, loss of life and damage to property*" (ISDR 2005a, p360). This statement implies an effective end-to-end early warning process adapted to the unique situation of the local communities at risk. Effective EWS provide useful information about approaching hazards well in time for the community at risk to take appropriate action according to a well-prepared plan that can save lives. An EWS is an essential component in disaster risk reduction (ISDR 2005a, 2006a) and is part of the preparedness phase of the well-known disaster Risk Reduction cycle of Preparedness, Response, Recovery, Mitigation, and back to Preparedness. Early warnings are defined by the South African National Disaster Management Framework of 2005 (DPLG, 2005) as the *provision of timely and effective information through identified institutions, which allow individuals, households, areas and communities (including disaster management structures) exposed to a hazard to take action to avoid or reduce the risk and prepare for effective response*.

Severe weather-related warnings refer to official early warnings of potential, imminent or existing threats of dangerous weather hazard(s) that may lead to a weather-related disaster within an identified area, for a specified period and according to predetermined thresholds. The public release of such a severe weather warning is intended to draw out appropriate reaction by disaster management structures as well as communities deemed at risk, thus enabling them to take active steps to avoid or reduce their risk and safeguard life and property.

2.3.2 Context of disaster risk reduction in South Africa

The South African disaster risk management environment is regulated by the Disaster Management Act of 2002 (DPLG, 2002) and its implementation instrument, the Policy Framework for Disaster Risk Management (DPLG, 2005). These legal instruments define the environment within which effective EWS can function. This includes the establishment of national, provincial and municipal disaster management centres (NDMC, PDMCs and MDMCs), and the integration and co-ordination of activities, including, among others, focussing on the reducing or preventing of disaster risk, preparedness and the roles of organs of state and disaster management centres in terms of early warnings. According to the National Disaster Management Framework (DPLG, 2005) the NDMC is the overall governance institution responsible for the EWS against hazards in general. It is thus the custodian of the multi-hazard early warning system in South Africa.

The SAWS Act of 2001 (SAWS, 2001) defines the Severe Weather Warning Service (SWWS) as an integral part of the organization's meteorological service, and as a public good activity. The SWWS functions as a component of the Multi-Hazard Early Warning System (MHEWS). The flow of severe weather hazard-related information is described in Figure 2.3. Technical Monitoring Agencies, such as SAWS, monitor relevant hazards and issue warnings to the national, provincial and relevant municipal disaster management structures for their preparedness actions. Warnings are also issued by the technical monitoring agencies to the public via the media, while disaster management structures also have a responsibility to relay warnings to the communities at risk in their local regions.

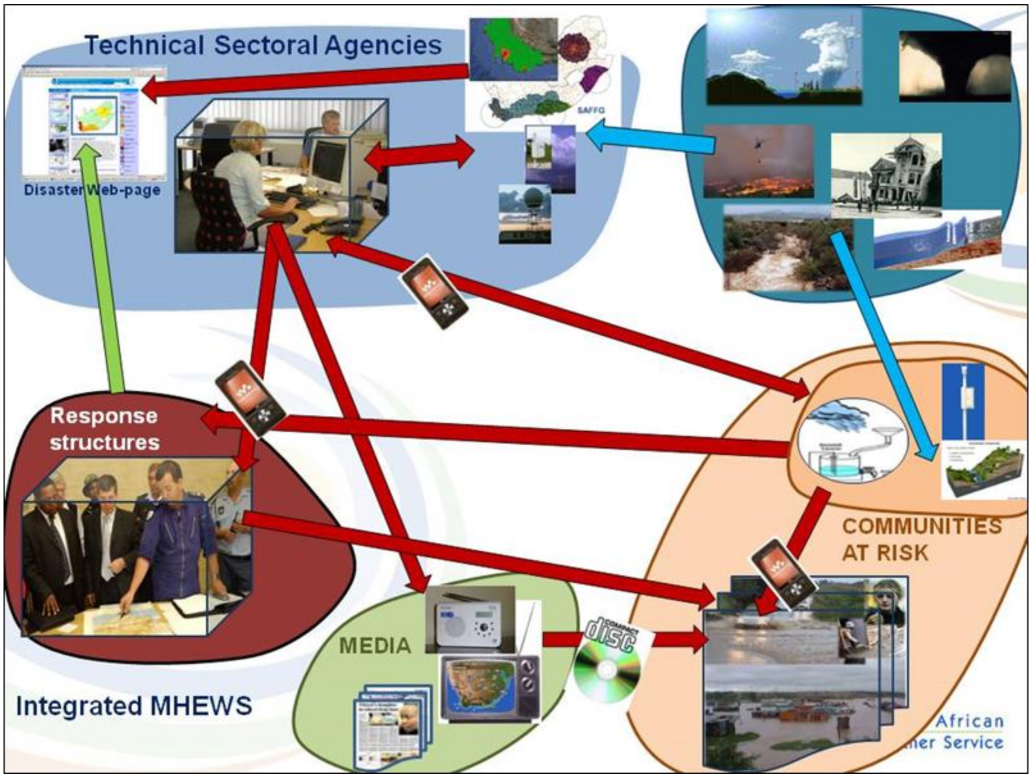


Figure 2.3: A graphical illustration of the information flow in the South African Multi-Hazard EWS. (Source: Developed by Poolman, 2008)

2.4 WARNINGS AGAINST FLOOD DISASTERS

As discussed in Section 2.2, the most prominent natural disasters in South Africa are flood disasters based on the number and the impact of disasters (Figure 2.1) according to the CRED data. Compared to other hazards such as droughts, wild fires and windstorms, floods were more numerous, and have a significantly wider impact on people and their livelihoods. Furthermore, flood disasters constituted 44% of all reported weather-related disasters (excluding drought) in South Africa, mostly in the form of flash floods. In the USA, most weather-related deaths are associated with flash floods (Davis, 2001).

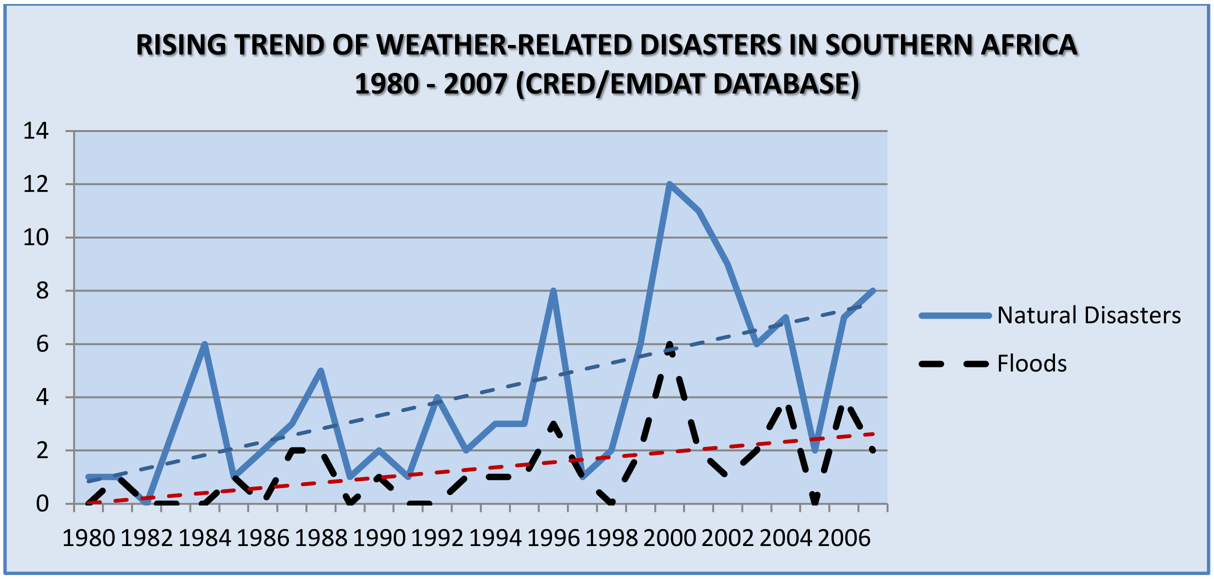


Figure 2.4: Trends of the number of natural disasters in comparison with flood disasters in Southern Africa according to the CRED disaster database. (Source: CRED/EMDAT).

The American Meteorological Society (AMS, 2012) as well as the WMO International Glossary of Hydrology (WMO, 2011) defines a flood as the "*overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged*". Compared to a riverine flood, which builds up and causes flooding over many days, the WMO (2008, pp. 16) defines flash floods as "*excessive water flow events that develop within a few hours – typically less than 6 hours – of the causative rainfall event*". The simplest definition for a flash flood is "*too much water, too little time*" (Davis, 2001, pp. 482). There are various types of floods identified around the world (WMO, 2011), ranging among others from flash floods and riverine floods to seasonal floods, multi-event floods, estuarine floods and ice-jam floods. The latter is related to flooding caused by a sudden break of an ice floe constriction in streams in colder regions. Different types of floods affecting South Africa could be summarized from Holloway *et al.* (2010) and WMO (2011):

- *Riverine floods* are usually the consequence of sustained, heavy rainfall over many days in a catchment that lead to an increased accumulation of water levels in the larger rivers exceeding the capacity of the channel and causing spilling of water over the banks into natural flood plains. As the flood wave moves downstream adjacent areas to the rivers are inundated by flood waters as the water level overflow's a river's banks. These floods can be exacerbated when sluice gates in dams have to be opened to prevent them from overtopping. The flood wave can take many days to move down the river and cause flooding even in remote areas;

- *Flash floods* are consequences of heavy rain events that cause sudden flooding in small river streams. The flash flooding occurs within 6 hours of the heavy rain event. They could also occur in small streams or dry riverbeds. The short warning and response time lead to high risk for the deaths;
- *Urban floods* are flash floods that occur in basins altered by humans when heavy rain collects on impervious surfaces in cities (like roads, parking areas, etc.) resulting in more water than what could drain through the sewer systems. These include flooding of streets, underpasses, low-lying areas or storm drains;
- *Road floods* are similar to urban floods, resulting in flooded roads, highways, underpasses and bridges that are particularly hazardous to traffic. Debris clogging inlets to pipes or channels aggravates the problem;
- *Pooling*, also called *rising floods,* arises when an area is flooded through build-up of water, but no significant river flow is evident. This happens typically in the Cape Flats in informal settlements close to wetlands;
- *Storm surges* and *coastal floods* are the result of abnormally high levels of water caused by intense storm systems (like tropical cyclones, or intense extra-tropical cyclones) coinciding with high tides, and which push against the coast line into river mouths and estuaries, or severely damage coastal infrastructure;
- *Estuarine floods* occur when the seaward flow of rivers and streams meet with landward flow of sea water at estuaries during high tides or significant inland rain.

Each of these types of floods needs to be dealt with in a specific manner. The response time of large catchments leading to riverine floods, for example, vary from many hours to days

(Pegram, 2007). By comparison, small catchments can have response times in the order of hours resulting in flash floods. Forecasting technology used for one type of flooding therefore cannot necessarily be applied to other types of flooding. Riverine floods, flash floods and storm surges are dealt with in different ways with different technological systems, and even different institutions in some cases. This research focuses more specifically on flash flood warning systems, which are least predictable but are the biggest types of threat of the above flood types (Davis, 2001), both internationally and in South Africa.

Trends of natural disasters versus flood disasters between 1980 and 2007 in Southern Africa as constructed from the CRED/EMDAT database (Figure 2.4) show an increase in natural disasters and floods. The increase in disasters can be attributed to a number of causes, including climate change and variability, demographic changes and improved reporting of disasters. Figure 2.5 shows a distribution of flood events over South Africa as reported in the Caelum newspaper events database of SAWS (Caelum, 2010). The coastal district municipalities of the Western Cape, Eastern Cape and Kwa-Zulu Natal Provinces, as well as the economic hub of the Gauteng Province, had a higher incidence of flood events than most of the country. This can be attributed to the higher occurrence of flood producing weather systems, as well as the higher population density increasing vulnerability. The obvious exception is the large district municipalities in the western-central parts of the country where the population density is relatively quite low, however, at the same time they border the Orange and Vaal Rivers where riverine flood events are more frequent. The higher occurrence of flood events in the more populous rural regions of KwaZulu-Natal Province and the Eastern Lowveld region also emerges as noteworthy.

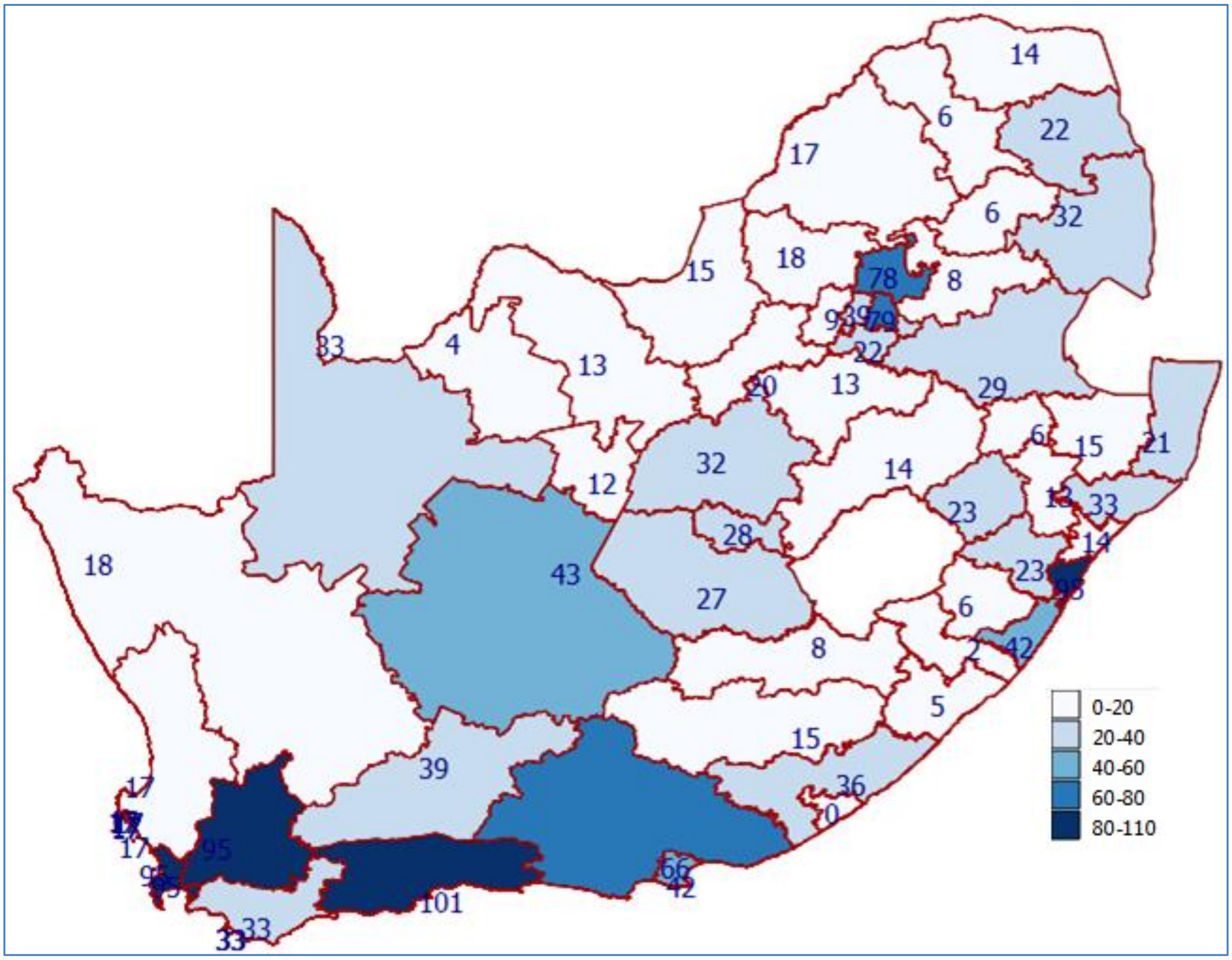


Figure 2.5: Distribution of flood events in South Africa from 1900 till 2009 as reported by newspapers and summarized in the SAWS Caelum. The number of flood events for the period for each district municipalities are indicated. (Source: Caelum, SAWS)

Warnings against flash floods are neither strictly hydrological nor purely meteorological in nature. It is a typical hydro-meteorological problem due to its nature as a hydrological hazard responding very quickly (within 6 hours according to the definition) to a meteorological phenomenon (rainfall) (WMO, 2011). For this reason, and since it operates a 24 hour 7 days a week monitoring service, the SAWS takes the lead in issuing flash flood warnings. The Department of Water Affairs (DWA), on the other hand, issues warnings for riverine floods, which have longer response times and are essentially hydrological problems.

The flash flood warning system of SAWS depends on a number of supporting systems and datasets, including rainfall forecasts from numerical weather prediction models, radar and satellite information, and recently on the hydrological guidance provided by the SAFFG hydrometeorological modelling system for the potential of flash flooding. Prior to the introduction in 2010 of the SAFFG to SAWS forecasters had to rely on a generic threshold of 50 mm of rain beyond which a warning was issued for "heavy rain with possible flash floods". The forecaster had no idea of the hydrological conditions of the soil and its likely response to heavy rain. The SAFFG, as a hydrometeorological modelling system, now provides an indication of what the likely potential for flooding in small river basins, due to the soil moisture conditions and other related hydrological factors, may be.

Since the SAFFG system is an important component in this particular study, it will be discussed in more detail in the following section.

2.5 THE SOUTH AFRICAN FLASH FLOOD GUIDANCE SYSTEM

2.5.1 Introduction to the South African Flash Flood Guidance System

In order to issue flash flood warnings weather forecasters need to know "how much rainfall over a small catchment could lead to potential flooding in that catchment?" The answer to this basic question requires a hydrometeorological solution that usually evades forecasters. By using flash flood guidance computation an attempt to provide such guidance is made and the concept was used in the USA since the 1970s (Georgakakos, 2006). The arrival of satellite- and radar-based precipitation estimates, and GIS-based databases related to catchment properties have allowed the development of more comprehensive operational systems that could simulate the flash flood guidance concept distributed over numerous small river basins in real-time (Georgakakos, 2004). The flash flood guidance concept was introduced in the Central American Flash Flood Guidance system (CAFFG) in 2004 (Georgakakos, 2005). The CAFFG provides guidance on potential flash floods, not as a forecast, but as diagnostic information to be used by experienced forecasters along with other data, tools and systems to determine the potential of flooding in small basins in the next 1, 3 or 6 hours.

SAWS upgraded its weather radar network in mid-2000 by installing a number of new S-band weather radar systems, which enhanced its rainfall estimation ability within the radar detection range. Technology implemented on the products of the new Meteosat Second Generation satellite (MSG) in the same period allowed for more skilful satellite-based rainfall estimation in southern Africa (De Coning and Poolman, 2011). This paved the way for the operational implementation, based on CAFFS, of both the SAFFG in South Africa by October 2010 and the Southern African Regional Flash Flood Guidance system (SARFFG) over the Southern African Development Community (SADC) in 2014 by the Hydrologic Research Center (HRC) in San Diego, USA. SAFFG covers 5366 small catchments (averaging from 50 to 100 km^2) over the main metropolitan areas of South Africa, as well as the flash flood prone Cape South Coast. Comparatively the regional SARFFG, implemented by HRC under a WMO project in Southern Africa, covers nine countries in SADC with 15454 basins, of which 4760 cover the entire South Africa, at an average size of 150 to 200 km^2 (Figure 2.6). Precipitation estimation based on the weather radar systems, the MSG satellite and real-time rain gauges are used to update the flash flood guidance information hourly for each of the 5366 small river basins.

The major difference between the SAFFG and the SADC regional SARFFG is that the latter, covering the entire South Africa (Figure 2.6b), updates the flash flood guidance for its larger catchments every 6 hours using only satellite rainfall estimation, compared to hourly by SAFFG. The latter also uses radar precipitation estimates where available. In terms of South Africa, the SAFFG thus compliments SARFFG as a high-resolution (in space and time) version of SADC SARFFG, able to highlight and “zoom into” more detail at the flash flood prone metropolitan regions.

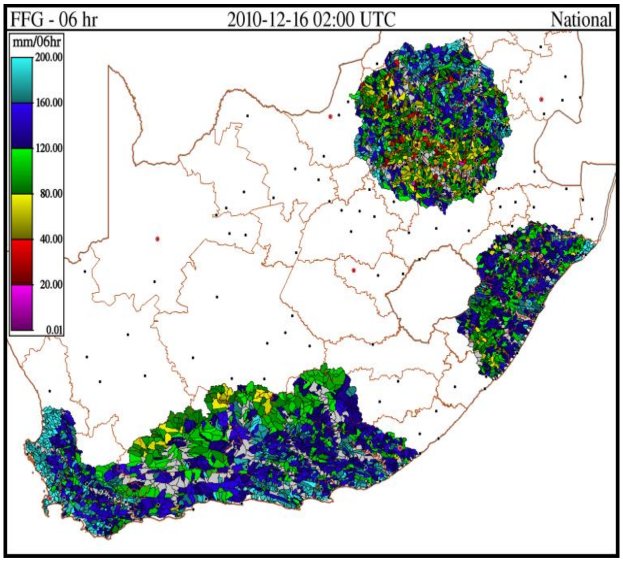


Figure 2.6a: Domain of the SAFFG, covering flash flood prone regions in South Africa with high resolution catchments of 50 – 100 km2

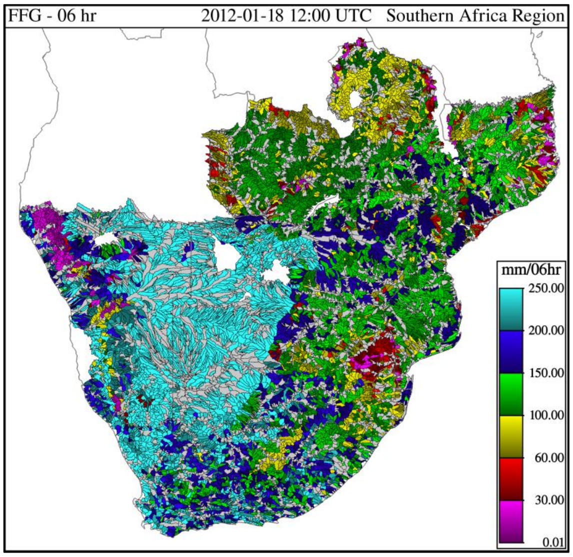
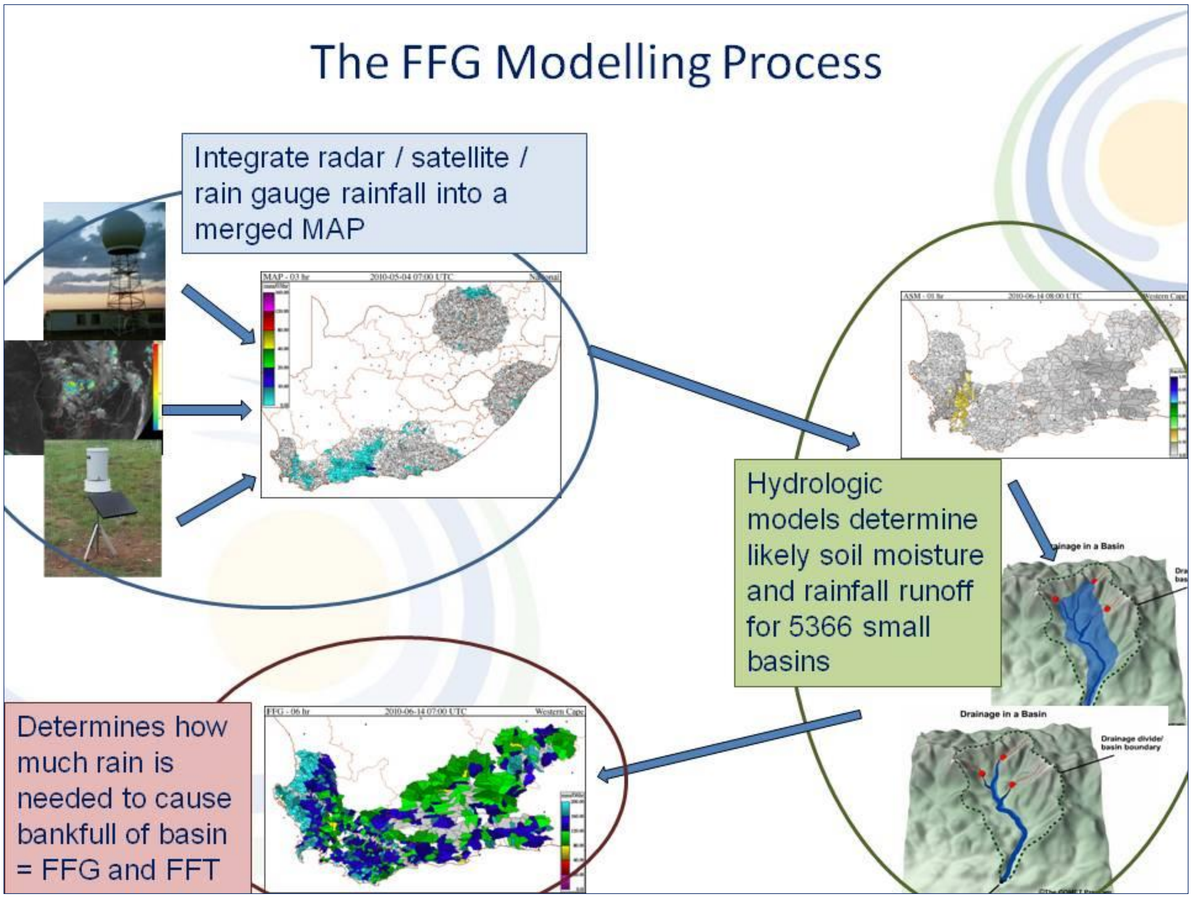


Figure 2.6b: Domain of the regional SARFFG covering 7 countries, but at a lower resolution of approximately 200 km2 compared to SAFFG.

2.5.2 Modelling concept and products

The FFGS models the hydrologic response of small river basins to the rainfall received and provides guidance to weather forecasters and disaster managers on the potential for flash flooding for each of these basins. It is thus a true hydro-meteorological system, designed to answer the basic question of weather forecasters mentioned above of "how much rainfall over a small catchment could lead to potential flooding in that catchment?" Georgakakos (2004, 2006) and Ntelekos et al. (2006) describe in detail the modelling concepts applied in the FFGS, and Sperfslage et al. (2010) provides information on the SAFFG. A summary of models and applications is provided in more detail below.



The FFG Modelling Process

Integrate radar / satellite / rain gauge rainfall into a merged MAP

Hydrologic models determine likely soil moisture and rainfall runoff for 5366 small basins

Determines how much rain is needed to cause bankfull of basin = FFG and FFT

Figure 2.7: The hydrological modelling through integration of meteorological variables is shown in the graphic. In the case of the SAFFG this process is repeated every hour with the latest rainfall information available, and for SARFFG this is repeated every six hours with satellite rainfall estimation information only. (Source: Developed by Poolman, 2010)

There are essentially four main components in the modelling system of FFGS as is implemented in the SAFFG and SARFFG (Figure 2.7). These are:

- Integration of rainfall estimation from different sources into a basin average rainfall product;
- Modelling the soil moisture deficit based on the rainfall estimation;

- Relating the basin's distinctive threshold runoff (the effective rainfall amount needed should the basin be completely saturated) to flash flood guidance (FFG) given the soil moisture deficit;
- Comparing the flash flood guidance value with observed rainfall as an indicator of possible imminent flash flood threat (FFT), or to a nowcast of rainfall for possible flash flood threat up to the next six hours.

2.5.3 System preparation

The FFGS, as implemented in SAFFG and SARFFG, is essentially a spatially-distributed modelling system. This means that it models the hydrologic response to rainfall of each of the small river catchments over a large area to provide spatial information on the potential for flash floods. The flash flood prone regions in South Africa (for SAFFG) were delineated into small catchments using a Geographical Information System (GIS) and digital elevation data of 90m resolution available at the time. The minimum basin size was set to 30 km^2 for areas where radar precipitation estimation was available and 100 km^2 where only satellite precipitation estimation was available. The catchments are at least a few grid lengths of the satellite and radar rainfall fields in size to allow acceptable precipitation estimates from radar and satellite.

Characteristics of the catchment geometric properties and stream cross-section geometric properties (including catchment size, channel length, channel slope, stream top width and hydraulic depth at bank full) were determined through GIS processing of the digital elevation data, or through regional relationships (Carpenter *et al*., 1999). Other information needed for catchments, including soil type and depth, land-use, vegetation, etc., were received from various official sources in GIS format, for example the Agricultural Research Council, DWA and the Chief Directorate of Surveys and Mapping. This information needed in the hydrological modelling of the catchments was interpreted to corresponding information for each FFGS catchment.

2.5.4 Rainfall estimation

In the SAFFG, rainfall estimation is based on remote sensing platforms such as weather radar systems and the MSG satellite, both of which are indirect methods of rainfall measurement, but with the advantage of good spatial and temporal detail (Pegram *et al*., 2007; De Coning and Poolman, 2011). Radar and satellite-based rainfall estimation are provided to the SAFFG system and are assumed by the latter to be the best available rainfall estimation from these platforms. Still, to compensate for the errors in precipitation estimation by radar systems and satellite, dynamic and climatologic bias correction schemes are employed on both sets of data using available rain gauge information received either hourly, or at least daily.

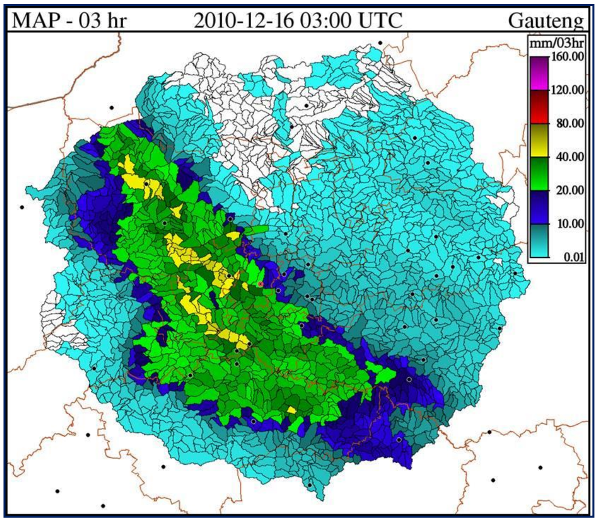


Figure 2.8a: 3-hour accumulated mean areal precipitation (MAP) field for the SAFFG covered by the Irene radar near Pretoria.

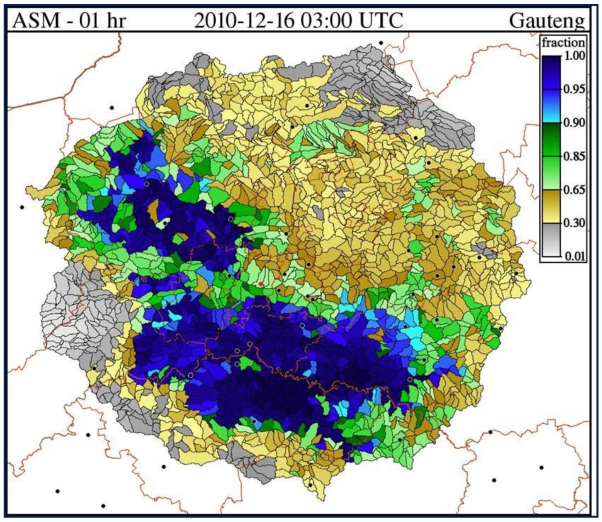


Figure 2.8b: 3-hour soil moisture fraction (ASM) for the same area and date as in Figure 2.8a.

Bias-corrected radar and satellite rainfall estimation data are processed every hour to provide the latest mean areal precipitation (MAP) estimates for the previous 1-hour, 3-hours and 6-hours, used as the precipitation forcing in the soil moisture and flash flood guidance models (see example Figure 2.8a). In regions where radar estimates are available, the radar based bias-corrected MAP fields will be used as the precipitation field for the subsequent models. Should the radar, however, not be available, the system will automatically use corresponding satellite MAP fields. The SADC regional SARFFG uses only satellite MAP fields and is bias corrected with available rain gauge data. Precipitation estimation by radar and satellite are key ingredients to the FFGS, and assumed by the system as pseudo observations for soil moisture calculations.

2.5.5 Modelling soil moisture deficit

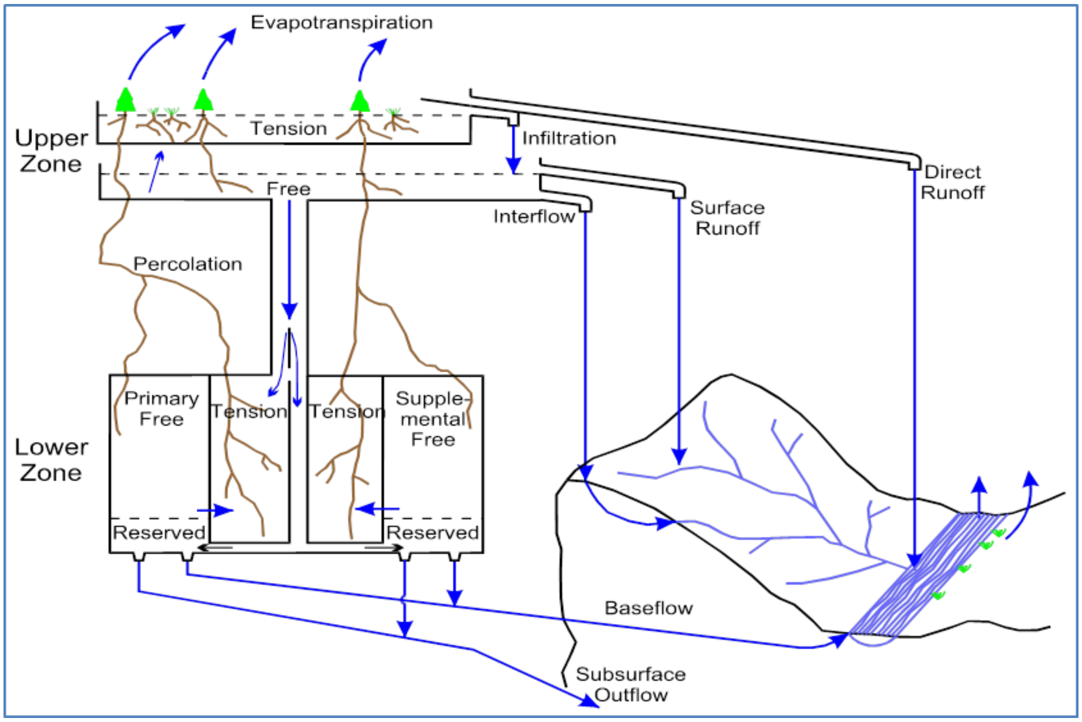


Figure 2.9: Graphical representation of the Sacramento Soil Moisture Accounting Model components (Source: COMET, 2010)

Soil moisture deficit is modelled with the Sacramento soil moisture accounting model, adapted for use in the FFGS as described by Georgakakos (2006). Runoff is modelled in the upper and lower soil zone components (direct and saturation excess surface runoff, interflow, baseflow) (Figure 2.9) from the MAP and evapotranspiration estimates for the catchment. Evapotranspiration is computed from the location, climatological and vegetation properties of each catchment. The state of the soil moisture is computed every hour (SAFFG) and every six hours (SARFFG) for each small FFGS catchment and provided to the FFG model as the current state of soil moisture deficit (see example in Figure 2.8b) to compute the FFG values.

2.5.6 Flash flood guidance model

Flash flood guidance (FFG) is defined *as the average amount of rainfall over the catchment of a given duration (1, 3 or 6 hours) required causing bank full flows (i.e. minor flooding) at the outlet of the catchment*. FFG is thus a conservative estimate of the amount of rainfall needed to cause minor flooding, answering the question asked by forecasters mentioned earlier.

FFG is determined using the relationship of the fixed threshold runoff value of the basin and the soil moisture deficit at the time. Threshold runoff, on the one hand, is the runoff volume (and hence the effective rainfall) needed for bank full after accounting for all losses of water such as interception and soil moisture storage. Threshold runoff is thus the residual rainfall amount needed for bank full at the catchment outlet if the catchment is completely saturated, and is a one-time calculation for a given catchment done during the setup of the system. FFG, on the other hand is the actual rainfall needed, of which some part will be absorbed by unsaturated soil, and is computed on a real-time basis since it depends on the saturation level of the catchment. FFG will thus by definition be more than, or equal to, the threshold runoff amount.

To find the FFG, basic rainfall-runoff curves are needed for the basin with the given soil moisture deficit calculated for the catchment in the previous model (Section 2.5.5). The flash flood guidance model uses this soil moisture deficit to determine this basic rainfall-runoff curve for the particular basin at that particular time. This is done by running “what if” scenarios using the hydrologic model to calculate the runoff that different (increasing) rainfall values will generate given the same soil moisture state at the time. From these estimates, rainfall-runoff relationships (the curves in Figure 2.10) can be determined for the particular catchment given the current state of soil moisture. The effective rainfall needed (i.e. the flash flood guidance value, or FFG) can then be determined through these relationships (curve) from the pre-determined runoff value that will lead to bank full (i.e. threshold runoff). This is done for 1, 3 and 6 hour rainfall durations (see the example in Figure 2.10).

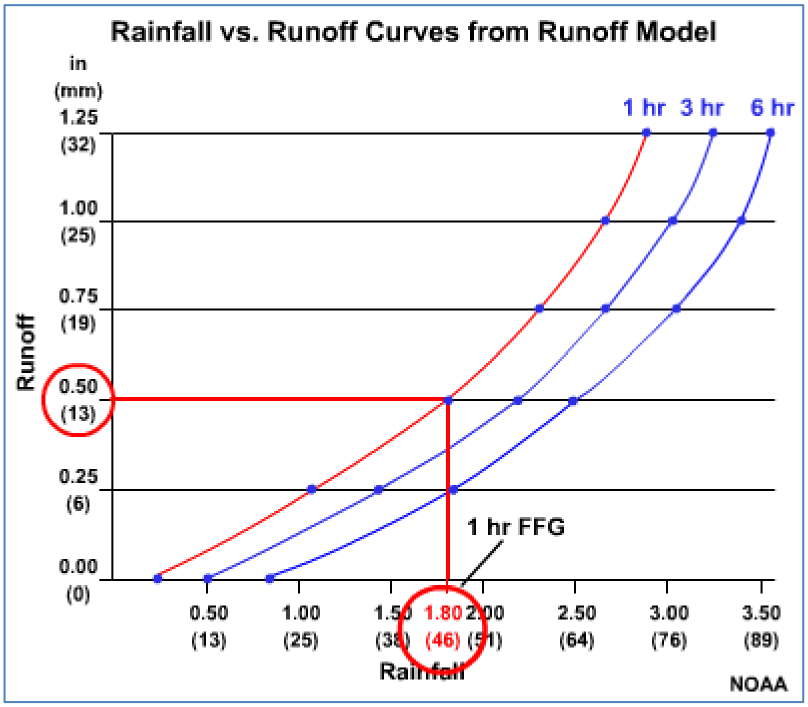


Figure 2.10: Example rainfall-runoff curves for 1, 3, and 6 hour durations calculated for a specific soil moisture deficit for a specific FFGS basin (Source: COMET, 2010). The 1-hour FFG is determined by relating the threshold runoff (i.e. runoff that will cause bank full flow at the catchment outlet) with the rainfall through these curves for the given soil moisture deficit.

Threshold runoff calculations assume natural stream channels, and therefore do not apply to modified channels and river sections. Fire-burn areas temporarily modify the runoff characteristics of a catchment, which cannot be taken into account by the FFG model system assuming the natural conditions. Similarly, streams that are channelled are still treated by the FFG model system as if they were natural streams, and therefore the modelled FFG values will be unrepresentative and considerably higher in these cases than should be if channelling was taken into account. This applies for a very small number of streams (less than 0.1% of all the catchments in SAFFG), however, they tend to be important as they relate to urban flooding in cities with high impact to people and infrastructure. Reservoirs in streams also interrupt the geomorphologic relationships and therefore basins with reservoirs are excluded from FFG calculations.

2.5.7 Determining flash flood threat

To determine whether a flash flood is imminent in the particular catchment or not, the most recent rainfall estimates (MAP) must be compared with the corresponding period's flash flood guidance value (FFG). Areas with excess rainfall, i.e. where the observed rainfall amount is larger than the FFG value (positive flash flood threat – FFT), are potentially experiencing a flash flood. Maps of the basins with positive FFT provide spatial insight into potential problem areas (see example in Figure 2.11b). Similarly, if a nowcast of MAP for the next few hours are compared with the similar period's FFG, then a potential for future flash floods up to the next 6 hours can be determined, and predicted FFT maps can be prepared. In the SAFFG and SARFFG nowcast MAP is produced through persisting the previous 1, 3, or 6 hours accumulated rain for the next 1, 3, and 6 hours respectively. In general convective conditions this is mostly not a representative forecast since convective storms tend to move relatively quickly. During strong synoptic forcing the persisted rainfall nowcast has more value and tend to produce useful FFT values for the next few hours.

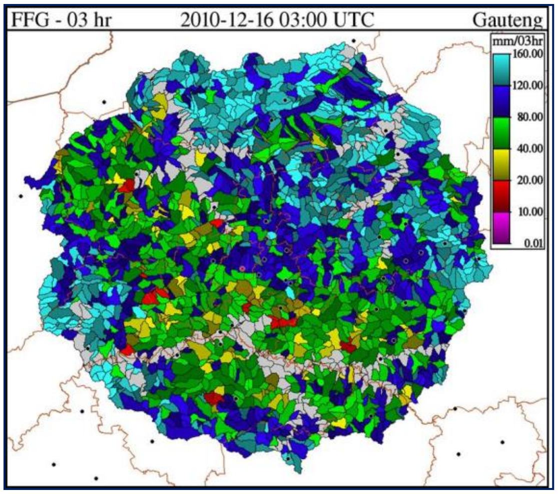


Figure 2.11a: 3-hour flash flood guidance (FFG) from the SAFFG for the same area and date as in Figure 2.8a.

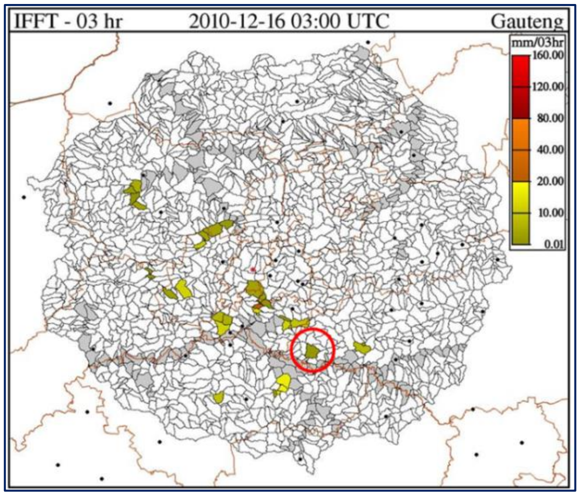


Figure 2.11b: 3-hour imminent flash flood threat (FFT) from SAFFG for the same area and date as in Figure 2.8a. The basin circled in red is elaborated on in Figure 2.12.

As an example, a graphical presentation of how the main relevant parameters in the SAFFG evolved hourly in a flash flooding situation in a SAFFG basin southeast of Johannesburg on 15 and 16 Dec 2010 is provided in Figure 2.12 (see also the red circle in Figure 2.11b). The response of the SAFFG parameters to the heavy rain (the red line MAP06) is quite evident both for the first rain episode 2-8 am local time on the 15th, and the second rain episode from 8 pm on the 15th to about 14 pm on the 16th. The soil moisture saturation level (ASM_Perc in top green line) jumped twice to higher saturation levels with each of the rain episodes. The FFG06 dropped with both rain episodes to just under 40 mm around 2 am on the 16th of December. Between midnight and 08 am on the 16th the red MAP06 line rose above the blue FFG06 line, indicating that more rain was received on average in that basin than needed for minor flooding to occur, as indicated by the rise of the purple FFT06 line. This was the danger period for this basin reaching a peak at about 3 am when the FFT06 indicating excess rain (also indicated by the red line MAP06 above the blue FFG06 line) was at its highest.

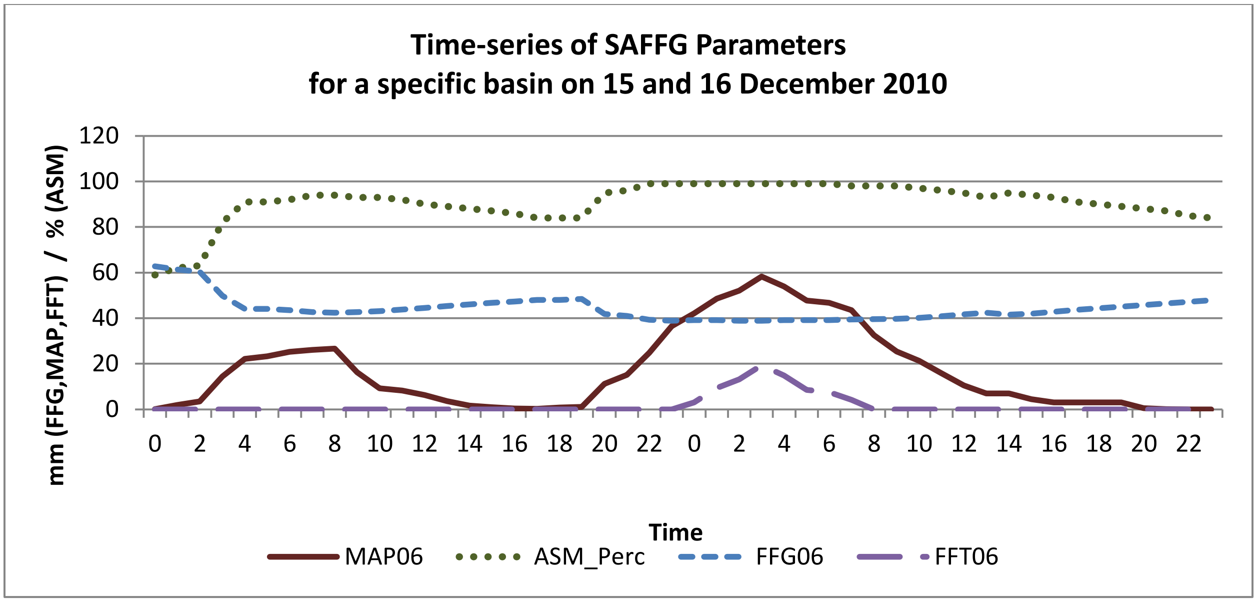


Figure 2.12: A graphical representation of the four main parameters of the SAFFG as they evolved during the flash flood event of 15/16 December 2010 for a specific basin in Dipaleseng Local Municipality. ASM_Perc is the top layer soil moisture percentage saturation, MAP06 the 6 hour accumulated MAP as observed by SAFFG from radar data, FFG06 is the 6-hour flash flood guidance, and FFT06 is the 6-hour flash flood threat if the MAP06 of the previous 6 hours is persisted for the subsequent 6 hours. (Source: Developed for this thesis from SAFFG data by Poolman, 2013)

2.5.8 Application of FFGS within the flash flood warning system

The SAFFG modelling system runs on a computer server at the SAWS head-office in Pretoria. Radar, satellite and rain-gauge information is ingested into the model every hour for the previous 1, 3 and 6 hours, and the relevant soil moisture, FFG and FFT products are prepared as text format data for each basin, and graphical maps for the national domain covered. These text format data are then disseminated to smaller computer servers in the regional offices in Cape Town, Port Elizabeth and Durban where regional graphical products are prepared. Forecaster display systems are hosted on all the computers that provide access to forecasters to all the relevant products.

FFGS is a diagnostic system for flash floods and not a predictive system in itself (Georgakakos, 2004). It models the response of small catchments to rainfall, and provides guidance information to forecasters that was not available previously on the likely hydrological response of small river basins on predict rainfall. They use the SAFFG products with forecasts or nowcasts of precipitation to assess the potential for flash flooding during a rain event, and if necessary issue warnings for flash floods. Since flash floods are local in nature with a very short lead-time, it appears to be best if forecasters in the regions can assess the SAFFG guidance together with other local operational information such as rainfall reports, river-level reports and even phone calls from the public or disaster managers.

During the roll-out of the SAFFG, forecasters were trained on basic hydrological concepts, and on the operation of the system. Workshops were also conducted with disaster managers and hydrologists in the affected regions to inform them about the system and its strengths and weaknesses.

2.6 SUMMARY

In this chapter an overview of early warning systems in general, and the developments around the South African flash flood warning system in particular has been provided. The main hydro-meteorological modelling system in the South African flash flood warning system is the SAFFG and SARFFG. The SAFFG will also be one of the main contributors to the impact model developed in SWIFS and described in Chapters 4 and 5. Therefore, a more detailed description of the SAFFG modelling system was provided as a backdrop for Chapters 4 and 5, based on the accounts provided in Georgakakos (2004, 2006), Ntelekos *et al*. (2006) and Sperfslage *et al*. (2010).

The main conclusions derived thus far in this chapter are:

- Flood disasters have the most adverse impact of all natural disasters in South Africa to people, their livelihoods and infrastructure. EWS are essential to save lives and property, and are far more cost-effective than relying on post-disaster response and recovery measures. Effective EWS provide useful information about approaching hazards well in time for the community at risk to take appropriate action according to a well prepared plan that can save lives;

- The potential increase of flood disasters due to societal changes and climate change drives the need to improve the EWS against flood and flash flood disasters. The associated increasing vulnerability to flood disasters requires timely dissemination of useful information to aid disaster management and vulnerable communities to take action to avoid or reduce the negative impact of a hazard;
- Attempts are being made to reduce flash flood disasters in South and Southern Africa through the introduction of the SAFFG and SARFFG systems as components of a flash flood early warning system. One of the main weaknesses of the SAFFG and SARFFG systems as they are implemented is their inability to provide relevant information at an extended lead-time beyond 6 hours to disaster managers to foster early preparedness against possible adverse impacts. A precipitation predictive element using numerical weather prediction systems and taking into account forecasting uncertainty could address this challenge and is the objective of Chapter 4;

In the conclusions of the Third International Conference on Early Warning held in 2006 in Bonn, Germany, Jan Egeland, the Under Secretary General for Humanitarian Affairs of the United Nations, summed it up: *"Mankind will never be able to master natural hazards – they will continue to strike, as we have seen in recent years, despite the increased sophistication of technological means. But, by being better prepared and by devising realistic and practical early warning mechanisms for all communities, we will decrease the risk of hazards turning into disasters*" (ISDR 2006a, p 5).

Developing "practical early warning mechanisms", as Jan Egeland stated in the previous paragraph, require, among others, an understanding of forecast uncertainty, and how it affects decision-making by users such as disaster managers. Forecast uncertainty is an inherent feature of weather and hydrological forecasts, which are major components of Impact Forecasting. The question is, how should forecast uncertainty be quantified that it can add value to the eventual decision making processes of disaster managers? This topic will be addressed in the next chapter.

CHAPTER 3
DECISION MAKING UNDER FORECAST UNCERTAINTY

3.1 INTRODUCTION

Describing forecast uncertainty requires a clear understanding of the origin of forecast uncertainty and how it accumulates through an early warning chain. The impact of forecast uncertainty on users, and what their requirements are to effectively use forecast uncertainty in their decision-making processes, is discussed in this chapter as further background to the problem of impact forecasting. SWIFS will attempt to address aspects of forecast uncertainty in its development, as will be explained in subsequent chapters.

3.2 UNDERSTANDING FORECAST UNCERTAINTY

3.2.1 The origin of forecast uncertainty

Uncertainty is inherent in the forecasting of weather events and is an important factor to be considered when developing forecasting systems at all time-scales (WMO 2008a, NRC 2006, Morss *et al*., 2010, Morss *et al*., 2008) but is also posing a significant challenge to the provision of effective forecast information by weather services to their user community. Forecast uncertainty is even a larger challenge for rare events which occupy a small scale in space and time and involve high impact severe weather events like thunderstorms (e.g. tornadoes, hailstorms), gales and local heavy rain (Murphy, 1991). These events can have a tremendous impact on societies, economy and the environment, but they tend to be under the most complicated weather phenomena to predict skilfully with high specificity in time and space.

Thus, what is forecast uncertainty?

Forecast uncertainty stems from chaos theory and the non-periodic nature of the atmosphere as described by Lorenz (1963, 1969a, 1969b) in what is popularly called the butterfly effect

(Palmer, 2008). The butterfly effect states metaphorically that the flap of a butterfly's wings in Brazil may set off a tornado in Texas. Lorenz, a pioneer of chaos theory, found that small differences in the initial state of a repeated weather forecast may result in large variations in the long-term behaviour of the predicted weather systems compared to the first forecast (Lorenz initially used the metaphor of the flap of a seagull's wings changing the course of weather). Thus the predicted behaviour of weather systems is very sensitive to the initial conditions, or the accurate observation of the atmosphere's condition at the initial state. As a simple example, a ball on a hill may roll to a different location or valley if it is put on a slightly different initial position on the hill a second time. Similarly, adding an observation of temperature or wind to the initial set of observations describing the atmosphere at the beginning of a numerical forecast cycle may result in completely different behaviour of the weather systems and consequently the related weather phenomena (Lorenz, 1963, 1969a). The forecast thus cannot be deterministic, for example predicting the same exact temperature at a location, with every subsequent forecast from slightly varying initial conditions is not possible. It would be similar to adding another bump in the path of the ball rolling down the hill, changing its direction even slightly.

Lorenz (1969b) also found that this initial difference (or error) between the two forecasts can be confined to the smallest scale growing rapidly in a very short time, and at the same time inducing differences or changes at slightly larger scales where these will grow slower. These differences in turn will cause changes at even larger scales where they again will grow although at a slower rate. Hence, the notion that the flap of a butterfly's wings may set off a tornado does not imply the butterfly is directly responsible for the tornado, but it might cause small changes in the larger atmospheric patterns which eventually, through a chain of events and up-scaling of the errors, may result in large-scale weather conditions, which in turn could cause a tornado elsewhere. It also implies that, on the one hand, a small error in estimating the strength of a thunderstorm could amplify the error in forecasting it within the lifecycle of the thunderstorm, for example an hour, but this error may have a feedback to the larger-scale synoptic weather system causing an error that may amplify only within a day or two. On the other hand errors on the larger scale will quickly result in errors on the smaller scales which can have significantly different consequences on the weather experienced by man. From this it is clear that atmospheric predictability is limited, and its boundary will differ for different scales of weather phenomena as described above. Beyond this predictability boundary the forecast becomes random since the errors will become larger than the resolvable scale of the phenomenon itself.

Thus, forecast uncertainty refers to the fact that a single deterministic, perfect forecast of future weather patterns cannot be made from an imperfectly observed atmosphere (Lorenz, 1969b). In fact, from Lorenz's discussion it is clear that reasonable deterministic forecasts are only possible for the next few days, beyond which the amplification of the forecast error may effectively render the forecast worthless. He attributes the inability to deliver perfect forecasts to three basic reasons:

- The governing set of physical laws describing atmospheric behaviour is not strictly deterministic;
- Furthermore, these laws are not perfectly known;
- The atmosphere cannot be perfectly measured, in other words it is impossible to know the temperature or wind at every point of the earth's surface and in the free atmosphere at the initial time of the forecast.

Important consequences of these results are that any single weather forecast cannot be reliable without an indication of the error, or forecast uncertainty, or reliability (NRC 2006, Murphy 1991, Palmer 2008, Toth *et al*. 2007). In the NRC (2006, p6) report on communicating forecast uncertainty, the authors state that "*uncertainty is a fundamental characteristic of hydrometeorological prediction, and no forecast is complete without a description of its uncertainty*".

Another important consequence of these results is that whereas larger-scale weather patterns (cold fronts, low pressure systems) can be more accurately predicted deterministically over longer time-scales of days (since the forecast error amplifies slower), smaller weather phenomena such as thunderstorms, heavy downpours etc., are less predictable at the same timescales (since errors at the smaller timescales grow much quicker). Thus, as the scale of the phenomenon (tornado, flash flood) gets smaller, then the effective deterministic forecasting timescale becomes shorter.

Over the last couple of decades, weather forecasting science has developed improved forecasting technology (Toth *et al*., 2007) to quantify weather forecast uncertainty by means of ensemble prediction systems (EPS). In this way, forecast uncertainty information has become available that can facilitate improved decision making by users of forecasts. This has developed into an important area for research and development, and many weather services are increasingly considering EPS information in their forecasting processes (Tennant *et al*., 2007). What is lacking generally is the integration of this type of forecast uncertainty information with uncertainty information elsewhere in the decision-making chain outside the realm of meteorology (as shown in Figure 3.1), and effectively transferring it to the user in an understandable way (NRC, 2007).

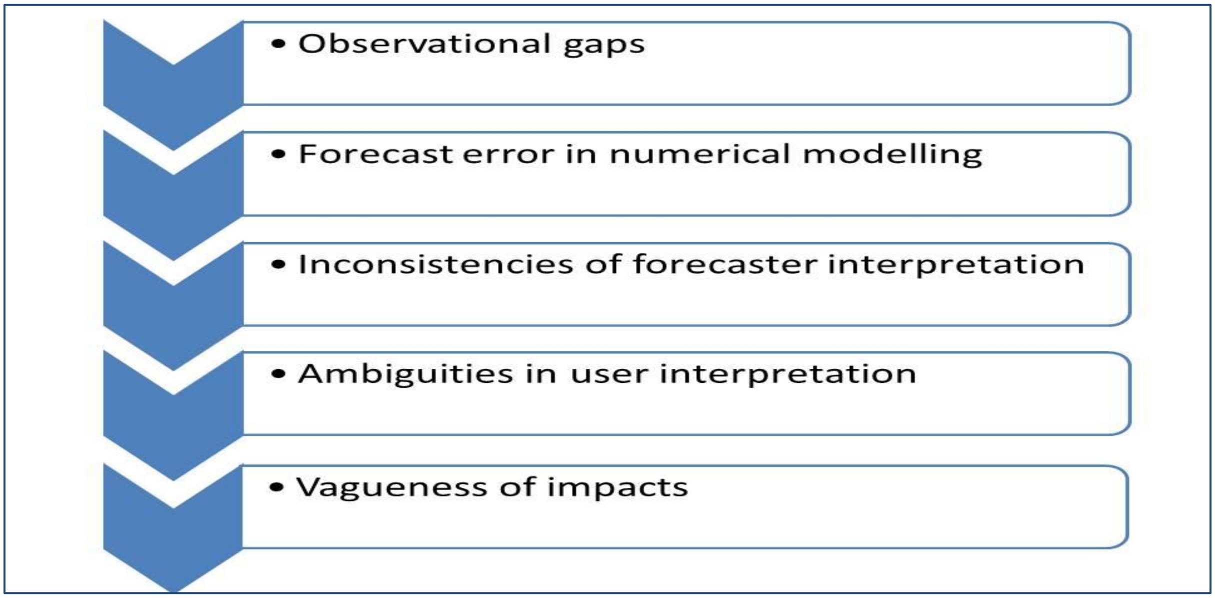


Figure 3.1: Uncertainty accumulation through the warning chain.

From the previous discussion, the problem of forecast uncertainty has its roots in the earliest parts of the warning chain, and it is compounded with additional uncertainty features with each successive link in the warning chain. The uncertainty therefore arises from atmospheric observations, forecast errors by Numerical Weather Prediction (NWP) models in an atmosphere with limited predictability, inconsistency in the interpretation of NWP forecasts and data by forecasters, the way in which forecasts are composed, and from user interpretation of the forecast (WMO 2008a). Golding (2009), for example, argues that to understand flood risk it is important to understand the accumulation of uncertainty from the initial hazard (for example the rain storm) through the disaster chain to the impact itself (inundation process) (Figure 3.1).

The following sections will elaborate briefly on uncertainty features within the main components of the warning chain.

3.2.1.1 Uncertainty in observations

The forecasting process for floods and flash floods requires good measurement of the rainfall in real time. Collier (2007) summarized the features of the rainfall measurement from rain-gauges, radar or satellite observations in terms of flood forecasting. In this summary rain-gauges are shown to provide the most accurate measure of rainfall at a point (Collier, 2007). Their ability to accurately capture areal rainfall, however, is severely limited by the areal deployment density of rain-gauges. In many catchments this density is either very low or there are no gauges. This is a particular problem in South Africa, and even worse in other countries in southern Africa where real-time rainfall measurement through rain-gauges is limited (Terblanche *et al*., 2001). The result is poor areal rainfall accuracy, particularly when heavy rain of localised convective systems leads to flooding.

Weather radar is capable of providing remotely sensed rainfall measurements over large spatial areas in real time from a single location (Terblanche *et al*., 2001; Collier, 2007). Compared to the direct measurement of rain at a point by a rain gauge, however, weather radar provides indirect measurement of rain by a statistical relationship between measured reflectivity and rainfall. Errors can arise from the so-called “bright band”, anomalous propagation and ground clutter, among others.

Similarly satellite rainfall estimation is an indirect estimation of rainfall through statistical relationships between cloud top temperatures, numerical model parameters and rainfall (De Coning *et al*., 2011). The value of satellite estimation lies in its large spatial coverage over areas sparsely populated by rain gauges where no radar coverage is available, typical of large areas in Africa. Unfortunately, the accuracy of satellite rainfall estimation is worse than radar. In an operational flash flood forecasting environment in areas with no radar coverage, however, real time measurements from geostationary satellites is the only source of rainfall estimation that can provide hourly rainfall estimations over a large area (De Coning *et al*., 2011; Collier, 2007).

Despite the inaccuracies of radar and satellite rainfall estimation, calibration through rain gauge data can result in quite accurate rainfall fields that can be used in flash flood modelling systems (Collier, 2007; De Coning *et al*., 2011; Georgakakos, 2011).

3.2.1.2 Uncertainty in numerical weather prediction and rainfall forecasting

NWP models are tools used in the weather forecasting process to predict the changes in weather patterns from an initial state into a future scenario (Warner, 2011). These models use weather observations to define a three-dimensional initial state of the model atmosphere in a way that is consistent with the data and the model dynamics. The observations are interpreted to the model grid points which could be a few kilometres apart. This implies there is a void between grid points where the model has no indication of the atmospheric properties. The NWP model at best therefore *approximates* the real atmosphere. Physical-based equations are then applied in discreet time steps of a few seconds to calculate the change of principal parameters such as pressure, temperature, wind and humidity from the previous state of the atmosphere into the future. In this process there is a variety of unavoidable sources of uncertainty, or forecast errors, as described in detail by Warner (2011) and summarized below.

These sources of forecast error can be divided into errors in the initial conditions, and errors of the modelling process:

- Initial conditions:
    - The incomplete description of the initial atmosphere on grid points (model resolution);
- Errors in the modelling process:
    - Lateral boundary conditions for limited area models;
    - Parameterization of physical processes such as rainfall generating processes and land/water surface conditions;
    - Numerical approximations used for the dynamical prediction.

Uncertainty in initial conditions arises from various sources, including instrument calibration errors, siting of instrumentation, appropriately representing the typical atmospheric conditions, and communication errors. Additional errors can be introduced through the data assimilation process that ingests the data into the model atmosphere.

For limited area models, lateral boundary conditions introduce errors from the larger-scale model through the process of linking the boundary conditions with the higher resolution limited area models. Errors in parameterization of physical processes arise from assumptions in the simulation of these processes. Errors associated with dynamical prediction include numerical approximations to accommodate the discrete space and time resolution in the model atmosphere.

These errors associated with dynamical processes tend to be initially largest at small scales, but affect larger scales such as mid-latitude weather systems after a few days. In Section 3.1.1 it was concluded that larger-scale weather patterns (cold fronts, low pressure systems) can be relatively accurately predicted deterministically over time-scales of a few days since the forecast error amplifies slower. However, smaller weather phenomena such as thunderstorms, heavy downpours etc., are less predictable at the same timescales (since errors at the smaller timescales grow much quicker).

Flooding is usually caused by rainfall which can result from atmospheric process at various spatial and time scales, such as tropical cyclones, mesoscale cloud systems, or small-scale thunderstorms which are too small to be effectively resolved by typical NWP systems (Golding, 2009). For this reason, Collier (2007) argued that high resolution NWP with a resolution of a few kilometres could produce useful forecasts of convective storms in future, but this will require assimilation of weather radar information. He emphasized that forecasts at the nowcasting level need to be probabilistic to capture model uncertainties.

3.2.1.3 Uncertainty in hydrological forecasting of flash floods

Various studies describe the uncertainty of flash flood forecasting based on hydrometeorological modelling systems (Carpenter and Georgakakos, 2004, 2006; Georgakakos, 2006; Ntelekos *et al*., 2006; Collier, 2007; He *et al*., 2009; Golding, 2009; Norbiato, 2009; De Moel and Aerts, 2011; Silvestro *et al*., 2011).

Uncertainty in hydrologic models is driven largely by runoff factors and the movement of the flood wave down the river channel (Golding, 2007). This relates to the impact of the flooding on debris flow and modifications of the banks and dam structures by the flooding. The shape of the river channel, channel characteristics and generalization of parameterization and input data contributes to the uncertainty (De Moel and Aerts, 2011). Uncertainties in the inundation process become important when the river banks are breached.

To deal with these uncertainties, hydrological models need to be carefully calibrated to fit the hydrographs produced from river gauge data (Collier, 2007). For ungauged streams calibration of the models becomes challenging and regression techniques have to be applied which increase the uncertainty in the modelling. The optimization process of models attempts to address uncertainties in the sets of observations against which the model predictions are matched.

From the arguments in Section 3.1.2.1, that flash floods are usually the consequence of smaller-scale weather phenomena, it follows that the predictability of flash floods is severely affected by the predictability of these driving weather systems. The fine scales needed for flash flood forecasting (basin size of on average 50 km^2) and the uncertainty in the hydrologic parameters and modelling at those scales amplify this problem, thereby limiting its deterministic predictability to nowcasting time-scales. Golding (2009) concluded that uncertainty of rainfall predictions are significantly larger than uncertainty in hydrologic models, particularly for smaller-scale flood events where the rain could fall in a different small catchment than predicted. Consequently if the flood forecast is based on rainfall forecasts, the rainfall forecasts will predominantly drive the uncertainty function compared to the hydrologic forecasts (Collier, 2007; Golding, 2009). Collier (2007) agreed that the quality of flood forecasts will be determined by the quality of the rainfall forecasts. Silvestro *et al*. (2011) confirmed this conclusion by stating that in the case of flood forecasting for small- and medium–sized basins uncertainty relating to hydrologic modelling is an order of magnitude smaller than the uncertainty within the rainfall forecast. He *et al*. (2009) found that uncertainties of precipitation input also dominate flood forecasting in larger river basins.

Addressing the problem of forecast uncertainty in an integrated, hydrometeorological system such as the SAFFG is a complex process. Eventual forecast uncertainty in the SAFFG system is a combination of uncertainty associated with different model elements throughout the chain from data integration and model components to the eventual presentation and use of forecaster products by the disaster manager. Table 3.1 proposes a high-level overview of the major uncertainty components in the SAFFG modelling chain as deduced from the discussion in this section, the likely sources of uncertainty in each component and how it can be, or are, mitigated to minimize overall uncertainty as far as possible. The hydrometeorological modelling concepts of the FFGS are described in detail in Section 2.5. Ntelekos *et al. (*2006) discuss the uncertainties associated with the FFGS. The following summary is based on their discussion.

The precipitation input into the FFGS is based on rainfall estimation of either radar and satellite (in the case of SAFFG) or satellite only (in the case of SARFFG), both bias corrected using rain gauge information. Considerable errors are associated with both radar and satellite rainfall estimation (see also De Coning and Poolman, 2011) since both are indirect measurements of rainfall. Radar precipitation estimation is calculated from the intensity of the reflection of the radar beam using relationships such as the Marshall-Palmer equation. In the case of satellite precipitation, however, estimation depends usually largely on the cloud top temperatures. Other components of the FFGS that contribute to the uncertainties in the system include the inherent uncertainty in the data used for basin delineation and basin hydrological feature representation. Soil moisture modelling and runoff modelling also add to the uncertainty.

Threshold runoff is a critical parameter in the FFGS, used to determine the FFG value itself (see Section 2.5 for detail). Determining the threshold runoff value for each basin has to be based on a number of assumptions since the data required for its calculation, such as channel cross-sectional parameters, are not readily available and have to be determined from GIS (Geographical Information System) analysis or regional relationships with other catchment characteristics. These considerations lead to initial state uncertainty in the Threshold Runoff calculations.

Hydrologic modelling in the FFGS is based on the Sacramento soil moisture accounting model (Georgakakos, 2006). Uncertainty exists in the parameters of the hydrological model and initial conditions based on the uncertainty associated with spatial distribution of rainfall, and are larger during dry conditions than in wet conditions of the basin.

Through experimentation, Ntelekos *et al. ,* (2006) found that threshold runoff uncertainty is more significant than uncertainty associated with the hydrologic modelling. Of these the uncertainty associated with the channel top width, hydraulic depth, the drainage area and length of the main stream contributes most to uncertainty in threshold runoff. They concluded that more accurate measurements of these variables could reduce the uncertainty in the FFGS modelling.

Table 3.1: Major components of forecast uncertainty in the FFGS deduced from the information described in the text. (Source: various authors)

FFGS Component	Sources and impacts of uncertainty in the system modelling chain	Mitigation of uncertainty
1. Basin delineation and hydrological feature representation	Satellite resolution, quality of GIS information used for parameterization of basin and soil properties in 50 km^2 basins, assumptions regarding the stream cross section properties	Meticulous preparation of parameterization and basin properties using the best available information
2. Radar and satellite estimation of rainfall, and bias correction, calculation of mean areal precipitation (MAP)	Radar and satellite are both covering the basin with indirect measurements of rainfall bias corrected by actual point measurement by available gauges. Inherent quality of the radar and satellite information, including radar calibration, rainfall algorithms, etc., impacts on uncertainty.	Continuous efforts in improving the methodology and algorithms of rainfall calculations from remote sensing platforms. Technical care of radar, satellite and rain gauges.
3. Hydrological modelling of soil moisture and flash flood guidance	Inherent uncertainty in hydrological modelling parameters based on remote sensing information (channel top width, etc.), and spatial distribution of rainfall.	Careful adjusting of hydrological modelling during development phase
4. Prediction of rainfall for the next 6 hours and up to 24 hours	The system has no rainfall prediction capability, but uses persistence to provide a prognostic value for at the most the next 6 hours.	NWP based ensemble forecasting methods describe forecast uncertainty
5. Forecaster interpretation of SAFFG products	Forecaster ability to combine uncertainty of rainfall prediction with flash flood guidance (FFG) of required rainfall per basin.	Effective use of NWP as deterministic or ensemble systems.
6. Effective use of forecaster information and SAFFG products in decision making by disaster management.	Interpretation and understanding of forecasting products by disaster manager. The current complexity of SAFFG products hampers effective use in user decision making.	Tailored products to suit user decision making, addressing impact forecasting

In this thesis, the author has little choice but to assume a deterministic calculation of the FFG values in the FFGS, because the FFGS used were operationally implemented to produce deterministic FFG values. This study is mainly concerned with investigating forecasting of flash flood potential. From the conclusions presented in this section, it is evident that in the case of flash flood forecasting the uncertainty in rainfall forecasts overshadows the uncertainty associated with the hydrologic modelling (Georgakakos, 2005). Consequently the main focus will be an attempt to describe the rainfall forecast uncertainty in order to increase the lead time of flash flood potential from nowcasting to short-range forecasting timescales up to one day.

3.2.1.4 Uncertainty in the impact of hazards

Golding (2009) argued that the risk of an event depends on the probability of the occurrence of the event, and its impact in terms of deaths, people affected and damage of all possible outcomes. He further reasoned that the uncertainty of the event lies in its location, timing and intensity. Uncertainty of the impact of the flooding event (which depends largely on the depth and velocity of the water flow, rate of rise and the duration), however, also lies in the uncertainty of the source of flooding which is usually weather-related.

De Moel and Aerts (2011) highlighted four components of flood risk modelling, each contributing to the overall uncertainty. These four components are the flood hazard, elements at risk (such as accurate description of land use), the value of the elements at risk, and the sensitivity of these elements at risk to hydrologic conditions. The uncertainty concerning elements at risk relates to the generalizations in the data input such as land-use maps, limited land-use classes, different methods to determine the value of elements at risk, etc. They concluded that absolute estimates of risk display large uncertainty. Notwithstanding these limitations, proportional changes in flood damages, i.e. the change in flood damage as percentage of the base situation, however, are providing useful information.

3.2.2 Describing forecast uncertainty through ensemble prediction systems (EPS)

One way of describing forecast uncertainty arising from numerical modelling is through EPS (NRC, 2006; Toth *et al.*, 2007; Warner, 2011; Landman *et al.,* 2012). This applies both for meteorological and hydrological modelling. In EPS, a number of model configurations are run in parallel, each defining different conditions of the initial state based on the model errors described in Section 3.1.2.1. The purpose of this ensemble of model runs is to collectively describe as much as possible of the relevant uncertainty domain associated with the forecasts from the given set of initial conditions as illustrated in Figure 3.2. In this example each of the five ensemble model runs are represented by a different trajectory and started from a slightly perturbed initial set of observations. The dashed line would depict the so-called control run that was initialized with the most optimum analysis of all data. The solid circle in the final predicted domain resembles the mean of the ensembles. At the end of the forecast timescale the range of solutions differ more than they did at the initial time.

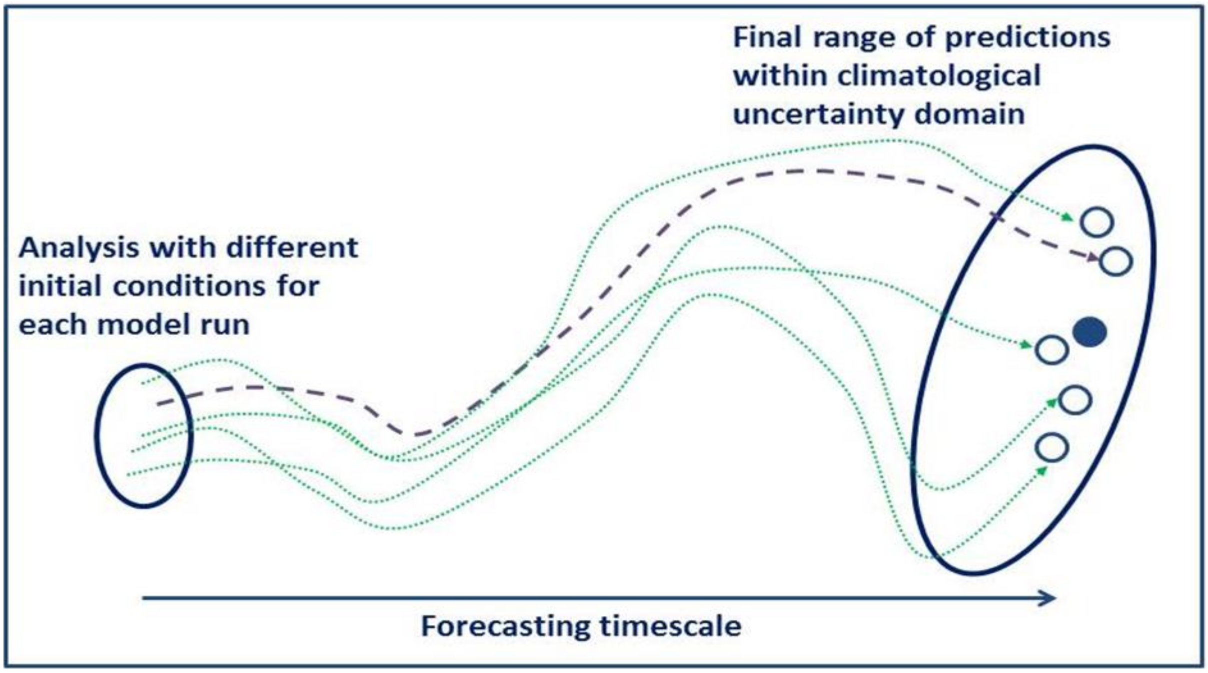


Figure 3.2: Schematic of model predictions in an ensemble prediction system. Details are in the text. Adapted from Warner (2011).

Studies (Warner, 2011) have shown that the ensemble mean is generally more accurate than the predictions of individual ensemble members, although this information is of little use without a description of the ensemble spread (Collier, 2007). Valuable information about extreme events can be gleaned from the Probability Density Function (PDF) of the frequency distribution of a forecast variable. Probabilistic information can be calculated from the relationships between ensemble members that can be an indication of uncertainty and confidence in the forecasts useful in decision supporting systems. The spread among ensemble members, or between consecutive EPS runs, are indicative of the consistency that can be attributed to a forecast (Collier, 2007). A smaller spread between EPS members or a smaller difference in forecast outcomes between consecutive runs implies more consistency and therefore more confidence in the predicted outcome. This is symptomatic of the existence of a more predictive atmospheric pattern, compared to periods when there are larger differences between members or EPS runs. Warner (2011) concludes that EPS is more useful than individual deterministic forecasts, and it is therefore not surprising that EPS has led to improved forecast skill. EPS has led to improvements in weather forecasting (Toth *et al*., 2007; NRC, 2006; Collier 2007; Warner, 2011*)* both at the medium range (longer than three days), and at the short range (less than three days). The challenge is to extract useful information from EPS.

3.3 THE PROBLEM OF FORECAST UNCERTAINTY FOR USERS IN EARLY WARNING SYSTEMS

3.3.1 Decision-making by disaster management during early warnings

Typically, disaster managers have to decide when and where to initiate proactive or response activities in the face of likely flooding or other weather-related hazards based on weather forecasts and warnings. Personal discussions invariably reveal that they do not want complex information, “just tell me what is going to happen, when, where and how serious it is”. However, probability information, linked to their particular decision making scenarios, will give the disaster manager far more valuable information to prompt his decision than a deterministic “rain” or “no rain” forecast with unknown uncertainty information.

Forecasters tend to unintentionally withhold valuable uncertainty information from users (Morss *et al*., 2008, 2010; NRC, 2006). In some cases forecasters argue that communicating uncertainty will negatively impact on their integrity. In this way a weather forecaster, to some extent, actually makes a decision for disaster managers instead of letting the latter decide at what uncertainty level he/she will react. This was typically the case in the Red River flooding in 1997 in the USA (Pielke 1999, cited in NRC, 2006, p112) when the lack of uncertainty information in the forecast, which could have made a difference, contributed to insufficient preparation of authorities and the general public. In this case, the forecasters provided a specific forecast of the expected peak of the flood wave, which turned out to be far lower than what was experienced. The city of Grand Forks, North Dakota, USA, prepared for the predicted height but had no information that a higher peak is possible. Severe flood damage occurred in the city. The damage could have been less severe if city engineers were told what the forecast error range was. This would have indicated the potential height above the expected forecast that the flood wave could have, and indeed had, reached.

3.3.2 User need for uncertainty information

The challenge of effective communication of forecasts is a growing concern of hydrometeorological communities. Various publications highlight the need for improving the communication of forecasts to enable users to make effective decisions in their particular environments (ISDR, 2005a; NRC, 2006; Vogel and O'Brien, 2006; Auld,2008; WMO, 2008a; Morss *et al.,* 2008; Demuth *et al.* , 2009; Golding, 2009; Joslyn *et al.,* 2009a, 2009b, 2010; Morss *et al.,* 2010). These users range from the person in the street to decision makers such as disaster managers and airline pilots. The level of sophistication of users implies different levels of requirements for weather forecast information, and particularly for uncertainty information.

More sophisticated users usually have a better understanding of the reasons for uncertainty, and will probably grasp how to use such information in their decision making processes (WMO 2008a). As scientists begin to understand the complexities of forecast uncertainty and find ways to quantify it through, for example, probability distributions from EPS, the question about the need for conveying uncertainty information has risen dramatically, prompting calls for more research around this topic. In the field of disaster management, the ISDR (2005a) also appeals for more research in developing user-friendly products, with attention given to forecast uncertainty in decision-making of disaster managers. According to Joslyn (2009b) some scientists argue that all public forecasts should have an indication of forecast uncertainty, and others question the kind of uncertainty information needed by the users. The reality is that very few forecasts provide any information on forecast uncertainty, apart from maybe the probability of precipitation (Roulston, 2006; Joslyn 2009b; Morss *et al*., 2010). Even after being exposed to probability of precipitation for many years, few users really understand what is meant by a 60% chance of precipitation. It is intriguing, however, how users unknowingly interpret deterministic forecasts with a measure of uncertainty. Morss *et al*. (2010) found in their study that when users are provided with a deterministic forecast of rainfall or temperature approaching a critical threshold, many of them will chose protective action even if the threshold has not yet been reached. Similar results were shown when 95% of respondents chose a range of temperatures around a given deterministic value as the most probable temperature expected (Morss *et al*., 2008). The authors' conclusions in these two cases were that these users interpreted the forecast with an uncertainty factor. This uncertainty, however, was interpreted differently between the respondents. It is clear that the real challenge lies in providing uncertainty information in such a way that it is understandable and makes a real difference to the decision-making context of the user (NRC, 2006).

There are various reasons why uncertainty information needs to be conveyed to users (WMO, 2008a; NRC, 2006). On a daily basis, users need to make decisions based on the weather forecast affecting their lives and livelihoods. Even though they may request a specific deterministic forecast, they still need to weigh their options for a particular action or different contingencies. Depending on the decision-making context, different users will also have their own thresholds of forecast uncertainty for the same forecast that will prompt a particular reaction. These differences also depend on their differing cost/loss scenarios (costs of protection or action versus the potential losses due to the impact of the event). Thus, different users have different needs for uncertainty in a forecast depending on their context, cost/loss and other decision-making considerations. Consequently, the overall conclusion of various studies (Morss *et al*., 2010; NRC, 2006; WMO, 2008a; ISDR, 2005a) is that users should receive all the uncertainty information they need to make their own decisions, rather than be provided with recommended decisions from forecasters with generalized thresholds. In basic terms: by keeping uncertainty information away from the user, forecasters are actually making decisions on the users' behalf.

Apart from improving decision making, forecast uncertainty information can help to manage user expectations and promote user confidence (WMO, 2008). Users generally expect that a forecast must always be correct. By providing a deterministic forecast (for example: the temperature will be 24°C) the forecasting community actually promotes such an expectation. Since some situations are, however, more predictable than others, there is a need for better information sharing to create more realistic expectations and understanding of the situation. That is why weather forecasters generally feel comfortable talking to a user face-to-face or on the phone where they can convey their confidence through their choice of words and the user can get a sense of the uncertainty of the situation. It is well known that users who receive uncertainty information openly and who have a better feeling for the inherent uncertainty in weather forecasting are more likely to have more confidence in the weather forecaster (WMO, 2008).

Despite the previous arguments in favour of providing uncertainty information, disaster managers sometimes argue that all they want is a simple answer and that they do not have the time to interpret results (WMO, 2008; Poolman, 2009). The question therefore remains if disaster managers really need and want uncertainty information for short-term weather forecasts to improve their decision making as argued by some authors (Auld, 2008; NRC, 2006), or should forecasters provide them with deterministic forecasts because that is what they want and need? This is a fundamental question that needs to be answered before we can investigate the format in which uncertainty information should be packaged for them. Morss *et al. (*2008) investigated this question as it applies to the general public. Their findings were that a significant majority of respondents could use uncertainty information, and that many preferred uncertainty information in some or other form in the forecasts.

3.3.3 Conveying forecast uncertainty information to users

There are various ways to convey uncertainty information to users. Probability of occurrence is many times viewed as if it is identical to uncertainty. This approach, however, is only one way of expressing uncertainty (NRC, 2006; WMO, 2008a). Various other means of expressing uncertainty may work better in different circumstances, or with different parameters, and with different user groups. Among these, are terminology ("chance of" or "possible"), and visual depictions in the form of graphs indicating the spread of possibilities, charts or maps, etc. Still, probability is a useful and, in some cases, an easily calculated way of expressing uncertainty, and therefore it is important to understand how it should be interpreted. This is a widely debated topic which cannot be dealt with exhaustively in this study.

Testing people's perception about their confidence in forecasts, Morss *et al*. (2010) found a variable response which implies that people have different perceptions about the uncertainty of forecasts. By providing uncertainty information to users, this variable response should be narrowed in order for users to have more explicit information to base their confidence levels on.

Morss *et al*. (2008, 2010), tested the use of probabilistic information as well as forecasting ranges in comparison with deterministic forecasts. They found that the ranges they tested did not significantly change the decision-making of many respondents compared to their subjective interpretation of uncertainty associated with deterministic forecasts as the latter approaches a threshold. When provided with probabilities of exceeding the threshold, however, more respondents adapted their decision making and took protective action as the probabilities increased. They also found that few people correctly interpreted probability of precipitation, either given as a percentage (60% chance of rain tomorrow) or in worded format (rain likely tomorrow). They concluded that, although many community members do not necessarily understand probabilities correctly, they still find value in such forecasts through their own interpretation. Thus, it is more important that the forecast probability can be used by the user in his decision-making than to accurately understand the meaning of probabilities.

Consequently, it still is an acceptable way of conveying uncertainty in daily forecasts as tested in their studies (NRC, 2006).

Morss *et al*. (2008) investigated different ways of conveying precipitation and temperature uncertainty information. A particularly interesting test was where they provided respondents with three different uncertainty interpretations of bi-modal temperature forecasts under two sets of different explanations: one set explaining that a cold front may modify the conditions, and the other set without this added explanation. Those respondents that received the additional explanation clearly preferred a non-percentage (i.e. worded such as "most likely 30°C but may be 25°C") explanation of the uncertainty above a percentage format (such as "80% chance of 30°C and 20% chance of 25°C"). This result points towards the importance of providing additional information to explain a situation and thereby providing context to the numerical values. They also found respondents would prefer probability being provided in precipitation forecasts, but not necessarily in temperature forecasts. This could be due to their familiarity to probability of precipitation (being provided for decades) compared to the deterministic way temperature has been conveyed. Alternatively, it could point towards different decision-making needs for different parameters.

In another study Joslyn *et al*. (2009b) concluded that it is important to understand the psychological aspects of how the user understands uncertainty and his decision making processes. Typically a decision maker needs to consider various potential outcomes when presented with forecast uncertainty, each with a particular level of uncertainty and impact. They argued this is especially difficult where quick decisions are made, since the human capability limits the number of factors that can be processed simultaneously. This may provoke a counter effect where the uncertainty is ignored and the forecast interpreted deterministically.

It is clear, however, that more research is needed to understand how weather forecast uncertainty should be utilized and packaged in more user-oriented products to enable more sophisticated users to make more effective decisions. Moreover, as described in Section 3.2

the only way to extend the lead-time of warnings effectively is by adding an uncertainty component into the information, particularly for small-scale phenomena such as flash floods.

3.4 INFORMATION NEEDS BY DISASTER MANAGEMENT

3.4.1 Decision making relating to uncertainty

In order to develop appropriate user products for disaster management structures, it is necessary to have some understanding of their decision making processes and decision support systems. In preparation of the implementation of the SAFFG, capacity building workshops were conducted in 2009 with four groups of disaster managers in the Cape Town, George, Port Elizabeth and Johannesburg (Poolman, 2009). The report of this capacity building activity involving 67 disaster managers and their support personnel (such as GIS experts, local fire chiefs, etc.) from predominantly municipal disaster management centres provides useful insight to disaster management decision making and their needs regarding flash flood warning products.

The majority of disaster managers in these sessions, on the one hand, conceded that they should rather be prepared for an eventuality, and stand down when it does not occur, than risk not being prepared when a potential hazard strikes. They can live with a false alarm, but do not want an event to be missed and be unprepared. Supporting staff, on the other hand, do not have to make life-saving decisions and have a different opinion: they do not want false alarms, and prefer that the forecasters wait until they are quite sure before issuing a warning, in the process sacrificing lead-time (see Figure 3.3). Their view is that false alarms will eventually lead to people not believing the warnings. The disaster managers did not share this concern regarding their own decision making, and they seem to have a better understanding of the complexity and uncertainty associated with forecasting.

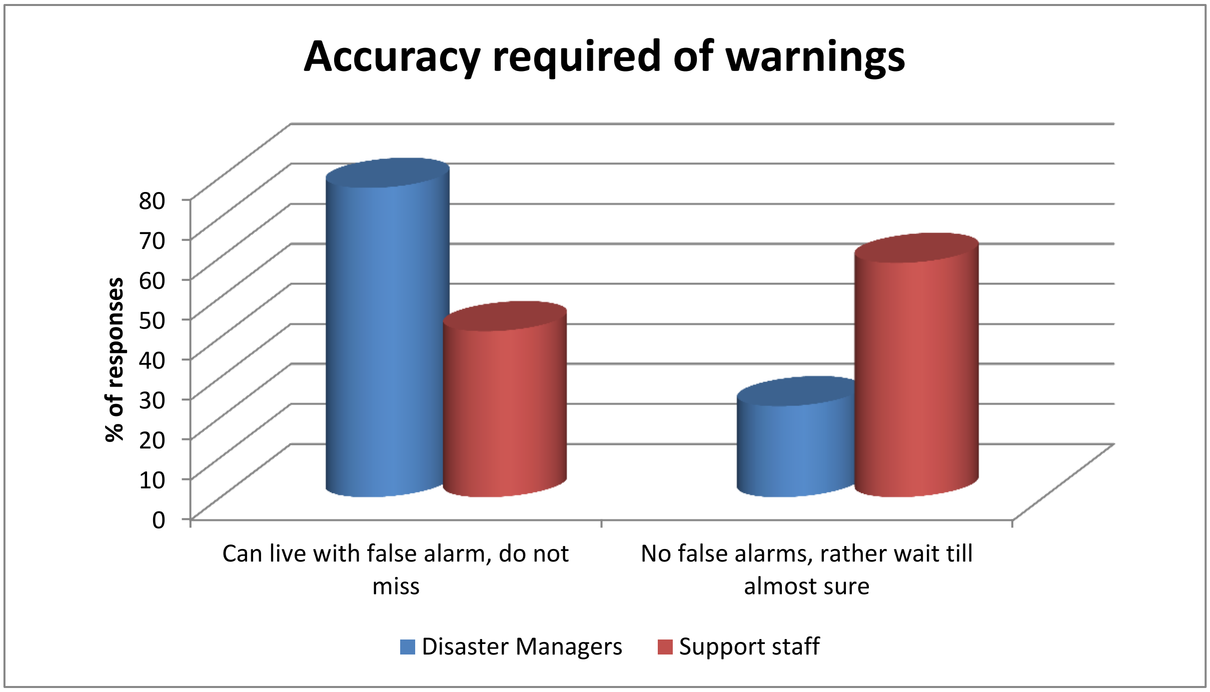


Figure 3.3: Responses from disaster managers versus supporting staff on the issuing of warnings with longer lead-time at the risk of higher false alarms (left) or issuing warnings with a short lead-time but with high accuracy (Poolman, 2009).

The vast majority (more than 94%) of both disaster managers and support staff were positive about their own ability to use probabilistic information on flooding two or more days in advance in their particular decision making environment. Their preferred threshold for action was 60% (47% of the respondents) with 30% probability regarded as their threshold by 30% of the respondents. Although this report did not elaborate what disaster managers understood by a 60% probability, Morss *et al* (2010), however, concluded that even though many people may not interpret probability information correctly, they still are able to use it in decision-making within their own contexts.

3.4.2 Decision making relating to consequences and impacts of floods

Disaster managers have to be prepared to deal with a variety of consequences of flash floods during an event. In a study for the Water Research Commission at four Municipal Disaster Management Centres in the Western Cape Province (Poolman, 2013) the impacts of flood disasters and related decision making processes were highlighted:

- For all Disaster Management Centres (DMCs) deaths and disruption of people's livelihoods are the biggest impact of flooding;
- In the Cape Town metropolitan DMC, the major issues are road flooding due to, among others, storm water system problems that result in traffic problems, and ponding (rising water tables) that flood informal settlement houses and roads. They also experience problems with mudslides and rock falls in Constantia and the Chapman's Peak area;
- For the rural DMCs, major issues were road flooding and bridges being washed away that lead to farms to be isolated for short periods (Holloway *et al.*, 2010). In many cases this lead to the evacuation of small communities, or the need for relief operations, often through the expensive involvement of helicopters;
- In all cases, adverse impacts to schools and hospitals are a major concern;
- Another important impact for the rural regions was damage to agriculture and associated communities (E.g. farmers, labourers, etc.).

These impacts require specific decisions to be made at various times prior and during a flash flood alert. Following a flood advisory, 1 – 2 days prior to receiving a flood warning, DMCs advice municipalities to clean storm water systems and road departments to inspect their problem areas. It is also important at this time to inform the administrative heads of municipalities, and generally to create awareness of what can happen in the event of a severe rainfall event. The request is "rather provide too much data, and do not miss the event". Information needed for the above mentioned preparation activities include:

- A heavy rain watch issued at least at the spatial scale of Local Municipality (LM);

- Historical information of similar events to define typical impacts;
- Reaction measures on the web;
- An indication of which specific areas are more under threat.

When a warning is received, which implies that flooding is imminent within the next few hours, various additional activities take place. DMCs pass the warnings on to municipalities, line departments, emergency services including traffic departments and police, defence force, the general public, media and the agriculture sector. Causeways, bridges and roads are closed where necessary, helicopters are put on standby, people alongside rivers are warned to take the necessary action, and preparations are made for possible evacuation. At this stage the lead-time is limited to a few hours for critical decisions to be made by disaster managers. Information needed include:

- Warnings and updates at LM level that are meaningful, for example the location, severity, duration and expected dissipation of hazardous event;
- Information at micro level (ward) regarding where flooding could occur, rain amounts and intensity;
- Flash flood potential and likely impact of the event for small basins;
- Information on the impact over mountainous areas;
- Satellite and radar imagery showing position and movement of weather system;
- Rainfall information in real-time;
- Access to information in a user friendly format, that could also easily be used (cut and paste) for onward sending to other decision makers.

3.5 SUMMARY

The problem of forecast uncertainty, and how it affects user decision making processes, has been discussed in this chapter. Forecast uncertainty poses a real threat to any prediction system and has to be taken into account right through the entire warning chain. This includes all the hydro-meteorological modelling components, human factors and impact determination.

In the case of flash flood systems, however, the dominant component is rainfall forecasting. EPS and probabilistic forecasting are useful to provide information on the uncertainty of a forecast which can be used to allow more effective risk-based decision making during flash flood events (Sene, 2008).

The main conclusions derived in this chapter are:

- Uncertainty is inherent in the forecasting of weather events and is an important factor to be considered when developing forecasting systems over all time-scales (WMO 2008a, NRC 2006, Morss *et al*., 2010, Morss *et al*., 2008). The problem of forecast uncertainty has its roots in the earliest parts of the warning chain, and it is compounded with additional uncertainty features with each successive link in the warning chain;
- Uncertainty of rainfall predictions are significantly larger than uncertainty in hydrologic models (Golding, 2009), particularly for smaller-scale flood events where the rain could fall in a different small catchment than predicted. Consequently if the flood forecast is based on rainfall forecasts, the rainfall forecasts will predominantly drive the uncertainty function compared to the hydrologic forecasts (Collier, 2007; Golding, 2009);
- As the scale of the phenomenon becomes smaller (e.g. tornado, flash flood), the effective deterministic forecasting timescale becomes shorter. To increase the lead time of flash flood potential from nowcasting to 24 or 36 hours, it is important to provide a description of the forecast uncertainty. One way of describing forecast uncertainty is through probability information determined from EPS (NRC, 2006; Toth *et al*., 2007; Warner, 2011; Landman *et al.,* 2012). Probability information can provide the disaster manager with far more valuable information to prompt his decision than, for example, a deterministic “rain” or “no rain” forecast. The real challenge lies in providing uncertainty information in such a way that it is understandable and makes a real difference to the decision-making of the user (NRC, 2006);
- Even though many disaster managers do not explicitly request uncertainty information, various research results provided overwhelming evidence that their decision support

systems require some kind of expression of forecast uncertainty to be able to make useful decisions.

All of the above relates to the basic question of disaster managers (Poolman, 2013): with reference to a weather-related hazard, what is going to happen, where and when, and what will the impact be? This relates to the problem of distinguishing between the likelihood and level of impact of flash flood threats in unpopulated areas versus those in populated areas. Description of this likelihood and level of impact early enough will provide significant support to the decision making processes of disaster managers regarding the level and location of intervention. An attempt is made in this thesis to provide support to disaster managers by developing an impact forecasting system of the likelihood of impacts of flash floods with extended lead-time. Chapter 4 investigates a precipitation predictive element using numerical weather prediction systems taking into account forecasting uncertainty. Chapter 5 describes the link between a predictive component with the identification of the likely impacts based on the distribution of societal and infrastructure related vulnerability.

CHAPTER 4

INCREASING THE PREDICTIVE LEAD-TIME OF FLASH FLOOD GUIDANCE

4.1 INTRODUCTION

A flash flood *impact forecasting* system such as SWIFS requires integration of two main components: (1) future *forecasts of the potential of flash floods*, and (2) information on the *impact of flash floods* on people and their living environment. This chapter will focus on the first element, namely forecasting of the potential of flash floods in the SAFFG river basins with a lead-time of up to 18 hours. Chapter 5 addresses the second element, the identification of impacts related to potential flash floods and their integration with forecasting of future flash floods.

The SAFFG is designed as a nowcasting system and it does not provide flash flood guidance information on potential flooding in small river basins beyond the next 6 hours (see description of SAFFG in Chapter 2). As discussed in Chapter 3, disaster managers have a need for an extended lead-time on warnings to make critical preparedness decisions. Sene (2008) is of the opinion that this is particularly necessary when the catchment response time is less than the reaction time of disaster managers, which is often the case in flash flood situations. In these situations, additional lead-time is quite important. The issuing of warnings must be triggered early enough to allow the warning to reach users with enough time to implement preventative measures such as evacuation, closing of river crossings or installing flood barriers. Extended lead-time is also important to develop "*What if?*" scenarios for operational decision-making.

Rainfall information is the key dynamical input into the SAFFG modelling system that affects the soil moisture state, and thus the eventual flash flood guidance value (see Chapter 2 for more detail on the SAFFG modelling process). Consequently, rainfall forecasts could be used to extend the lead-time of flash flood warnings (Sene, 2008). The challenge is, however, to forecast accurately the amount of rain likely to fall in the next 18 hours over the small river basins used in the SAFFG. Another challenge is to project the FFG values from the SAFFG system to the next 18 hours. These projected values per basin can then be compared with predicted MAP for corresponding durations over each basin (Figure 4.1). Basins where rain in excess of the FFG value is forecast (i.e. more rain is expected to fall than is required given the state of soil moisture) could then be deemed to be in potential danger of flash flooding in the next 18 hours. If an indication of the uncertainty of this expected rain could be determined then the likelihood of flooding in a particular basin could be expressed to provide for uncertainty in the forecast as described in Chapter 3. By combining this uncertainty of expected rain with the number of FFG basins, with an excess of forecast rain relative to all basins within a Local Municipality (LM), the uncertainty of the entire episode could be expressed as the likelihood of flash flooding within a LM. These options need to be explored.

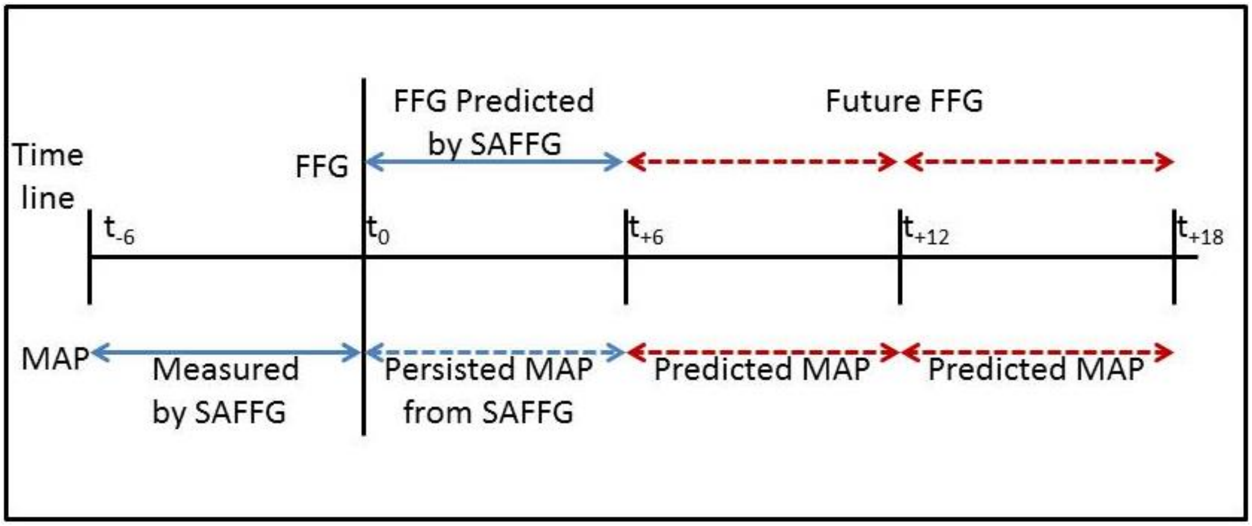


Figure 4.1: A schematic presentation of the timeline of events in the SAFFG. Time t0 is the initialization time of the models, and tn is the time at n hours before or after t0. At time t0 the MAP of t-6 - t0 measured through the SAFFG system is used to calculate the forecast FFG field for t0 - t6. This MAP is then also persisted for the t0 - t6 period to compare with forecast FFG to identify basins where the likelihood for rain to be in excess of the FFG rain exists, indicating potential flash floods.

Rainfall forecasting is one of the most difficult tasks in the science of weather prediction due to the variability and the complexity of the physical processes related to rainfall, and the need for accurate forecasting of other variables it depends on (Stensrud, 2007). Forecasting of rainfall up to 6 hours ahead used to be based on extrapolation techniques or statistical modelling using radar data (Collier, 2007; Sene, 2008). Another approach is based on subjective forecasting by a forecaster based on heuristic rules and conceptual models developed from meteorological principles (Collier, 2007; Davis, 2001). This is the more traditional approach used by forecasters over decades using the skill and experience of forecasters with little guidance from NWP models. Both these approaches have serious limitations due to over-simplification of the atmospherics physics and dynamical processes. A more objective way of dealing with this problem is by means of NWP models that forecast rainfall based on model physical principals (Theis *et al*., 2005; Collier, 2007; Lean *et al*., 2008; Sene, 2008; Golding, 2009; Warner, 2011; Landman *et al*., 2012). As discussed in Chapter 3 and by Sene (2008), however, uncertainties associated with these NWP systems need to be taken into account.

4.2 FORECASTING RAINFALL USING NUMERICAL WEATHER PREDICTION SYSTEMS

4.2.1 General concepts

The science of weather forecasts has developed significantly over the past decades with most of the improvement of skill due to the development of NWP models (Stensrud, 2007; WMO, 2009). The grid resolution of NWP systems has decreased steadily over the years and is now ranging from a few kilometres to 15 kilometres in regional models. Since only weather systems that are eight or more times larger than the grid spacing can be effectively resolved by NWP, smaller subgrid-scale weather phenomena still need to be approximated through parameterization schemes within the NWP model (Stensrud, 2007; Lean *et al*., 2008; Warner, 2011). This is particularly the case with convective systems. Individual convective elements require grid spacing of between 25 m and 1000 m to be resolved directly. Stensrud (2007) and Warner (2011) describe a variety of parameterization schemes that exist. These schemes include convective schemes, and also schemes dealing with heat transfer, the boundary layer, soil, vegetation and cloud cover. Each of these parameterization schemes introduces inaccuracies due to their particular inherent approximations that can affect important features of subgrid-scale convection, which impact on forecasts of rainfall in severe thunderstorms. Trigger functions that determine the activation time and place for convection schemes also play an important role. These uncertainties affect forecasting features of convective precipitation such as onset time, location of convection, duration of the rain event and the diurnal cycle of convection (Stensrud, 2007, Lean *et al.,* 2008). Accurately representing the diurnal cycle of convection by convective parameterization schemes is a major problem in NWP models, although promising new research indicates that this deficiency will eventually be resolved (Bechtold *et al.,* 2014)

By definition, the amount of rainfall at a grid point represents the average amount of rain forecast over a box with the size of the model resolution and centred over the grid point (Stensrud, 2007; Warner, 2011). As mentioned earlier, NWP models often have difficulty in accurately forecasting the exact rainfall location, onset timing of convection, and even total amount of rainfall (Theis *et al.,* 2005; Stensrud, 2007; Lean *et al.,* 2008, Bechtold *et al.,* 2014). This can differ between model configurations when, for example, the same basic model system is used, but with different initial conditions or parameterization schemes.

According to Lean *et al*. (2008) precipitation forecasts also change when increasing the resolution for the same general model configuration. In their study, they compared rainfall prediction of the Unified Model (UM) from the United Kingdom Met Office at configurations for 12 km, 4km and 1 km resolutions. Convective parameterization was switched off in the 1 km version. Generally, a significant improvement of rainfall prediction was found with smaller grid box resolution, mainly due to the explicit modelling of precipitation compared to using a parameterization scheme necessary at 12 km. Typically, it was found that the 12 km model tends to initiate convection on average 1-2 hours too early, and it tends not to have a realistic shower structure, which could lead to an underestimation of rainfall peaks. Additionally, the 12 km model tends to produce too much light rain and too little heavy rain compared to observations due to the averaging of rain over a larger grid box compared to the 4 km and 1 km models.

4.2.2 Addressing uncertainty of rainfall forecasting

From the previous discussion, rainfall forecasting is indeed quite problematic and difficult to predict accurately (see also Ebert, 2001; Theis *et al*., 2005). Nevertheless, it is the most important meteorological variable required to increase the lead-time of flash flood forecasts. When attempting to use a single NWP model to predict rainfall accurately for small river basins, as used in the SAFFG and SARFFG, the uncertainty linked to model prediction of rainfall is significant and can become quite challenging, as described in Section 4.2.1. This refers particularly to the uncertainty of the location of convective elements, amount of rain and the problem of the timing of convective precipitation during the day. These challenges can be addressed through an ensemble of NWP forecasts, as discussed in Chapter 3 (Ebert, 2001; Theis *et al*., 2005; NRC, 2006; Toth *et al*., 2007; Collier, 2007; He *et al*., 2009; Warner, 2011; Landman *et al*., 2012).

According to these authors, there are various ways to create Ensemble Prediction Systems (EPS), ranging from probabilistic forecasting from a single deterministic model (Theis *et al*., 2005) to poor man's ensembles (Ebert, 2001; Landman *et al*., 2012), single-model ensembles and ultimately multi-model ensembles (Tennant *et al*., 2007; Toth *et al*., 2007; He *et al*., 2009; Warner, 2011). Single-model EPS consist of multiple runs of the same model with slightly different initial conditions. These systems require significant computer processing power are typically run by large weather centres internationally. Combining the single-model EPS of different institutions result in multi-model EPS. Many weather services only have the computer resources to run a single deterministic model at resolutions larger than required by a flash flood forecasting system. If the products from the single deterministic model runs of various weather services are available at a weather service a poor man's ensemble system can be constructed (Ebert, 2001; Landman *et al*., 2012).

The simplest approach available to small weather services running their own NWP model is to describe uncertainty through probabilistic precipitation forecasts from this single deterministic model as proposed by Theis *et al. (*2005). Their proposal describes a post-processing procedure to determine a probabilistic rainfall forecast on each grid-point of a single limited area model simulation. They do this by "looking in the local neighbourhood of a point to get a set of forecasts and use this set to derive a probabilistic forecast" (Theis *et al*., 2005: p260). The basis of their procedure relies on the conjecture that the rainfall forecast at a grid-point is an indication of the rainfall in the spatial-temporal neighbourhood of the grid-point and not necessarily at the grid-point itself due to location and temporal errors of rainfall prediction. This is an attempt to address potential location errors (the thunderstorm is maybe a few tens of kilometres away from the forecast one) and onset timing errors (a few hours earlier or later than forecast). The neighbourhood is thus defined both in space (all grid-points within a specified radius around the focus grid-point) and in time (similar surrounding grid-points of earlier and later output time steps). Probabilistic information is determined by comparing the number of grid-points in the neighbourhood that exceeds certain thresholds. In their evaluation of the methodology, they found that the probabilistic precipitation forecast derived through this system always compares better to the observations than the direct (deterministic) model output. This methodology also provides information about forecast uncertainty, whereas the direct deterministic model output gives the impression that the forecast is 100% certain. Furthermore, this methodology is more important for convective rainfall, which has much higher spatial variability and is thus more prone to forecast uncertainty, than stratiform rainfall.

4.2.3 NWP in the South African Weather Service

The operational NWP system of SAWS is the 12 km resolution limited area version of the UM covering southern Africa up to the equator (UM-SA12) (see Figure 4.2). This model is a non-hydrostatic model with a terrain following height-based vertical coordinate system of 38 levels

(Davies *et al*., 2005). It is a grid-point model on a latitude-longitude grid that supports limited area model configuration using the same code. Initial values and boundary conditions are supplied by the United Kingdom Met Office global UM.

Two configurations of the UM-SA12 are used in this study. Both are run once a day operationally based on the initial field at 00:00 UTC (Universal Time Coordinated, similar to Greenwich Mean Time) for a forecast out to 48 hours (Landman *et al*., 2012). These two configurations are:

- Xaana: This configuration does not have a data assimilation system, and is an early run available by 03:30 UTC in the morning;
- Xaang: This configuration does have a continuous data assimilation cycle, and is available by approximately 06:45 UTC to the forecasters.

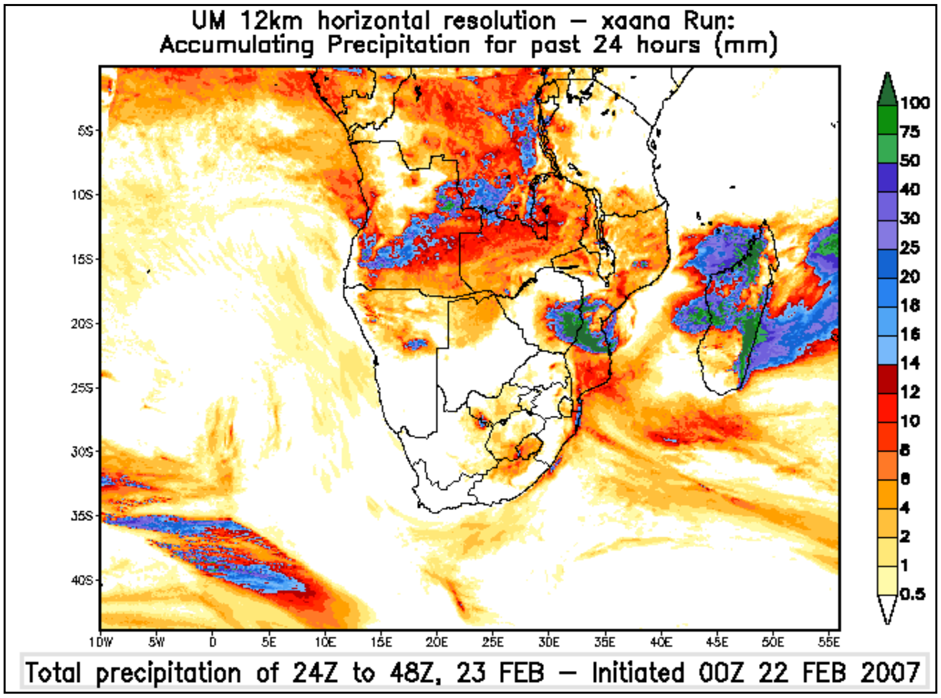


Figure 4.2: Domain of the 12 km version of the Unified Model running at SAWS (UM-SA12)

4.3 DEVELOPING A FLASH FLOOD OUTLOOK METHODOLOGY

4.3.1 Overview of basic steps

As described in Chapter 2, the FFGS is a diagnostic system for flash floods and not a predictive system in itself (see Chapter 2 for a detailed description of this process). In this study, the methodology of Theis *et al.* (2005) is explored in the context of the FFGS to provide a predictive component for the SAFFG. A scheme was developed using the NWP system of SAWS to determine the likelihood of forecast MAP exceeding future FFG values for the SAFFG basins for the next 18 hours.

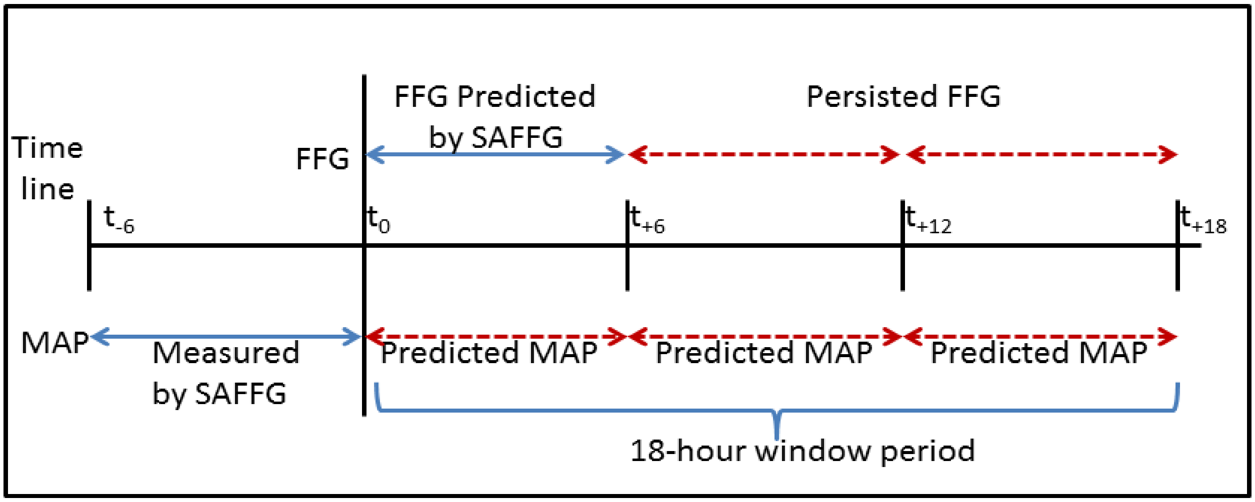


Figure 4.3: The MAP for t_0 - t_6 and the periods beyond are generated from a hybrid EPS system based on the deterministic UM-SA12 model. The future FFG fields for the next few 6-hour periods beyond time t_6 are persisted from the initial t_0 - t_6 period. (Adapted from Figure 4.1 to develop flash flood potential outlooks)

The first step was to prepare probabilistic NWP-based rainfall forecasts for each river basin for the next 18 hours. This required determining a MAP value for every small river basin from the NWP forecast rainfall data of each of different UM-SA12 configurations. This NWP based MAP values needed to be bias corrected before they could be used to compare against the SAFFG system's FFG rainfall values. Subsequently, an EPS based on the approach of Theis *et al.* (2005)

that combines the MAP amounts of the surrounding basins was developed to predict probability of precipitation in the basin for the next few 6-hour periods. The second step was to determine future FFG fields in the context of the SAFFG system. Finally, an outlook of potential flash floods in various basins and in each LM is determined by comparing the probabilistic MAP over an 18-hour window period with its particular future FFG amount (see Figure 4.3 for a graphical illustration).

4.3.2 Data

The UM-SA12 output data for both the xaang and xaana configurations were extracted from the NWP archive of SAWS. The data were archived daily for the 00:00 UTC run for each model, with hourly-accumulated forecast rainfall values on the 12 km x 12 km grid out to 48-hours.

SAFFG data were extracted from the SAFFG archive that existed from April 2011. Individual data files were available for a few cases between October 2010 and April 2011. Data files for each hourly SAFFG update run were archived consisting of the basin average values for each SAFFG basin for various fields, inclusive of:

- 6-hour accumulate MAP (a final bias corrected mean areal precipitation value for each SAFFG basin);
- 6-hour FFG values per basin;
- 6-hour Flash Flood Threat (FFT) fields per basin.

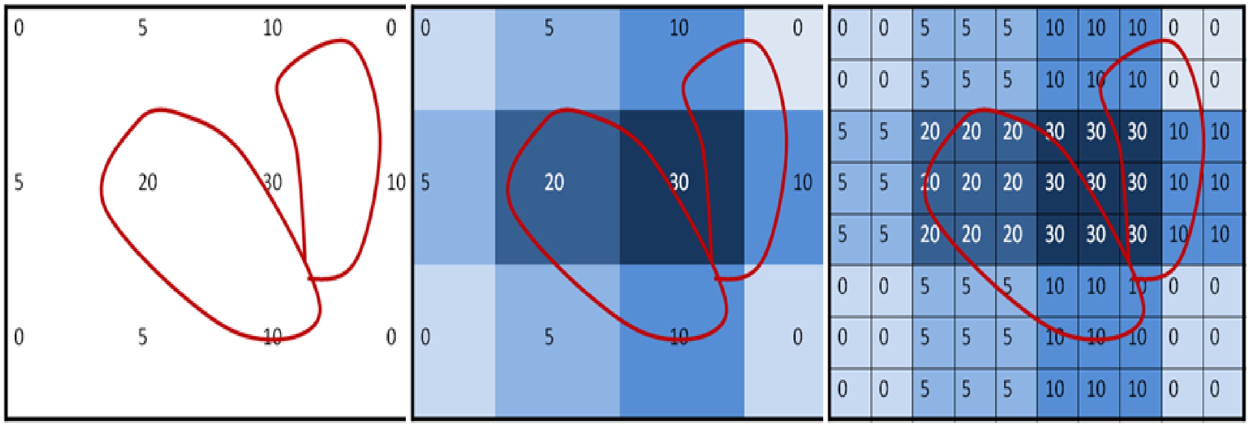
The SAFFG observed MAP amounts (see Section 2.5.4) were derived in the SAFFG system from radar observations where available, otherwise from satellite-based rainfall estimation fields, both bias corrected using rain gauges. In this study, these MAP values of the SAFFG system were assumed to be “observations”. This was deemed acceptable, since the FFG fields of the SAFFG are determined using these same radar/satellite based MAP values of SAFFG as rainfall “observations” to calculate soil moisture and ultimately the FFG value. It is against this FFG value that UM-SA12 generated MAP was compared to assess flood potential, using the same SAFFG basins as common spatial scale.

4.3.3 Preparing probabilistic NWP-based rainfall forecasts per basin

4.3.3.1 Determining a MAP value from NWP models for each SAFFG basin

The hourly precipitation forecasts of the UM-SA12 models, integrated into 6-hour totals, were used to calculate UM-SA12 forecast mean areal precipitation (UM-MAP) values for each SAFFG river basin. This was done for both available UM-SA12 model configurations xaana (no data assimilation) and xaang (continuous data assimilation). The basic approach is similar to the approach used in the SAFFG system.

As mentioned earlier, a precipitation value at a NWP model grid point represents the average rain at a grid box around the grid point (Warner, 2011) with the size of the model resolution (12 x 12 km or 144 km^2 in the case of UM-SA12) as depicted in Figures 4.4(a) and (b). At the resolution of 12 km, the small size of SAFFG basins implied that it would be difficult to find more than one grid point in each river basin. This was overcome by interpolating the 12 km grid to a 4 km grid using an “equal block” approach. Thus, the 4 km grid boxes within an initial 12 km grid box are allocated the same value as the associated 12 km grid box (Figure 4.4 (b) and (c)), but represent now only a 4x4 km domain. In this way, it was possible to calculate UM-MAP for most SAFFG basins as a simple average from at least four grid boxes of the 4 km resolution grid that resides within the basin. For those few basins that still did not have four associated grid points, the nearest four 4 km grid points were identified using an inverse-weight scheme to determine their relative contribution to that basin’s UM-MAP.



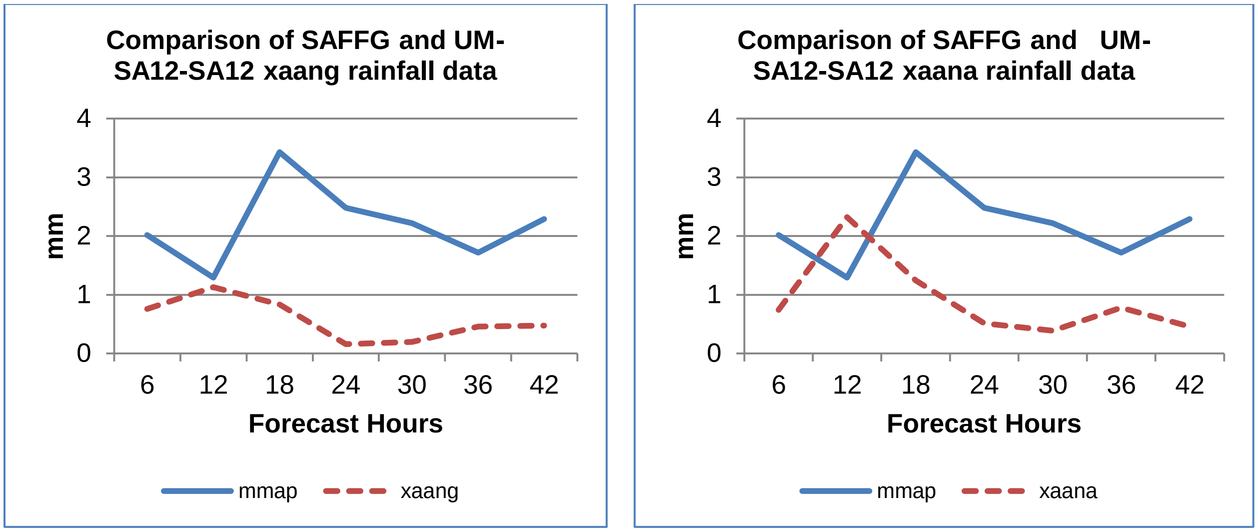
(a) **(b)** **(c)**

Figure 4.4: Example of interpolation of 12 km grid boxes to 4 km grid boxes for calculation of UM-SA12 UM-MAP amounts. (a) Distribution of 12 km grid points relative to imaginary SAFFG basins. (b) Representative grid boxes of 12 km precipitation grid points. (c) Interpolation of 12 km grid boxes to equal 4 km grid boxes used to calculate UM-MAP amounts.

The processing of UM-SA12 rainfall into a UM-MAP field was done by means of Geographical Information System (GIS) and FORTRAN code computer programs. GIS shape files of both the SAFFG basins and the re-gridded 4km UM-SA12 rainfall data were loaded into a GIS system. Using a GIS function, the relevant NWP grid points associated with each river basin were identified. Calculating the UM-MAP was then done through a FORTRAN program.

4.3.3.2 Bias correcting the UM-MAP forecasts

In line with the discussion of NWP problems in Section 4.2.1, the inability of the UM-SA12 NWP models to predict realistic amounts of rainfall in a basin was quite evident. The UM-MAP fields of the UM-SA12 simulations (xaang and xaana) were significantly lower compared to the MAP derived for the observed rainfall field of SAFFG. Differences between the different configurations of UM-SA12 (xaana and xaang) were also evident.



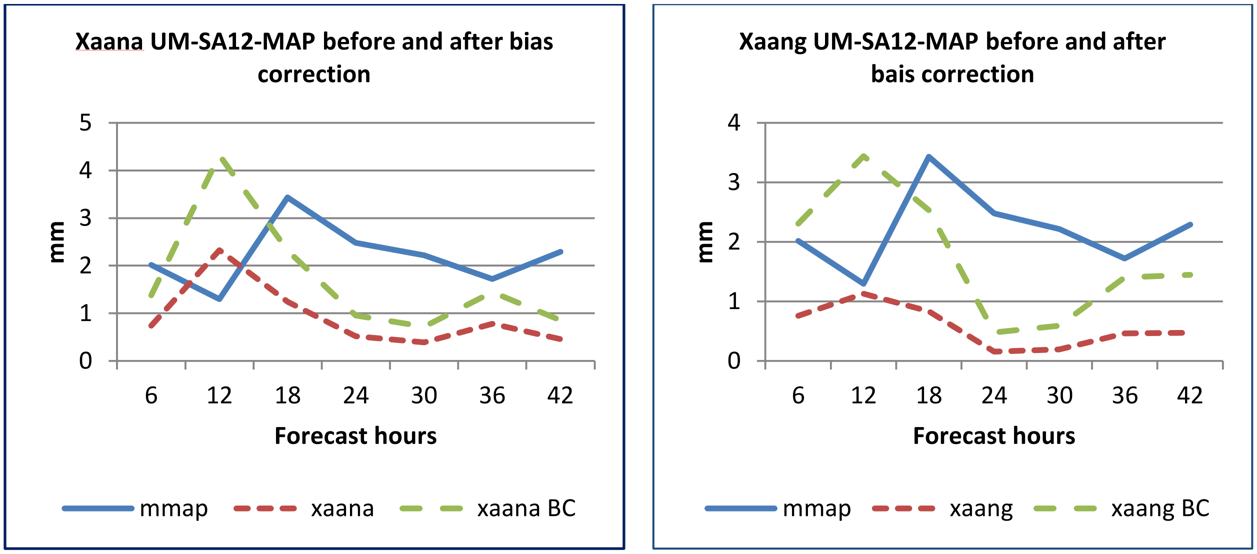
(a) **(b)**

Figure 4.5: Comparison of SAFFG and UM-SA12 rainfall (in mm) under the Irene radar domain, averaged over 25 cases and per basin. The dotted lines (xaang and xaana) are averaged UM-SA12 predictions for the xaana and xaang model configurations, and the solid lines (mmap) the SAFFG MAP averages for the same basins over the 25 cases. Panel (a) show the xaang model comparison and (b) the xaana model comparison.

As example, Figures 4.5 (a) and (b) show vast underestimation of 6-hour forecast UM-MAP, averaged over 25 heavy rainfall cases and over the 2101 basins under the Irene radar domain near Pretoria, compared to the corresponding SAFFG observation MAP values. This emphasized the need for bias correcting each NWP model's UM-MAP to enable fair comparison with FFG values for the same basins from the SAFFG system. A bias correction factor for each model was calculated as follows:

$$\text{BCF} = \Sigma(\text{UM-MAP}) / \Sigma(\text{MAP})$$

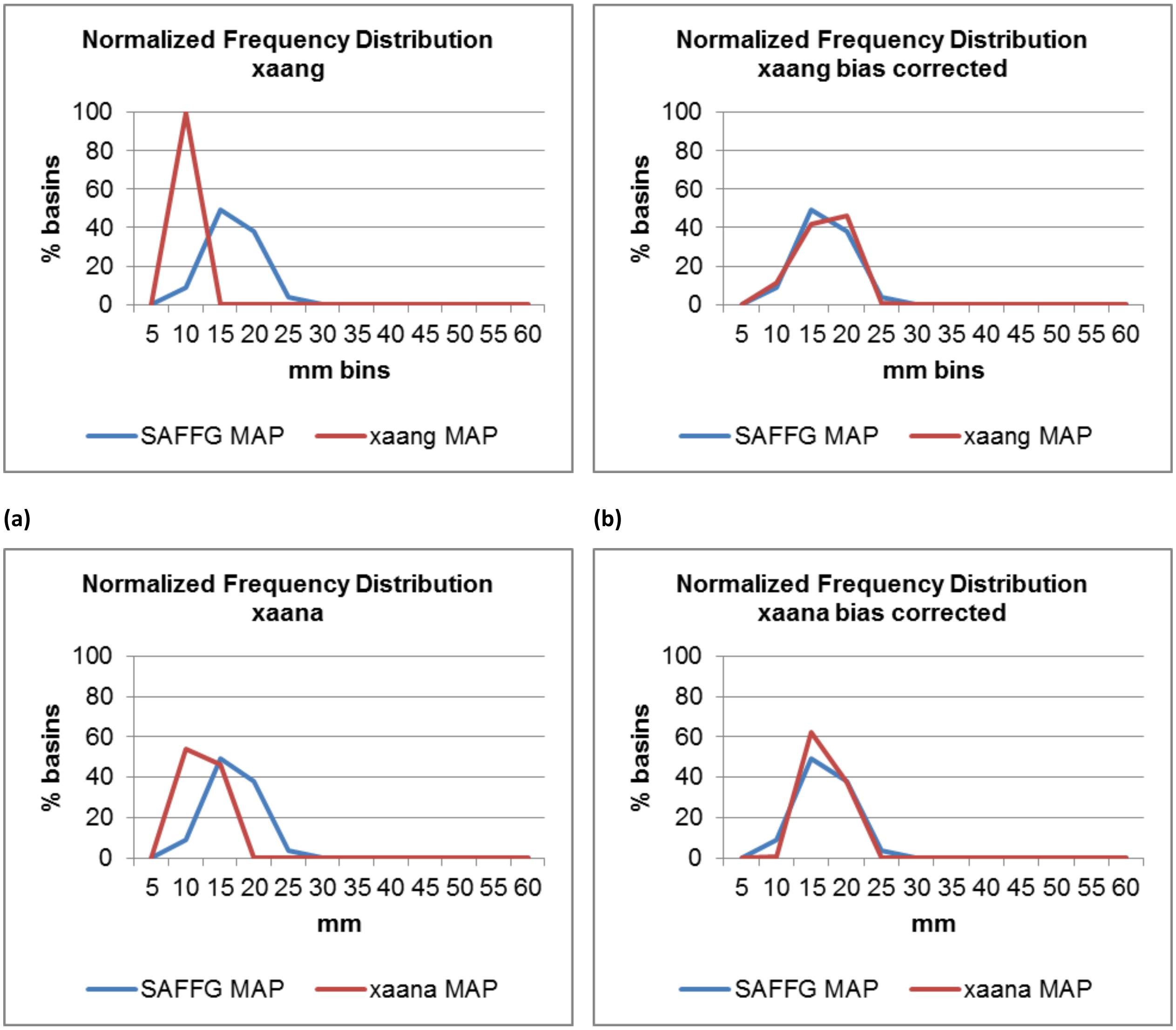
where BCF is the bias correction factor, UM-MAP is the relevant UM-SA12 amounts, and MAP is the corresponding observed SAFFG MAP amounts. The sum was calculated over al 2101 basins covered by the Irene radar for 25 cases in 2011 with significant convective rain (days when at least one rainfall station reported 50 mm or more in 24 hours). For the xaana configuration the BCF was 1.86 and for the xaang configuration 3.05. The corrective impact of bias correction to the quantity of rainfall is shown in Figure 4.6. What also stands out clearly is the problem of early initiation of convection, as discussed by Lean *et al.* (2008) in Section 4.2.1.



Xaana UM-SA12-MAP before and after bias correction

Xaang UM-SA12-MAP before and after bais correction

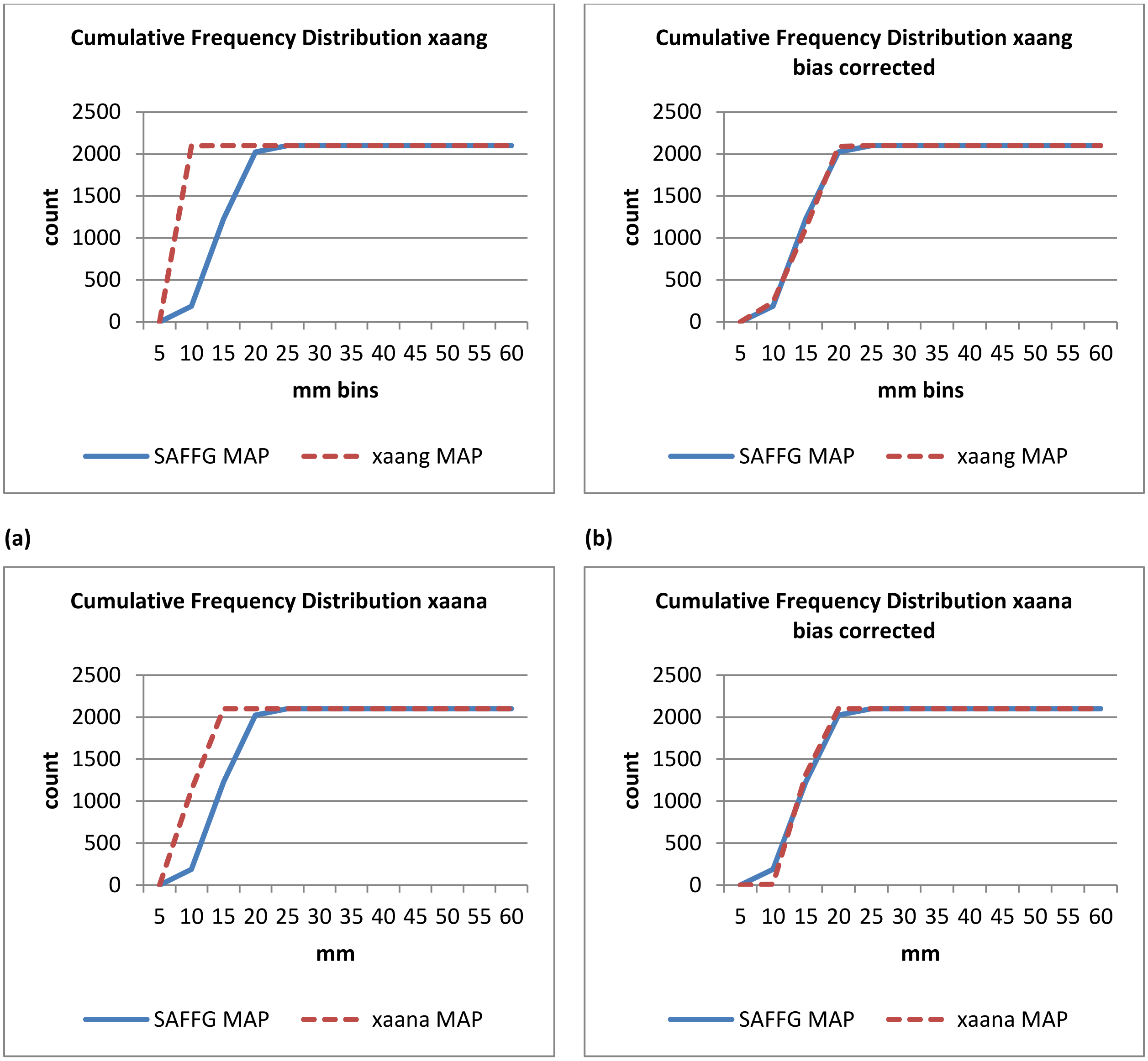
Figure 4.6: Comparison of the sum of the UM-MAP amounts of all basins covered by the Irene radar on 10 January 2012 for the xaana and xaang model configurations, to the SAFFG MAP (mmap) amounts of the same basins. The panel on the left shows the xaana model comparison (BCF=1.86) and the panel on the right the xaang model comparison (BCF=3.05) before (short dashed line) and after (long dashed line) bias correction. The solid lines are the SAFFG observed MAP.



(a) **(b)**

(c) **(d)**

Figure 4.7: The normalized frequency distributions of the uncorrected and bias corrected rainfall distributions for the xaang UM-SA12 configuration is presented in panels (a) and (b), with the corresponding distributions for xaana in panels (c) and (d) respectively.



(a) **(b)** **(c)** **(d)**

Figure 4.8: The cumulative frequency distributions of the uncorrected and bias corrected rainfall distributions for the xaang UM-SA12 configuration is presented in panels (a) and (b), with the corresponding distributions for xaana in panels (c) and (d) respectively.

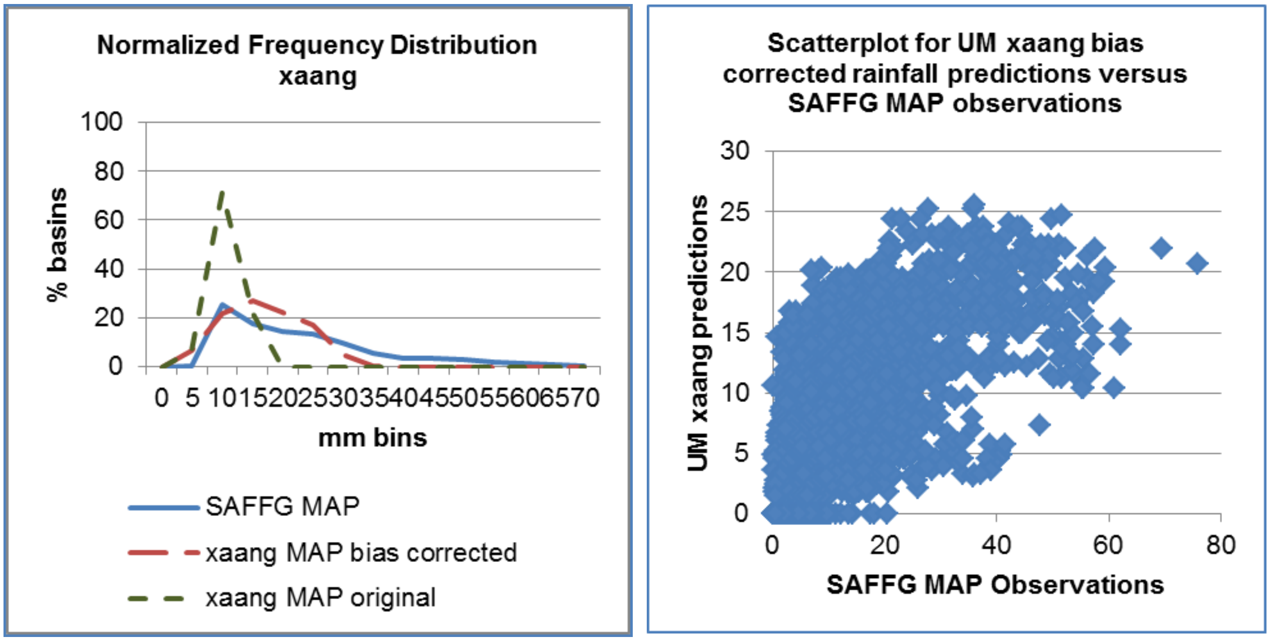
A problem related to the underestimation highlighted in Section 4.2.1 was the tendency of the 12 km version of the UM in the Lean *et al. (*2008) experiments to produce too much light rain and too little heavy rain. This is also clearly illustrated in Figure 4.7 (a) and (c) for xaang and xaana, respectively, with the positive corrective impact of the bias correction evident in Figure

4.7 (b) and (d). In Figure 4.8, the cumulative frequency distributions confirm the impact of bias correction to this problem.

The bias correction scheme described above is by no means the optimal scheme, but it does provide a “climatological” bias correction based on 25 cases that produced heavy rain. The bias correction factor differs between the different days, and the ideal will be to adjust dynamically the BCF for each individual day. This was not attempted in this scheme and is a recommendation for future work.

4.3.3.3 Addressing uncertainty through a hybrid ensemble approach

Within each NWP model, the problem of location of convection implies that even though the model may be quite accurate in predicting convection for a region, it may be misplacing the rain compared to where and when it actually occurred (see Sections 4.2.1 and 4.2.2). This is illustrated in Figure 4.9 (b) in a scatter plot for 30 October 2011 of the bias-corrected UM-MAP values and the corresponding SAFFG observed MAP values. The wide scatter of data illustrates the problem of accurate spatial distribution of NWP rainfall predictions, particularly for small areas such as the SAFFG basins. Since the model did predict convective rain for the day, it may well have the broad pattern in place, but the exact positioning of convective elements may be in neighbouring basins. Figure 4.9 (a) also demonstrates a case of severe underestimation where the highest uncorrected model forecast value in the entire xaang configuration of the UM-SA12 model domain for this day was only about 9 mm, whereas SAFFG measured more than 60 mm as the highest. Following bias correction, the characteristics of the rain are similar even though there are spatial alignment discrepancies. In addition, as discussed earlier, the UM-SA12 models also tend to start convection too early in the day, which implies that timing within the correct 6-hour period maybe quite wrong.



(a) (b)

Figure 4.9: The figure on the left (a) depicts a comparison of the normalized frequency distribution for uncorrected and bias corrected xaang data for 2101 basins under the Irene radar on 30 October 2011. On the right (b) is a scatter plot of bias corrected basin specific UM-MAP rainfall predictions and the corresponding SAFFG observed MAP values for the same data as in (a).

Following from the discussion in Section 4.2.2 a hybrid ensemble approach as described by Theis *et al.* in 2005 was used in an attempt to describe the uncertainty of both the spatial location and the convection timing challenges through probabilistic forecasting from the deterministic UM-SA12 model. They identified a “neighbourhood” of grid points from the same model around the target grid point whose rainfall values could just as well be associated with the target grid point. In this study, however, the bias corrected UM-MAP values of SAFFG basins described earlier were used instead of rainfall on NWP grid points. The main reason for this approach was that this allowed the ensemble scheme to calculate probabilistic information on the basic rainfall value used in the SAFFG system, i.e. MAP, over a small basin. Furthermore, SAFFG MAP rainfall values were used as “observations” for the bias correction scheme as described in the previous section. Lastly, this allowed for a fair comparison between the model ensemble predictions and the FFG basin average values that were generated from these MAP "observations".

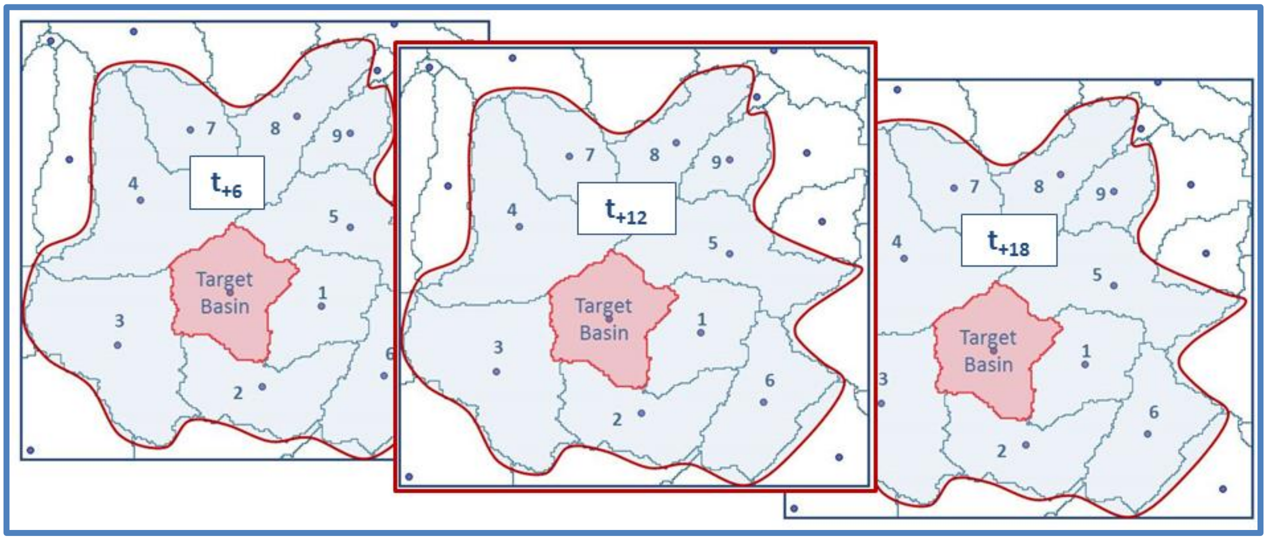


Figure 4.10: Graphical examples of 10 SAFFG ensemble member basins for the t+12 NWP forecast period associated with the target basin, and the associated basins of the previous 6-hour period and 6-hour subsequent period. This provides in total 30 EPS members for the target basin over 18 hours.

Hence, for this hybrid ensemble approach (hereafter-called HyEPS) the "neighbourhood" consisted of the 9 closest SAFFG basins around each target SAFFG basin identified using a centroid function in GIS. In this way, the possibility was accommodated that the UM-MAP over any of the 9 neighbouring basins could actually be associated with the target basin due to model error. In addition, the potential offset in timing of the convection by the UM-SA12 was covered by considering an extended period of 18 hours as a single target outlook window period instead of the operational SAFFG guidance limit of 6 hours (see Figure 4.3). This is done by including the same 10 basins from the previous 6-hour prediction period, and of the following 6-hour prediction period into the ensemble set. The set of ensemble members for each basin thus consisted of 30 bias corrected UM-MAP values from the 30 basins in its neighbourhood (see Figure 4.10), covering a period of 18 hours.

4.3.3.4 Flash flood outlook products from the hybrid ensemble system

From the HyEPS, probabilistic related information was extracted representing the 18-hour window period. These included the ensemble average (EPSave) and the ensemble maximum value (EPSmax) which is the highest UM-MAP value of all 30 members. Both values could be compared with the basin specific FFG value to identify the potential magnitude of flash flood events, with EPSmax representing the rainfall for the extreme scenario for the target basin. The Flash Flood Potential (FFP) of each basin over the 18-hour window period was calculated as the probability of the basin ensemble exceeding the last known FFG value of the basin. This was done by calculating the percentage of ensemble members in the 30-member basin ensemble set that exceeded the FFG value of the basin. Finally, the flash flood hazard index for a LM (LM-FFH) was determined as the percentage of SAFFG basins within a local municipality with a positive FFP. These parameters represented the basin specific potential for flash floods and the LM flash flood hazard risk over the 18-hour forecast period. For comparison, this was done for both xaang and xaana configurations of the UM-SA12 model.

The computations described above used the precipitation forecast products of a deterministic model and do not require large computer resources. Hence, it is quite suitable to be applied in smaller weather services, even those not running their own NWP model but that have access to the gridded rainfall output of a model run at a regional or global weather centre.

4.3.4 Projecting flash flood guidance information to the next 18 hours

Referring to Figure 4.1, future 6-hour FFG values are needed to compare with the predicted UM-MAP values in order to identify which basins could receive more rain than required for bank full at the basin outlet, and thus potential flooding. This implies that the soil moisture, and then the FFG for future 6-hour periods, needs to be modelled based on the previous 6-hour's MAP. In the current configuration of the SAFFG modelling system available for this study, however, it is not possible to predict FFG values beyond 6 hours in advance. Although such an approach would be ideal, it will require a substantial change to the hydrological modelling system.

Consequently, the only other approach is to extrapolate, or persist, the latest available 6-hour FFG values in 6-hour periods up to 18 hours in the future as shown in Figure 4.3. This approach assumes that the soil moisture content, and thus the FFG values in the basins, should not change significantly in the subsequent 18 hours. This assumption is not completely true, particularly if significant rain would fall which could lead to saturation of the top soil and reducing FFG values. However, it is deemed an acceptable assumption for this limited additional period based on Figure 4.11.

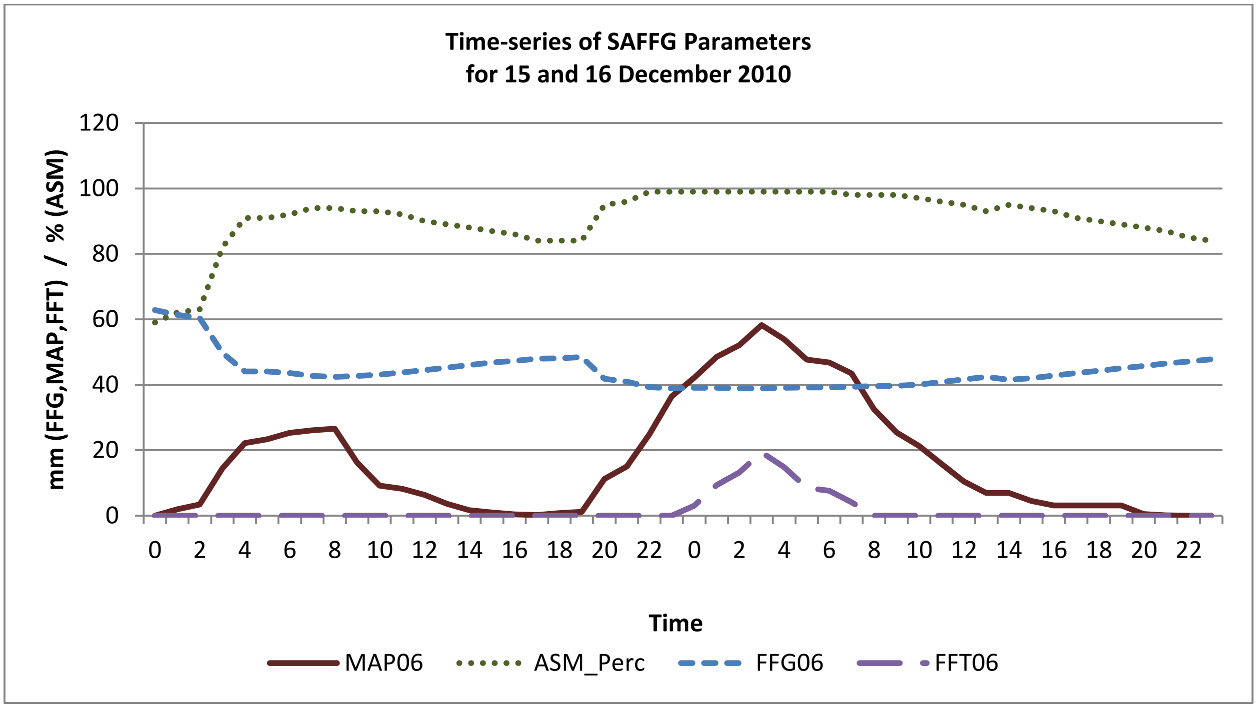


Figure 4.11: A graphical representation of the four main parameters of the SAFFG as they evolved during the flash flood event of 15 and 16 December 2010 for a specific basin in Dipaleseng Local Municipality. ASM_Perc is the saturation percentage of the top-layer soil moisture, MAP06 the 6 hour accumulated MAP as observed by SAFFG from radar data, FFG06 is the 6-hour flash flood guidance, and FFT06 is the 6-hour flash flood threat if the MAP06 of the previous 6 hours is persisted for the subsequent 6 hours.

Figure 4.11 is a graphical presentation of how the main relevant parameters in the SAFFG evolved hourly in a flash flooding situation in a typical SAFFG basin south of Johannesburg on 15 and 16 December 2010. Two rain episodes can be identified from the MAP06 graph in Figure 4.11. The first rain episode lasted from 02:00 to 10:00 UTC on the 15 December 2010, and the second rain episode lasted from 18:00 UTC on the 15th to 14:00 UTC on the 16th. The response of the SAFFG soil moisture saturation (ASM_Perc) and FFG06 parameters to the heavy rain (the solid line MAP06) is quite evident in both rain episodes. The soil moisture saturation level (ASM_Perc in top dotted line) jumped from 60% to about 90%, settled slowly and then jumped from 85% to 100% where it stayed a while before settling slowly again. The FFG06 was already at about 60 mm and dropped with the first rain episode to just over 40 mm. It again settled slowly to about 50 mm before it dropped again with the second episode to about 39 mm. Whenever the rainfall reduced or stopped the FFG06 rose relatively slowly.

If the FFG06 was persisted at its level of 48 mm on 18:00 UTC on the 15 December 2010 for the next 12 hours it would have been too high at midnight when the actual values dropped to 39 mm due to the rain that fell between 18:00 UTC and 24:00 UTC. Thus, by keeping the FFG06 at a previous level in a period when more rain is expected a conservative estimate of potential flooding is created since the FFG06 is likely to drop due to the rain. The same will happen if an extended dry period is followed by a sudden downpour. If the FFG06 at 00:00 UTC on the 16 December 2010 was persisted at its value of 39 mm for the next 12 hours, it would have been too low compared to the slowly declining actual FFG06 to higher values. FFG06 rose in this situation, however, because no rain fell and the flash flood threat disappeared. Lastly, this case was a real extreme rainfall case where 133 mm of rain fell in that area between 18:00 UTC on the 15 December 2010 and 08:00 UTC on the 16 December 2010. Yet, the basins still responded relatively slow over the next 12 hours compared to rain episodes, particularly when the rain stops.

From this discussion, it is assumed that it is a reasonable approach to persist the FFG06 values for the next few periods in the absence of a capability to model its future values. An outlook of potential flash flooding can then be regarded as a conservative estimate.

4.3.5 Determining a flash flood outlook for the next 18-hour window period

The 3-step *flash flood forecast modelling process* could be summarized as follows:

(1) Prepare NWP-based probabilistic rainfall forecasts for each basin for the next 18 hours:
    - Determine 6-hour UM-MAP for each basin from the gridded deterministic NWP 6-hourly output;
    - Perform a bias correction on these UM-MAP values;
    - Apply the hybrid ensemble approach to the MAP values to address forecast uncertainty for the 18-hour forecast window period.

(2) Project the last known 6-hour FFG values for each basin to the next 12 and 18 hours;

(3) Compare the forecast HyEPS rainfall information per basin for the 18-hour window period with the projected FFG values for the same period to determine the likelihood of potential flash flooding in a SAFFG basin (FFP), and in LM (LM-FFH) – see Section 4.3.2.4 for more detail.

This process is followed for each of the SAFFG basins to provide a potential for flash flooding in the next 18 hours, and a risk of flash flooding in the corresponding LM.

4.4 RESULTS AND CASE STUDIES

4.4.1 General

Flash flood events are extreme events. For the 24 months for which the SAFFG archived data were available only two extreme event cases could be identified in the Gauteng Province radar region, with a number of SAFFG basins indicating a flash flood threat. Information for the flash flood event of 15-16 December 2010 was also captured and could be used. For the KwaZulu-

Natal Province radar region, only five cases of potential flash flooding were available in the 24-month period due to the unavailability of the S-band radar in Durban from October 2011 to April 2012. A number of significant flash flood events occurred over the last 24 months, but, unfortunately, they were outside the SAFFG domain.

Consequently, it was more practical to assess the flash flood outlook system based on the HyEPS through a few case studies. Since the SAFFG system is based on UTC, the case studies will be referenced to UTC, 2 hours earlier than SAST.

Products produced were the 6-hour accumulated deterministic (bias-corrected) UM-SA12 forecasts of basin average rainfall for both the xaana and xaang configuration where available, as well as the HyEPS forecast products described in Section 4.3.2.4. These results are presented and discussed in four individual case studies, each highlighting another aspect of this methodology.

4.4.2 Case Study 1: Eastern Cape flash floods of 20 October 2012

4.4.2.1 Description of the event

On 20 October 2012, a cut-off low-pressure system caused heavy rain and flash flooding over the Eastern Cape Province of South Africa. Significant damage was caused to infrastructure and homes near Port Alfred where people were forced to leave their homes due to flooding. Houses of 57 residents in the nearby informal settlement were damaged and hundreds of residents were without water or electricity (SAWS, 2012b). Cars were submerged and some formal houses were flooded with up to 2m of water. A bridge was washed away and the damage to infrastructure and cars was estimated to be more than R1 billion. The N2 national road between Port Elizabeth and Grahamstown was washed away at a gully outside Grahamstown resulting in the road to be closed and severely disrupting traffic.

4.4.2.2 Simulating the rainfall outlook through HyEPS

The rainfall patterns as shown by the MAP images in Figure 4.12 were reasonably well forecast by the 20th 00:00 UTC run of the UM-SA12 xaana model configuration, although it underestimated the amount of rain that fell near Port Alfred 12 hours later. The UM-SA12 xaang run forecast much more rain, but misplaced the peak amounts to occur between 18:00 UTC and midnight on the 20th (Figure 4.13). These two runs, therefore, provide opportunity for an interesting comparison of the application of the deterministic model pseudo-ensemble system by forecasts for the same event of two different model configurations.

For each basin, the 6-hour rainfall measured by SAFFG MAP has been averaged for the three 6-hour periods within the relevant 18-hour window period. A comparison of the average rainfall for the 18-hour window periods of 0-18 and 6-24 is provided (Figure 4.14). The model average is the average of all 30 members of the ensemble (each 6 hours in length) relevant to the particular basin and covering the same 18-hour window period, done for xaang and xaana configurations respectively. It is quite evident that the UM-SA12 with the xaang configuration did not capture the average rain positioning correctly as compared with the SAFFG MAP average on the left hand side of Figure 4.14 for both periods. This was mostly due to the erroneous timing of the rainfall by the xaang configuration as the rainfall moved southeast out over the ocean. The xaana configuration, however, performed better in capturing the timing, although the peak amounts were too low.

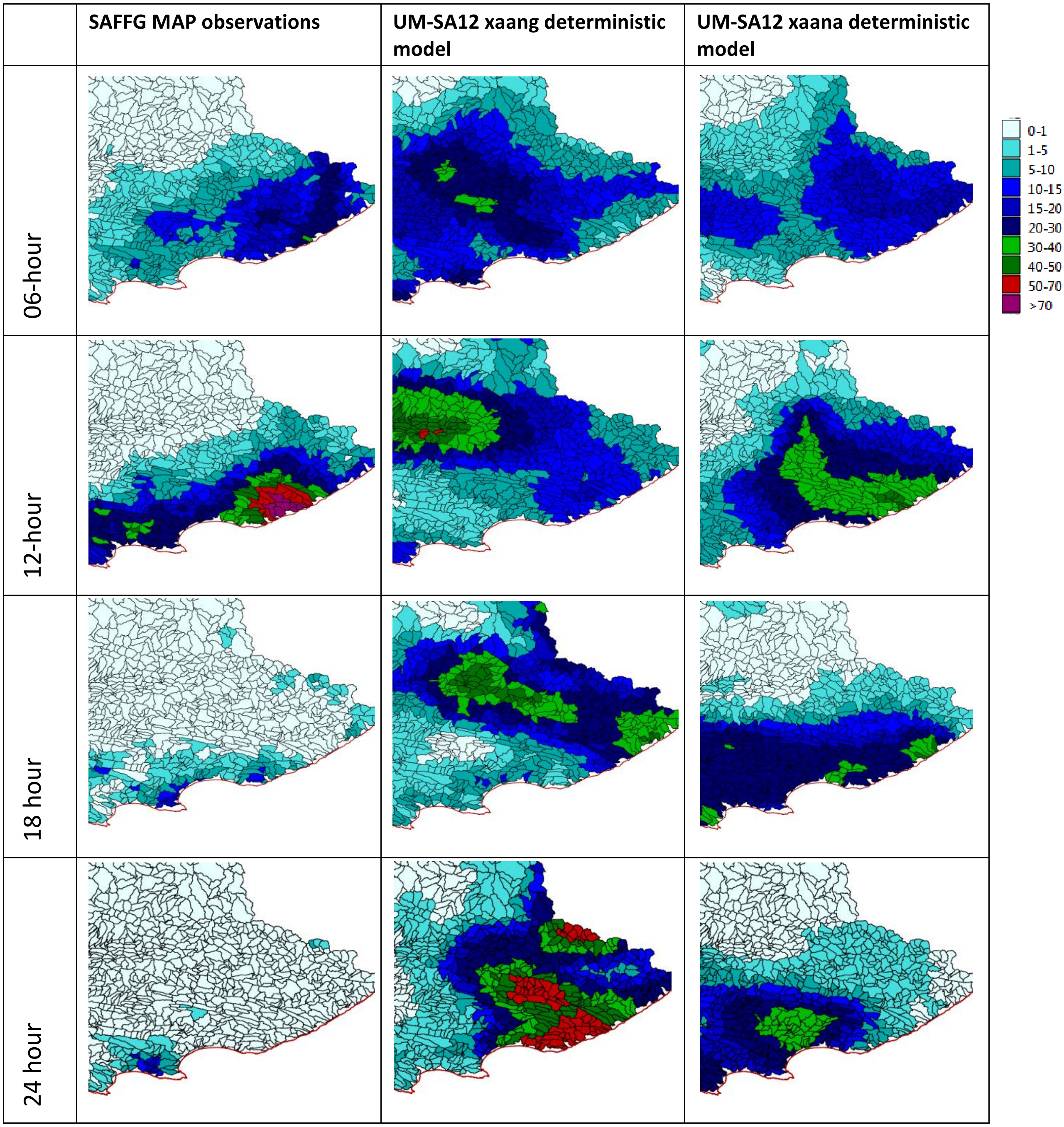


Figure 4.12: Comparison of the SAFFG MAP rainfall observations with the UM-SA12 xaang deterministic rainfall forecast and the UM-SA12 xaana deterministic rainfall forecast of the 20th 00:00 UTC model runs for 06-, 12-, 18- and 24-hours. The rainfall scale is in mm.

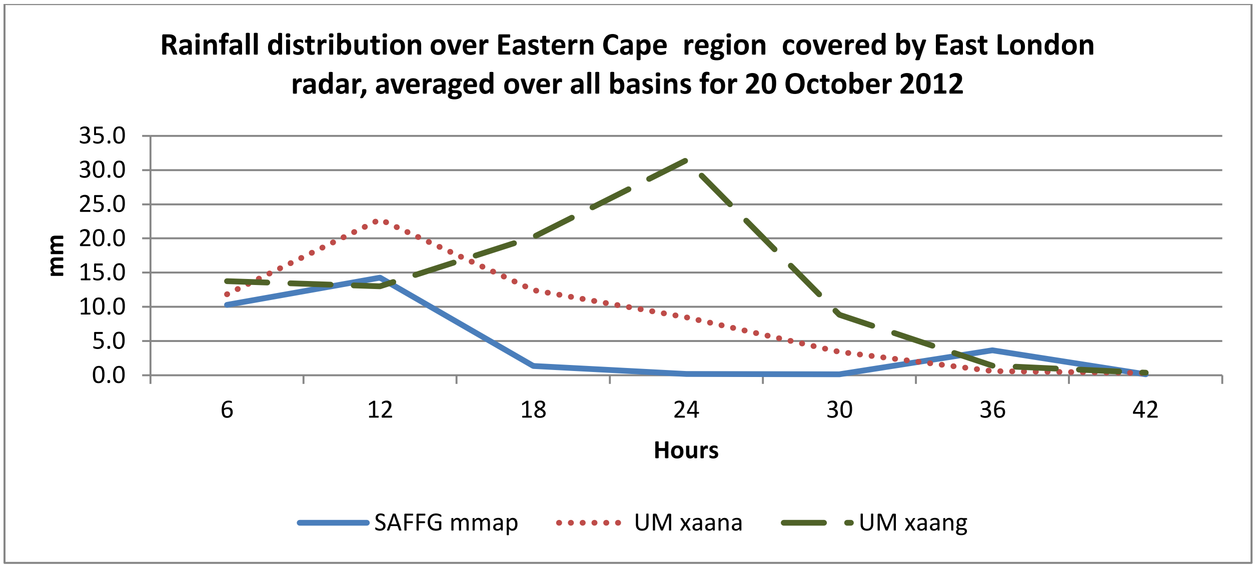


Figure 4.13: The rainfall distribution averaged over all the basins in the East London radar region of the Eastern Cape Province of South Africa on 20 October 2012. The solid line is the observations as represented by SAFFG MAP. The dotted line is the rainfall forecast of the xaana configuration of the UM-SA12 initiated at 00:00 UTC and the dashed line the associated UM-SA12 forecasts using the xaang configuration

The main purpose of this case study was to determine the potential for flash flooding in small river basins from NWP forecasts. Consequently, the most important product was the FFP of each basin over the 18-hour window period, calculated as the probability of the basin ensemble UM-MAP values (or the percentage of members) exceeding the representative FFG values of the basin for the same 18-hour window period. This implies that the members with the highest values for each basin will be important to identify, since they have the best chance of exceeding the FFG value of the basin. A chart with the highest rainfall value of all ensemble members for a particular basin is a simple representation of this methodology from a rainfall perspective. Figure 4.15 shows rainfall maps of the maximum 6-hour rainfall value from all 30 members of the ensemble for each basin for the two 18-hour window periods under discussion using the two model configurations. The SAFFG MAP observation maximum was just the highest of the 3 relevant observed 6-hour periods for the basin. Again the xaang model configuration overestimated the rainfall in the wrong areas, although the xaang configuration's 6-24 hour window period provided quite good forecasts for the areas that did received the highest rainfall in this period around Port Alfred. The xaana model configuration performed much better with the highest values in the Port Alfred area, though much lower values than experienced.

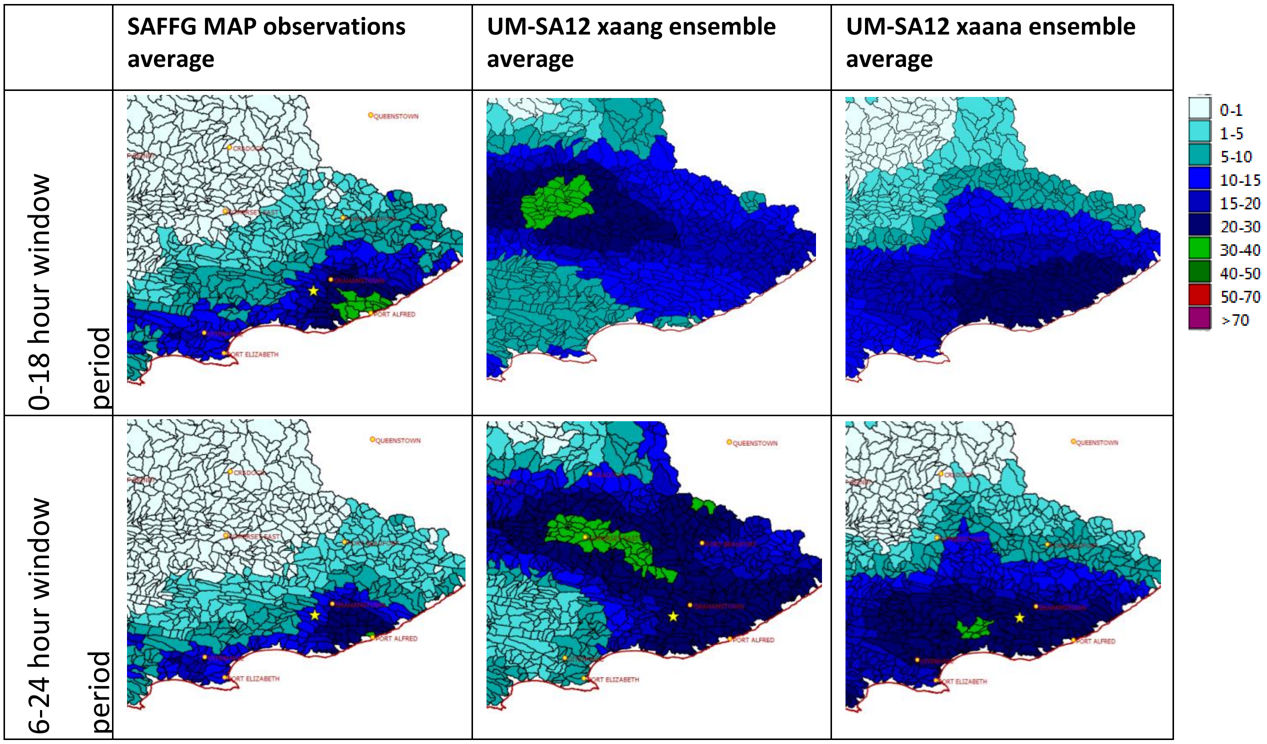
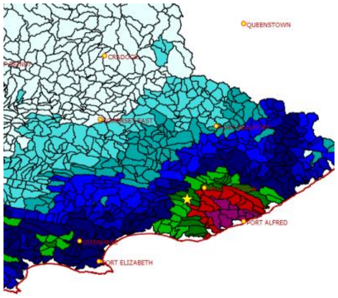
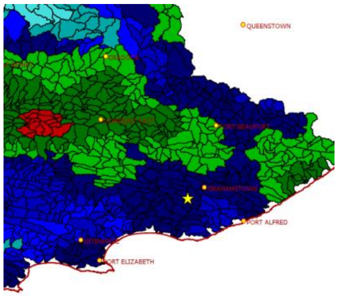
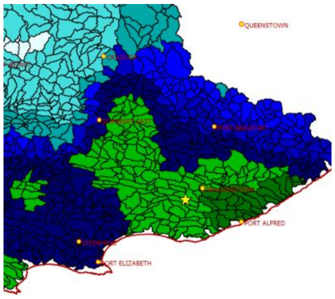
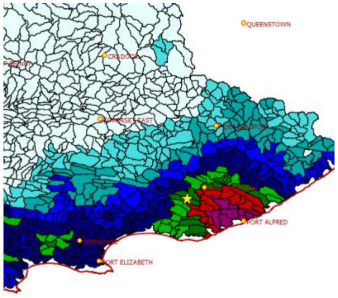
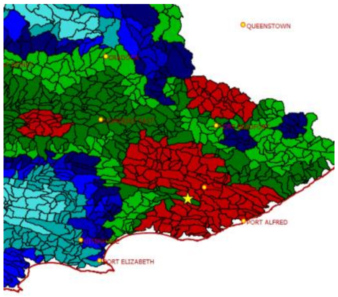
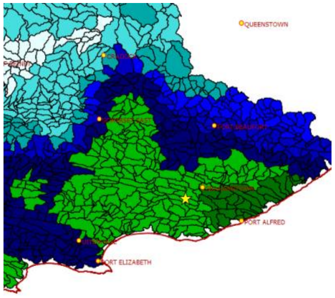


Figure 4.14: Comparison of the 6-hour SAFFG MAP average rainfall observations over the relevant 18-hour window periods with the average UM-SA12 xaang and UM-SA12 xaana ensemble forecasts for the same periods for 20 October 2012. The rainfall scale is in mm.

Verification metrics were calculated for both the ensemble average and the ensemble maximum rainfall fields of the UM-SA12 forecasts using the xaana and xaang configurations compared to observed SAFFG MAP fields for the two 18-hour window periods. The domain covered is the same as in the images in Figure 4.15 and involved 432 small river basins. A contingency table was prepared for each forecast, determining event "Hits", "False alarms", "Misses" and "Correct Non-events". This data was used to calculate a variety of scores including the Critical Success Index (CSI), Hanssen-Kuipers Score (KSS) and Heidke Skill Score (HSS) (Wilks, 2006; Jollife and Stephenson, 2012).

	SAFFG MAP observations maximum rain	**UM-SA12 xaang ensemble maximum rain**	**UM-SA12 xaana ensemble maximum rain**
0-18 hour window period			
6-24 hour window period			

- ⬜ 0-1
- 🟦 1-5
- 🟦 5-10
- 🟦 10-15
- 🟦 15-20
- 🟦 20-30
- 🟩 30-40
- 🟩 40-50
- 🟥 50-70
- 🟪 >70

Figure 4.15: Comparison of the 6-hour SAFFG MAP maximum rainfall observations over the relevant 18-hour window periods with the maximum UM-SA12 xaang and UM-SA12 xaana ensemble forecasts for the same periods of the 20 October 2012. The rainfall scale is in mm.

These three scores were identified since they measure the attributes of quality, namely

- "Accuracy" (i.e. the level of agreement between forecasts and observations, measured by CSI);
- "Discrimination" (i.e. the ability of forecasts to distinguish between occurrences and non-occurrences of the event, or tells a user if he can rely on the forecast, measured by KSS);
- "Skill" (i.e. the accuracy of forecast compared to the accuracy of being correct by chance, measured by HSS). For CSI, KSS and HSS a score of "1" is a perfect score.

Figure 4.16 depicts a graphical illustration of the verification results. From all three indicators it is evident that the xaana configuration of the UM-SA12 performed the best. The xaang configuration performed the worst with the 0-18 hour forecast actually misleading, particularly for the higher thresholds beyond 15 mm. This applied for all three attributes of accuracy, discrimination and skill. The xaang configuration 6-24 hour forecast performed better at higher thresholds than lower thresholds for skill and discrimination as measured by HSS and KSS respectively. Consequently, though the UM-SA12 forecasts for the 18-hour forecast window were not perfect, the xaana configuration, particularly, produced useful forecasts. The xaang 6-24 hour showed some skill above chance and the ability to discriminate between occurrences and non-occurrences at the higher thresholds.

It can thus be concluded that the HyEPS ensemble rainfall forecasts provided useful outlooks for the rainfall over the two 18-hour window periods in this particular case study.

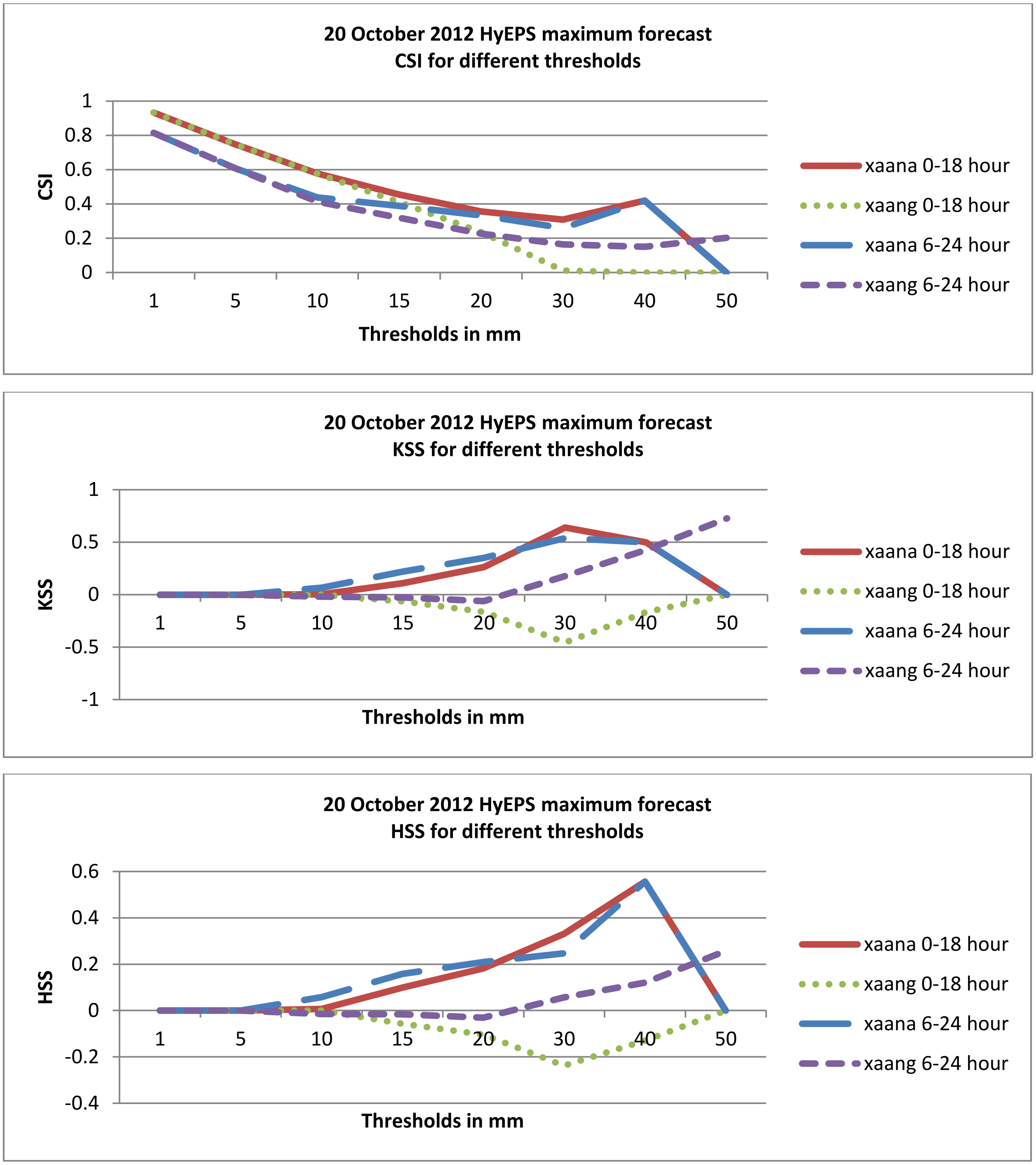


Figure 4.16: Verification statistics for the HyEPS maximum forecasts for the UM–SA12 xaana and xaang configurations for the 0-18 and the 6-24 hour window periods for different rainfall thresholds on 20 October 2012. The top panel shows the CSI, the middle panel the KSS and the bottom panel the HSS.

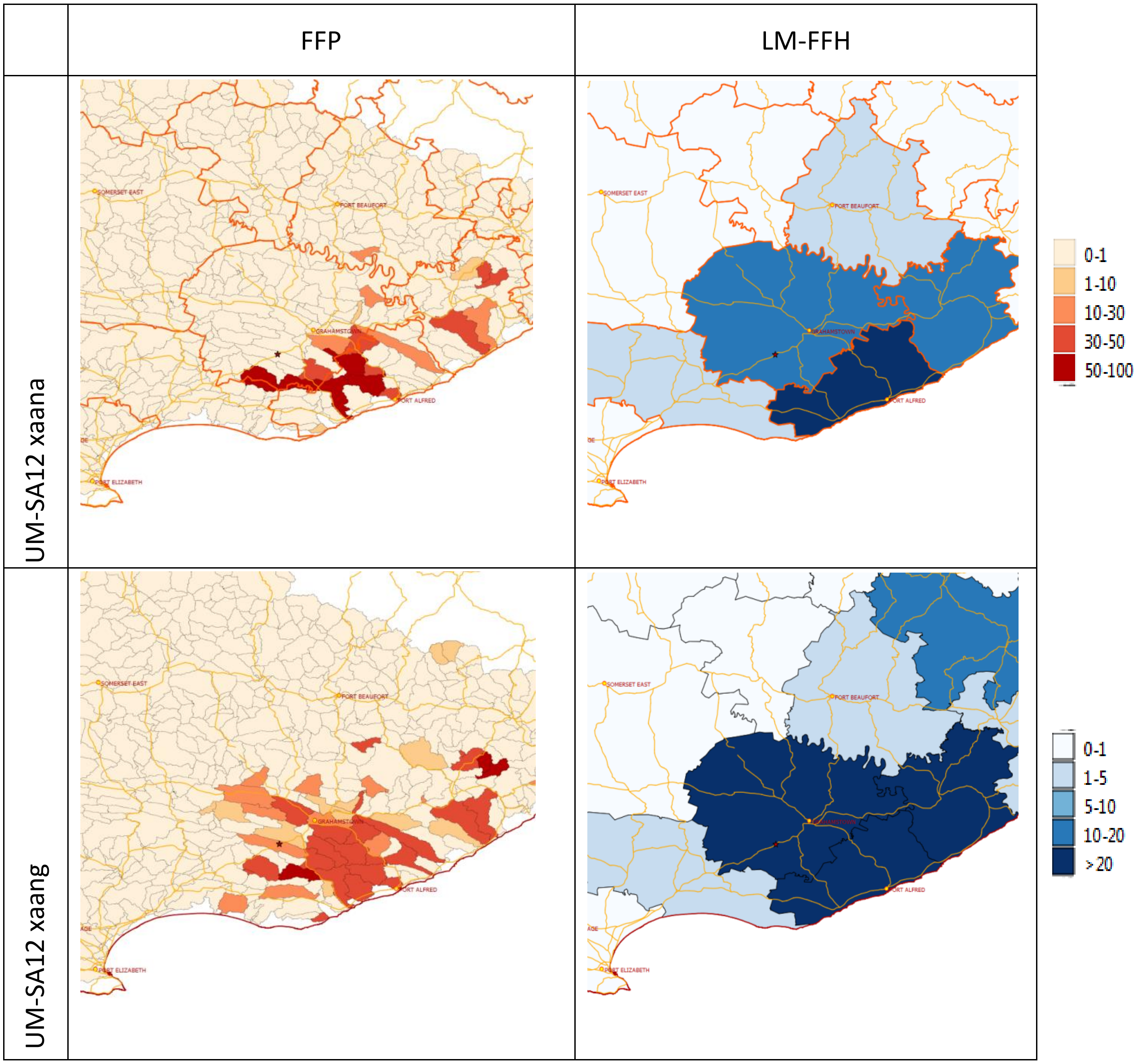


Figure 4.17: 6-24 hour FFP (left) and LM-FFH (right) fields of the UM-SA12 xaana and UM-SA12 xaang runs of 20th 00-hour based on the 12-hour FFG.

4.4.2.3 The 18-hour flash flood outlook

The probabilistic FFP values for the case study of 20 October 2012 are presented in Figure 9 (left panels) of both the xaana and xaang configurations of the UM-SA12 for the 6-24 hour window period. FFP was calculated as the percentage of ensemble members that would have exceeded the persisted 12:00 UTC FFG value for the particular basin. The right hand panels (LM-FFH) in Figure 4.17 indicates the number of SAFFG basins in the FFP products that show an outlook of potential flooding in a local municipality compared to all the basins of the particular local municipality and is aimed purely as a "heads up" of likely adverse conditions.

Based on the HyEPS forecasts both the xaana and xaang configurations of UM-SA12 identified by 12:00 UTC that the Ndlambe local municipality (which includes the town of Port Alfred) had a high likelihood of potential flash flooding in the 6-24 hour window period. Both model runs also forecast a higher FFP potential in the Kowie River running into Port Alfred, with the xaana configuration indicating more than 66% of the members expected more rain than required for potential flash flooding in this basin during this period.

The LM-FFH and FFP thus accurately provided an early outlook of the flash flooding in Port Alfred that occurred later that day. As a reference, the SAFFG system in hindsight identified the same basins would have flooded given the rainfall as estimated from the East London radar.

4.4.3 Case Study 2: Gauteng flash floods of 20 April 2013

4.4.3.1 Description of the event

A cut-off low-pressure system caused heavy rain over southern Gauteng and KwaZulu-Natal on the 20 April 2013 which resulted in damage to property and infrastructure and left 136 people homeless near the Klipspruit south of Johannesburg (SAWS, 2013). Cars were trapped in floodwater, roads were closed and people had to be rescued. An upper air trough caused a band of severe storms to move from the southwest through the Gauteng radar region in the late afternoon and overnight on 19 April 2013 (see left most column in Figure 4.18), reaching its peak overnight between 18:00 and 24:00 UTC where after it dissipated by the afternoon of the 20th.

Rainfall and HyEPS probabilistic products were produced for four runs of the UM-SA12 xaang and UM-SA12 xaana configurations of the model based on initialisation times of 19th 00:00 UTC and 20th 00:00 UTC. Differences in the rainfall products from these four UM-SA12 model runs were compared between the two model configurations, and between subsequent runs of each configuration.

4.4.3.2 Rainfall forecast results from HyEPS

Figures 4.18 and 4.19 illustrate that both the UM-SA12 xaang and xaana deterministic model runs of the 19th 00:00 UTC did simulate the rain band, but peaked far too early between 12:00 and 18:00 UTCs on the 19th and then stopped the rain again too early by midnight on the 20th. The xaana configuration also forecast much lower values than the xaang configuration. In comparison, the xaang and xaana UM-SA12 runs of the 20th 00:00 UTC, started with quite heavy rainfall in the Gauteng radar region, though the rain area in the xaang configuration was displaced too far to the east. Both these runs moved the rain area to the northeast faster than actually happened, with the xaang configuration the quicker of the two. The early peak of the UM-SA12 xaang deterministic forecast of the 19th compared to the observations is quite evident in Figure 4.19. What is striking is how both the xaana and xaang configurations of the 20th responded by predicting a significant amount of rain within the first 12 hours of their runs as was measured by SAFFG MAP. The reason for their response will be speculation until a thorough analysis of the model runs was conducted, which is not within the scope of this thesis. Most probably, however, it is related to a correction of the initial fields that the xaana and xaang model- runs were based on at 20th 00:00 through the data assimilation systems (Stensrud, 2007; Lean *et al*., 2008; Warner, 2011).

In Figure 4.20, the average rainfall for the 18-hour window period from 00:00 to 18:00 UTC on 20 April 2013 measured by SAFFG MAP is shown. In comparison the HyEPS average rainfall forecasts by the xaana and xaang configurations of UM-SA12 for the same period is also shown in the same Figure. The broad pattern of the HyEPS average forecast of the xaana configuration is visually remarkably closer to the MAP average over the 18-hour period than the pattern of the xaang configuration. This is in line with a casual inspection of Figure 4.18 and Figure 4.19.

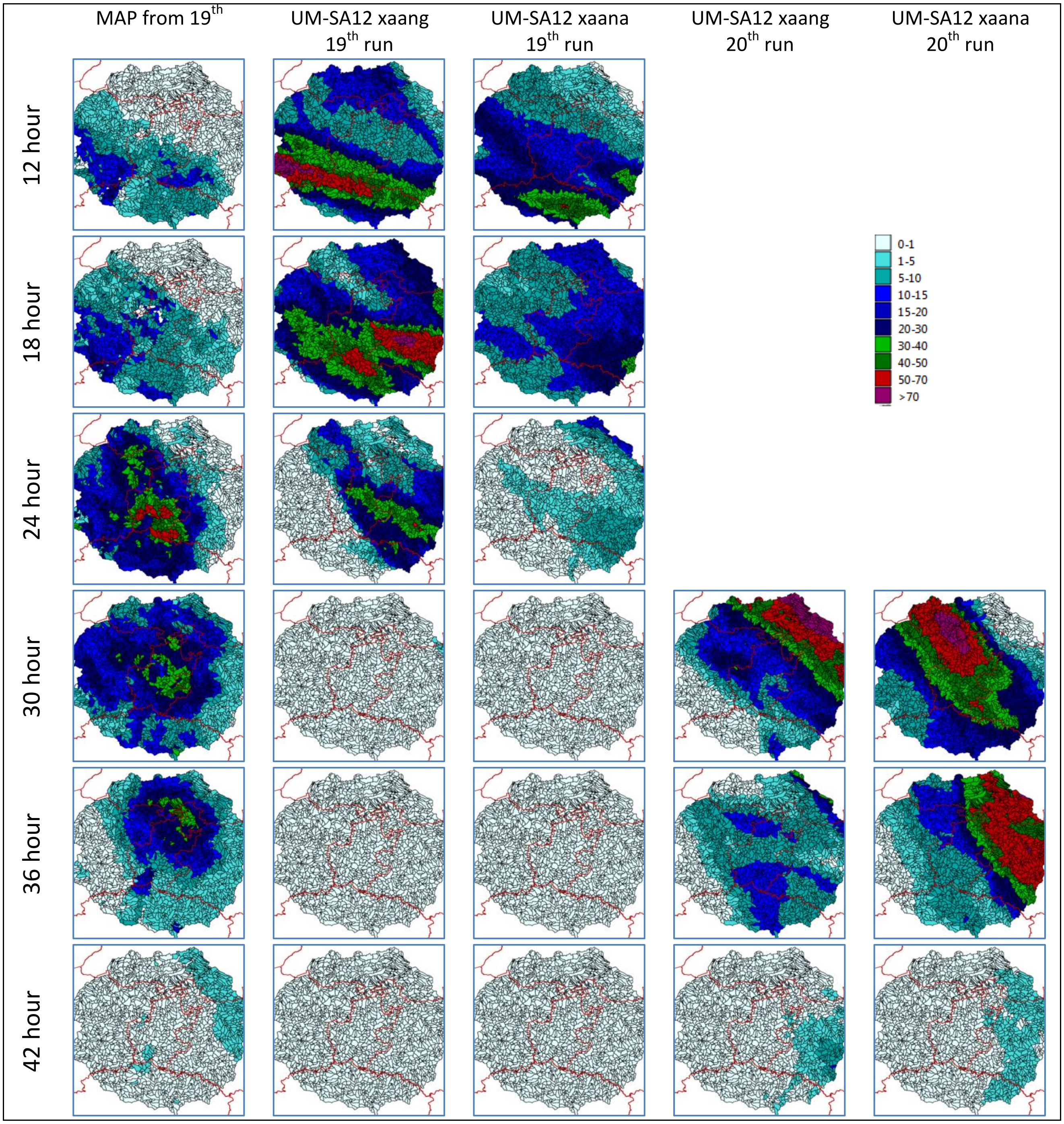


Figure 4.18: Comparison of the MAP and UM-MAP for 19 and 20 April 2013. The first column is a graphical representation of 6–hour rainfall from SAFFG observed field (MAP) for the period 12:00 UTC on the 19th up to 18:00 UTC on the 20th (42 hours into the forecast period). Columns 2 to 5 depicts the corresponding UM-MAP of two deterministic configurations of the Unified Model (xaang and xaana) of the 19th 00:00 UTC model runs (columns 2 and 3), and the 20th 00:00 UTC model runs (columns 4 and 5). The rainfall scale is in mm.

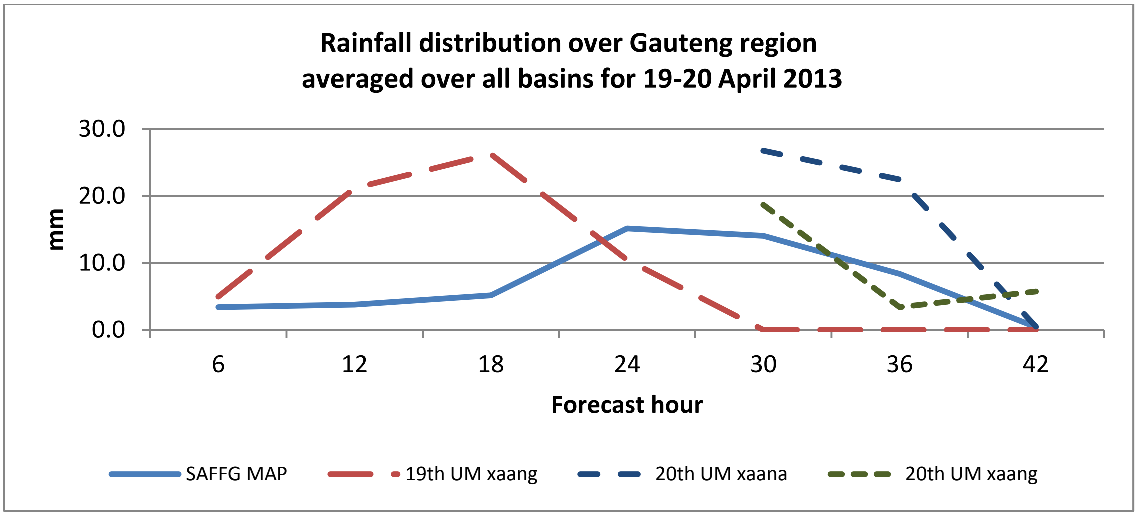
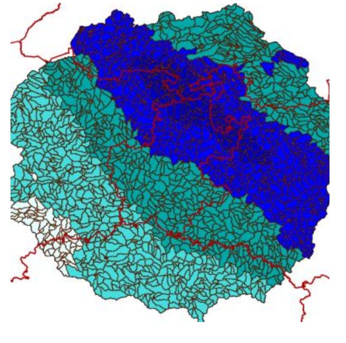
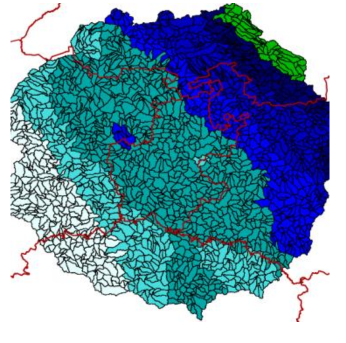
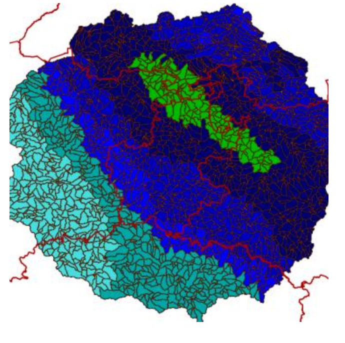


Figure 4.19: Rainfall distribution averaged over the entire Gauteng radar region on 19 and 20 April 2013. The solid line is the observations as represented by SAFFG MAP. The long dashed line is the UM-MAP of UM-SA12 xaang configurations of the 19th 00:00 UTC, the short dashed line the UM-SA12 xaana configuration of the 20th 00:00 UTC, and the dotted line the UM-SA12 xaang configuration of the 20th 00:00 UTC.

	SAFFG MAP observations average rain	UM-SA12 xaang ensemble average rain	UM-SA12 xaana ensemble average rain
0-18 hour window period			

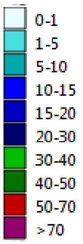


Figure 4.20: Comparison of the 6-hour SAFFG MAP average rainfall observations over the 00:00 to 18:00 hour window period with the average UM-SA12 xaang and UM-SA12 xaana ensemble forecasts for the same period of 20 April 2013. The rainfall scale is in mm.

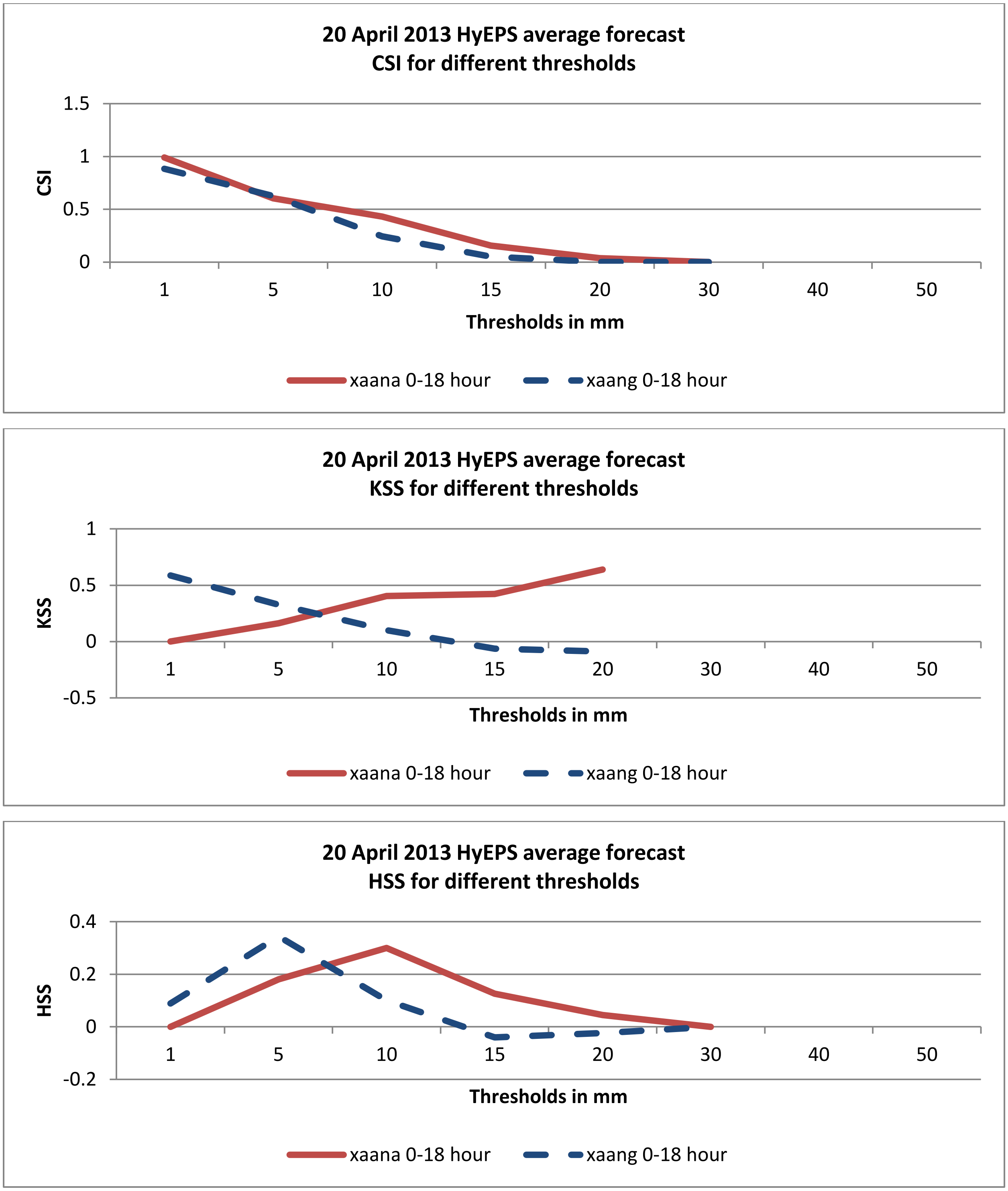


Figure 4.21: Verification statistics for the HyEPS average forecasts for the UM–SA12 xaana and xaang configurations for the 0-18 hour window periods for different rainfall thresholds based on the 20 April 2013 00:00 UTC runs. The top panel shows the CSI, the middle panel the KSS and the bottom panel the HSS.

As for Case Study 1, verification metrics were again calculated. For this case study it was done for the 00:00 to 18:00 hour window period of 20 April 2013 using the HyEPS average rainfall fields of the UM-SA12 forecasts of the xaana and xaang configurations of the 20th at 00:00 UTC. These HyEPS average forecasts were compared to the average of the observed SAFFG MAP fields for the same period. As in Case Study 1, the Critical Success Index (CSI), Hanssen-Kuipers Score (KSS) and Heidke Skill Score (HSS) were calculated and displayed in Figure 4.21.

Both the xaana and xaang configurations of UM-SA12, displayed high levels of accuracy at low thresholds of 1 and 5 mm as measured by CSI in the top panel in Figure 4.21. This means there were a higher level of agreement between forecasts and observations at those low thresholds. The accuracy decreases rapidly for the thresholds from 15 to 30 mm for both model configurations, although the xaana configuration fares better than the xaang configuration. Beyond 30 mm, for thresholds of 40 and 50 mm, the score is zero since the HyEPS average forecasts and the SAFFG average MAP did not have rainfall in this range (see Figure 4.20).

The KSS (middle panel in Figure 4.21) shows two opposite trends between the HyEPS average rainfall of the xaana configuration and the xaang configuration of UM-SA12. The xaana configuration displays poor ability to discriminate (i.e. distinguish between occurrences and non-occurrences) at low rainfall thresholds, but this ability increases to moderate levels by the 20 mm threshold. In contrast, the xaang configuration shows moderate ability to discriminate at low thresholds, but this ability decreases to negative values at 15 and 20 mm thresholds. The reason for this can be seen in Figure 4.20. At low thresholds, the xaana configuration forecasts rain in all basins, though the MAP image shows basins in the southwest where no rain was observed. The xaang configuration also had no rain forecast in those basins. On the other hand, at high thresholds, the xaana configuration forecasts a similar northwest-southeast rain band as the MAP image, but in the xaang configuration, this rain band was displaced to the northeast. Consequently, xaana shows better ability in this case to place the heavier rain band where the MAP image showed it, and thus provided a more reliable forecast than the xaang configuration.

The xaang configuration displayed better skill in the lower range of thresholds than for higher thresholds as measure by HSS in the bottom panel of Figure 4.21. The xaana configuration displays overall moderate skill, particularly around the 10 mm threshold. The xaana configuration shows better ability to forecast the rain distribution than a random forecast would, whereas the xaang configuration was worse than a random forecast at 15 and 20 mm thresholds.

For this case study, it can be concluded that the UM-SA12 model forecasts expected a heavy rain band to move through the Gauteng region, but the model runs of the 19th 00:00 UTC failed in predicting the rainfall accurately from a timing perspective 24 to 36 hours in future (Figure 4.18). The xaang configuration produced the better forecast of the two configurations and had the broad pattern in place, but about 12 hours too early. The UM-SA12 forecasts based on the 20th 00:00 UTC analysis fared better, and both the xaana and the xaang configurations forecast rainfall from the early hours of the morning. The xaana configuration provided the best forecast quality forecast according to the verification results. Additionally, the EPSave provides promising evidence that the HyEPS system of 30 members could add useful information on the likelihood of rainfall over the 18-hour window period.

4.4.3.3 Flash flood outlook results

Figure 4.22 shows the LM-FFH and FFP for both UM-SA12 xaana and xaang configurations based on the model runs of 20th 00:00 UTC. The FFG of SAFFG was persisted from 00:00 UTC. Verification of the FFP and LM-FFH is problematic, since this should be done against reports of real flash flood events within the basins and LMs. The SAFFG FFT is the result of a prediction by hydro-meteorological models of soil moisture and flash flood guidance and therefore cannot be regarded as a representation of real flash flood events. Furthermore, FFT is only valid for 6-hour periods whereas FFP, on the other hand, describes the flash flood potential for an 18-hour period.

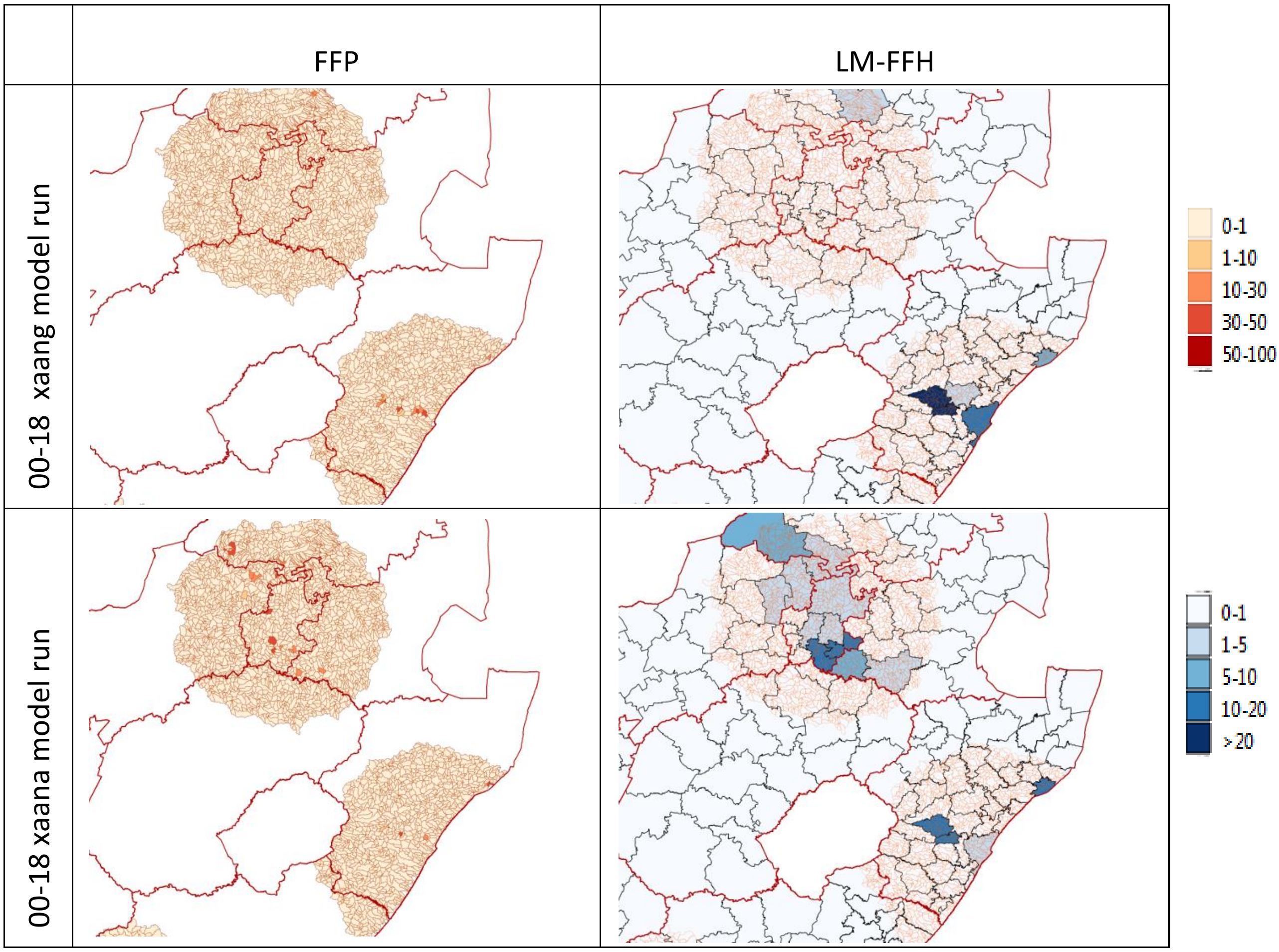


Figure 4.22: Flash flood potential (FFP) and LM-based flash flood hazard risk (LM-FFH) for the 0-18 hour window period for the xaang configuration (top panels) and the xaana configuration (bottom panels) of the UM-SA12, based on the 00:00 UTC analysis of 20 April 2013.

Reports of flash flooding were received for the Klipspruit and the Kliptown area in Soweto near Johannesburg (SAWS, 2013). The SAFFG FFT information indicated potential flooding between 0 and 6 hours in one basin further to the north of this region. The FFP based on the xaang configuration indicated two basins with positive flash flood potential during the 0-18 hour period, but they were quite a distance away to the northeast of Pretoria. The FFP based on the xaana configuration, however, indicated a potential for flash flooding in 25 basins for the same 0-18 hour period, including four in the Klipspruit area (Figure 4.23) with a probability of 30 to 33%. Consequently, the LM-FFH for the xaana configuration was able to identify the associated local municipalities with moderate to high flash flood risk.

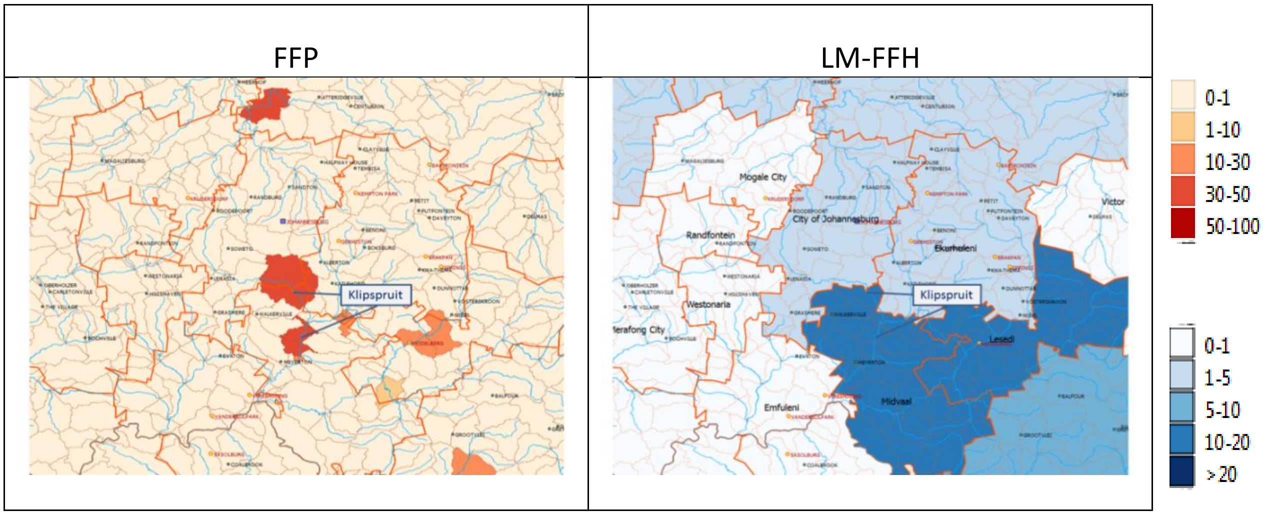


Figure 4.23: Zoomed in images of the FFP (left) and LM-FFH (right) of the xaana model for the Klipspruit region where flooding occurred on 20 April 2013 in the 0-18 hour window period.

4.4.4 Case Study 3: Gauteng flash floods of 16 December 2010

4.4.4.1 Description of the event

More than 133 mm of rain fell overnight on 15 and 16 December 2010 in Gauteng Province as a line storm associated with an upper-air trough moved from southwest to northeast over the province. In Vereeniging, more than 100 mm fell in just 8 hours between 20:00 SAST (South African Standard Time) on the 15th and 06:00 SAST on the 16th (Figure 4.24). Severe flash flooding occurred in several places, starting overnight in the southern parts and in the morning of the 16th over the northern parts of the province. The flooding caused severe infrastructure damage, some fatalities and people were displaced.

The duty forecaster of the SAWS, using the SAFFG system (Figure 4.26), monitored the progress of the line storm on the night of 15-16 December 2010. The first warnings were issued at 21:00 SAST on the 15th (Figure 4.25). From 23:00 SAST on the night of the 15th a flood watch (diagonally shaded in Figure 4.25) were issued for the southern district municipality of Sedibeng and upgraded to flood warnings (grey shaded in Figure 4.25) 2 hours later. By 06:00 SAST on the 16th flood warnings were also issued for the central and northern metropolitan areas. The SAFFG system as a nowcasting tool, however, did not allow the forecaster to issue an outlook of potential flash flooding earlier to disaster management. Consequently, most of the warnings were issued overnight leaving no time for reaction by disaster management. A forecasting system, based on NWP, may have provided useful advance information.

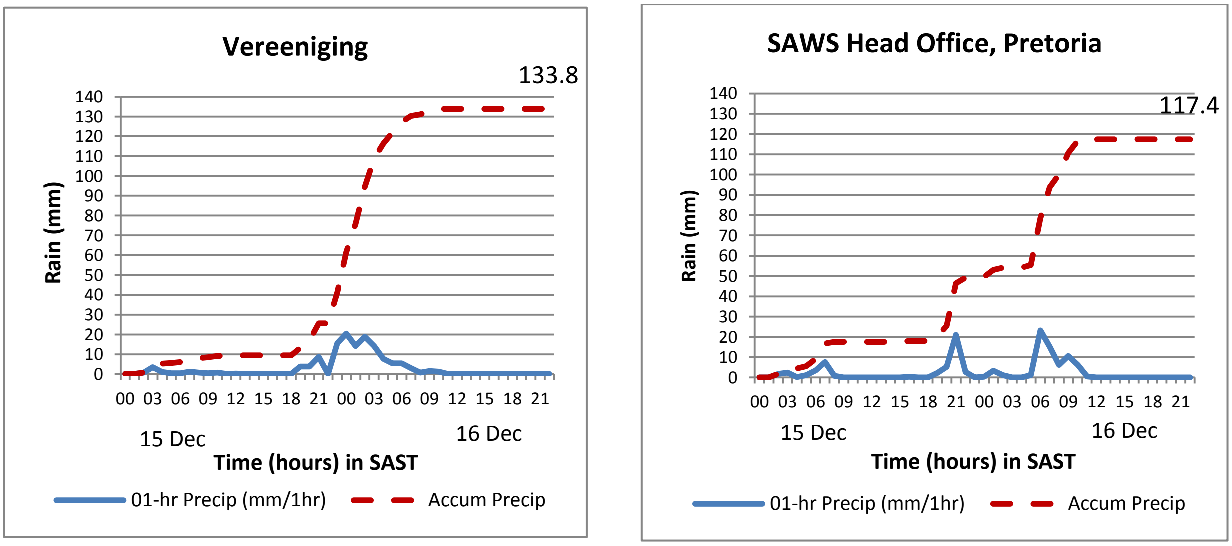


Figure 4.24: Rainfall from automatic weather stations of the SAWS at Vereeniging (left) and Pretoria (right) on the 15 and 16 December 2010. The solid lines represent hourly rainfall, and the dashed lines accumulated rainfall over the two days.

	Hours of the night of 15th to morning of 16th in SAST															
District	**21**	**22**	**23**	**00**	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**
Sedibeng			▨	▨	■	▨	■	■	■	■	■	■				
West Rand							■	■	■	■	■	■				
Ekurhuleni										■	■	■	■	■	■	
Johannesburg	■									■	■	■	■	■	■	
Tshwane	■									■	■	■	■	■	■	

Figure 4.25: Flash flood watches (diagonally shaded) and flash flood warnings (grey shaded) issued during the night and morning of 15-16 December 2010 for various district municipalities in the Gauteng region.

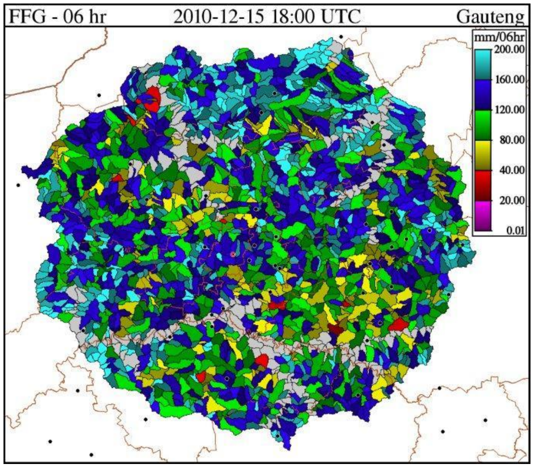
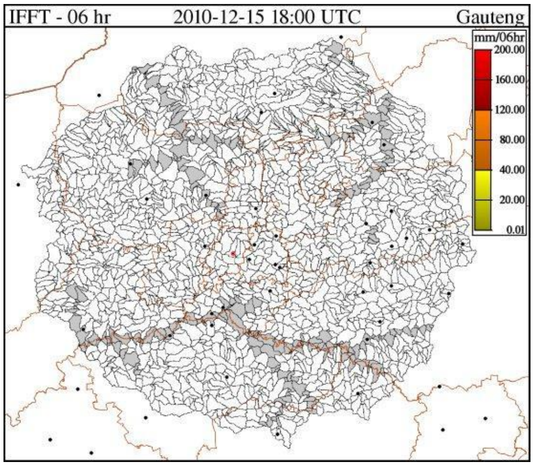
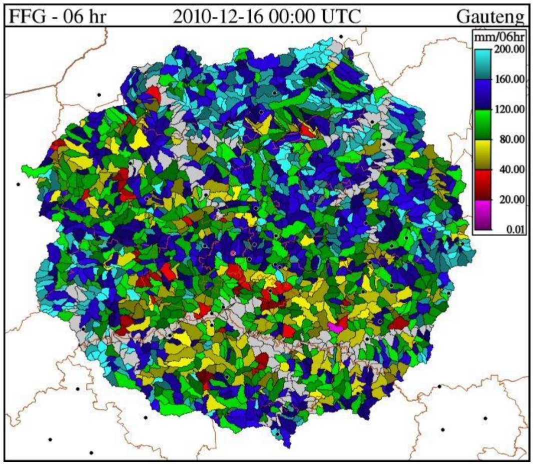
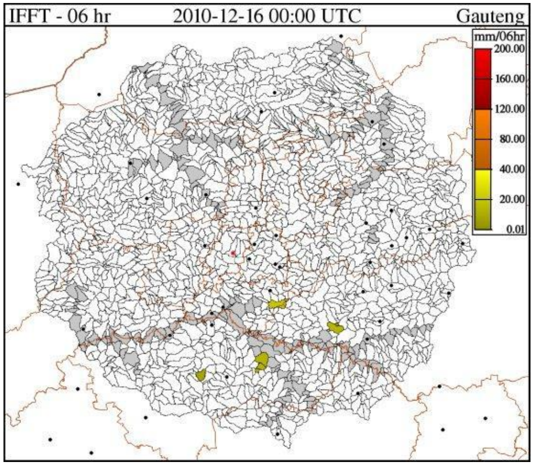
	Flash Flood Guidance: Red shading show basins where little rain is needed for flooding	**Flash Flood Threat: Green shading show basins with excess rain above Flash Flood Guidance**
15 Dec 20:00 SAST		
16 Dec 02:00 SAST		

Figure 4.26: Representative FFG and FFT fields from the SAFFG for the night of 15-16th December 2010. The times on the maps refer to UTC. The rainfall scale is in mm.

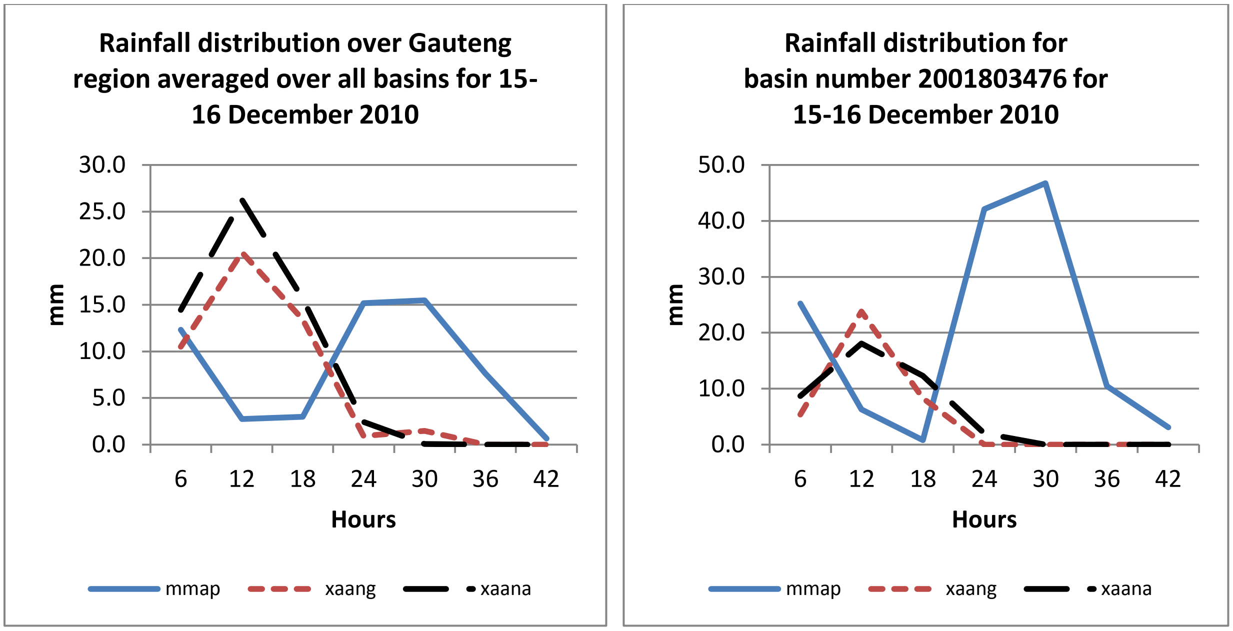
4.4.4.2 Results

The significant rainfall started in the evening and the flash flooding peaked from midnight to early morning. This resulted in the FFG values to drop significantly between 18:00 UTC and 24:00 UTC (Figure 4.26) due to the rainfall increasing the soil moisture in the basins and thus leading to less rain needed for potential flash flooding. Similar to case study 1, both the UM-SA12 xaang and xaana configurations forecast the rain to peak 12 to 18 hours too early (Figure

4.27). A HyEPS forecast based on persisting the higher 12:00 UTC or 18:00 UTC FFG values would not have indicated potential flooding in this case. Furthermore, a HyEPS forecast based on 24:00 UTC FFG would have been too late as the flash flooding already started by midnight.

This situation provides the opportunity to test another approach, by developing scenarios based on an expected drop of the 12:00 UTC or 18:00 UTC FFG values due to the forecast rain. This lowering of FFG values will have to be based on a statistical approach. An evaluation of the FFG values for this case revealed that the FFG levels dropped on average just more than 10% from 18:00 UTC to 24:00 UTC due to the rain, with the 75th percentile drop almost 20% and the maximum drop 65% from 18:00 UTC. Two potential scenarios could be developed, namely to drop the 12:00 UTC and 18:00 UTC FFG values by typically 10% and 20% and compare each of these values with the HyEPS system.

For demonstration purposes, and with the freedom of hindsight in this case study, an idealized scenario was created by taking the FFG values at 24:00 UTC as a representation of the adjusted 12:00 UTC or 18:00 UTC FFG scenario instead of lowering the real 12:00 UTC or 18:00 UTC FFG arbitrarily by 10% or 20%. The FFP and LM-FFH based on the UM-SA12 xaana and xaang model runs are presented in Figure 4.28. In this idealized scenario, the only 18-hour window period that produced useful results was the 6-24 hour outlook due to the large offset in the peak time of the UM-SA12 rainfall forecasts compared to the observed situation shown in Figure 4.27. The FFP of both xaana and xaang configurations indicated that a few basins in the southern part of the area had a significant flash flood potential, close to those that the FFT indicated and where the flash flooding started during that period.



Rainfall distribution over Gauteng region averaged over all basins for 15-16 December 2010

Rainfall distribution for basin number 2001803476 for 15-16 December 2010

Figure 4.27: The rainfall distribution for 15 and 16 December 2010, averaged over the entire Gauteng radar region (left) and for a specific basin in the Sedibeng district in the south (right). The solid line is the observations as represented by SAFFG MAP. The short dashed line is the rainfall forecasts of UM-SA12 xaang run of the 15th at 00:00 UTC and the long dashed line the UM-SA12 xaana run.

It can be concluded that a scenario-based outlook, using an adjusted FFG field scenario, can provide a reasonable outlook for potential LM flash flood risk early in the day, even though the NWP models forecast the rain to peak too early. These adjustments could be based on lowering the FFG values with 10% and with 20% based on the high NWP forecast rain peaks.

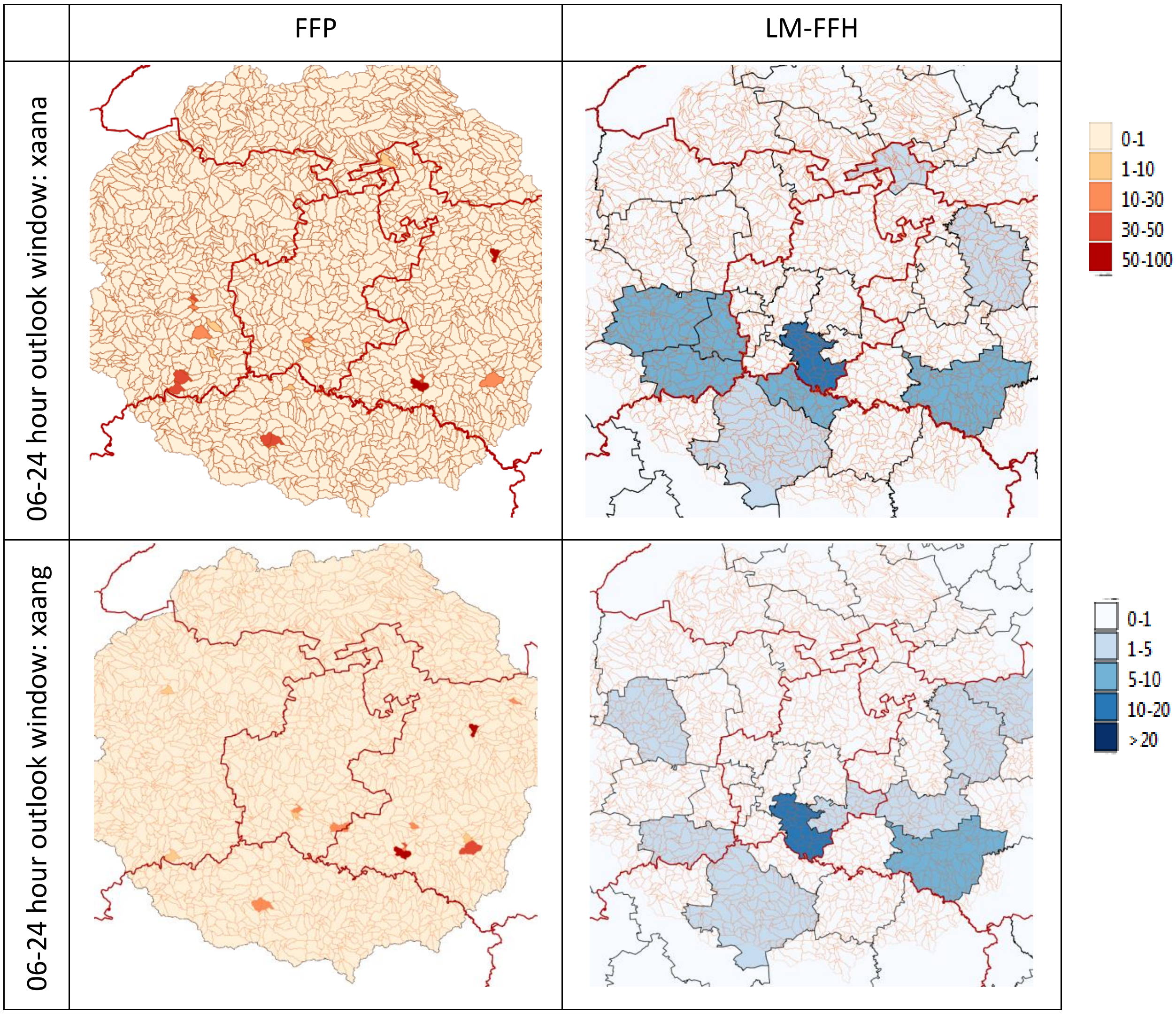


Figure 4.28: FFP and LM-FFH fields of the UM-SA12 xaana (top row) and xaang (bottom row) runs of 15th 00:00 UTC based on the 24:00 UTC FFG as an idealized scenario for the 06-24 hour window period.

4.4.5 Case Study 4: Gauteng and KwaZulu-Natal flash floods of 07 September 2012

4.4.5.1 Description of the event

A cut-off low-pressure system moved over South Africa on 6 and 7 September 2012 causing heavy rain in places over Gauteng, Mpumalanga, KwaZulu-Natal and the Eastern Cape (SAWS, 2012a). Flash flooding occurred in Pretoria, Johannesburg and Ekurhuleni in Gauteng, and around Durban in KwaZulu-Natal.

4.4.5.2 Results

The UM-SA12 xaana configuration products were not available for this day. The UM-SA12 xaang configuration's model run of 07th 00:00 UTC forecast the eastward propagation of the event reasonably well, although it forecast far too much rainfall particularly at 06:00 UTC (Figure 4.29 and 4.30). The EPS average forecast of HyEPS tempered the rainfall forecast somewhat. In terms of the Hit Rate (HR) and False Alarm Rate (FAR) the 12:00 UTC forecast, using the traditional MAP persistence forecast, did quite well (Figure 4.31), but the deterministic UM-SA12 xaang configuration performed poorly. In contrast, HyEPS EPSave based on the UM-SA12 xaang configuration did well and outperformed the deterministic forecast significantly.

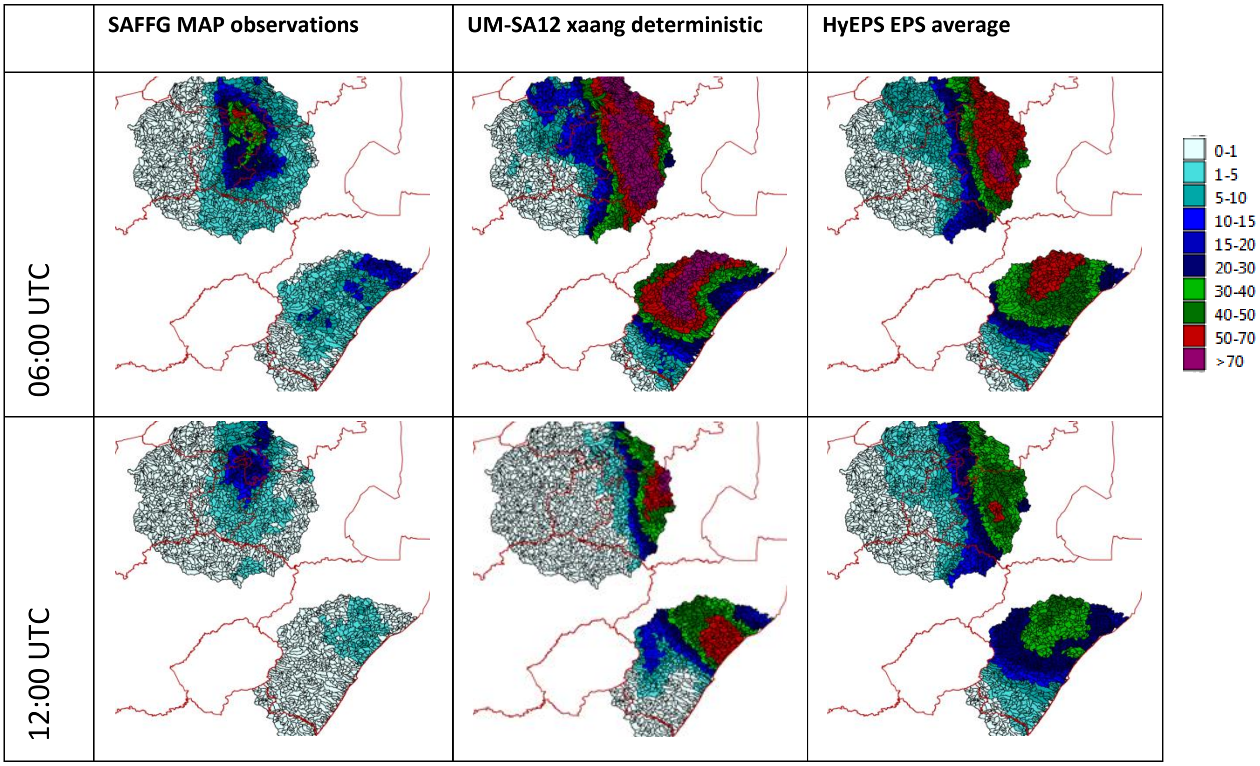


Figure 4.29: Comparison of the SAFFG MAP rainfall observations with the UM-SA12 xaang deterministic forecast and the HyEPS EPSave for 6:00 UTC and 12:00 UTC on 7 September 2012. The rainfall scale is in mm.

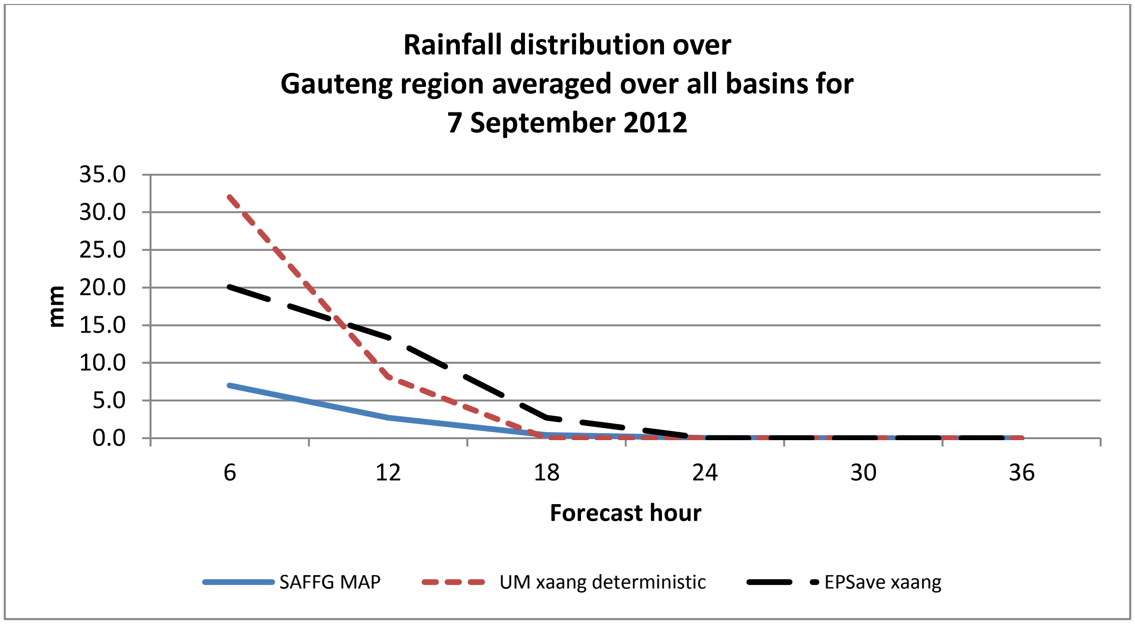


Figure 4.30: Rainfall distribution averaged over the entire Gauteng radar region for 7 September 2012. The solid line is the observations as represented by SAFFG MAP. The short dashed line is the rainfall forecast of UM-SA12 xaang configuration of the 07th 00:00 UTC, the long dashed line the EPSave of HyEPS of the UM-SA12 xaang run.

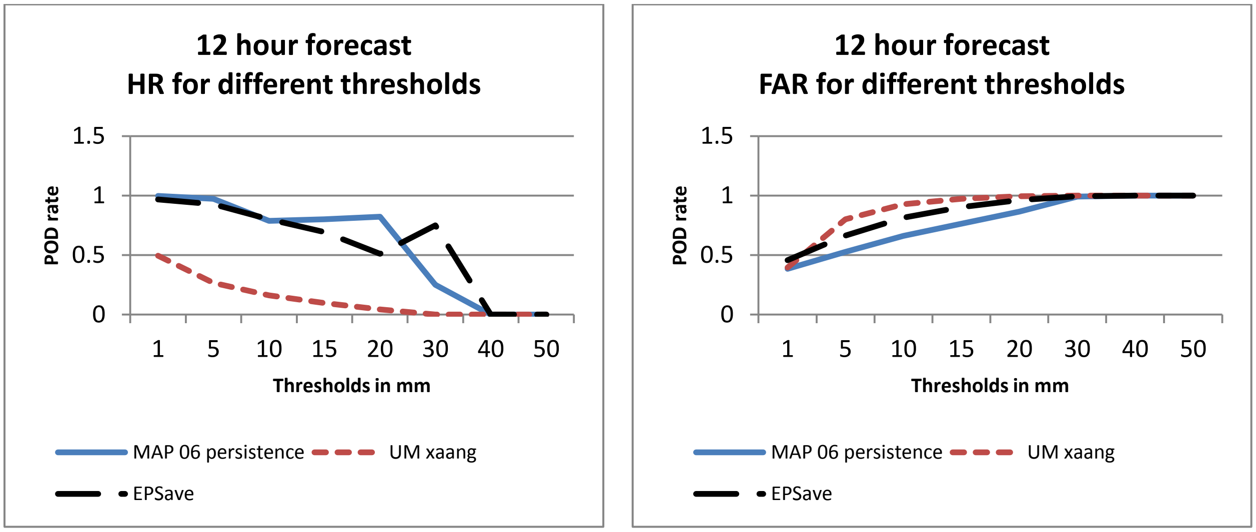


Figure 4.31: Comparison of the Hit Rate (HR) and False Alarm Rate (FAR) for the 12:00 UTC forecast on 7 September 2012 based on MAP 06:00 UTC persistence (solid line), UM-SA12 xaang deterministic model (short dashed line) and HyEPS EPSave (long dashed line).

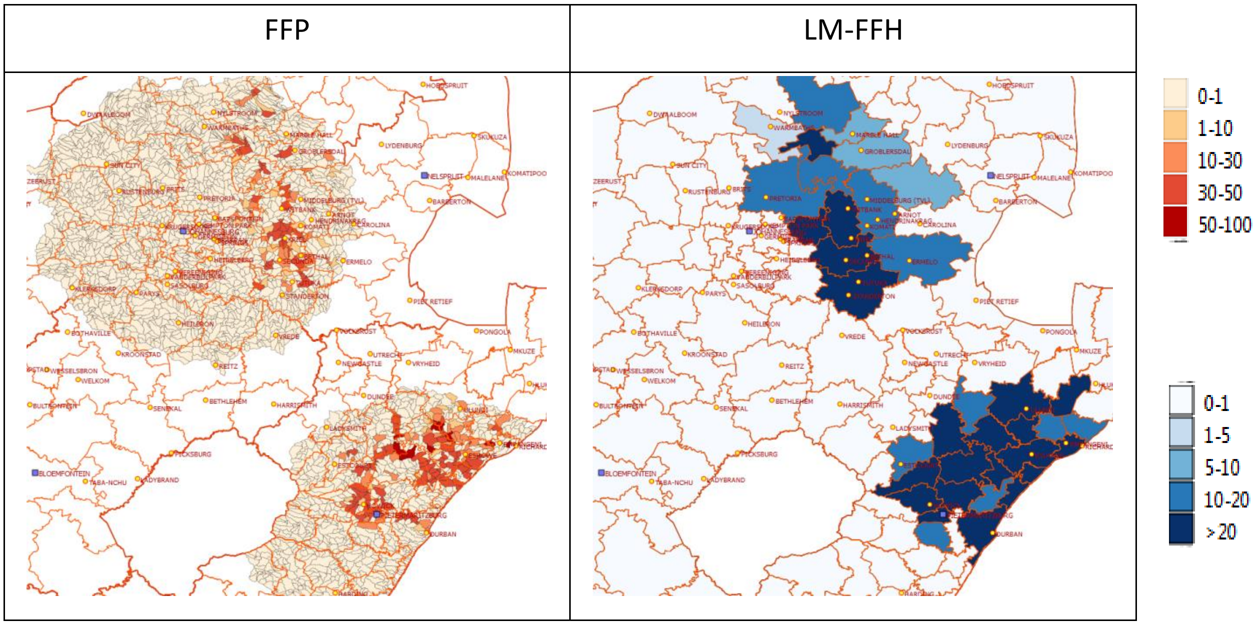


Figure 4.32: 0-18 hour FFP (left) and LM-FFH (right) fields of the UM-SA12 xaang configuration of 07 September 2012 00:00 UTC based on the 06:00 UTC FFG.

The 0-18 hour FFP and LM-FFH products based on the HyEPS system (Figure 4.32) provided information on the likelihood of flash flooding for the areas mentioned earlier that experienced flash flood events. It is quite possible that the system over forecast the FFP and LM-FFH due to the significant over prediction of rainfall amounts referred to earlier. This can only be verified with detailed actual event information, which is unfortunately not readily available.

It can be concluded that for this case the ensemble based UM-SA12 HyEPS forecast added considerable value above the deterministic UM-SA12 forecast to enhance the outlook of potential flash flooding.

4.5 DISCUSSION

Based on the HyEPS forecasts the UM-SA12 with both the xaana and xaang configurations were able to identify potential flash flooding in an 18-hour window period based on persisted FFG values for the case studies described in this chapter. This suggests that the forecast rain from a deterministic NWP model can provide useful information of potential future rainfall patterns at the small basin scale if suitably bias corrected and used in a hybrid EPS as described here. In this way, provision is made to some extent for the uncertainty associated with the NWP forecasts.

The advantage of the HyEPS forecasts is that the 30 rainfall ensemble members in the neighbourhood of each basin represent the entire 18 hours in 3 equal 6-hour periods (10 members each). This accommodates largely the NWP problem of timing of convection as also experienced in some of these case studies. By using the closest 10 members for a 6-hour period, the likelihood of spatial errors of the development of a convective system compared to the NWP prediction is taken into account to some extent. The optimum size of this neighbourhood was not investigated and such further work would be a recommendation from this study.

The rainfall forecast from all 30 EPS members, compared with the target basin's FFG value (persisted throughout the 18-hour window period), provides FFP as a probability which represents an outlook of the likelihood of flash floods for an 18-hour period for a particular basin. Similarly, LM-FFH (the percentage of basins with positive FFP in the LM) represents the flash flood hazard risk within a local municipality over the 18-hour period. The LM-FFH thus provides an early warning to disaster managers within the municipality of potential flooding somewhere in the municipality. The FFP focus attention on the likely basins within the local municipality with best potential to be in danger of being flooded.

Bias correction of the UM-SA12 forecasts is important to provide more realistic rainfall amounts. The BCF could differ between regions with different radar systems. It could also differ between regions using radar based rainfall estimation and regions using satellite based rainfall estimation such as the Western Cape. For this reason, no case study was attempted over the Western Cape yet.

Any methodology using NWP relies heavily on the ability of the NWP system to provide a reasonably good rainfall prediction. The HyEPS is quite tolerant of small spatial or time deviations due to the 30-member EPS approach. If the forecasts deviate too far from the correct positioning or timing of the rainfall peak, however, then not even HyEPS will be able to provide a useful outlook.

No sensitivity in the performance of the prediction system was found related to the different regions of the cases studies. From the case studies, it is argued that the system should perform better with large rainstorms, caused by large-scale weather systems (such as cut-off lows, or tropical depressions) than with smaller and/or fast moving convective systems or line storms. This could be linked to the improved predictability of the rain associated with the large weather system, as was the situation in case studies 1 and 4.

A major limitation in the approach followed here is the assumption that the FFG values can be persisted for another 12 or 18 hours. How valid was this assumption? In Case Study 1 of 20 October 2012, the real-time FFG from the SAFFG archive was lower than the HyEPS maximum rainfall for the xaana configuration of UM-SA12 for the basins in the Kowie River just upstream of Port Alfred between 04:00 UTC and 23:00 UTC. Consequently, these basins would have had a potential for flash flooding in the Kowie River flowing into Port Alfred between those hours based on the HyEPS rainfall forecast available already early in the morning. For this case study, the assumption of persistence of the FFG is thus valid.

4.6 CONCLUSION

Disaster managers require more lead-time than 6 hours to prepare and react appropriately to threatening disasters. The SAFFG and SARFFG systems only provided a nowcast for the next 6 hours based on rainfall persistence. For the first time an ensemble-based NWP forecast, HyEPS, addressing the uncertainty in NWP rainfall forecasts, provided an extended outlook for an 18-hour forecast window (see Figure 4.3) of the potential for flash flooding (through FFP) in a SAFFG basin and the risk of flash floods in local municipalities (through LM-FFH). Whereas the HRC has used NWP in other versions of the FFGS to extend the lead-time beyond the traditional

6 hours (Georgakakos, personal communication), it was with a deterministic model not taking into account the uncertainty associated with rainfall forecasting as was done in the HyEPS.

Other conclusions may be summarized as follows:

- The flash flood outlook products can play an important role in supporting the decision-making processes of forecasters and disaster managers by drawing their attention to the likelihood of flash flooding with a lead-time of up to 18-hours.
- The 6-hour nowcast of the SAFFG system is based on the persistence of the previous 6-hour rainfall in to the coming 6 hours period, which is for most thunderstorm systems not an appropriate assumption. NWP provides the most appropriate means of addressing the forecast of rainfall for the next 24 hours, but uncertainties associated with rainfall forecasts by NWP is a serious limiting factor.
- The HyEPS provided evidence that an ensemble system of 30 members from a deterministic model could address these uncertainties and add considerable value above the deterministic UM-SA12 forecasts on the likelihood of rainfall in the small river basins of the SAFFG over an extended 18-hour window period. Casual investigation of initial products of the SARFFG indicates that the HyEPS approach could be even more successful over the larger SARFFG basins. This could be due to reduced uncertainty in location of convective rainfall over the larger basins, but requires further investigation.
- The optimum size of the ensemble members from a deterministic NWP model depends on the scale of the phenomena predicted and needs to be determined.
- The assumption that the FFG values can be persisted over the next 18 hours is generally a reasonable assumption. This approach can be followed with reasonable success in the current configuration of the SAFFG and SARFFG. The ideal situation would be to integrate the NWP rainfall forecasts into the FFGS modelling systems to predict dynamically the changes in FFG based on the NWP rainfall forecasts. A major enhancement of the FFGS modelling system would be required, however.

- An exception occurs when the NWP rainfall forecasts peaks more than 12 hours earlier than the real rainfall peak. In such a case, a scenario-based outlook needs to be followed. This implies that in cases where the NWP models forecast the rain to peak too early, lowering the available FFG values with 10% or 20% can provide a reasonable estimate of the FFG values needed for an outlook for potential LM flash flood risk early in the day.
- Ensemble rainfall forecasts from a deterministic model can be successfully integrated into subsequent user applications to address the problem of uncertainty of rainfall forecasts by NWP models.
- Few developing countries using the FFG technology can afford the computer resources to run a high resolution EPS. The development of ensemble forecasts from deterministic model products can be performed on workstations or personal computers at the smaller weather services of developing countries not able to run a NWP system.

The main conclusion from this study is that the HyEPS forecasting system fulfils the first component of a flash flood impact forecasting system, namely the *future forecasts of the potential of flash floods* as described in Section 4.1. The second component relating to the provision of *information on the impact of flash floods* will be addressed in the next chapter.

CHAPTER 5

THE IMPACT MODEL FOR THE SEVERE WEATHER IMPACT FORECASTING SYSTEM

5.1 INTRODUCTION

In the introduction of Chapter 4 it was stated that a flash flood i*mpact forecasting* system such as SWIFS requires integration of two main components: (1) future *forecasts of the potential of flash floods*, (forecasting model) and (2) information on the *impact of flash floods* on people and their living environment (impact model). Chapter 4 dealt with the first element, namely forecasting of the potential of flash floods in the SAFFG river basins with a lead-time of up to 18 hours. The second element, the identification of impacts related to potential flash floods and their integration with forecasting of future flash floods, is the focus of this chapter.

In Chapters 1 and 3 it was argued that users of early warnings (disaster managers or the public) are unable to translate the complex scientific information into disaster risk levels. For these reasons Auld (2008, P 122) stated that research and development is needed to move from weather prediction to risk prediction *"that can identify general impacts, prioritize the most dangerous hazards, assess potential contributions from cumulative and sequential events to risks and identify thresholds linked to escalating risks for infrastructure, communities and disaster response*." This was supported by the arguments in Chapter 3 that disaster managers need to know: what is going to happen, where and when, and what will the impact be.

This situational urgency could depend on more variables than merely geographical location (WMO, 2012). For example, heavy rainfall during the afternoon rush hour on a week day could be more damaging than during a weekend. Impact forecasting requires a systematic methodology, or model, that can translate the forecast of weather hazards into relevant impact variables given factors such as those mentioned above.

5.2 AN OVERVIEW OF IMPACT-BASED SYSTEMS

The WMO (2012) has prepared an initial guidance document related to impact forecasting to provide some early insight into the issue and how some National Meteorological Services (NMSs) are working in that direction. Some NMSs have developed their own versions of what they call impact forecasting systems. More often than not this is merely a generalized indication of what typical impacts could be associated with specific hazards. Many times generalized advice on proactive or preventative measures is provided. It appears that few of them have a dynamic system for public warnings able to use the spatial variability of various impact parameters (societal, economic, environmental, etc.) to determine different levels of impacts applicable to an area. Some specific additional activities related to impacts are:

- The European Meteoalarm system (Meteoalarm, 2013) provides a colour-coded classification that intensifies from yellow to orange to red depending on the expected severity of the weather hazard itself, and then by default increasing generalized levels of consequences. Although Meteoalarm does not explicitly model the impact for each area based on the vulnerability of the area, it does indicated different levels of severity of the hazard. This is in itself an important component of an impact forecasting system that not only the likelihood of the hazard but also its severity will lead to different levels of the eventual impact. For example: a flash flood just overtopping a river bank could have less damaging consequences than a flash flood 5 metres above the river bank. This depends also on the local area and the variation of the vulnerability along the particular river bank, which Meteoalarm does not take into account.
- In the UK Met Office operational public warning system (www.metoffice.gov.uk) the forecasters make an assessment of both the likelihood and the generalized impact level according to a matrix to set the final colour code for the warning in a "weather impact matrix" (see Figure 5.2). Once again no detail of impacts specific to an area is provided to the general public. It may be different to emergency services.

- Within the US National Oceanic and Atmospheric Administration (NOAA) an experimental "impact-based warning" product is currently tested focussing on tornadoes (www.crh.noaa.gov/crh). The system is tested as a public product, providing more information, including impact information, to disaster managers and the general public. The aim is to prompt better public response and decision making. Whereas the impact information is again generalized depending on the severity level of the expected tornado, this example is an interesting case regarding its societal impact since it targets the information directly to the public. Some feedback received on this system was particularly negative based on the language used as to create panic instead of providing useful information. This reiterates that a careful approach is needed when working with the general public as user group.

Two other international research and development activities focus at the opposite extremes of impact information, either in high local detail or large-scale regional impact information. These are discussed below:

- The UK Met Office is on the forefront regarding the research and development of methodology around impact forecasting. In 2002 the UK Met Office launched the Severe Weather Impact Model which proposed a method to relate severe weather hazards with impacts at postal code level in the UK (UK Met Office, 2002). Various algorithms linked severe weather to impact factors such as property, public services, transportation, emergency services and utilities to determine the number of people affected, economic loss, the scale of damage and the scale of disruption, among others. The purpose of the model was to provide this information to the emergency services and other clients as specialized services. At one stage it was contemplated to relate hazardous weather to the required number of beds needed in hospitals, for example in the case of flu linked to changes in temperature. Recently this initiative is taken further by a government partnership, which includes the UK Met Office, on the development of the Hazard Impact Model. Little information is available as the system is still under development. From personal communication (Robbins, 2012) it is deduced that it links more hazards with vulnerability information and data sets through algorithms, using, among others, GIS. For example, the Hazard Impact Model provides information on the risk to vehicles overturning on roads due to different strengths of wind gusts. Naturally, these types of detailed impact forecasting are highly specialized and require quite detailed data sets not necessarily available in South Africa.

- The Global Disaster Alert and Coordination System (GDACS) is an international coordination mechanism under the United Nations umbrella (www.gdacs.org) aiming to provide information in the first phase after major disasters when planning of assistance is done (De Groeve *et al*., 2009). GDACS is run with the United Nations Office for the Coordination of Humanitarian Affairs (UN-OCHA) as its secretariat. It provides alerts and impact estimations following major disasters through a multi-hazard disaster impact assessment. Its focus is mainly to provide rapid high level impact assessments to governments, international organizations and disaster managers during the first phase after disasters. GDACS is not an impact forecasting system, rather a rapid impact assessment system. The methodology used by GDACS on impact assessment, however, is of interest. The focus is mainly on tropical cyclones, earthquakes and tsunamis in terms of identification and impact assessment. Detection of global floods is done using remote sensing technology, but impact information linked to flooding is still lacking. Nevertheless, the modelling approaches used in tropical cyclones and earthquake impacts are broadly similar to the UK Met Office Severe Weather Impact Model, although the data sets are focussing rather on the global-scale and not the high detailed local-scale as the Severe Weather Impact Model does.

All these examples in this section illustrate that impact forecasting can have many and quite complex approaches. It is important to clearly define the methodology, or model, to be used to identify the impacts and link them with the predicted hazard. The model needs a well-defined objective, focussed on a specific user group with a clear scope. Also important is to define what is meant by “impacts” and the level of detail that is required to achieve the relevant objective.

The depth and complexity could be quite detailed as illustrated by the Hazard Impact Model of the UK Met Office, or it could provide a global overview, as illustrated by the GDACS approach.

Before this model can be defined, it is necessary to understand what is meant by “impacts”, and how it relates to disaster risk and vulnerability.

5.3 VULNERABILITY, DISASTER RISK AND IMPACT

5.3.1 Vulnerability to weather-related disasters in South Africa

The single most important weather-related natural disaster affecting South Africa is flooding (Chapter 2, Section 2.2). Between 1920 and 2008 floods were the most numerous, cause the most deaths and resulting in the most significant impact to people, their livelihoods and infrastructure between 1920 and 2008 (CRED, 2014). This is also reflected in the Relative Impact Score calculated from the CRED data (refer to Table 5.1 and Figure 5.1), which compares a single representation of all the consequences as listed by CRED (CRED, 2014) in number of deaths, number of people affected, number of people homeless, number of people injured and economic damage. Households, communities and municipalities suffer considerable damage and disruption to their livelihoods and infrastructure as streams rapidly flood and low lying areas become inundated.

There is a clear increase in the number of reported floods in South Africa since 1961 to 2005 (Figure 5.2) according to the Caelum (Chapter 2, Section 2.2) (Caelum, 2010). This should be reflected against the background of the country’s population growth from 17.4 million in 1960 to 47 million in 2008 (World Bank, 2010), and the subsequent urbanization in the provinces mostly affected, which partially explains the increase in disastrous events.

Table 5.1: Relative Impact Score for hazards affecting South Africa from 1920 to 2008 according to CRED. The middle five rows represent the percentage of the number of occurrences of the specific impact of each hazard to the total number of occurrences for that impact of all the hazards. The bottom row is the relative impacts score as an average of the five percentages.

	Earthquake	Epidemics	Extreme Temperature	Floods	Insect Infestation	Slides	Volcano	Wave/Surge	Wild Fires	Wind Storm
% Deaths	3.7	14.5	2.8	61.4	0.0	1.8	0.0	0.0	5.0	10.8
% Affected	0.1	11.1	0.0	20.5	0.0	0.0	0.0	0.0	0.1	68.2
% Homeless	0.0	0.0	0.0	68.0	0.0	0.0	0.0	0.0	12.9	19.1
% Injured	9.2	0.0	0.0	2.8	0.0	0.0	0.0	0.0	28.6	59.3
% Damage	1.0	0.0	0.0	61.1	0.0	0.0	0.0	0.0	0.5	37.4
Relative Impact Score	**2.8**	**5.1**	**0.6**	**42.8**	**0.0**	**0.4**	**0.0**	**0.0**	**9.4**	**39.0**

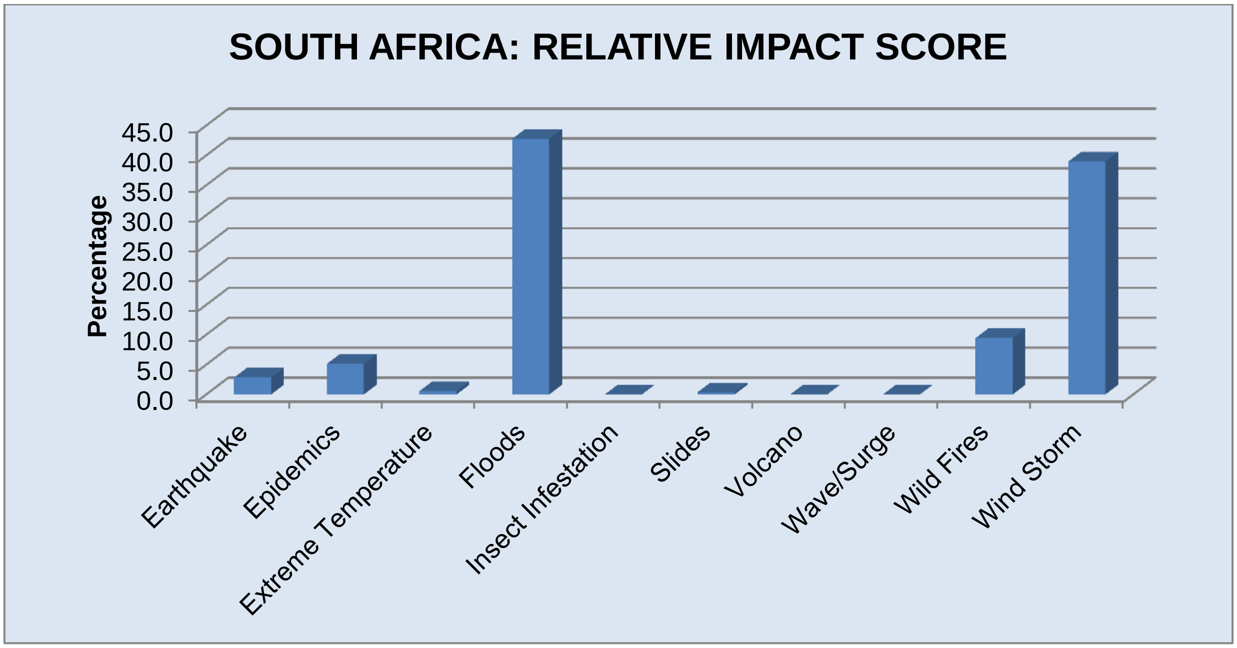


Figure 5.1: Relative Impact Score of various disasters (excluding drought as a slow onset disaster) reported in CRED disaster database for South Africa.

An important factor that will lead to an increase in the impact of weather-related disasters in some areas is population migration. The South African Risk and Vulnerability Atlas (SARVA,

2013) indicates a significant trend of population growth from 1996 to 2007 due to, among other factors, migration to the Province of Gauteng, and to the cities of Cape Town and eThekwini (Durban), as well as other large towns. In 2004 38% of the population lived on 2% of the land area in these urban areas.

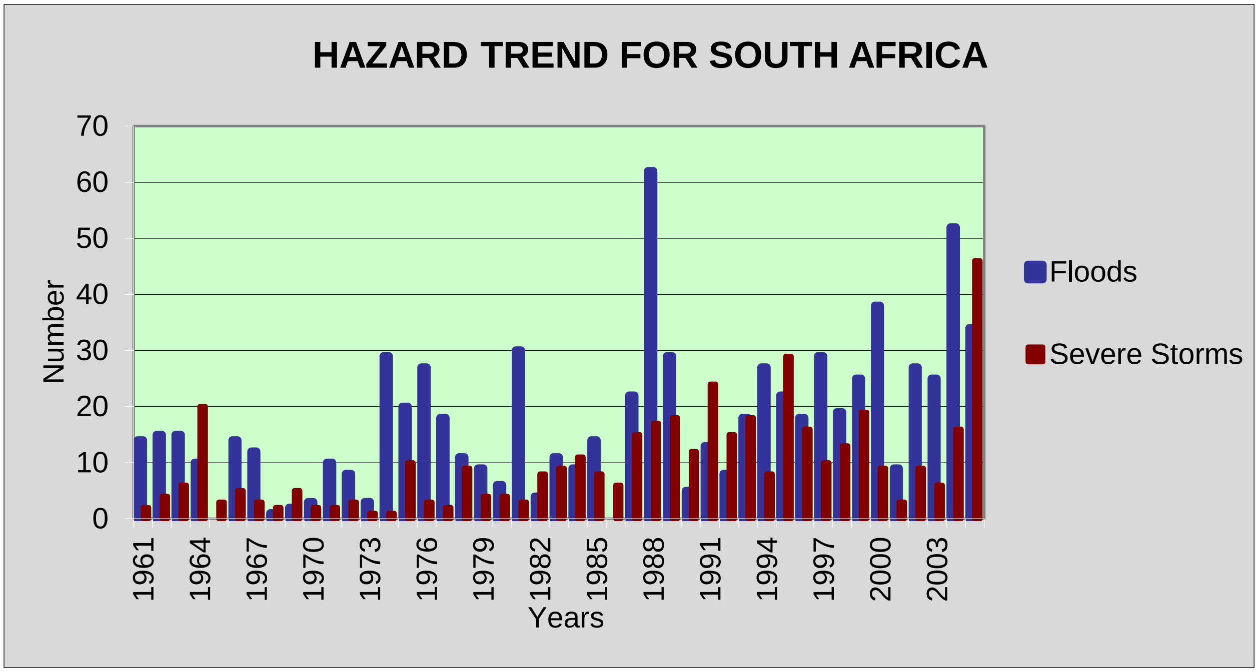


Figure 5.2: Trend of floods and severe storms in South Africa between 1961 and 2005 according to SAWS Caelum

The level of poverty is another major driver of social vulnerability (SARVA, 2013), although difficult to capture, with two contrasting areas of poverty and vulnerability in cities and metros versus rural areas. The high levels of migration to the metropolitan areas raise the unemployment levels as well as the inequality of living standards in these cities and metropolitan areas (Holloway *et al.,* 2010). Many people find a home in informal settlements near the cities, alongside rivers and streams potentially increasing their vulnerability to flooding. Urban settlements (defined as functional urban areas) house 71% of the population (SARVA, 2013) whereas 21% are living in dispersed rural settlements. At the same time 61% of people under a minimum level of living stay in the urban settlements and 31% in the rural settlements, indicating the higher relative levels of poverty in rural regions. The dependency of unemployed people (less than 14 years of age or older than 65 years) on the employed is the highest in the rural areas of the provinces of the Eastern Cape, KwaZulu-Natal, North-West and Limpopo. The likely increase in frequency and intensity of thunderstorms over Gauteng province due to climate change (SARVA, 2013) may exacerbate the vulnerability issues in future. Increase in rainfall intensity could lead to an increase in flooding. All these above mentioned factors add pressure in terms of social vulnerability to flooding in the affected regions, urban or rural.

Two different studies from other countries in Africa provide useful insights into the flood vulnerability in areas similar to rural areas in South Africa. Kienberger (2012) did spatial modelling of the social and economic vulnerability to floods in the Búzi district in Mozambique. Mozambique has made significant progress in improving their institutional response mechanisms and sharing of data since the devastating floods caused by tropical cyclone Eline in February/March 2000. Whereas the focus is largely on preparedness and response, mitigation and risk reduction still need to be addressed in Búzi. The purpose of this study was to provide decision makers with appropriate information at district level on flood vulnerability indicators. The Búzi district was severely hit by the floods of 2000 and 2007. It is an area with a high level of poverty consisting of small villages and subsistence farming, and the city of Beira on the coast. In his case, Kienberger (2012) defined vulnerability as a function of susceptibility (or sensitivity) and adaptive capacity. Following brainstorming sessions with 16 experts, Kienberger identified a set of indicators for flood vulnerability (Table 5.2) to which he had spatial data access. In his case he was limited by a lack of census data from which social vulnerability (or sensitivity and adaptive capacity) could be deduced. The reasons for identification of these indicators are thoroughly discussed by Kienberger (2012).

In their study of community response to flood risks in western Kenya, Nyakundi *et al. (*2010) reported the rural region to have high absolute poverty levels with deteriorating infrastructure and high Human Immunodeficiency Virus infection / Acquired Immunodeficiency

Syndrome (HIV/AIDS) prevalence undermining the economic growth of the region. The impacts of flooding measured against the socio-economic background mentioned above led to increasing vulnerability of these populations where education levels were very low. Housing structures were predominantly made of mud with thatch roofs. Damage to housing was reported to be very high during floods. Access to clean water was also becoming a challenge during the flood season in parts of Kenya with 94% of the respondents using streams for water live in the high risk area. Flooding was becoming a growing public health problem that led to diseases such as malaria, typhoid, cholera, dysentery, etc. An interesting observation in the report is that the advantages of living close to the river in the floodplain was more important than the known health risks caused by floods. This was evidently a matter of economic survival for the community. Food and water shortages occurred during the flood season. Few deaths were reported and these were mostly attributed to flash floods and resulted from drowning or collapsed walls or roofs. The importance of traditional flood knowledge was generally regarded as also being very important. Traditional flood knowledge was not only about "Old people's bones aching" (Nyakundi *et al*., 2010: p 354), but also about knowledge of where it rained for prolonged periods and of increasing river levels. Alarmingly though, young people were not very interested in traditional knowledge claiming there are currently better methods for flood prediction. The findings of these two studies of vulnerability and impacts of floods in rural regions are also important for rural communities of South Africa which have similar profiles to those in the two cases noted.

The NDMC is currently busy with a process to develop an Indicative Risk Profile for South Africa on GIS for various hazards, including floods, based on a number of indicators that can be spatially represented (NDMC, 2013, personal communication). Significant progress has been made to gather relevant data for indicators to prepare the Indicative Risk Profile for floods although it is still work in progress. The focus is on the social, economic, technological and environmental dimensions of vulnerability. Adaptive capacity for climate risk management is viewed in dimensions that consider indicators based on institutional and management, programmatic, people and competencies, and physical resources. These indicators are prepared at a mesozone level described in more detail in Section 5.4.2. They address many of the vulnerability indicators mentioned in the previous paragraphs based on the more qualitative description of sensitivity as defined by the ISDR. Some of their indicators are, however, of a quantitative nature and are useful as vulnerability indicators to develop the impact model described in this study.

Table 5.2: Social and economic vulnerability indicators identified by Kienberger (2012) for the Búzi district in Mozambique

Social vulnerability indicators	**Economic vulnerability indicators**
Access to health services	Access to local markets
Access to education	Crop density
Distance to conflicts (important in Mozambique from their historical conflicts)	Ecosystem service (for food provision through subsistence farming)
Access to water	Access to road infrastructure
Early warning system (availability of local disaster management committees)	Distance to cities
Potential rescue opportunities (access to accommodation centres)	

5.3.2 Understanding disaster risk

There are numerous definitions of disaster risk and its associated terminology (hazards, vulnerability, coping, exposure, etc), all depending on the requirement and interpretation of the particular author (Fuchs *et al*., 2012; Kienberger, 2012; Pelling, 2011; Scheuer *et al*., 2011; ISDR, 2010; ISDR, 2009; Sene, 2008; Gad-el-Hak, 2008; Jordaan, 2007; Thywissen, 2006; ISDR 2005a; Wisner *et al*., 2004). The ISDR (2005a, p6) defines disaster risk as "*the probability of harmful consequences (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions*".

Wisner *et al*. (2004) provides two models on the relationship between vulnerability and hazards to risk through their introduction of the Pressure And Release model (PAR model or sometimes called the Crunch model) and the Access model. They describe vulnerability as a function of the exposure of a community to a hazard, and its capability (or lack thereof) to cope with and recover from the impact of the hazard.

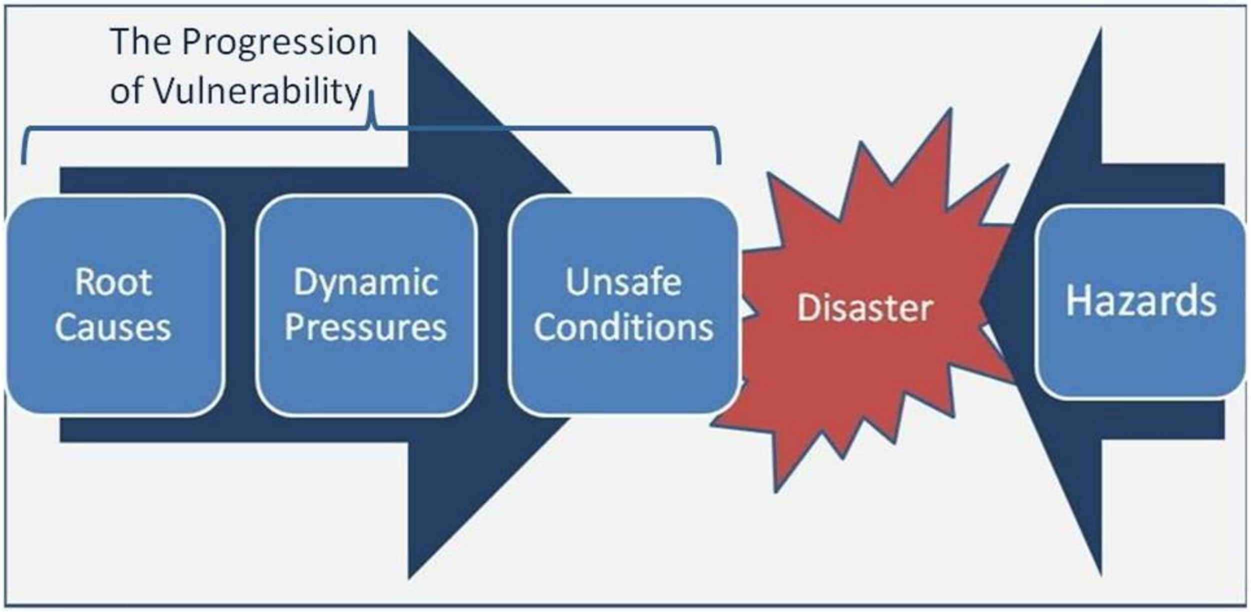


Figure 5.3: The Pressure And Release model (PAR model), according to Wisner *et al*. (2004)

The PAR model described by Wisner *et al*. (2004) explains how a natural disaster occurs through the combination of hazards and vulnerability. It attempts to emphasize the role of vulnerability of communities in disaster risk, and particularly how vulnerability can be traced back from unsafe conditions, caused by the impact of economic and social dynamic pressures on underlying root causes that appears to have little to do with causing the disaster (see Figure 5.3). The "pressure" of the two opposing forces of vulnerability and hazard on people could lead to a disaster. "Release" refers to relieving the pressure causing a disaster by reducing the vulnerability in the root causes or dynamic pressures. Though Wisner *et al*. (2004), focus most of their attention on the vulnerability side, it stands to argue that the pressure on a disaster can also be released by enhanced prediction of the hazard (Auld, 2008).

The Access model of Wisner *et al*. (2004), focuses on the pressure point itself where the disaster is the consequence. It describes what happens with vulnerability as the disaster unfolds and the process of how the hazard impacts upon people and their response. The Access model also shows how the coping mechanisms in different societies or hazard preparedness actions (such as flood protection embankments) can change the impacts of the disaster.

The relationship between hazards, vulnerability and disaster risk can be expressed in numerous ways in attempts to define the interactions between risk and causative factors, as is shown by Gad-el-Hak (2008), Jordaan (2007) and Wisner *et al. (*2004). The most general description of these expressions is (ISDR, 2005a, 2010; Wisner *et al*., 2004):

Risk = Hazards x Vulnerability .... (1)

Hazards of a hydro-meteorological nature are defined by the ISDR (2009, pp18) as a "*Process or phenomenon of atmospheric, hydrological or oceanographic nature that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage*". Vulnerability is defined as "*the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard*" (ISDR, 2009, pp30). It refers to the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards.

A popular way to further describe risk is to include the ability of a community to deal or cope with the disaster explicitly in the relationship (Frantzova, 2008; Jordaan, 2007):

Risk = (Hazards x Vulnerability) / Coping Capacity ...... (2)

These relationships express risk in terms of the probability or likelihood of a hazard and the vulnerability of the threatened community. The relationship in equation (2) explicitly includes the ability of the community to cope with the potential disaster through their own resources. Coping is described as the process or actions where established practices and institutions could be used to respond to a specific hazardous event when it occurs (Pelling, 2011). Thus an increase in either the hazard threat or the vulnerability of a community will increase the risk of lives lost and negative impacts on their livelihoods. On the other hand an increase of the coping capacity of the community in equation (2) will reduce the risk to the community.

Other descriptions include "exposure" in the relationship (ISDR, 2009; ISDR, 2010; Fuchs *et al*., 2012, Kienberger, 2012; Peduzzi *et al*., 2009; Wisner *et al*., 2004):

$$\textbf{Risk = Hazards x Vulnerability x Exposure} \qquad \ldots\ldots\ (3)$$

Exposure is defined as "*people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses*" (ISDR, 2009, pp15).

An important factor in exposure to floods is the inundation caused by flooding (Hagen and Lu, 2011). Inundation information helps to identify roads, villages and communities at risk of being flooded. Inundation information is unfortunately not easily available, particularly for large areas, since the necessary input data do not exist.

Fuchs *et al. (*2012) found that there exist differences in the approaches to vulnerability between social scientists and natural scientists in line with their particular disciplinary training: whereas social scientists generally define vulnerability in terms of socio-economic factors impacting on people, natural scientists tend to view vulnerability in terms of process scenarios and impacts on the built environment. They argued that these two viewpoints must be integrated and that physical factors (structural) and socio-economic factors (economic, institutional and social) are interdependent and interacting in vulnerability.

Peduzzi *et al*. (2009) presented risk as a formula similar to equation (3) in order to assess global exposure and vulnerability to find a quantifiable value called the Disaster Risk Index. In the case of risk of human losses the exposure is related to the population living in a given exposed area. Vulnerability depended on the socio-political-economic context of the population and was described as a non-dimensional number between 0-1. This was quantified from a linear regression analysis of 32 socio-economic and environmental indicators.

Kienberger (2012) took a similar approach in his work to spatially model vulnerability to floods in the Búzi district in Mozambique. He explicitly stated that his focus was mainly on the district level and not on the community level, although he did take community level input into account. Since he had to produce vulnerability in a spatial-temporal scale it was important that the indicators used to derive it was on the same scale and could be integrated into a GIS system. Of the various dimensions of vulnerability, he focussed on four, namely economic, social, environmental and physical. Other dimensions such as cultural and institutional were not considered in his system.

Scheuer *et al. (*2011) followed Kienberger's approach in modelling flood vulnerability and applied it on the city of Leipzig in Germany by integrating economic, social and ecological vulnerability with coping capacity. They defined risk similar to the quantitative definition used in natural sciences and engineering as the probability of negative consequences:

$$\textbf{Risk} = \textbf{Probability} \times \textbf{Damage} \qquad \ldots\ldots\ (4)$$

In their definition damage, and thus flood vulnerability, "depends on the number and value of elements at risk and their susceptibility, and it is also related to the exposure of those elements at risk to the hazard, expressed by flood severity and probability" (Scheuer *et al*., 2011, p733). In this definition vulnerability will change as the probability or severity of the hazard changes, and is different from the ISDR definition of risk as a product of hazard and vulnerability as explained by Fuchs *et al. (*2012). In their opinion, the approach of Scheuer *et al*. (2011) allows for an integrative view of flood risk management, not only between social, economic and ecologic consequences of flooding, but also due to their consideration of susceptibility and exposure within the vulnerability definition. As an additional viewpoint, they also differentiated between a *starting-point* view of vulnerability, which excludes coping capacity, and an *end-point* view of vulnerability, which includes coping capacity.

In the fourth assessment report of the IPCC (2007a) the IPCC took a slightly different view by defining vulnerability to climate change as a function of exposure, sensitivity and adaptive capacity:

Vulnerability = (Exposure x Sensitivity) / Adaptive Capacity ….. (5)

Balica *et al*. (2012), who developed a flood vulnerability index used by UNESCO (2013), adopted this definition. They described exposure as *the values present where the floods occur, including goods, people, agricultural land, etc.* Though the definition of sensitivity, or susceptibility, is still unclear in the literature according to Balica *et al. (*2012, p79), they regarded sensitivity to be "*the elements exposed within the system which influence the probabilities of being harmed at times of hazardous floods*". In the social dimension of vulnerability this relates to the awareness and preparedness of communities of the flood risk, social relations, institutional development and communities with special needs (age, disability, etc.).

Midgley *et al. (*2011) also followed the approach of the IPCC described above when they developed maps for climate risk and vulnerability in southern Africa. They found that in a GIS environment the indicators for exposure and sensitivity elements of vulnerability were better described and quantified than the indicators for adaptive capacity. In their study they produced climate impact fields for 2008 and 2050, in addition to vulnerability fields based on equation (5). These climate impact fields were based upon a combination of the exposure and sensitivity elements, but excluding adaptive capacity following the starting-point view of vulnerability of Scheuer *et al*. (2011). This climate impact field thus represented the impact of climate change irrespective of local coping capacity influences. They combined the sensitivity, exposure and adaptive capacity layers through a simple summation approach to “enable a uniform influence of each category” (Midgley *et al*., 2011, p8):

Impact = (sensitivity + exposure) …. (6)

Vulnerability = (sensitivity + exposure + adaptive capacity) …. (7)

In equation (7) the adaptive capacity indicator values were inversed. The effect of the hazard (precipitation and temperature change due to climate change) was combined as indicators in the exposure element of their methodology for both impact and vulnerability. Impact due to climate change is defined by Midgley *et al*. (2011) as the effects of climate change on natural and human systems without considering adaptation.

The definition of disaster risk described earlier in this section by the ISDR (2005a) could be interpreted as the probability of adverse impacts of these hazards on communities due to their vulnerability. Golding (2007, p2) stated that the “risk of an event varies according to the probability of the event and its impact in terms of death, injury, damage, etc”. The introductory guidelines of WMO (2012) to impact forecasting points out that the impact of a severe weather event will differ in space and time. When non weather-related variables associated with vulnerability and exposure is linked with weather conditions, the totality of the impact can be created. This message enables disaster managers and communities to take action to prevent or minimise adverse effects of hazardous weather. The WMO (2012) then expressed these concepts as follows:

Impact = Hazard x Vulnerability x Exposure …. (8)

Where impact is the totality of the impact experienced, hazard is a meteorological condition that can vary with time, vulnerability is the inherent sensitivity of the person to the hazard, and exposure is a time and space dependent non-weather variable which affect the totality of the impact.

In the example provided by the WMO (2012) the hazard is a 10% chance for rain of more than 50 mm in an hour. The vulnerability will vary, for example, with population density: high in build-up areas, and low in mountainous areas. Exposure will relate to other, non-weather-related variables, for example time of the day: if it happens during rush-hour exposure will be high, but if it happens over a weekend it may be low.

The Pitt Report on the UK Floods of 2008 (Evans *et al*., 2008) also addressed this question stating that flood risk implies potential impact which is the combination of the probability of flooding and the consequences of that level of flooding. The consequences are the harm flooding can cause in social, economic or environmental terms.

This discussion explores some of the complexity of defining vulnerability to be used in a spatial mapping concept of impact forecasting, as is the intention in this study. There does not appear to be a clear cut definition of vulnerability (Balica *et al*., 2012) that is the *de facto* option to use in impact forecasting. The relevant choice depends on the purpose of the risk identification approach, the methodology that will be followed, and the availability of data and information in a spatial format if needed.

5.3.3 Defining "Impact Forecasting" within disaster risk reduction

From the previous discussion it can be reasoned that in the disaster risk reduction environment impact forecasting has a slightly different focus on vulnerability than an indicative risk assessment would have. A general risk assessment determines the general total vulnerability in terms of exposure (quantitative indicators) and sensitivity (qualitative indicators) that any community in the country faces to the hazard should it occur in the future. This type of risk assessment is aimed at developing adaptive and mitigation measures to reduce the vulnerability over time. Impact forecasting, on the other hand, is concerned with the quantitative expression of harmful consequences due to an imminent hazard on a specific threatened community that would require quick response from disaster management. For example, whereas a general indicative risk assessment would be concerned with population pressure which is a function of population density, household density, etc., impact forecasting would be concerned with the number of people in danger of being flooded, and the likelihood of this occurrence. Therefore the definition of impact forecasting to be used in this study leans towards the arguments expressed by Golding (2007), Evans *et al*. (2008), WMO (2012) and Robbins (2012, *personal communication*).

Based on these arguments it is postulated that an appropriate expression to define impact forecasting within the disaster risk environment in this study could be as follows:

> ***Impact forecasting*** *refers to the likelihood and the magnitude of adverse impacts, or harmful conditions, to communities under threat based on their vulnerability and due to an imminent severe weather hazard.*

Magnitude can be expressed in terms of either the number or the value of the vulnerability indicator. Likelihood is the probability of occurrence of the imminent severe weather hazard for a specific area. Since the aim of this study is to spatially present impacts taking into account the uncertainty of the hazard to occur, this definition could be expressed mathematically as follows, adapted from equations (3), (4), (5), (6) and (8):

Risk of Impact = likelihood (Hazard) x magnitude (Vulnerability)

With: **Vulnerability = Exposure + Sensitivity**

And therefore:

Risk of Impact = likelihood (Hazard) x magnitude (Exposure + Sensitivity) ... (9)

where:

- *Risk of Impact* is the risk or likelihood of adverse, harmful consequences that negatively affect or disrupt people and their livelihood (death, injuries, evacuation, displacement, etc.), communities, infrastructure, economic structures or the ecology. The impact could vary with severity of the expected hazard. Impacts can be classified into the social, economic, ecologic and physical impact dimensions (NRC, 2006b).

- *Likelihood of Hazard* is the probability of occurrence of the hazard (flash flooding in this study) and could include an expression of different levels of severity.
- *Vulnerability* is a function of the Exposure and Sensitivity and relates mainly to a combination of the various dimensions of vulnerability relevant to the specific hazard:
    - *Exposure* relates to "*people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses*", according to the (ISDR, 2009, pp15). The size of the population living in a flooded area is a typical example of exposure.
    - *Sensitivity* of the community or system to the hazard, relates to *the system characteristics due to social or institutional factors which influence the likelihood of being harmed*, such as the number of people with special needs (age, disability, etc.). The example mentioned in Section 5.3.1 of the increased impact of heavy rain on traffic during afternoon rush hour compared to that over a weekend afternoon relates also to sensitivity.

Following Midgley *et al*. (2011) this definition does not take adaptive or coping capacity into account, since the purpose of impact forecasting is to advise in advance on possible adverse impacts before any coping activities could be activated. Therefore, this would be a starting-point view of vulnerability as discussed by Scheuer *et al*. (2011). The above definition of impact forecasting and equation (9) will be used in this study, given a number of assumptions:

- For demonstrative purposes the dimensions of vulnerability to be considered are limited to social and structural dimensions. Other dimensions (economic, environmental, cultural, psychological, political and institutional) are not considered yet.
- Furthermore, vulnerability is mapped on a spatial-scale in a GIS and is expressed categorically on 5 levels based on each indicator's magnitude: 1 is the lowest and 5 the highest vulnerability.

- Similar to Kienberger (2012) the focus will be on vulnerability at the district level and not at the community level which requires detailed vulnerability assessments not possible for such a large spatial area covered in this study.

For simplicity, primary level hazards and impacts, and secondary level (or knock-on) hazards and impacts are not separated. In other words, the primary hazard is defined here as flash flooding, leading to impacts such as collapsed bridges and roads, health impacts, deaths, etc. The fact that the flash flood (primary hazard) actually damaged the sewage system (primary impact), following which the sewage system became a secondary hazard that lead to pollution (secondary impact, and tertiary hazard), resulting in the health consequences (tertiary impacts) and even deaths are not considered in that way. Only the primary hazard with all relevant subsequent impacts, also from secondary or tertiary hazards, that occurs during the time of flooding is considered.

5.3.4 The impact of flood disasters at regional level

Jongman *et al*. (2012) provided an overview of flood risks over different spatial-scales. These scales can range from global to regional and to local, with information needs specific to each of them. Flood risk estimates are needed at each scale supporting different decision making needs using for example rapid flood assessment models.

- *Global-scale* assessments focus on flood risk at country level and are useful for international funding support decisions. The types of data needed are country-scale indicators of flood hazards and vulnerability. A typical example would be the GDACS system (De Groeve *et al*., 2009).
- *Regional-scale* assessments focus on flooding along rivers and coasts. Data needs are more detailed regional information, including elevation and data with in-country spatial variability. This is useful for decision making at area level such as local municipalities or smaller. It can be used for quick estimates of danger levels and areas under risk.

- *Local-scale* assessments look at assets and people at local and individual level where, for example, it could identify suitable evacuation routes in a given area, etc. This scale requires very high resolution model and elevation data. Community level risk assessments are needed which requires significant time and effort to collect and analyse.

A series of studies have also been conducted to determine the impact of flood events over the Western Cape Province during the period between 2003 and 2009. Risk assessments were done at regional and on a local-scale. The results of these studies were summarized by Holloway (2010) in a very thorough document called Risk and Development Annual Review (RADAR) for the Western Cape Provincial Disaster Management Centre (PDMC). Thirteen flooding events resulted in R2.95 billion direct costs (sustained by public sector entities and farms) in damage between 2003 and 2009, at least 5 deaths and thousands of people affected. Table 5.3 is a summary of the impacts which affect South Africa as reported in RADAR and supported by NRC (2006b) and by Van der Linde and Strydom (2008).

Against the backdrop of the discussions in this Chapter up to this point, SWIFS is defined, focussing on forecasting the impact of flash floods on the regional scale as a starting point. This development of SWIFS is described in the next section.

Table 5.3: Typical flood-related impacts for four dimensions due to severe weather events in the Western Cape between 2003 and 2009 as reported in RADAR and other resources.

DIMENSION	SPECIFIC IMPACT
Social	• Loss of lives, injuries • Communities, settlements cut off • People displaced / evacuated ○ informal settlements, rural areas and farm workers ○ formal settlements • Health impacts: respiratory infections, malaria, cholera, dysentery
Physical	• Stormwater management system damage / disruption • Sewage plants damaged / disabled • Roads, bridges and road passes flooded and damaged • Low cost housing and other homes damaged / flooded • Health facilities damaged or isolated • Schools damaged or isolated • Water supply disruption / damage • Large dam and farm dam damaged • Major facility damaged / flooded (industrial, sports, electricity)
Economic	• Cultivated land damaged (fruit plantations, maize, etc) • Livestock deaths • Business premises damaged • Electricity supply disruption • Tourism disruption • Road, railway and airport transport disruption
Ecologic	• Estuaries flooded and damaged • Animals drowning • Pollution of water, ground • Slope failure and rock falls

5.4 DEVELOPMENT OF THE SEVERE WEATHER IMPACT FORECASTING SYSTEM

5.4.1 Intended outcomes of SWIFS

The impact model in SWIFS combines the extended lead-time hazard forecasting module developed in Chapter 4 with the vulnerability indicators to determine the level of likely imminent impact due to the hazard. The main objective of the impact model developed in this study is to determine the *risk level (low to high) and magnitude of adverse impacts due to potential hazards (in this case flash floods) expected at regional level (in river basins and local municipalities) within the next few hours to support the decision making process of the user (disaster management agencies) during these critical few hours*.

The specific objectives of the impact model are:

- Identify preference areas requiring more urgent disaster management intervention;
- Identify the potential level of impacts for each dimension (social, structural) and collectively based on the likelihood of the hazardous conditions in the next few hours;
- Provide user relevant representations of the magnitude of these imminent impacts.

For this purpose the impact variables for each dimension must be quantified and on a detail level and format that is valid over the entire country without comprehensive vulnerability studies needed.

The motivation for modelling at the regional level, or in this case mesozone (see Section 5.4.2 for a discussion on mesozones) and municipal level, and not at the local level is related to the availability of indicator data over the entire country at an appropriate scale. The benefit of the mesozone level modelling is that it provides the municipal disaster managers with an integrated spatial overview of the dimensions of the impact and hotspot areas, or areas of most significant impacts, within a municipality and at smaller level (Kienberger, 2012). The focus is the collective impact for quick first assessment and the individual quantitative impact of specific indicators. These impacts and the associated vulnerabilities can be decomposed and explored by the municipal disaster manager through combining the larger-scale information with local community knowledge to identify the specific local impact hot spots and reactive measures.

5.4.2 Vulnerability data

An important contribution to the South African vulnerability mapping and information capacity is the innovative Geospatial Analysis Platform (GAP) developed by the CSIR in 2006 (Naude *et al*., 2007; Van Huyssteen *et al*., 2009; CSIR, 2013). The GAP enables relational regional analyses across boundaries in units known as mesozones. The country is divided into approximately 25,000 mesozones of on average 50 km^2. A variety of data, including census data, economic data, ecologic data and satellite data have been scientifically rescaled from different scale data sets to the mesozone-scale. The mesozones provide comparable information relevant for each specific mesozone for a more fair comparison of various indicators on a standard and almost similar sized scale. Figure 5.4 illustrates the spatial mapping uniformity of mesozones within irregular sized local municipalities. In this case the CSIR rescaled the population numbers gathered from census information to show the number of people in each mesozone. This provides a better comparative spatial mapping capability.

This mesozone data form the basis of the vulnerability indicator data developed by the CSIR and made available for general use. The mesozone-scale is also used by the NDMC (2013, personal communication), in developing an indicative risk profile of the country for various hazards, and by the South African Risk and Vulnerability Atlas (SARVA, 2013). The NDMC developed additional vulnerability indicators on mesozone-scale which were made available for consideration in this study to determine the impact of flash flood hazards at mesozone level.

Since the magnitude of the impact also needs to be determined, the vulnerability indicators as far as possible are required to be quantitative and not only qualitative. The indicators also have to be spatially available at the mesozone-scale. This limits the availability of the number of indicators from the total set provided by the NDMC and CSIR to this study.

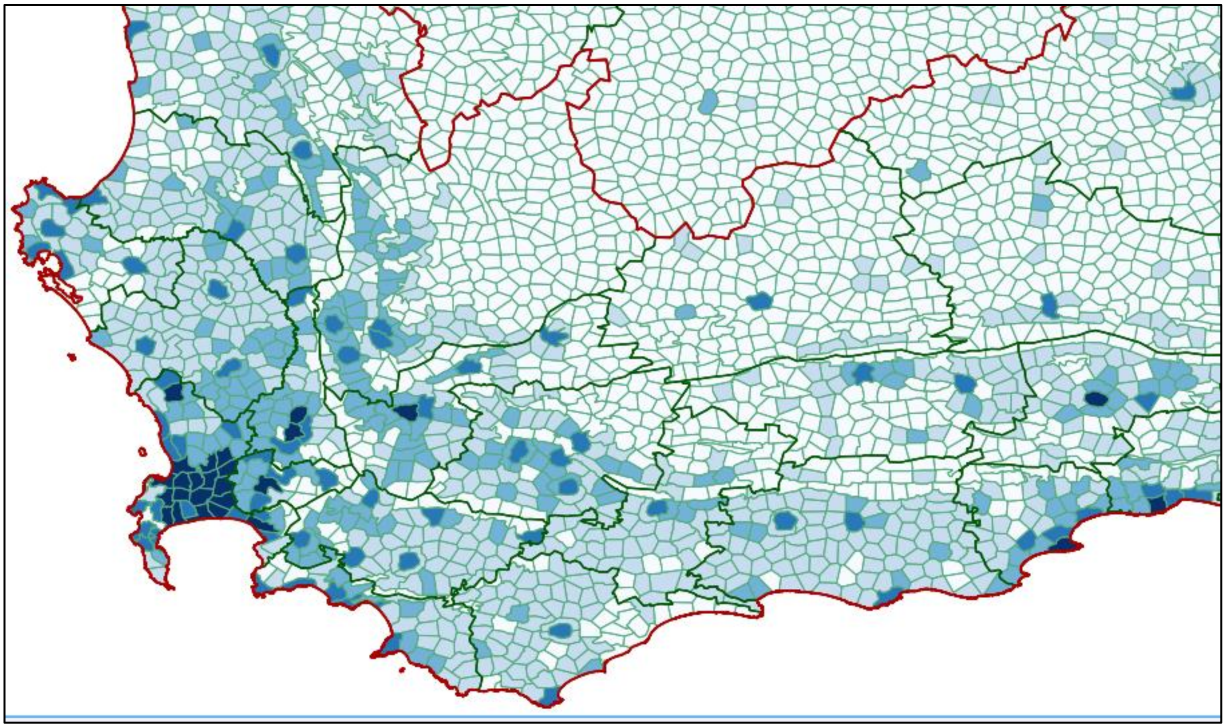


Figure 5.4: Example of a mesozone map illustrating population numbers per mesozone as captured from census information. The green lines indicate larger local municipality areas. The entire South Africa is delineated in similar sized mesozones.

5.4.3 Vulnerability and impact indicators

Midgley *et al. (*2011) pointed out that little consensus has been reached in research over the last ten years regarding the choice of indicators for climate change assessments. Consequently the choice of indicators has been determined by the underlying research question. Their final list of indicators was based on data availability at the required resolution, quality of the data and overall meeting user needs. Weights for combining the different indicators were determined relative to their importance for the research question and the confidence they had in the dataset to truly represent the detailed geographical distribution of the variable accurately. Pyle (2006) studied the risk due to severe thunderstorms in the Eastern Cape Province of South Africa. He identified population density, education and income, and age as social vulnerability indicators, and type of dwelling, road density and access to communications as structural vulnerability indicators associated all hazards related to severe thunderstorms.

Table 5.4: Exposure and sensitivity indicators relevant to the social and structural vulnerability dimensions. The weights for each indicator used in the series of algorithms described in the text are also shown in the table, adding to 1.0 for each dimension.

VULNERABILITY DIMENSION	EXPOSURE		SENSITIVITY	
	Indicators (quantitative)	Weights	Indicators (descriptive)	Weights
Social dimension	• Population number	• 8	• Age • Poverty index	• 1 • 1
Structural dimension	• Number of building structures • Number of bridges • Number of schools • Number of health centres	• 1 • 1 • 1 • 1	• Road density	• 1

For SWIFS the choice of indicators used in this thesis in the social and structural vulnerability dimensions were based on feedback from a small group of disaster managers attending the 2013 conference of Disaster Management Institute of Southern Africa (DMISA). In the questionnaire they were asked to rank a list of available indicators in terms of their particular importance to flash floods. From these results, and the information from SARVA (2013) discussed in Section 5.3.1, indicators were identified for the social and structural dimensions. These indicators and their weights used in the impact model are listed in Table 5.4. The weight of each indicator was determined according to the importance of the indicators from the feedback from the disaster managers, their availability in a relevant GIS format and the confidence in the available datasets. Although the number of schools and of health centres was identified by disaster managers as important in both social and structural dimensions of vulnerability, they were used only in the structural dimension to avoid possible "double counting".

Based on the impact relationship as defined by expression (9) in Section 5.3.3 the impact model combines a set of vulnerability indicators with a hazard likelihood index for each mesozone to determine the likelihood and magnitude of the potential imminent adverse impact in that particular mesozone. The vulnerability and resultant impact risk scores are determined through a series of algorithms that relate the vulnerability indicators within each dimension with each other and eventually with the hazard likelihood.

As a preparatory step vulnerability scores were determined for the two dimensions, namely social and structural vulnerability. For each dimension the relevant exposure and sensitivity indicators were classified into 5 categories using frequency distributions, ranking from the lowest (category 1) to the highest vulnerability (category 5). The vulnerability score for the social dimension for each mesozone was subsequently determined through a weighted combination of the exposure and sensitivity indicators in each mesozone:

$$\mathbf{Social\_Vuln(i) = (}\boldsymbol{a}\mathbf{X(i) + }\boldsymbol{b}\mathbf{Y(i) + }\boldsymbol{c}\mathbf{Z(i) + \ldots.)} \qquad \mathbf{\ldots..(10)}$$

where *a, b, c* are the weights adding up to 1.0, and X, Y and Z are the different social vulnerability indicators for mesozone (i). Structural vulnerability for mesozone (i) was found in a similar way:

$$\mathbf{Structural\_Vuln(i) = (}\boldsymbol{k}\mathbf{P(i) + }\boldsymbol{m}\mathbf{Q(i) + }\boldsymbol{n}\mathbf{R(i) + \ldots.)} \qquad \mathbf{\ldots.(11)}$$

The combined total vulnerability was then calculated through a combination of the social and structural vulnerability:

$$\mathbf{Total\_Vuln(i) = 0.5(Social\_Vuln(i)) + 0.5(Structural\_Vuln(i))} \qquad \mathbf{\ldots..(12)}$$

These vulnerability fields are static fields representing flash flood vulnerability for each mesozone over the country. The dynamic variable in SWIFS is the flash flood hazard likelihood field, which changes from event to event depending on the particular weather scenario.

In Figure 5.5 a graphical representation of the results of the vulnerability calculations for social vulnerability, structural vulnerability and the final combination into total vulnerability are presented. The importance of population numbers in the densely built up regions in the social vulnerability map is quite prominent as expected. The increased vulnerability due to poverty and the number of elderly and children (represented by the age indicator), however, is apparent particularly in the rural regions of the Eastern Cape, KwaZulu-Natal and the Limpopo Province. Structural vulnerability is strongly influenced in the rural regions by road density and the number of bridges.

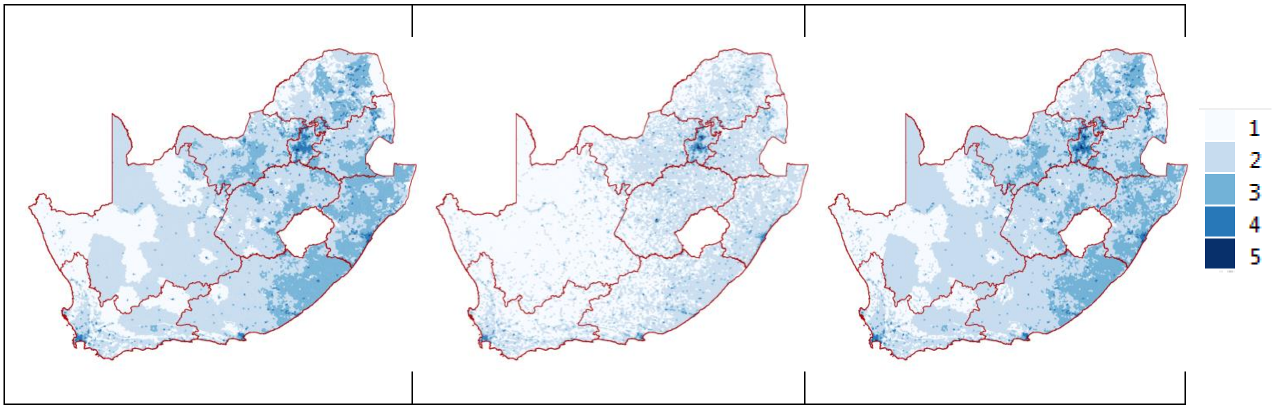


Figure 5.5: Graphical representation of the social vulnerability (left), structural vulnerability (centre) and the resulting combined total vulnerability (right panel).

5.4.4 Description of SWIFS

SWIFS is an integration of the forecast model (predicting the dynamic hazard-related variables) into the final impact model (combining the hazard forecast with the static vulnerability information). For each event the following steps were performed in SWIFS, based on the pre-determined static vulnerability fields:

i. As a first step the flash flood hazard likelihood for each SAFFG basin was determined by the forecast model through the HyEPS and SAFFG as discussed in Chapter 4;

ii. Then the hazard likelihood for each mesozone was obtained per event from the FFP values of associated SAFFG basins.

iii. The mesozone hazard FFP was then classified into a hazard index of 5 categories ranking from no likelihood (category 0) to the highest hazard likelihood (category 4);

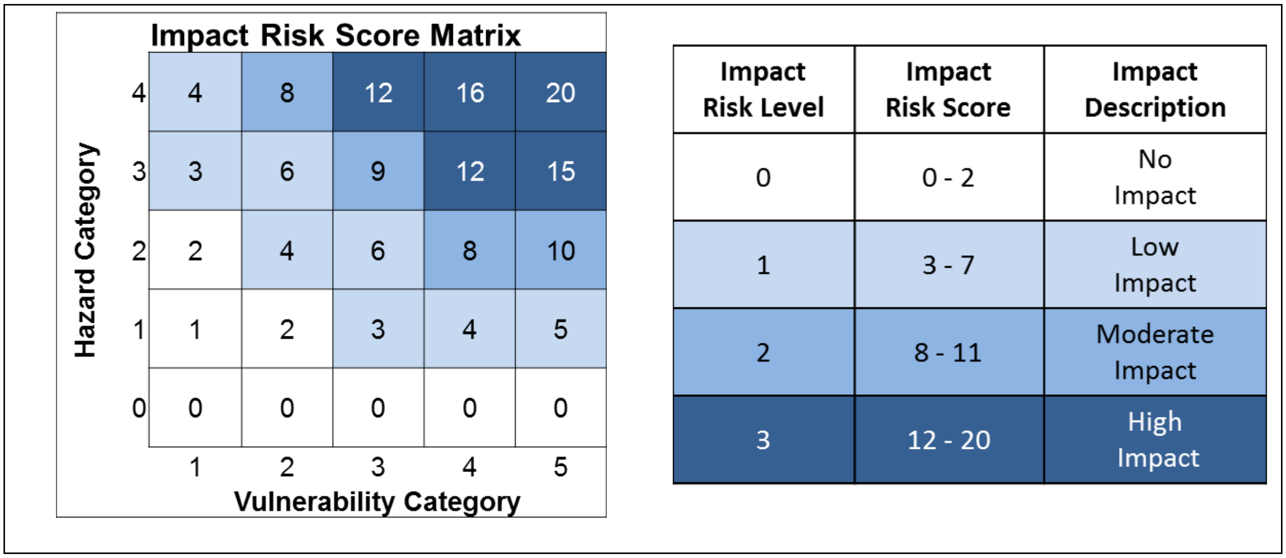
iv. From this the impact risk score ranging from 0 to 20 for each mesozone was determined by multiplying the pre-determined combined total vulnerability (ranked from 1 to 5) with the event specific hazard index (ranked from 0 to 4):

$$\textbf{Impact\_Risk\_Score(i) = Hazard\_Index(i) x Total\_Vuln(i)} \qquad \textbf{.....(11)}$$

v. To simplify the output, an impact risk level index was determined by classifying the twenty-level impact risk score into a four-category impact risk level index through a look-up table described graphically in Figure 5.6.

vi. To complete the picture the quantitative estimate or magnitude of the impact in a local municipality was determined from the original quantitative values of the indicators for the specific mesozone under threat, for example the population number per affected mesozone.

An overview of the entire process is graphically presented in Figure 5.7.



Impact Risk Score Matrix

Hazard Category	1	2	3	4	5
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
0	0	0	0	0	0

Vulnerability Category

Impact Risk Level	Impact Risk Score	Impact Description
0	0 - 2	No Impact
1	3 - 7	Low Impact
2	8 - 11	Moderate Impact
3	12 - 20	High Impact

Figure 5.6: Impact Risk Score matrix (left) from which the final Impact Risk levels (right) were determined according to the different risk score categories in the matrix.

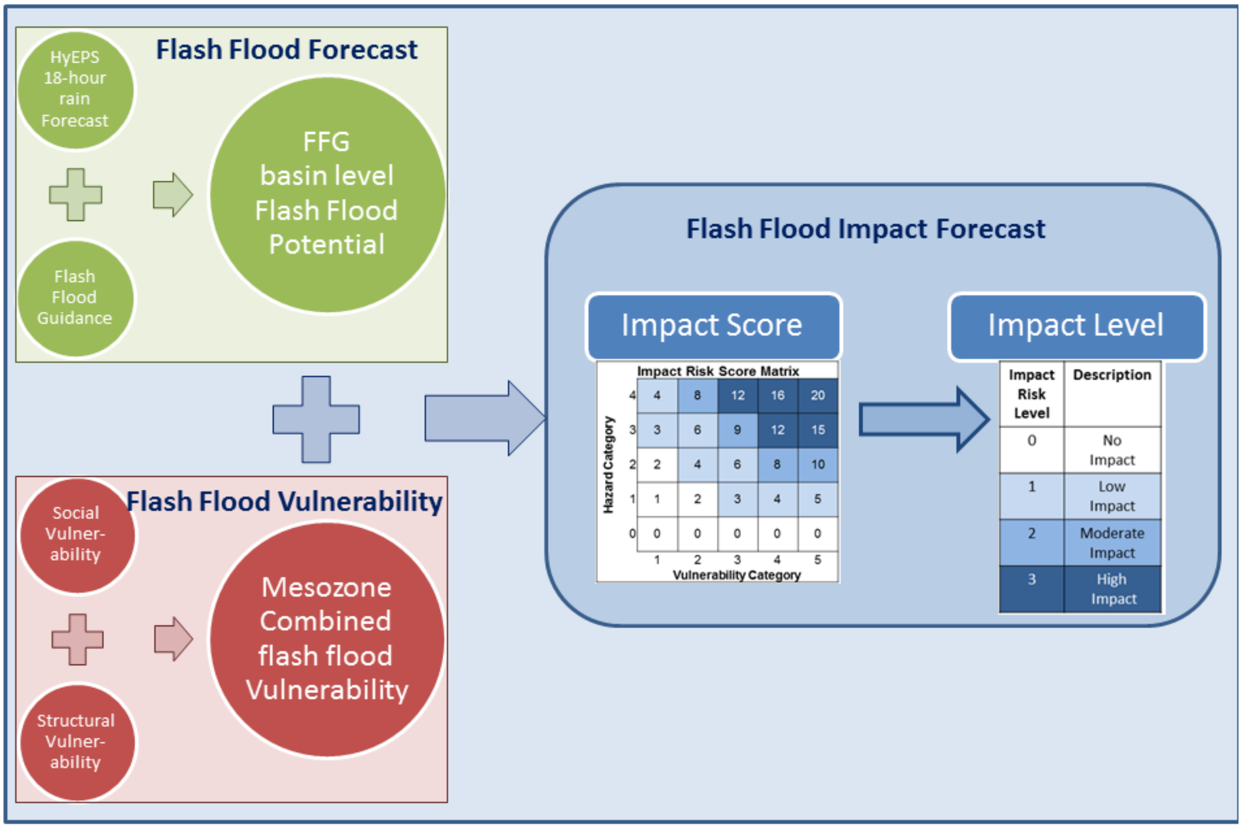


Figure 5.7: Graphical representation of the SWIFS conceptual framework as described in the text.

5.5 RESULTS AND CASE STUDIES

5.5.1 Case Study 1: Eastern Cape flash floods of 20 October 2012

5.5.1.1 Description of the event

For easy reference the description of the event as described in Chapter 4 is repeated here. On the 20 October 2012 a cut-off low caused heavy rain and flash flooding over the Western and Eastern Cape (SAWS, 2012b). The N2 national road between Port Elizabeth and Grahamstown was severely damaged when the road collapsed. The road was closed severely disrupting traffic. Significant damage was caused to infrastructure and homes near Port Alfred where people were forced to leave their homes due to flooding. Houses of 57 residents in the nearby informal settlement were damaged and hundreds of residents were without water or electricity. Cars were submerged and some houses were flooded with up to 2m of water. A bridge was washed away and the damage to infrastructure and cars was estimated to be more than R1 billion.

5.5.1.2 Results

The results of the entire SWIFS process as predicted for the 12-30 hour forecast period for this case of 20 October 2012, based on the persisted 12 hour FFG values, are presented in Figure 5.8 and Table 5.5. Panels (a) and (b) in the top row of Figure 5.8 describe the results of the HyEPS forecast of the likelihood of flash flooding in the next 18 hours based on the persisted 12-hour FFG values as discussed in detail in Chapter 4. The flash flood hazard index for the local municipalities shown in panel (a) is intended to be used in a dashboard display system to draw the attention of forecasters and disaster managers to potential hazardous conditions somewhere within a municipality. Panel (b) is the flash flood likelihood as predicted by the HyEPS system, transferred from river basins to associated mesozones, which is the scale that is used for the vulnerability indicators. This product draws attention to the small-scale areas most likely to experience problems based on the hydrological modelling in the SAFFG system, and the UM-SA12 ensemble forecast from the HyEPS.

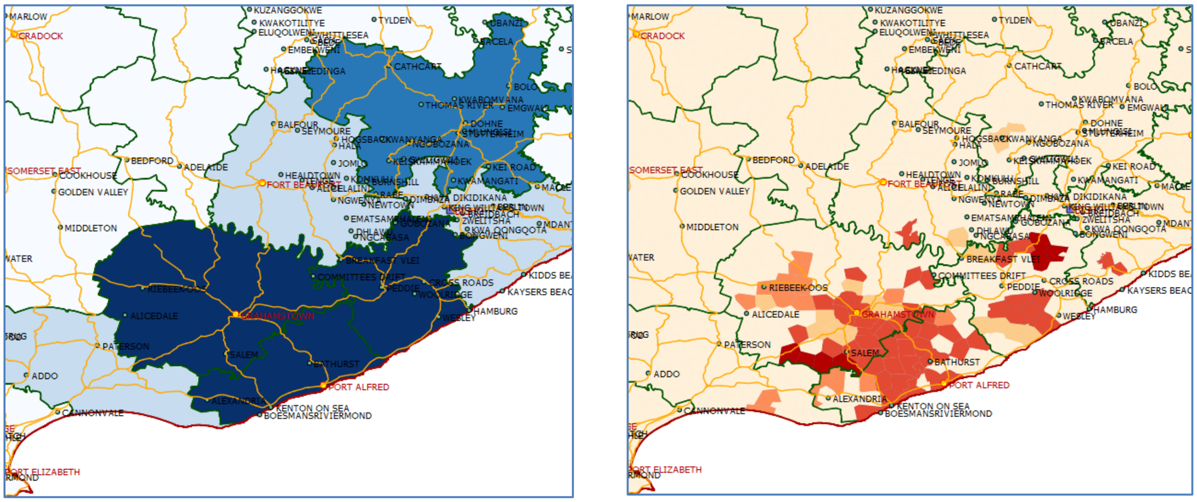
Panel (c) shows the total combined flash flood vulnerability of that particular region in general determined earlier according to the processes described in Section 5.4.3. Following the combination of the mesozone FFP (Panel (b)) with the flash flood vulnerability in panel (c) as described in Section 5.4.3, the four-category impact risk level indices for this event are determined as depicted in panel (d). This last panel (d) in Figure 5.8 thus shows the hotspot areas, or areas of most significant flood-related impact, in the next 18 hours depending on the expected potential of the flash flood hazard threat and the inherent social and structural vulnerability of the region.

The magnitude of the expected impact is shown in Table 5.5 as illustration for the Ndlambe local municipality with a more detailed map of the municipality. The mesozone covering the town of Port Alfred, which experienced significant damage during the eventual flooding event, had an impact level of 3 (the highest level) with a population of 27000 people, 10 schools, 2 health centres, 6 bridges and 1 airport. The magnitude information for impact levels 2 and 1 mesozones in the same local municipality is also provided in Table 5.5 and is extracted directly from the mesozone data as prepared by the CSIR GAP system (CSIR, 2013). Similar information can easily be provided for other local municipalities for mesozones with impact levels of 3, 2 and 1.

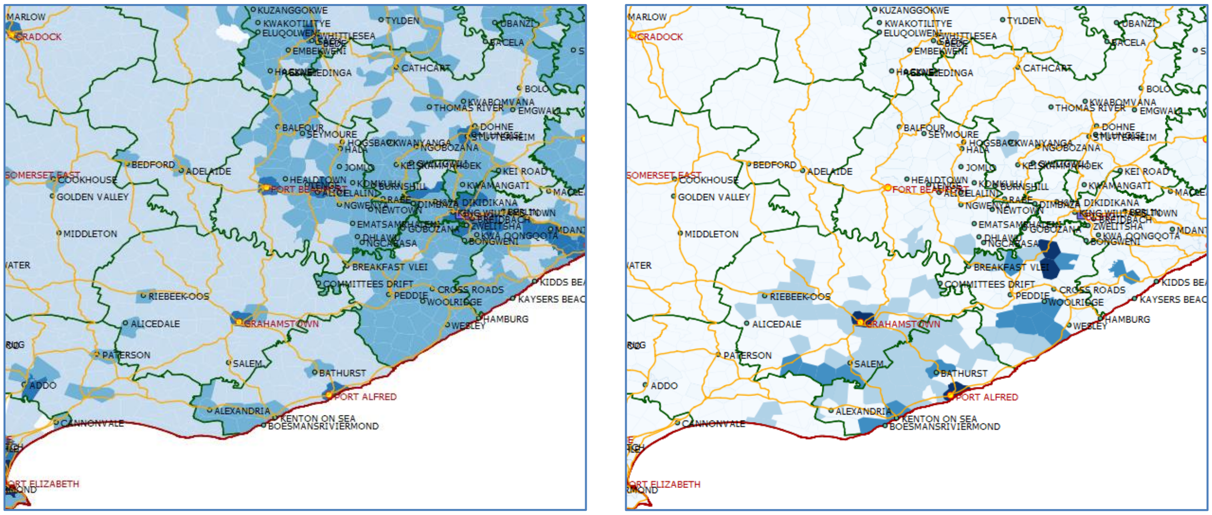
The combination of FFP in Figure 5.8 panel (b) and the likely impact in panel (d) with the additional information of the magnitude of the potential impact from Table 5.5 provides the disaster managers with advanced guidance to aid their decision making in the 18 hour period prior to the expected flooding event.

The contrast between mesozones with the same impact levels can be quite significant. For example, in the Makana local municipality the mesozone covering the major town of Grahamstown has a population of more than 60,000 and a resultant vulnerability index of 4. In comparison a rural mesozone in the Ngqushwa local municipality has only around 4000 inhabitants, but with a high poverty level and large percentage of elderly and children among the inhabitants. Consequently, the vulnerability index for the latter mesozone is on level 3.

The expected flash flood hazard level determined by HyEPS, however, is higher in the rural mesozone (level 4) than in the mesozone covering Grahamstown (level 3). The resultant expected final impact risk levels for both are thus level 3 based on Equation 11.



(a) LM-FFH **(b) Mesozone FFP**



(c) Total vulnerability **(d) Total impact risk level**

Figure 5.8: Impact forecasting products for 20 October 2012 as predicted for the 12-30 hour forecast period.

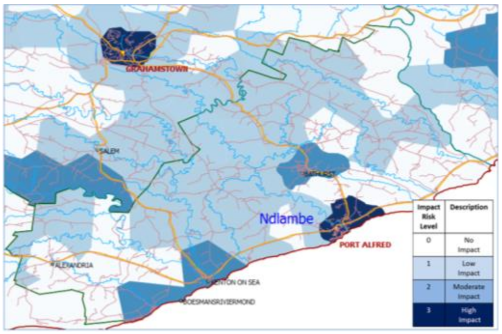
Another contrast is between the same mesozone covering Grahamstown and a mesozone in the Nkonkobe local municipality, both with a flash flood hazard index of 3. Whereas

Grahamstown has a vulnerability index of 4, the second mesozone has a very small population and a vulnerability index of only 2. The resultant impact risk level of the latter mesozone is only 1 compared to the 3 of Grahamstown, even though they have similar flash flood hazard levels. Taking into account this type of information, disaster managers have to decide on the most effective distribution of their resources between various hotspots. The additional lead-time of up to 18 hours would have been quite useful in this particular case study.

Table 5.5: Example of flash flood impact magnitude product for 20 October 2010 as predicted for the 12-30 hour forecast period for the Ndlambe local municipality in the Eastern Cape.

PREDICTED SEVERE WEATHER IMPACT DETAILS

AFFECTED LOCAL MUNICIPALITY:	**Ndlambe**
Date:	20-Oct-12
Time Period:	12:00 - 06:00
Hazard type:	Flash floods
Hazard likelihood (highest):	4
Impact level (highest):	3



Impact Risk Level:		**HIGH (3)**							
AFFECTED TOWNS (if no town identified, a summary of affected mesozones is provided)	**Impact level (0-3)**	**Flash Flood Likelihood (0-4)**	**Total Vulnerability (1-4)**	**Nr of people at risk**	**Nr of homes in area**	**Nr of Schools**	**Nr of Health Centres**	**Nr of Bridges**	**Nr of Airports**
PORT_ALFRED	3	3	4	27217	5733	10	2	6	1
TOTAL				27217	5733	10	2	6	1

Impact Risk Level:		**MODERATE (2)**							
AFFECTED TOWNS (if no town identified, a summary of affected mesozones is provided)	**Impact level (0-3)**	**Flash Flood Likelihood (0-4)**	**Total Vulnerability (1-4)**	**Nr of people at risk**	**Nr of homes in area**	**Nr of Schools**	**Nr of Health Centres**	**Nr of Bridges**	**Nr of Airports**
BATHURST	2	3	3	7448	1624	4	0	0	0
KENTON_ON_SEA	2	3	3	14375	2820	5	1	4	0
BOESMANSRIVIERMOND	2	3	3	1917	390	2	0	2	0
TOTAL				23740	4834	11	1	6	0

Impact Risk Level:		**LOW (1)**							
AFFECTED TOWNS (if no town identified, a summary of affected mesozones is provided)	**Impact level (0-3)**	**Flash Flood Likelihood (0-4)**	**Total Vulnerability (1-4)**	**Nr of people at risk**	**Nr of homes in area**	**Nr of Schools**	**Nr of Health Centres**	**Nr of Bridges**	**Nr of Airports**
20 other mesozones	1	3	3	5973	1500	17	0	37	0
TOTAL				5973	1500	17	0	37	0

5.5.2 Case Study 2: Gauteng flash floods of 20 April 2013

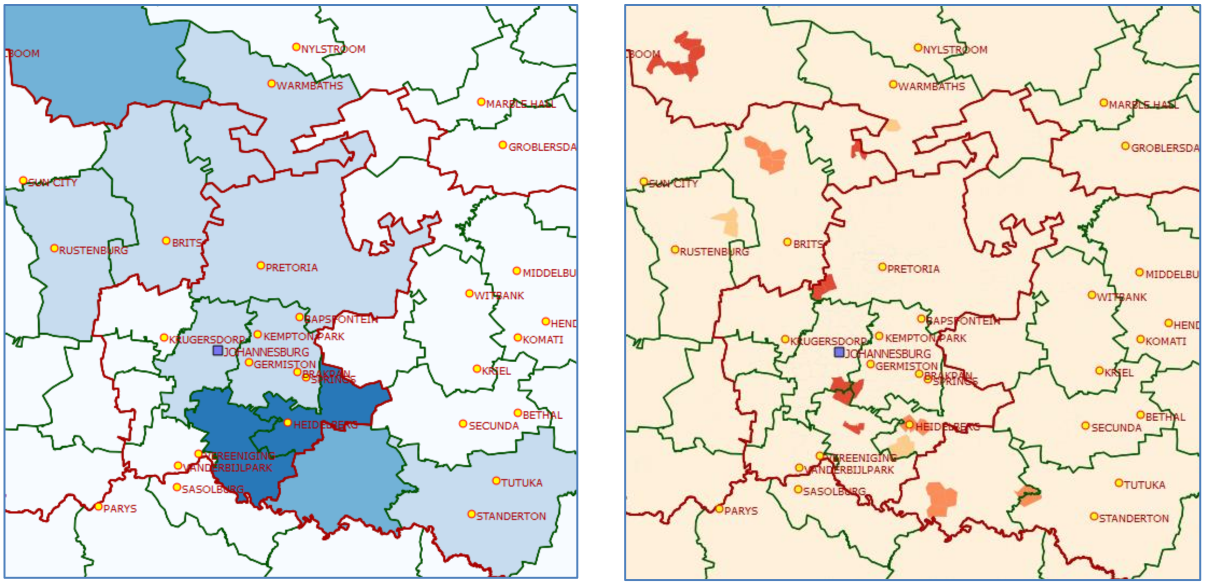
5.5.2.1 Description of the event

Heavy rain over southern Gauteng on the 20th of April 2013 caused damage to property and infrastructure and left 136 people homeless near the Klipspruit south of Johannesburg (SAWS, 2013). Cars were trapped in flood water, roads were closed and people had to be rescued. An upper air trough caused a band of thunderstorms to move from the southwest through the Gauteng radar region on the 19th late afternoon and overnight, reaching its peak overnight between 18:00 and 00:00 UTC and dissipated by the afternoon of the 20th.

5.5.2.2 Results

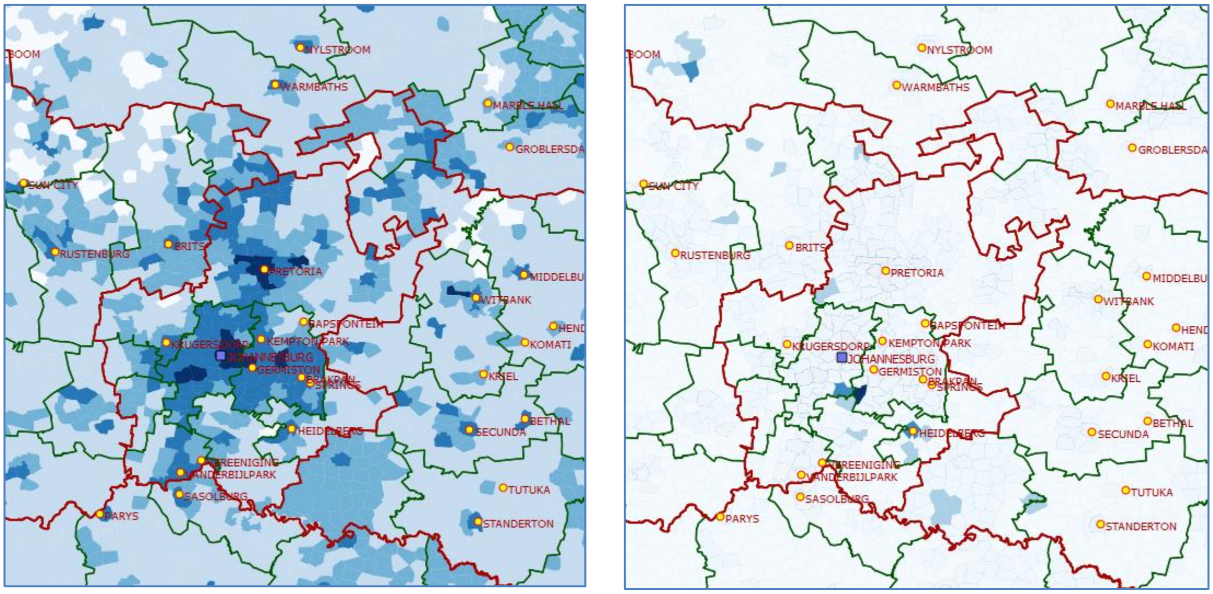
The results of the Impact Forecasting system for the 0-18 hour period on the 20th for this case are presented in Figure 5.9. In Figure 5.10 the FFP and impact risk level for the specific area around the Klipspruit south of Johannesburg is highlighted. Similar to the previous case study, the top row of Figure 5.9 describes the results of the HyEPS forecast of the likelihood of flash flooding in the 0 - 18 hour period based on the persisted 0-hour FFG values as discussed in detail in Chapter 4. The flash flood hazard index for the local municipalities is shown in panel (a) and in panel (b) the mesozone-scale flash flood potential as predicted by the HyEPS system. Panel (c) show the total combined flash flood vulnerability of that particular region and panel (d) shows the impact hotspots through the four-category impact risk level indices.

The HyEPS system indicated a moderate to high potential of flash flooding in a northwest-southeast zone over the area (LM flash flood hazard index and FFP in Figure 5.9 (a) and (b) respectively). The highest impact was expected in the Midvaal local municipality south of Johannesburg, where the Klipspruit area is located, and near the town of Thabazimbi in the upper left corner of Figure 5.9 (d).



(a) **LM-FFH**

(b) **Mesozone FFP**

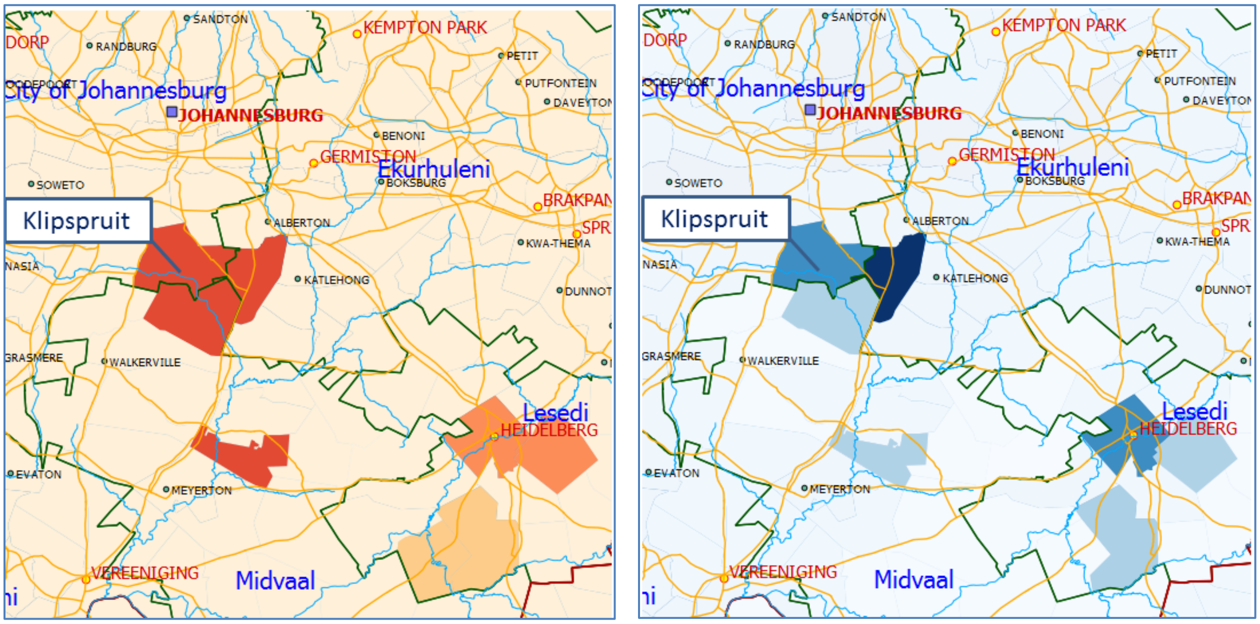


(c) **Total vulnerability**

(d) **Total impact risk level**

Figure 5.9: Impact forecasting products for 0-18 hours on 20 April 2013 over the Gauteng Province region.

Figure 5.10 illustrates possibly the two most important variables of the Impact Forecasting system for the Klipspruit area south of Johannesburg, namely the probability of flash floods (flash flood potential) produced by the 30 members of the HyEPS system, and the associated likely impact hotspots (impact risk level) that resulted from the impact equation (Equation (11)). The influence of the vulnerability information in the impact equation is clearly illustrated in this case. Figure 5.10 (a) shows an area with high likelihood for flash floods indicated by the "Klipspruit" label. In Figure 5.10 (b) the same area has three different levels of likely impact from "low" (bottom mesozone of the same group), to "moderate" for the mesozone on the left, and finally "high" for the mesozone on the right of this group. The main reason for this difference lies in the fact that the mesozone on the right is labelled by the CSIR GAP system as a densely populated area where more than 36900 people live with about 20 schools and a resultant total vulnerability of level 4 out of 5. The mesozone at the bottom of this group has vulnerability of only level 2 due to its population of only about 1500, having no schools, but a number of bridges. Clearly, in this case, the focus should be on possible urban flooding in the high impact mesozone, and safeguarding of bridges over the Klipspruit in the second mesozone.



(a) Mesozone FFP

(b) Total impact risk level

Figure 5.10: Impact forecasting products for 0-18 hours on 20 April 2013 zoomed to focus on the flash flood affected Klipspruit area south of Johannesburg.

5.5.3 Case Study 3: Gauteng flash floods of 16 December 2010

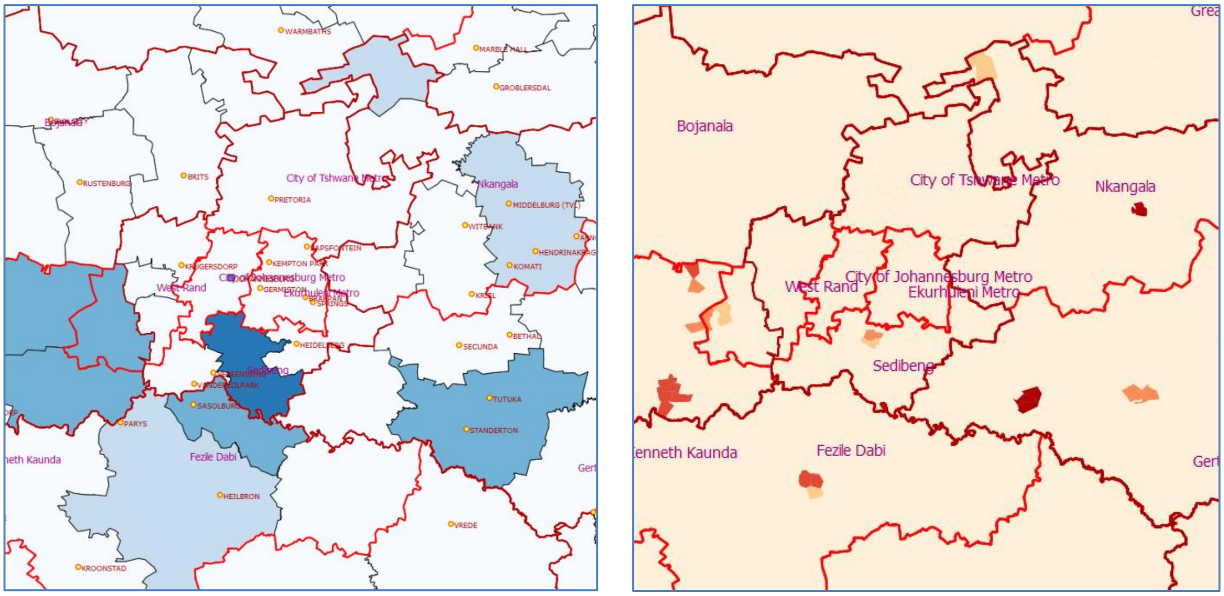
5.5.3.1 Description of the event

More than 133 mm of rain fell overnight on 15 and 16 December 2010 as a line storm moved from southwest to northeast over the Gauteng radar region. In the Vereeniging region more than 100 mm fell in just 8 hours between 22:00 SAST on the 15th and 06:00 SAST on the 16th (see Figure 4.24). Severe flash flooding occurred in several places, starting overnight in the southern parts and in the morning of the 16th over the northern parts. The flooding caused severe infrastructure damage, some fatalities and people were displaced.

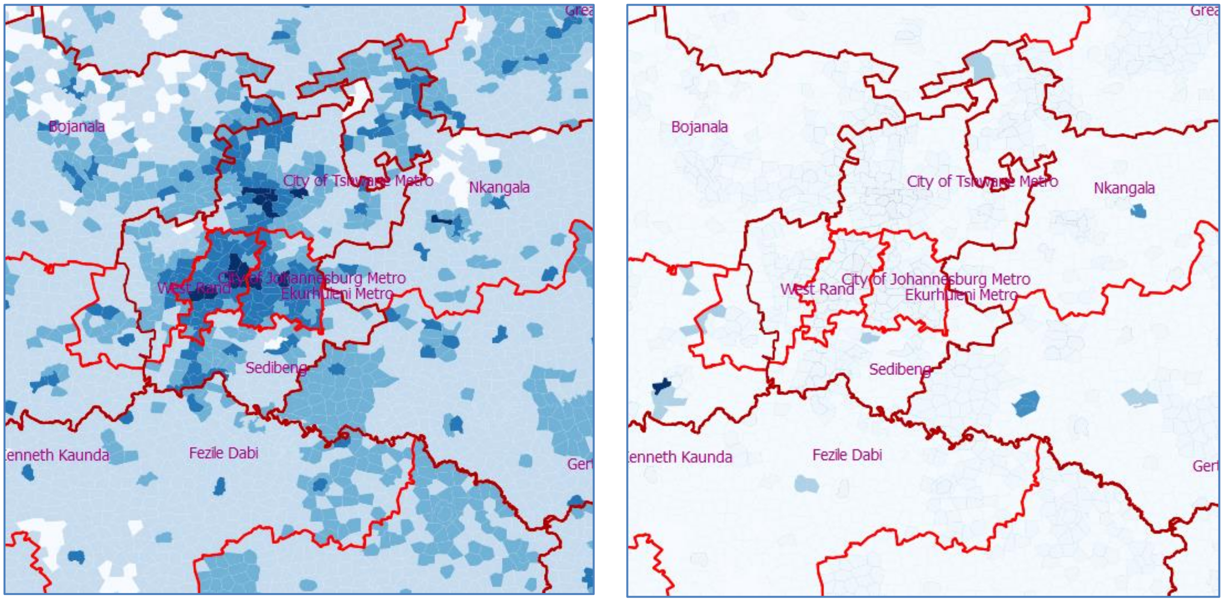
5.5.3.2 Results

As described in Section 4.4.4 the system was well dealt with by the SAFFG system providing nowcasts up to 6 hours in advance, but the NWP models were not able to capture the rainfall timing well at all. Most of the rain fell overnight on the 15th into the early hours of the 16th, however the models peaked the rain 12 to 18 hours to early. In Section 4.4.4.2 an idealized scenario was created by using the 24-hour FFG as a proxy for a statistically lowered 06-hour FFG in anticipation of expected lower future FFG values due to rain predicted for the day by the NWP models. Even in this situation the number of SAFFG basins, and thus their associated mesozones, indicating flash flood potential were far less than in the real situation.

In Figure 5.11 the same Impact Forecasting products described in the previous two case studies are shown for this case. The local municipality flash flood hazard index product (Figure 5.11 (a)) focussed the attention mostly on the areas south of Johannesburg, although it was based on only a few mesozones (Figure 5.11 (b)). Consequently, the impact risk level products were not as promising as what eventually happened. This case illustrates again the critical importance of good and accurate rainfall forecasts for the effectiveness of application systems such as the SAFFG and the Impact Forecasting system.



(c) LM-FFH **(d) Mesozone FFP**



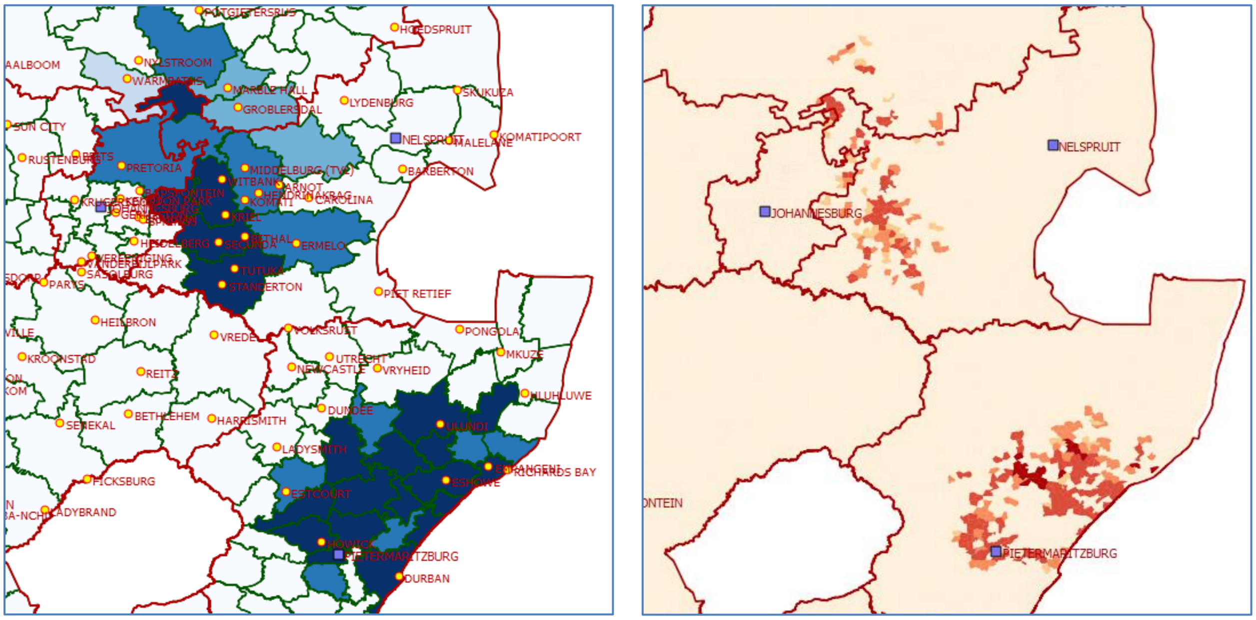
(e) Total vulnerability **(f) Total impact risk level index**

Figure 5.11: Impact forecasting products for the 6-24 hour period of 15 December 2010.

5.5.4 Case Study 4: KwaZulu-Natal flash floods of 7 September 2012

5.5.4.1 Description of the event

A cut-off low pressure system moved over South Africa on 6 and 7 September 2012 causing heavy rain in places over Gauteng, Mpumalanga, KwaZulu-Natal and the Eastern Cape (SAWS, 2012a). Flash flooding occurred in Pretoria, Johannesburg and Ekurhuleni in Gauteng, and in places in KwaZulu-Natal.

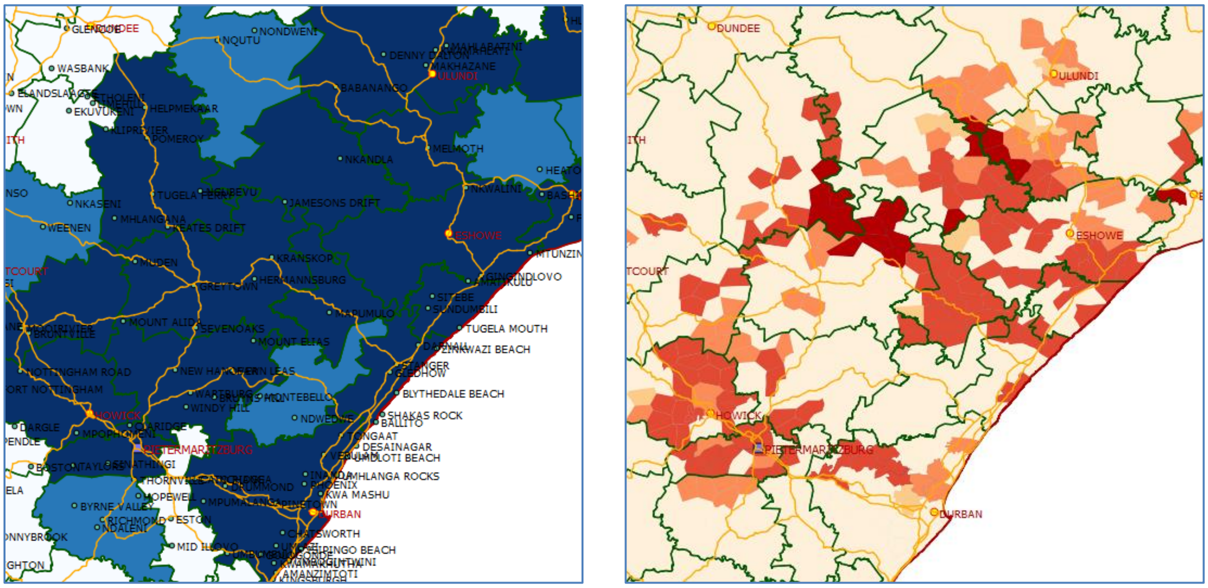


(a) LM-FFH **(b) Mesozone FFP**

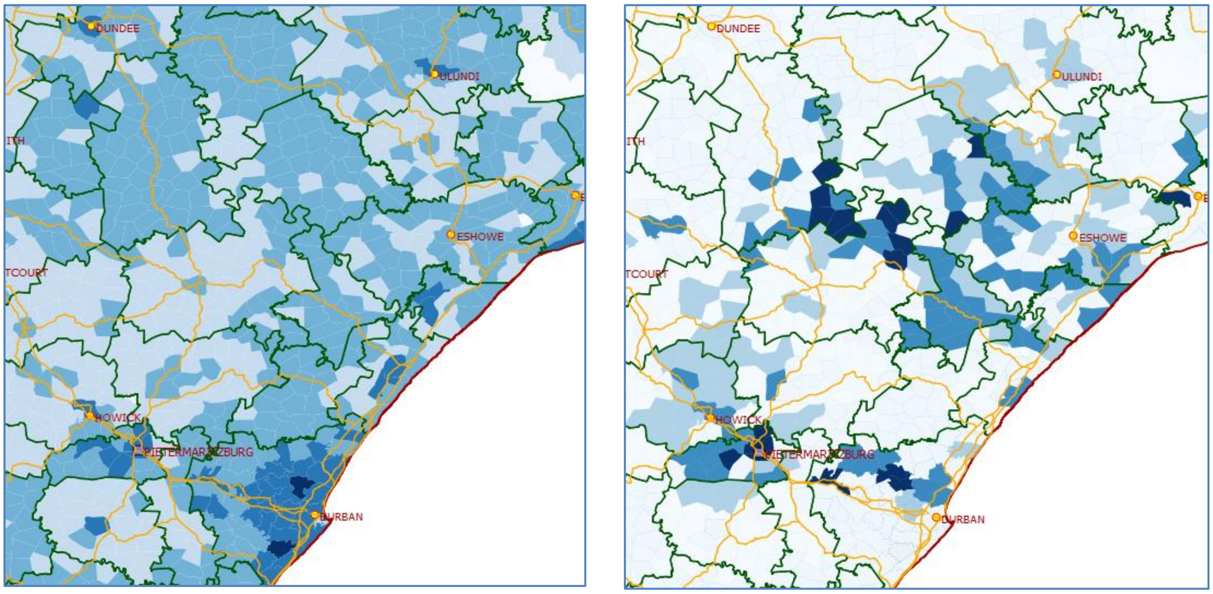
Figure 5.12: Flash flood forecasting products for the 0-18 hour period for 07 September 2012 over the eastern parts of South Africa.

5.5.4.2 Results

As described in Chapter 4 the NWP model over-predicted and misplaced the rain in the Gauteng region. In the KwaZulu-Natal region the rain forecast was better positioned, though it still over-predicted the amount of rain. The Mesozone FFP shown in Figure 5.12 (b) indicates a large number of mesozones with a positive likelihood of flash flooding in both regions. Consequently, the flash flood hazard index at local municipality level (Figure 5.12 (a)) identified a large number of local municipalities with potential flash flooding. More detailed products focussing on KwaZulu-Natal, similar to those in the previous case studies, are provided in Figure 5.13.



(g) LM-FFH **(h) Mesozone FFP**



(i) Total vulnerability **(j) Total impact risk level**

Figure 5.13: Impact forecasting products for the 0-18 hour period for 07 September 2012.

Based on the knowledge of widespread heavy rain in the preceding 2 days over a significant number of the local municipalities (PDMC-KZN, 2012), the likelihood for more flash flooding given the forecast of more rain by the NWP model should alert the disaster management authorities. A number of local municipalities subsequently did report flooding incidents on the 7th, some within the predicted impact areas and others outside the predicted area (PDMC-KZN, 2012). It is, however, unknown if the affected areas fell within the mesozones with the highest impact risk prediction, since the reports from the local municipalities did not provide enough detail in terms of locality of the incidents.

5.6 CONCLUSIONS

Impact forecasting requires a systematic methodology, or model, that can translate the forecast of weather hazards into relevant impact variables. Unlike the generalized indication of typical impacts that could be associated with specific hazards presented by some other weather services, SWIFS is a dynamic impact forecasting system for public warnings able to use the spatial variability of various impact parameters (societal, economic, environmental, etc.) to determine different levels of impacts applicable to an area.

The focus of this chapter was to describe the integrated SWIFS with the development and inclusion of the impact model in combination with the HyEPS forecast model. The impact model within SWIFS required as a first step the determination of the flash flood vulnerability component through the identification and combination of relevant vulnerability indicators. The final impact model was developed linking the forecasting of the probability of looming flash flood hazards (from the forecasting model developed in Chapter 4) with the flash flood vulnerability to identify the likelihood and magnitude of potential impacts. The implementation of this process was illustrated through four case studies of typical flash flood events that occurred around the country.

The case studies provided mixed results in terms of forecasting the likely impact of potential flash flooding up to 18 hours in advance. Quite promising results were achieved with the

Eastern Cape case of 20 October 2012, and reasonable results with the Klipspruit event in Gauteng of 20 April 2013. The results of the KwaZulu-Natal flooding of 7 September 2012 were rather mixed, but the flash flooding of 15 December 2010 yielded generally unconvincing outcomes. The problem is not so much with the impact identification component, which is based on static vulnerability information. The main factor for these mixed results clearly lies in the more variable rainfall forecasting component of SWIFS. This relates back to the uncertainties associate with NWP model forecasts thoroughly discussed in Chapter 4.

Nevertheless, the case studies, particularly the Eastern Cape flooding of 20 October 2012, provided reasonable proof that the concept of SWIFS can produce useful information of the potential impact of flash floods for the next 18 hours. It provides information to disaster managers to guide their decision making processes and focus attention on the hotspots where the largest impact most likely could be. It attempts to answer the question: "*what is going to happen, where and when, and what will the impact be?*" It translates complex scientific information into disaster risk products understandable to the user. This information enables disaster managers to take early action to prevent or minimise adverse effects of hazardous weather.

Other conclusions from this chapter are:

- The likely increase in frequency and intensity of thunderstorms over Gauteng Province due to climate change (SARVA, 2013) may exacerbate the vulnerability issues in future. Increase in rainfall intensity could lead to an increase in flooding. All these factors add pressure in terms of social vulnerability to flooding in the affected regions, urban or rural;
- The complexity of defining vulnerability to be used in a spatial mapping concept of impact forecasting in the literature, is quite evident. No clear cut definition of vulnerability that is the *de facto* option to use in impact forecasting emerged (Balica *et al*., 2012). The relevant choice depends on the purpose of the risk identification approach, the methodology that will be followed, and the availability of data and information in a spatial format if needed. In this chapter the vulnerability and impact concepts for the impact model was developed

uniquely for SWIFS. The definition for impact forecasting developed here links it to the likelihood and the magnitude of adverse impacts, or harmful conditions, to communities under threat based on their vulnerability and due to an imminent severe weather hazard.

The main objective of the impact model developed in this study is to determine the risk level (low to high) and magnitude of adverse impacts due to potential hazards (in this case flash floods) expected at regional level (in river basins and local municipalities) within the next few hours to support the decision making process of the user (disaster management agencies) during these critical few hours. The specific objectives of the impact model were:

- Identify preference areas requiring more urgent disaster management intervention;
- Identify the potential level of impacts for each dimension (social, structural) and collectively based on the likelihood of the hazardous conditions in the next few hours;
- Provide user relevant representations of the magnitude of these imminent impacts.

The mesozone data was quite useful allowing the impact model within SWIFS to focus on regional impacts at the mesozone level for quick first assessments and individual quantitative impacts of specific indicators. These impacts and the associated vulnerabilities then need to be decomposed and explored by the municipal disaster manager through combining the larger-scale information with local community knowledge to identify the specific local impact hot spots and reactive measures. Taking into account this type of information, disaster managers have to decide on the most effective distribution of their resources between various hotspots. The additional lead-time of up to 18 hours would have been quite useful to allow earlier appropriate decision making by disaster managers.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

Auld (2008) argued that users of weather information require a move from *weather forecasting* to *risk forecasting,* aimed at identifying the consequential impacts of hazards. *Impact forecasting* is recognized by the WMO (2012) as a relatively new direction in weather forecasting, and as a growing requirement by users for NMSs to go beyond basic forecasts of weather conditions to forecasting the societal, structural, economic and environmental consequences of these conditions. Impact forecasting allows the prioritization of areas potentially most vulnerable to the expected hazard for preferential disaster management intervention.

This study focused on the development of an impact forecasting system for flash floods in South Africa. The FFGS (SAFFG and SARFFG), as implemented, are essentially nowcasting systems providing guidance of potential flash floods with a 6-hour lead time. Users, particularly disaster managers, however, require longer lead times and information on potential impacts to facilitate early preparedness against possible adverse consequences of the flash floods. Accordingly, the primary objective of the research was to provide an extended outlook of the potential impact of flash floods through the development of the Severe Weather Impact Forecasting System, or SWIFS. Using the flash flood guidance information from SAFFG, the first component of SWIFS produces an eighteen-hour probabilistic outlook of the *potential occurrence of flash floods* based on a single-model ensemble forecast of rainfall (the forecasting model). The second component of SWIFS determines the *event specific societal and structural impacts* of these potential flash floods, based on the output of the first component and its interaction with the generalized vulnerability to flash floods of the affected region (impact model). The products of SWIFS include user-focussed information on the potential and occurrence of flash floods in local municipalities and small river basins, as well as products describing potential hotspots where the largest impact most likely would be on people and their living environment.

6.2 CONTRIBUTION TO SCIENCE

Both components of SWIFS, individually and in combination, are original work not previously attempted in this way with the FFGS in South Africa. Furthermore, the SWIFS impact forecasting concept contributes new and significant insight to the current international research on the application of short-term impact forecasting in a developing country. Operational application of SWIFS will provide users (disaster managers, forecasters, etc.) with additional information supporting their decision-making processes not available previously. It specifically applies to the use of the FFGS (such as SAFFG, SARFFG and others) as guidance on flash floods, not only in a nowcasting sense, but also as an outlook of the potential impact. Lastly, this development of SWIFS also provide the platform for future extension of the impact forecasting concept to other vulnerability dimensions (such as economic and environmental) and to other hazards (such as gales, snow, veld fires, severe thunderstorms, etc.) in South Africa.

6.3 OVERVIEW OF THE RESULTS

In Chapters 1 to 3 the background of the study is provided. The key findings of these chapters are summarized below:

- The expected increase in frequency of heavy precipitation and unprecedented extreme weather events according to the IPCC (2012), combined with social and demographic changes, could lead to an increased vulnerability of people living in flood plains and on river banks. This will increase challenges to early warning systems, demanding the improvement of the information provided to disaster managers for more effective preparedness and response activities. Research is required to progress beyond weather prediction to risk prediction of extreme weather events.

- Of all natural disasters in South Africa, flood disasters have the most adverse impact to people, their livelihoods and infrastructure. Effective early warning systems against floods provide useful information well in time to the community at risk, such as potential adverse impacts to people and their livelihoods, allowing them to take appropriate action to save lives and property.
- The SAFFG and SARFFG systems are important components of the flash flood warning system in South Africa aimed at providing guidance to forecasters when issuing flash flood warnings. One of the main weaknesses of these systems as they are implemented is their inability to provide relevant information at an extended lead-time beyond 6 hours to disaster managers to foster early preparedness against possible adverse impacts.
- Forecast uncertainty is an important factor to be considered right through the entire warning chain. Uncertainty of rainfall predictions is significantly larger than uncertainty in hydrologic models, particularly for smaller-scale flash flood events. To increase the lead-time of forecasting flash flood potential to 24 hours, uncertainty of forecasting rainfall has to be taken into account.
- There is overwhelming evidence that decision support systems of disaster managers require some kind off expression of uncertainty to be able to make useful decisions. A description of the probability of flash floods and the level of impact early enough will provide significant support to the decision making processes of disaster managers regarding the required level and location of intervention. One way of describing this forecast uncertainty is through probability information determined from EPS.

In Chapter 4 the development of a probabilistic rainfall ensemble prediction component, HyEPS, as the first component of SWIFS, is discussed. HyEPS is an original attempt to use rainfall ensembles from a deterministic NWP model to predict the potential for flash floods for the next 18 hours, in so doing taking into account NWP rainfall forecasting uncertainty. The key findings of this chapter can be summarized as follows:

- Disaster management requires more lead-time than 6 hours to prepare and react appropriately to threatening disasters. For this purpose, a rainfall forecasting element linked to the SAFFG nowcasting system is required. NWP provides the most appropriate means of objectively forecasting rainfall for the next 24 hours. To deal with forecasting uncertainty in NWP, ensemble prediction methodology should be used.
- In the absence of a traditional multi-model EPS, an ensemble of rainfall forecasts can be produced from an appropriate collection of grid point forecasts of a deterministic model to address forecast uncertainty associated with a single grid point forecast. HyEPS was developed based on this concept of an ensemble prediction system from a deterministic model.
- The HyEPS concept was tested in four case studies which presented encouraging indications that the ensemble approach provides improvement on persistence rainfall forecasting. It adds considerable value on the likelihood of rainfall in small river basins beyond the 6-hour persistence forecast of the SAFFG. Using HyEPS, additional lead-time for 18 hours or more on the likelihood of flash flooding can be provided, based on the FFG data from the SAFFG system. It provides probabilistic information to cater for the uncertainty in forecasts.
- The assumption that the FFG values can be persisted over the next 18 hours is generally a reasonable assumption. This approach can be followed with reasonable success in the current configuration of the SAFFG and SARFFG. The ideal situation would be to integrate the NWP rainfall forecasts into the FFGS modelling systems to predict dynamically the changes in FFG based on the NWP rainfall forecasts. A major enhancement of the FFGS modelling system would be required, however.
- An exception occurs when the NWP rainfall forecasts peaks more than 12 hours earlier than the real rainfall peak. In such a case, a scenario-based outlook needs to be followed. This implies that in cases where the NWP models forecast the rain to peak too early, lowering the available FFG values with 10% or 20% can provide a reasonable estimate of the FFG values needed for an outlook for potential LM flash flood risk early in the day.

- Ensemble rainfall forecasts from a deterministic model can be successfully integrated into subsequent user applications to address the problem of uncertainty of rainfall forecasts by NWP models.
- Few developing countries using the FFG technology can afford the computer resources to run a high resolution EPS. The development of ensemble forecasts from deterministic model products can be performed on workstations or personal computers at the smaller weather services of developing countries not able to run a NWP system, assuming access to gridded NWP output.
- The main conclusion is that the HyEPS forecasting system realizes the first component of a flash flood impact forecasting system: forecasting the potential of flash floods in the next 18 hours.

In Chapter 5 the development of the impact model as the second component of SWIFS is described. This required an investigation into the concepts of vulnerability and disaster risk, resulting in the development of descriptive and mathematical definitions for "Impact Forecasting". From the impact forecasting definitions followed the development of the impact model of SWIFS based on the integration of the flash flood vulnerability fields and the flash flood potential forecasts from the forecast model. This is done by including uncertainty associated with rainfall forecasts, add hydrological information, and combine it with vulnerability information to produce extended estimation up to 18 hours of the likely severity and the magnitude of the impacts of flash floods on mesozone level. The key findings of this chapter are summarized as follows:

- SWIFS is the first attempt to move beyond weather forecasting, or flash flood forecasting, to forecasting the impacts of flash floods based on the FFGS. It is also the first known attempt to produce objective impact forecasts in a developing country.
- The complexity of defining vulnerability in the context of flash flooding on mesozone-scale is exacerbated by the lack of a clear cut definition of vulnerability as the *de facto* option to use in impact forecasting. The relevant definition depends on the purpose of the risk

identification approach, the methodology that will be followed, and the availability of data and information in a spatial format if needed.

- In this study the vulnerability and impact concepts for the impact model were developed uniquely for SWIFS. The definition for impact forecasting developed here links it to the likelihood and the magnitude of adverse impacts, or harmful conditions, to communities under threat based on their vulnerability and due to an imminent severe weather hazard.
- Case studies provided proof that the concept of SWIFS can produce useful information of the potential impact of flash floods for the next 18 hours. In cases where mixed results were achieved, the problem was not with the impact identification component, but was rather associated with the variability in the rainfall forecast component due to the uncertainties of the NWP forecast. Nevertheless, the case studies proofed that the concept of SWIFS can produce useful information of the impact of flash floods addressing the question of disaster managers: "*what is going to happen, where and when, and what will the impact be?*"
- SWIFS translates complex scientific forecasts of flash flooding into disaster risk impact information understandable to the user. This information is aimed to aid disaster managers to take early preventative action to minimise adverse effects of hazardous weather by:
    - Identifying preference areas requiring more urgent disaster management intervention;
    - Identifying the potential level of impacts for each dimension (social, structural) and collectively, based on the likelihood of hazardous conditions;
    - Providing user relevant representations of the magnitude of these impacts.
- The mesozone data proofed to be quite useful to allow the impact model within SWIFS to focus on regional impacts at the mesozone level for quick first assessments and individual quantitative impacts of specific indicators. These impacts and the associated vulnerabilities then need to be decomposed and explored by the municipal disaster manager through combining the larger-scale information with local community knowledge to identify the specific local impact hot spots and reactive measures. Taking into account this type of

information, disaster managers have to decide on the most effective distribution of their resources between various hotspots.

6.4 CHALLENGES AND RECOMMENDATIONS

6.4.1 Forecast model

The HyEPS rainfall forecasts, based on the bias corrected UM-SA12 forecasts, provided useful forecasts of the likelihood of flash flooding in the 18 hours beyond the SAFFG nowcast. Any methodology using NWP relies heavily on the ability of the NWP system to provide a reasonably good rainfall prediction. The 30 rainfall ensemble members of the HyEPS forecasts in the neighbourhood of each basin representing the entire 18 hours attempted to address the problems of timing of convection and of spatial location errors associated with forecasting convective rain by NWP systems. If the forecasts deviate too far from the correct location or timing of the rainfall peak, however, then not even HyEPS will be able to provide a useful outlook. A number of recommendations related to the forecast model arose from this study:

- The optimum size of this neighbourhood was not investigated and should be addressed in a separate study.
- Bias correction of the UM forecasts is important to provide more realistic rainfall amounts. A more complete basin-specific, NWP model specific, climatological bias correction exercise should be carried out. The ideal situation would be to perform a dynamic bias correction on a daily basis since the BCF could also change from day to day depending on the weather regime.
- The different model runs, UM xaang and UM xaana, sometimes differ significantly in their forecasts as shown in the case studies. There is no consistency which model performs best in a particular situation. It is therefore advisable that if possible both models are used thereby enlarging the multi-model EPS size to double the number of members. This will ensure that the strengths of both models are captured and increasing the chances for a successful forecast as well as for more false alarms.

- A major drawback of the methodology applied in this study was the persistence of the FFG values from the latest available FFG fields for 18 hours into the future. This is not necessarily realistic as more or less rain in the ensuing 18-hour period can have a notable impact on the FFG value. It would be far better if the future FFG could be predicted by running the hydrological models into the future based on the HyEPS forecasts. This, however, would require more substantial computer resources, and a modification to the FFGS hydrological modelling system.
- As an alternative, based on the experience in the case studies, it is suggested that scenarios with FFG levels lowered by 10% and 20% should be prepared to provide for the potential impact of rainfall.
- SAFFG covers only a few high risk regions in South Africa and significant flash flood events have occurred elsewhere. It would be advisable to extend this system to the SADC SARFFG to cover the entire country, and eventually to other countries in the region.
- A major source of uncertainty in the SWIFS value chain is attributed to NWP rainfall forecasts. To reduce errors leading to this forecast uncertainty, it is advised that SAWS continue to enhance its NWP systems, and consider introducing the assimilation of quality weather radar data into its data assimilation system. An important improvement will be to reduce the resolution of the UM used in SAWS from 12 km to 4 km and even 1.5 km. This will remove the need for “equal block” interpolation from a 12 km to a 4 km resolution grid as currently required, and thereby will improve the rainfall fields used in SWIFS.

A significant advantage of the HyEPS methodology as used here is that it does not require significant computer power or the ability to run a NWP system. It can be done on a small computer using gridded rainfall products from a NWP ran elsewhere.

6.4.2 Impact model

The SWIFS concept tested in this study is able to identify the hotspots where the impact is likely to be more severe. The positive results of the Eastern Cape floods of 20 October 2012 provide confidence that the vulnerability assessment used in the impact model is generally on the right track. Since the impact forecast products are spatially scaled at mesozone level, they can be used in a GIS decision supporting system by disaster managers. A number of recommendations related to vulnerability analysis and impact assessment can be made to improve the impact model concept:

- It is advisable that more consultations be held with disaster management practitioners to confirm or adjust the vulnerability indicators used so far, as well as the weights when combining these indicators into social and structural vulnerability indices.
- New indicators based on the mesozone-scale need to be developed in partnership with subject specialists where necessary.
- Specific impact information used by disaster managers in the field should be obtained and included into the indicators where possible. This could typically be a list of bridges in a local municipality that regularly flood, or settlements frequently affected by flooding. A mechanism needs to be developed to include flood line related information into the impact model to determine the impact of inundation due to flooding.
- The enhancement of existing products and development of new products based on user requirements needs to be done in consultation with disaster management practitioners.
- Other impact dimensions, such as environmental impact and economic impact should be investigated, pending the availability of appropriate indicators.
- Refinement of the SWIFS model to include impacts on local scale should also be considered, depending on the availability of relevant vulnerability data.
- The same vulnerability and impact concepts could be used with the nowcasting or forecasting of other hazards such as strong wind, snow, severe thunderstorms, veld fires, etc. For each new hazard type the vulnerability indicators and weights need to be reconsidered to suit the impact of the specific hazard under consideration.
- The methodology tested on the SAFFG system should be applied to the SADC SARFFG in order to cover the entire South Africa with impact forecasting information. Depending on the availability of vulnerability information on an appropriate resolution, this methodology could be applied also to other countries.

- Weather services should be sensitive to the appropriate type and level of detail of the impact information that should be provided to disaster management in order not to interfere with the service and the mandate of disaster management agencies in this regard. Coordination with disaster management agencies will be very important. Forecasters, however, can use the impact information to assess the urgency and additional focus (or not) of warnings they issue.

6.5 FUTURE SCOPE OF WORK

From the recommendations in the previous sections, a number of specific activities need to be performed to enhance the operational application of SWIFS within southern Africa:

- To reduce the uncertainty of rainfall predictions a multi-model EPS should be used in the HyEPS to replace the EPS based on a single deterministic model. A variety of models used in a multi-model EPS would capture more of the rainfall uncertainty compared to deriving EPS from a single deterministic model. Accessing products from a multi-model EPS at the high resolution required is, however, an operational challenge.
- The SAFFG and SARFFG modelling systems need to be enhanced to use multi-model EPS to predict dynamically the 24-hour changes in FFG, instead of relying on the persistence of the FFG values from the latest available FFG fields for 18 hours into the future.
- In collaboration with municipal disaster management agencies and other relevant vulnerability experts the SWIFS model need to be refined to include impacts on local scale using flood lines and other related vulnerability indicators.
- The scope of SWIFS needs to be extended to other hazards such as strong wind, snow, severe thunderstorms and veld fires using appropriate vulnerability indicators for these hazards.

- SWIFS need to be applied operationally also to SARFFG to cover the entire South Africa, and eventually also the other countries in southern Africa participating in SARFFG. Developing appropriate vulnerability indicators for other countries will be a challenge.
- Coordination between forecasters and the various municipal disaster management centres in South Africa needs to be increased to establish effective operational application of impact forecasting products in support of risk related decision making.

6.6 FINAL CONCLUSION

SWIFS is the product of research to develop a basic impact forecasting system which links the science of weather-related forecasting with severe weather impacts at ground level. It adds value to the basic deterministic NWP model and the SAFFG nowcasting system by translating scientific probabilistic rainfall forecasts into an outlook of potential impact information understood by disaster managers. SWIFS has the potential to provide information to disaster managers that could guide their decision making processes and focus attention on the hotspots where the largest impact most likely could be. It attempts to answer the question: "W*hat is going to happen, where and when, and what will the impact be?*" by translating complex scientific information into disaster risk products understandable to the user. By using impact-based information the disaster manager is empowered to take early action to prevent or minimise the adverse effects of hazardous weather. SWIFS fulfils the purpose and objectives of this study as stated in Chapter 1.

The basic concept tested in this study requires further enhancement in partnership with disaster management practitioners to develop it into a fully functional tailor-made impact forecasting system for various severe weather hazards, taking into account the recommendations presented in the previous section. In time, as more specific vulnerability information becomes available and weather forecast models increase in resolution and accuracy, impact forecasting has the potential to become an essential part of weather forecasting practices to support not only disaster management operations, but economic and environmental activities at large.

REFERENCES

Adelekan I., 2011. Vulnerability assessment of an urban flood in Nigeria: Abeokuta flood of 2007. *Natural Hazards, 56, 215-231.*

AMS, 2012: American Meteorological Society Glossary of Meteorology, http://amsglossary.allenpress.com/glossary

Aubrecht C., D. Ozceylan, K. Steinnocker, S. Freire, 2012: Multi-level geospatial modellingof human exposure patterns and vulnerability indicators. *Natural Hazards*, Published Online 18 Sept 2012, DOI 10.1007/s11069-012-0389-9

Auld, H., 2008: Disaster Risk Reduction under current and changing Climate Conditions. *WMO Bulletin*, Vol. 57(2): 118 – 125

Balika, S., N. G. Wright, F. van der Meulen, 2012: A flood vulnerability index for coastal cities and its use in assessing climate change impacts. *Natural Hazards*, 64, 73-105.

Bechtold, P., N. Semane, P. Lopez, J. Chaboureau, A. Beljaars, N. Bormann, 2014: Representing equilibrium and nonequilibrium convection in large-scale models. *Journal of Atmospheric Sciences, 71, 734-753.*

Berz, G., 2005: Climate Change – Modest warming, dramatic effects. In Munich Re Group: *Knowledge Series: Weather Catastrophes and Climate Change – Is there still hope for us?*: 98 - 105

Boko, M., I. Niang, A. Nyong, C. Vogel, A. Githeko, M. Medany, B. Osman-Elasha, R. Tabo and P. Yanda, 2007: Africa. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Li9nden and C.E. Hansen, Eds., *Cambridge University Press*, Cambridge, UK,433-467

Caelum, 2010: South African Weather Service,

Carpenter, T. M., Sperfslage, J. A., Georgakakos, K. P., Sweeney, T., & Fread, D. L., 1999: National Threshold Runoff Estimation Utilizing GIS in Support of Operational Flash Flood Warning Systems. *Journal of Hydrology*, 224, 21-44.

Carpenter, T. M., and K. P. Georgakakos, 2004: Continuous streamflow simulation with the HRCDHM distributed hydrologic model. *Journal of Hydrology*, 298, 61 - 79

Carpenter, T. M., and K. P. Georgakakos, 2006: Intercomparison of lumped versus distributed hydrologic model ensemble simulations on operational forecast scales. *Journal of Hydrology*, 329, 174-185.

Collier, C.G., 2007: Flash flood forecasting: what are the limits of predictability? *Q. J. R. Meteorol. Soc.*, 133, 3-23.

CRED (2014) Centre for Research on the Epidemiology of Disasters International Disaster Database, Université Catholique de Louvain, Brussels, Belgium. URL: http://www.cred.be/ (Accessed 4 February 2014).

CSIR, 2013: http://www.gap.csir.co.za/

Davies, T., and M. J. P. Cullen, A. J. Malcolm, M. H. Mawson, A. Staniforth, A. A. White, N. Wood, 2005: A new dynamical core for the Met Office's global and regional modelling of the atmosphere. *Q. J. R. Meteorol. Soc*., 131, 1759 - 1782.

Davis, R. S., 2001: Flash Flood Forecast and Detection Methods. *AMS Meteorological Monographs*, Vol 28, No 50, Ch 12: 481-526

De Coning, E., and E. Poolman, 2011: South African Weather Service Operational Satellite based Precipitation Estimation Technique: Applications and Improvements. *Hydrol. Earth Syst. Sci*., 15, 1131-1145.

De Elia, R., and R. Laprise, 2005a. Diversity in interpretation of probability: implications for weather forecasting. *Monthly Weather Review*, 133, 1129 - 1143.

De Elia, R., and R. Laprise, 2005b. The unbearable lightness of probabilities. *Bulletin of the American Meteorological Society,* 86, 1224 - 1225

De Groeve, T. and P. Riva, 2009: Early flood detection and mapping for humanitarian response. *Proceedings of the 6th International ISCRAM Conference*, Gothenburg, Sweden, May 2009, 13 pages.

De Moel, H., and J. C. H. Aerts, 2011: Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. *Natural Hazards*, 58, 407 – 425.

Demuth, J.L., B.H. Morros and J.K. Lazo, 2009: Weather Forecast Uncertainty Information – An Exploratory Study with Broadcast Meteorologists. *Bulletin of the American Meteorological Society*, Nov 2009, 1614 - 1618

DPLG, 2002: National Disaster Management Act No 57 of 2002. *Department of Provincial and Local Government*, Pretoria, South Africa, 32 pp.

DPLG, 2005: National Disaster Management Framework of 2005. *Department of Provincial and Local Government, Pretoria, South Africa*, 270 pp.

Du Plessis, L. A., 2002: A review of effective flood forecasting, warning and response system for application in South Africa. *Water SA,* 28, No 2, April 2002, 129-137.

Ebert, E. E., 2001: Ability of a Poor Man's Ensemble to Predict the Probability and Distribution of Precipitation. *Monthly Weather Review*, 129: 2461 – 2480

Engelbrecht, F. A., J. L. McGregor and C. J. Engelbrecht, 2009. Dynamics of the Conformal-Cubic Atmospheric Model projected climate-change signal over southern Africa. *International Journal of Climatology*, 29, 1013-1033.

Evans, E.P., Simm, J.D., Thorne, C.R., Arnell, N.W., Ashley, R.M., Hess, T.M., Lane, S.N., Morris, J., Nicholls, R.J., Penning-Rowsell, E.C., Reynard, N.S., Saul, A.J., Tapsell, S.M., Watkinson, A.R., Wheater, H.S. (2008): *An update of the Foresight Future Flooding 2004 qualitative risk analysis. Cabinet Office*, London.

Frantzova, A., G. Mardirosian, B. Ranguelov: Methodology for complex risk analysis of floods in Bulgaria, 2008: *In Proc 3rd Int Scientific Conf on Water Observation and Information Systems*, Balwois, Ohrid, Macedonia, 27 – 31 May 2008, 1-8

Fuchs S., J. Birkmann, T. Glade, 2012: Vulnerability assessment in natural hazard and risk analysis: current approaches and future challenges. *Natural Hazards*, 64, 1969-1975.

Gad-el-Hak, M. (Ed), 2008: Large-scale Disasters: Prediction, Control, and Mitigation. *Cambridge University Press*, 576 pp.

Georgakakos, K. P., 2004: Mitigating Adverse Hydrological Impacts of Storm on a Global Scale with High Resolution: Global Flash Flood Guidance. *Proceedings of the International Conference on Storms, Storms Science to Disaster Mitigation*, Brisbane, Australia, 5-9 July 2004.

Georgakakos, K. P., 2005: Modern Operational Flash Flood Warning Systems based on Flash Flood Guidance Theory: Performance Evaluation. *Proceedings of the Inl Conf on Innovation, Advances and Implementation of Flood Forecasting Technology*, 9-13 Oct 2005, Bergen-Tromso, Norway, 10pp

Georgakakos, K. P., 2006: Analytical Results for Operational Flash Flood Guidance. *Journal of Hydrology*, 317, 81-103

Georgakakos, K. P., 2011: Overview of FFGS and Recent Developments. *Presentation at SARFFG* Steering Committee Meeting, Pretoria, South Africa

Golding, B.W., 2009: Uncertainty propagation in a London flood simulation. *Journal of Flood Risk Management,* 2 (2009), 2-15

Hagen, E., X. X. Lu, 2011:Let us create flood hazard maps for developing countries. *Natural Hazards*, 58, 841-843.

He, Y., F. Wetterhall, H. L. Cloke, F. Pappenberger, M. Wilson, J. Freer, G. McGregor, 2009: Tracking the uncertainty in flood alerts driven by grand ensemble weather predictions. *Meteorological Applications*, 16, 91 – 101.

Holloway, A., 2007: Severe weather compound disaster: August 2006 cut-off lows and their consequences in the Southern Cape, South Africa. *Report to the Western Cape Provincial Disaster Management Centre*, Oct 2007.

Holloway, A., G. Fortune, V. Chasi, 2010: RADAR Western Cape 2010 – Risk and Development Annual Review. *Creda Communications*, 101 pp.

Holton, J. R., 1992: An Introduction to Dynamic Meteorology. *Academic Press Inc*, San Diego, Californai, USA, 507 pp.

IPCC, 2007(a): Climate Change 2007: Synthesis Report. *IPCC,* Geneva, Switzerland, 102 pp.

IPCC, 2007(b): Summary for Policymakers. Climate Change 2007: Impacts, Adaptation and Vulnerability. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hansen, Eds., , 7-22

IPCC, 2011: IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. http://ipcc-wg2.gov/SREX/, Geneva, Switzerland, 29 pp.

IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D.

Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. *Cambridge University Press*, Cambridge, UK, and New York, NY, USA, 582 pp.

IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. *Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32

ISDR 2005a: Living with Risk: A Global Review of Disaster Reduction Initiatives. *ISDR*, Geneva, Switzerland

ISDR 2005b: Hyogo Framework of Action 2005 - 2015: Building the resilience of nations and communities to disasters. *Final report to the World Conference on Disaster Reduction*

ISDR 2006a: Early Warning – From Concept to Action. *The Conclusions of the Third International Conference on Early Warning,* 27-29 March 2006, Bonn, Germany.

ISDR 2006b: Global Survey of Early Warning Systems. *A Report Released at the Third International Conference on Early Warning*, 27-29 March 2006, Bonn, Germany.

ISDR 2008: Early warning systems can save lives when cyclones strike*. Press Release UN/ISDR* 2008/05

ISDR 2010: Terminology: Basic Terms of Disaster Risk Reduction. http://www.unisdr.org/eng/library/lib-terminology-eng%20home.htm

ISDR 2012: Platform for the Promotion of Early Warning: Basics of Early Warning. http://www.unisdr.org/2006/ppew/whats-ew/basics-ew.htm

Johnston, P. A., E.R.M. Archer, C.H. Vogel, C.N. Bezuidenhout, W.J. Tennant, R. Kuschke, 2004: Review of seasonal forecasting in South Africa: producer to end-user. *Climate Research*, 28:67-82

Jolliffe, I. T., and D. B. Stephenson, 2012: Forecast Verification – A Practitioner's Guide in Atmospheric Sciences, 2nd Edition. *Wiley-Blackwell*, Chichester, United Kingdom, 274 pp

Jongman, B., J. Kwadijk, Z. Stanton-Geddes, H. Winsemius, 2012: Flood Risks across Spatial Scales. Understanding Risk: Best practices in Disaster Risk Assessment, *Proceedings from the 2012 UR* Forum, Chapter 11, p61-65.

Jordaan, A. J., 2007: Disaster Risk Assessment at Municipal Level in South Africa. *Disaster Management Southern Africa*, September/December 2007, 14-16

Joslyn, S., S. Savelli, 2010: Communicating forecast uncertainty: public perception of weather forecast uncertainty. *Meteorological Applications*, 17, 180-195

Joslyn, S., L. Nadav-Greenberg, R. M. Nichols, 2009ba Probability of precipitation: assessment and enhancement of end-user understanding. *Bulletin of the American Meteorological Society*, Feb 2009, 185 – 193.

Joslyn, S., L. Nadav-Greenberg, M. U. Taing, R. M. Nichols, 2009b: The effects of wording on the understanding and use of uncertainty information in a threshold forecasting decision. *Applied Cognitive Psycholog*, 23: 55 – 72.

Kienberger, S., 2012: Spatial modelling of spatial and social vulnerability to floods at the district level in Búzi, Mozambique. *Natural Hazards*, 64, 2001-2019.

Klopper, E., 1999: The use of seasonal forecasts in South Africa during the 1997/98 rainfall season. *Water SA*, 25: 311 - 316

Landman, S., F. A. Engelbrecht, C. J. Engelbrecht, L. L. Dyson and W. A. Landman, 2012: A short-range weather prediction system for South Africa based on a multi-model approach. *Water SA*, 38, 765 – 773.

Lean, H. W., P. A. Clark, M. Dixon, N. G. Roberts, A. Fitch, R. Forbes, C. Halliwell, 2008: Characteristics of High-resolution Versions of the Met Office Unified Model for Forecasting Convection over the United Kingdom. *Monthly Weather Review*, 136: 3408 – 3424.

Lorenz, E.N., 1963: Deterministic Non-periodic Flow. *Journal of Atmospheric Sciences*, 20: 130 – 141

Lorenz, E.N., 1969a: Atmospheric Predictability as Revealed by Naturally Occurring Analogues. *Journal of Atmospheric Sciences*, 26: 636 – 646

Lorenz, E.N., 1969b: Three Approaches to Atmospheric Predictability. *Bulletin of the American Meteorological Society*, 50, December 1969, 345 - 349

Meteoalarm, 2013: Meteoalarm. http://www.meteoalarm.eu

Midgley, S. J. E., R. A. G. Davies and S. Chesterman, 2011: Climate Risk and Vulnerability Mapping in Southern Africa: Status quo (2008) and future (2050). *Report for the Regional Climate Change*

Programme for Southern Africa (RCCP), UK Department for International Development (DFID). OneWorld Sustainable Investments, Cape Town.

Morss, R. E., J. L. Demuth and J. K. Lazo, 2008: Communicating Uncertainty in Weather Forecasts: A Survey of the U.S. Public. *Weather and Forecasting*, 23: 974 - 991

Morss, R. E., J. K. Lazo and J. L. Demuth, 2010: Examining the use of weather forecasts in decision scenarios: results from a US survey with implications for uncertainty communication. *Meteorological Applications*, 17: 149 – 162

Murphy, A.H., 1991: Probabilities, Odds, and Forecasts of Rare Events. *Weather and Forecasting*,6: 302 – 307

National Disaster Management Centre (NDMC), 2013: *Personal communication*

Naudé, A., W. Badenhorst, L. Zietsman, E. Van Huyssteen, and J. Maritz, 2007: Geospatial Analysis Platform – Version 2: Technical overview of the mesoframe methodology and South African Geospatial Analysis Platform. *CSIR Report number*: CSIR/BE/PSS/IR/2007/0104/B

National Research Council (NRC) 2006: Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions using Weather and Climate Forecasts. *National Academies Press,* Washington D.C.

National Research Council, 2006b: Facing Hazards and Disasters: Understanding Human Dimensions. *National Academies Press*, Washington, DC, 408 pages

National Research Council, 2008: Integrating Multiscale Observations of US Waters. *National Academies Press*, Washington, DC, 210 pages, pp 74-76)

Neal, R. A., P. Boyle, N. Grahame, K. Mylne, M. Sharpe, 2013: Ensemble based first guess support towards a risk-based severe weather warning system. *Meteorological Applications*, Published online in Wiley Online Library, 15 pages

Norbiato, D., M. Borga, R. Dinale, 2009: Flash flood warning in ungauged basins by use of the flash flood guidance and model-based runoff thresholds. *Meteorological Applications*, 16: 65 – 75.

Ntelekos, A. A., K. P. Georgakakos, W. F. Krajewski, 2006: On the uncertainties of flash flood guidance: towards probabilistic forecasting of flash floods. *Journal of Hydrometeorology*, 7, 896 – 915.

Nyakundi, H., S. Mogere, I. Mwanzo and A. Yitambe, 2010: Community perceptions and response to flood risks in Nyando District, Western Kenya. JAMBA: *Journal of Disaster Risk Studies*, 3, 346-366.

Parker, D., 2005: Early Warning for Natural Hazard Mitigation. *Asian Disaster Management News* Vol. 11(1): 3 – 4

Parry, M., O. Canziani, J. Palutikof, 2008: Key IPCC Conclusions on Climate Change Impacts and Adaptations. *WMO Bulletin*, Vol. 57(2): 78-85.

PDMC-KZN, 2012: KwaZulu-Natal Monthly incidents report. *Provincial incidents report*, September 2012, 23 pp

Peduzzi, P., H. Dao, C. Herold, F. Mouton, 2009: Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index. *Natural Hazards Earth Systems Science*, 9, 1149-1159.

Pegram, G., S. Sinclair, M. Parak, D. Sakulski, N. Nxumalo, 2007. National Flood Nowcasting System: towards an integrated mitigation strategy. WRC Project 1429/1/06, *Water Research Commission*, Pretoria, South Africa.

Pelling, M., 2011: Adaptation to Climate Change – from resilience to transformation. *Routledge,* New York, 203 pages.

Poolman, E. R., H. Chikoore, F. Lucio, 2008: Public benefits of the Severe Weather Forecasting Demonstration Project in south-eastern Africa. *WMO Meteoworld*, Dec 2008: 1-5.

Poolman, E. R., 2009: Analysis of DMA questionnaires from 2009 SAFFG workshops. *SAFFG Internal Report SAFFG-Gen-007.1, South African Weather Service*, Pretoria

Poolman, E. R., 2013: Integration of Products into End-User Decision Making. *Water Research Commission, Deliverable 7 Report: Project K5/2068*, Pretoria, South Africa, 12 pp.

Pyle, D. M., 2006: Severe Convective Storm Risk in the Eastern Cape Province of South Africa. *Unpublished PhD Thesis. Rhodes University*, Grahamstown, South Africa, 219 pp.

Robbins, J., 2012: *Personal Communication*

Roulston, M.S., G.E. Bolton, A. N. Kleit and A. L. Sears-Collins, 2006: A Laboratory Study of the Benefits of Including Uncertainty Information in Weather Forecasts. *Weather and Forecasting*, 21: 116 – 122

SARVA, 2013: South African Risk and Vulnerability Atlas. http://www.rvatlas.org/

SAWS, 2012a: Climate Summary for South Africa: September 2012. *SAWS Climate Summaries*, Vol 23, 9. 23 pp.

SAWS, 2012b: Climate Summary for South Africa: October 2012. *SAWS Climate Summaries*, Vol 23, 10. 22 pp.

SAWS, 2013: Climate Summary for South Africa: April 2013. *SAWS Climate Summaries*, Vol 24, 4. 22 pp.

Scheuer, S., D. Haase, V. Meyer, 2011: Exploring multi-criteria flood vulnerability by integrating economic, social and ecological dimensions of flood risk and coping capacity: from a starting point view towards an end point view of vulnerability. *Natural Hazards*, 58, 731 – 751.

Sene, K., 2008: Flood Warning, Forecasting and Emergency Response. *Springer Science and Busines Media*, 303 pp

Silvestro, F., and N. Rebora, 2011: Quantitative flood forecasting on small- and medium-sized basins: a probabilistic approach for operational purposes. *Journal of Hydrometeorology*, 12. 1432 – 1446.

Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood and D. Wratt, 2007: *Technical Summary. Climate Change 2007: The Physical Science Basis, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds. Cambridge University Press, Cambridge, UK

Sperfslage, J., C. Spencer and K. Georgakakos, 2010: South African Flash Flood Guidance System *User's Guide. HRC Limited Distribution Report No. 32, Hydrologic Research Centr*e, San Diego, CA, USA, 210 pp

Stensrud, D. J., 2007. Parameterization Schemes: Keys to Understanding Numerical Weather Prediction Models. *Cambridge University Press*. Cambridge. 459 pp

Tennant, W. J., Z. Toth, K. J. Rae, 2007: Application of the NCEP Ensemble Prediction System to Medium-Range Forecasting in South Africa: New Products, Benefits, and Challenges. *Weather and Forecasting*, Feb 2007, Vol 22: 18 - 35

Terblanche, D. E., G. G. S. Pegram and M. M. Mittermaier, 2001: The development of weather radar as a research and operational tool for hydrology in South Africa. *Journal of Hydrology*, 2001, 241: 3-25.

Theis, S. E., A. Hense and U. Damrath, 2005: Probabilistic precipitation forecasts from a deterministic model: a pragmatic approach. *Meteorological Applications*, 12, 257-268.

Thielen, J., J. Bartholmes, F. Pappenberger, 2007: Application of Ensemble in Flood Forecasting. *ECMWF Workshop on Ensemble Prediction* 7-9 November 2007.

Thywissen, K., 2006: Components of Risk – a Comparative Glossary. Studies of the University: Research, Council, Education – *Publication series of UNU-EHS No2/2006*, United Nations University Institute for Environment and Human Security.

Toth, Z., P. Schultz, S. Mullen, J. Demargne, Y. Zhu, 2007: Completing the Forecast: Assessing and Communicating Forecast Uncertainty. *ECMWF Workshop on Ensemble Prediction* 7-9 November 2007.

UK Met Office, 2002: The impact of severe weather. *UK Met Office NWP Gazette*, September 2002.

UNESCO, 2013: Flood Vulnerability. http://unescoihefvi.free.fr/vulnerability.php

Van der Linde, T. and M. Strydom, 2008: Conducting risk identification and assessment to recognise potential hazards and vulnerable conditions. *Proceedings from the Conference on Disaster Risk Management in the Public Sector*, 18-20 Sept 2008, Johannesburg, South Africa.

Van Huyssteen, E., S. Biermann, A. Naude, A. le Roux, 2009: Advances in spatial analysis to support a more nuanced reading of the South African space economy. *Urban Forum*, 20, 195-214.

Vogel, C., and K. O'Brien, 2006: Who can eat information? Examining the effectiveness of seasonal climate forecasts and regional climate-risk management strategies. *Climate Research*, 33: 111-122

Warner, T.T., 2011: Numerical Weather and Climate Prediction. *Cambridge University Press*, New York, USA, 526pp

Wilks, D. S., 2006: Statistical Methods in the Atmospheric Sciences, 2nd Edition. *Academic Press*, Amsterdam. 627 pp.

Wisner, B., P. Blaikie, T. Cannon, I. Davis, 2004: At Risk, Second Edition, Natural hazards, People's vulnerability and disasters. *Routledge,* London, 471pp.

WMO, 2002: Executive Council Fifty-Fourth Session April 2002, *General Summary, Annex to Paragraph 5.1.8*

WMO, 2005: Guidelines for integrating severe weather warnings into disaster risk management. *WMO-No 1292*, Geneva, Switzerland

WMO, 2005b: THORPEX International Research Implementation Plan. W*MO Technical Document TD-1258*, Geneva, Switzerland.

WMO, 2006: Preventing and Mitigating Natural Disasters. *WMO-No 993*, Geneva, Switzerland

WMO, 2006a: Symposium on Multi-Hazard Early Warning Systems for Integrated Disaster Risk Management. *EWS Symposium 2006, Outcome Report.pdf,* WMO, Geneva, Switzerland.

WMO, 2007: Prospectus for the Implementation of a Flash Flood Guidance System with Global Coverage. *WMO CBS-MG-VII/Doc 5(7),* Geneva, Switzerland.

WMO, 2008a: Guidelines on the Communication of Forecast Uncertainty. *WMO TD No. 1422*, Geneva, Switzerland

WMO, 2008b: Final Report on the Severe Weather Forecast Demonstration Project for South-eastern Africa. *WMO GDPFS*

WMO, 2008c: *Guide to Hydrological Practices, Vol II, Chapter 7. WMO*, Geneva, Switzerland

WMO, 2009: WMO Statement on the Scientific Basis for, and Limitations of, Weather and Climate Forecasting. *WMO Final Report of the 54th Session of the Executive Council, Annex 5, Geneva*, Switzerland

WMO, 2011: Manual on Flood Forecasting and Warning. *WMO No. 1072*, Geneva, Switzerland

WMO, 2012: NMHSs Provision of Impact-based Information, Forecasts and Warning Products and Services. *WMO CBS-15 Doc 4.5.1(1) Annex to paragraph 4.5.1.9 of the general summary*: Decisions for the Open Programme Area Group on Public Weather Services.

World Bank, 2010. Data finder: population total. http://datafinder.worldbank.org/