QUANTIFYING RAINFALL USING RAIN GAUGES, RADAR AND SATELLITE – REAL-TIME TECHNOLOGIES TO FACILITATE CAPACITY BUILDING

Report

to the Water Research Commission

by

Roelof Burger, Henno Havenga, Farren Hiscutt,
Monray Belelie, Nisa Ayob and Paul Kucera

North-West University

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Obtainable from:
Water Research Commission
Private Bag X03
Gezina, 0031
South Africa

orders@wrc.org.za or download from www.wrc.org.za

ABSTRACT

Weather observation is the key to addressing many of the environmental challenges that we face. Severe weather events are recognised as one of the most likely risks, having the biggest impact on the economy. South Africa has a world-class weather observation infrastructure that is used to mitigate these impacts. This includes more than 15 radars, around 25 lightning detection sensors that provide 90% detection efficiency of cloud-to-ground lightning, with a locational accuracy of 500 m over most of the country, a multitude of automatic weather stations (AWSs) and more than 100 stations with a precipitation record older than 100 years. However, funding constraints have put a massive burden on this infrastructure. The biggest threat to its sustainability is capacity building. The purpose of this project is to address this concern by reviewing and developing technologies, and by doing so, to build capacity in the field of weather observation. The aim is to build capacity in weather observation, providing real-time observations of weather and precipitation for the study area; to explore and develop local innovative solutions for real-time observation; and to effectively communicate observations with interested parties. The project was launched with a media function that involved the South African Weather Service (SAWS) and the Water Research Commission (WRC). It was opened by the Minister of Environmental Affairs. Two PhD students and four MSc students participated in the project, while four other MSc students were indirectly involved. The project exposed 20 honours students to the technologies. At undergraduate level, a Geography and Applied Mathematics programme was developed at North-West University (NWU), which was aligned to the need for climatologists at SAWS. More than 1,500 learners from 26 schools visited NWU and participated in 12 activities that taught them the value of observations in understanding and preserving the natural environment. The Lekwena weather radar, the Internet of Things (IoT) data loggers and low-cost sensors were developed and used to expose students and the public to the technologies needed in South Africa to look after its infrastructure. The Lidar Radar Open Source Environment (LROSE) was implemented on the Lekwena radar. This provided the opportunity to transfer capacity to South Africa that could be implemented on the national radar network. A general survey showed that there is potential within South Africa to develop and improve existing nowcasting products, and that members of the public would even be willing to pay for this. Enhancing nowcasting capacity in the country will benefit the public, and ensure the sustainability of the national infrastructure.

EXECUTIVE SUMMARY

BACKGROUND

Weather observation is the key to addressing many of the environmental challenges that we face. Severe weather events are recognised as one of the most likely risks, having the biggest impact on the economy. South Africa has a world-class weather observation infrastructure that is used to mitigate these impacts. This includes more than 15 radars, around 25 lightning detection sensors that provide 90% detection efficiency of cloud-to-ground lightning with a locational accuracy of 500 m over most of the country, a multitude of AWSs and more than 100 stations with a precipitation record older than 100 years. However, funding constraints have put a massive burden on this infrastructure. The biggest threat to its sustainability is capacity building. The purpose of this project is to address this concern by reviewing and developing technologies, and by doing so, to build capacity in the field of weather observation.

OBJECTIVES AND AIMS

This project aims to do the following:

- Build capacity in weather observation
- Provide near real-time observations of weather and precipitation for a portion of the Highveld
- Explore and develop local innovative solutions to facilitate real-time weather observations
- Effectively communicate weather observations to interested communities.

The project team made substantial use of student involvement in every aspect of the project deliverables.

METHODOLOGY

Infrastructure was developed to facilitate access to data from this project on a real-time basis. This includes a microwave link between the Lekwena radar and the NWU, a web server to collate the real-time data, a server to provide access to the raw radar data, loggers and modems to transmit data from the rain gauge network and the AWSs, and a website. It is the first time that datasets of this kind are provided to the community at this level in real time in a research operation. Local, affordable weather station loggers were developed that make use of all current IoT communication technologies.

An exploratory study was conducted that focused on forecasting hailstorms, nowcasting hailstorms, the perceptions of individuals in dealing with and understanding hail, and the perceived benefits of hail nowcasts. Hailstorms were chosen as the hazard on which to focus in this project since they are one of the most prominent severe weather-related hazards in South Africa. Severe hail events were among the main sources of destruction and damage to property, agriculture and infrastructure over the Highveld.

HIGH-RESOLUTION RAINFALL OBSERVATIONS

South Africa hosts world-class infrastructure for rainfall observations. At least 100 stations are available for long-term climate studies. A total of 93 homogeneous rainfall regions have been identified in South Africa that use daily reporting rain gauges. Considering other variables, eight climate zones are typically considered. South Africa also has a network of 16 weather radars. This includes ten S-band Selex radars, two mobile X-band Selex radars and four old EEC C-band radars. While the radars do not all have consistent data availability, the network covers most of the densely populated and important agricultural areas. Considering the extent of the infrastructure, very few scientists and engineers are responsible for maintenance, evaluation and product development of this network compared to other nations with similar operational footprints.

TECHNOLOGIES TO FACILITATE REAL-TIME OBSERVATIONS

The project focused on a range of technologies to facilitate the real-time observation of rainfall and to communicate these observations to interested parties in a timely manner. A website was developed to provide access to all products and data. The Lekwena radar was equipped with a microwave link to provide real-time data to the internet. A low-cost, low-power logger was further developed that can be used to interface with most weather sensors. The ESD L151M data logger can interface with instruments using RS232, RS422, RS485, analogue signals, digital counters, TTL UART, SDI-12 and I2C. It is equipped with an XBEE socket that can work with different communication devices. This includes GSM and IoT protocols. The following IoT networks were evaluated: SigFox, LoRa and Thingstream. Each of these has its own strengths and weaknesses and can motivate their own use case. All the different communication protocols were interfaced with a database through a server. Low-cost solutions like the ones developed through this project provide an ideal platform to train students in the skills needed and to help improve the sustainability of the national infrastructure. The project further focused on implementing the new LROSE on the Lekwena radar. This is the next generation of the software currently used by SAWS on its network.

COMMUNICATION OF REAL-TIME OBSERVATIONS

Hail was used as an example of how climate services are currently communicated to the public. The project team interviewed forecasters at SAWS to document the typical processes that are used to forecast hail in South Africa. Forecasts typically constitute severe weather events up to 48 hours in advance. At the time of the study, SAWS did not have any dedicated nowcasters or products that send out communication and warnings within a two-hour window. Radar data is provided to third parties, but skilled forecasters are not involved in these products. An analysis of radar forecasts of hail for the last five years showed that the automated radar products are very skilled, but also suffer from a high false alarm rate. Thirty individuals were interviewed. People showed great interest in the nowcasting of weather. In general, individuals indicated that they would be willing to pay for products of this kind.

CAPACITY BUILDING AND COMMUNICATION

The core project team consisted of two PhD students (Runyararo Matandirotya and Juan van Loggerenveld) and four MSc students (Nisa Ayon, Henno Havenga, Edward Serumaga-Zake and Francois du Plessis). The MSc students' dissertations comprised different components of the project. Other postgraduate students also participated in activities associated with the project. These were Ncobile Nkosi, Marvin Qhekwana, Thapelo Letsoho and Lehohlohonolo Sello – all MSc students. Between 2017 and 2019, the project provided 20 honours students with the opportunity to build their own environmental sensors in NWU's Earth Observation module. Several honours research projects were conducted on aspects of the project, and two of the students eventually completed their MSc degrees on the project. An undergraduate programme, Geography and Applied Mathematics, was developed with insight from SAWS to meet the need for climatologists. A community service programme was developed alongside the Science, Engineering, Technology and Health Academy, a collaboration between NWU and the Ferdinand Postma High School in Potchefstroom. As part of National Science Week 2019, the project team coordinated a community service project that entailed about 1,500 schoolchildren from 25 different schools in the North West visiting NWU between 29 July and 2 August. The team also presented six public talks on the theme "The harsh realities of climate change". Brochures were developed for these activities.

CONCLUSIONS

A huge effort is needed to ensure the sustainability of South Africa's weather observation infrastructure. This project has shown that there is still potential to further develop products and services from this infrastructure to benefit the citizens of South Africa. This is particularly true in the nowcasting space that relies heavily on accurate and timely observations. The project also trained a number of undergraduate and postgraduate students through exposure to operational weather radar, innovative new technologies and community service activities.

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ABBREVIATIONS

ACRU	Agricultural Catchments Research Unit
API	Application Programming Interface
ARC	Agricultural Research Council
ARS	Automatic Rainfall Station
AWS	Automatic Weather Station
CCAM	Conformal-Cubic Atmospheric Model
CRG	Climatology Research Group
ENSO	El Niño Southern Oscillation
ESD	Electronic Systems Development
FAR	False Alarm Rate
GFS	Global Forecasting System
GIS	Geographic Information System
GLOBE	The Global Learning and Observation to Benefit the Environment
ICASA	Independent Communications Authority of South Africa
IoT	Internet of Things
LDS	Lightning Detection Sensor
LROSE	Lidar Radar Open Source Environment
NCAR	National Centre for Atmospheric Research
NCEP-MRF	National Centres for Environmental Protection Medium-range Forecast
NOAA	National Oceanic and Atmospheric Administration
NRF	National Research Foundation
NWU	North-West University
NWU-HPC	North-West University High Performance Cluster
POD	Probability of Detection
SADC	Southern African Development Community
SAWS	South African Weather Service
SETH	Science, Engineering, Technology and Health
SEVIRI	Spinning Enhanced Visible and InfraRed Imager

StatsSA	Statistics South Africa
SWAT	Soil and Water Assessment Tool
TBR	Tipping Bucket Rain Gauge
TITAN	Thunderstorm Identification and Tracking
TOPKAPI	TOPograhic Kinematic APproximation and Integration
TRAM	Thunderstorm Tracking and Monitoring
TTN	The Things Network
UCAR	Universities Corporation for Atmospheric Research
UM	Unified Model
USSD	Unstructured Supplementary Service Data
WAN	Wireless Area Network
WRC	Water Research Commission
WRF	Weather Research and Forecasting Model

CHAPTER 1: INTRODUCTION

Severe weather events can have a disastrous impact on societies. Nearly 90% of all disasters over the past 10 years have been caused by meteorologically related hazards, i.e. severe thunderstorms, floods and tropical cyclones (Buranszki and Horvath, 2014). Extreme weather events, which include hail, have been ranked by the World Economic Forum (2019) as the events that have the highest impact on societies and are the most likely to increase significant economic risks. Hailstorms were chosen to as the hazard of interest in this research project because they are considered the most prominent severe weather-related hazard in South Africa (SAWS, 2018).

High-resolution, real-time data is paramount for research and water resource management in South Africa, especially against the background of the weather-related hazards mentioned. Although the country is equipped with a state-of-the-art lightning and radar network, that advantage, together with an effective network of real-time reporting AWSs, data quality and accessibility, is declining. Funding and loss of capacity are severely constraining national institutions' ability to maintain this infrastructure and deliver quality data to the community. Access to real-time, scientific data is limited, adding another hurdle to potential innovation.

Big Data has become a household word among scientists in all fields. In weather, climate and atmospheric research, data on the current state of the atmosphere is gathered from a variety of sources, including weather stations, ships and aircraft, while the newest forms of weather and climate datasets have become advanced four-dimensional, self-describing products that are used to initiate advanced global weather and climate models (Kaltenbock et al., 2009; Huffman, 2016; Skamarock and Klemp, 2008). However, the best practices related to data management, storage and access have not kept up, with organisations often losing data through human error and negligence – in many cases avoidable through simple practices.

A second problem is giving scientists access to data. From a research and development perspective, this is important, as many university departments and young scientists do not have the capital power to acquire the necessary data to fully pursue their own initiatives. For these scientists, access to Big Data is more than just a perk. It is a powerful tool to improve their communities and institutions (Kitchin, 2014; Turner et al., 2015; Erkmann and Schildt, 2015).

It is clear that access to weather and climate data is a vital tool for sustainable development, damage mitigation and understanding climate change. Studies have already shown that we can expect various increases in extremes related to weather (Piketh et al., 2014). Scientists can improve their understanding of the possible impact by having access to data from multiple sources. Another benefit that a well-managed open database has for the scientific community is for other users to identify errors and uncertainties that might otherwise go unnoticed (Davies et al., 2016).

1.1 RATIONALE

Nowcasting is on the forefront in meteorology as it is the closest link that the public has to forecasts due to the frequency of severe weather such as hailstorms (Behen, 2016). The fundamental aim of providing warnings ahead of hail events is to empower communities and individuals to respond to the event, to decrease the risk of death, and to prevent property loss and damage. Nowcasting comprises a full description of current weather conditions, together with forecasts that are attained by the extrapolation of nowcasting models for a short period of up to two hours in advance. Within this time, severe thunderstorms are forecast with reasonable accuracy.

A forecaster using advanced satellite, radiosonde observations and radar data can make a short division of small-scale features, such as individual storms present in small areas, with an accurate prediction up to a few hours (White et al., 2009; Haiden et al., 2011). Therefore, it serves as a powerful tool in advising the public of dangerous, high-impact weather such as tornadoes, hailstorms, thunderstorms, lightning, damaging winds and flash floods. The public is interested to know how quickly warnings and predictions of severe weather can be released. It is therefore important that research within this sector continues, as it can aid in improving the public perception of nowcasts.

Access to timely and accurate data is important for capacity building and the development of new products. This is one of the concerns of the current national radar network not being used to its full potential. Radar – and more specifically polarimetric radar – has been shown to be the most advanced tool to operationally sample the microphysical and dynamic properties of storms (Hall et al., 1984; Bringi et al., 1986; Straka et al., 2000; Bringi et al., 2002; Gorgucci et al., 2002). Real-time estimates of rainfall intensity, total and type are possible on spatial scales of less than 1 km and on temporal scales of less than 10 minutes. The application of this data for decision support in water resource management and other sectors is vast and not yet exhausted in South Africa. Integrating weather radar with ground-based measurements, satellite remote sensing and numerical weather prediction provides the best available tools to quantify precipitation. Obtaining high-quality data from a network of radars and then adding value through derived products is a non-trivial task that requires significant resources. The SAWS lacks resources and the capacity to perform this task on its own. Most of the local research of the past two decades remains to be implemented operationally on the national infrastructure (Mittermaier and Terblanche, 2000; Pegram and Clothier, 2001; Terblanche et al., 2001; Terblanche et al, 2001; Clothier and Pegram, 2002; Pegram and Sinclair, 2002; Kroese, 2004; Kroese et al., 2006; Sinclair and Pegram, 2004; Sinclair and Pegram, 2005; Sinclair and Pegram, 2009; Wesson and Pegram, 2006; Vischel et al., 2007; Vischel et al., 2008).

South Africa is facing diminishing capacity in radar meteorology through the retirement of many experienced technicians, engineers and scientists. The SAWS has also lost many of its best radar personnel to local and international companies. The world-class infrastructure, which consists of two METEOR 60DX mobile X-band dual-polarised radars, ten Selex METEOR 600S S-band radars (one of which is a dual-polarised radar from Gematronics) and four old WSR-88C C-band radars, is currently not being used to its full potential. The NWU, along with the WRC, is building infrastructure and capacity to address these problems. International collaboration is essential to this cause.

The key aim of this project is to find innovative, cost-effective solutions to local challenges in real-time rainfall observations and build capacity in high-resolution quantitative precipitation estimation in order to ensure the sustainability of the national water resources infrastructure. This will be done by developing quantitative precipitation estimation technology and algorithms that use the existing infrastructure in South Africa to its full potential. The NWU has installed a re-engineered C-band weather radar, automatic rain gauges and AWSs in a portion of the Mooi River catchment as part of WRC Project K5-2751. This network provides an unparalleled suite of data to study rainfall estimation and develop new water resource management tools. It falls in the coverage area of the Irene, Bethlehem and Ottosdal S-band radars. The Mooi River network also has multiple land use categories, including urban, low-income, informal areas, agriculture and mining. It is therefore ideally placed to service a variety of research fields. This project aims to build capacity in stakeholders and national universities and, furthermore, enhance high-resolution, real-time quantitative precipitation estimates by using the existing infrastructure in the Mooi River network. This infrastructure will further help to continue the research focus on quantitative precipitation estimation and use of weather radar in surface hydrology, and provide a platform for local researchers to demonstrate the operational benefits of their products.

The SAWS currently has old EEC C-band weather radars in the national network. These radars use technology dating back to the 1970s. They are plagued by issues such as interference from local area networks, which prompted the acquisition of the much more expensive S-band radars. However, solutions to the problems facing C-band radars have been developed. The NWU acquired a similar old radar and re-engineered the transmitter using state-of-the-art, off-the-shelf technology, which will eliminate all the old technology that adds to the unreliability of these radars and enables the provision of data at a fraction of the cost so as to be on par with modern-generation radars. This will greatly increase the reliability of the radar network, also providing the ability to expand the national network by redeploying currently decommissioned C-band radars. It will also enable the retrieval of dual-polarised data from these old radars in a manner that is on par with the current state-of-the-art radars. Access to rainfall data is another challenge that is facing communities and researchers in South Africa. Data from existing infrastructure is only available to the general public at a cost.

This project developed human capital in the science and technology of water resource management, specifically high-resolution, qualitative precipitation estimation. This is absolutely necessary to ensure the sustainability of the more than R250 million weather radar infrastructure managed by SAWS.

1.2 AIM AND OBJECTIVES

This project aims to build local capacity by evaluating observations of rainfall and emerging technologies, providing the scientific community with products in near real time.

The objectives to reach this aim can be articulated as follows:

- Build capacity in quantitative precipitation estimation and weather radar to ensure sustainability in the precipitation monitoring infrastructure in South Africa
- Collate high-resolution, real-time weather radar, tipping bucket rain gauges (TBRs), disdrometers and general weather data for southern Africa, focusing on the Mooi River catchment area
- Explore and develop local, affordable technologies to facilitate real-time observations
- Communicate precipitation observations to interested communities using appropriate platforms

CHAPTER 2: METHODOLOGY

The approach taken to pursue the objectives stated in Section 1.2 is outlined in this chapter.

2.1 CAPACITY BUILDING

The capacity-building component of the project is implicit in the project team. The project team is made up of individuals from NWU and the National Centre for Atmospheric Research (NCAR) (Table 6.3) and comprises mostly of students. Most of the work done on the final report was also performed by the students on the project team. The students whose master's degree dissertations were directly aligned with the objectives of the project include Henno Havenga, Juan van Loggerenberg, Nisa Ayob, Monray Belelie, Francois du Plessis, Edward SerunmagaZake and Tlhomaro Marebane.

Capacity building in the science and technology of precipitation observation is the central aim of the project. Operating a weather radar, a network of rain gauges and other specialised equipment – like a disdrometer – provides the opportunity for hands-on training. The infrastructure developed by NWU, in collaboration with the WRC, provides an excellent opportunity for this type of training. Students and staff from NWU will develop and maintain the solutions proposed in this project.

In addition, a series of workshops with stakeholders and partners from other universities were held, which were attended by the project team. These include the following:

- An LROSE workshop on open source radar software
- An ATMRESET 2017 workshop on remote sensing
- A regional workshop on technologies and severe weather prediction

Table 1.1: The project team

Name	Affiliation	Role
Roelof Burger	NWU	Principle investigator
Paul Kucera	NCAR	Collaborating scientist
Henno Havenga	NWU	MSc student
Runyararo Matandirotya	NWU	PhD student
Jaun van Loggerenberg	NWU	PhD student
Monray Belelie	NWU	PhD student
Nisa Ayob	NWU	MSc student
Ncobile Nkosi	NWU	MSc student
Francois du Plessis	NWU	MSc student
Edward Serunmaga-Zake	NWU	MSc student
Sello Lehohlohonolo	NWU	MSc student
Marvin Qhekwana	NWU	MSc student
Tsapelo Letsoho	NWU	MSc student
Tlhomaro Marebane	NWU	Research intern

2.1.1 Collaboration with NCAR

The Thunderstorm Identification and Tracking (TITAN) suite of software has formed the backbone of weather radar in South Africa for the past three decades. The company EOL is currently the custodian of TITAN. It is busy expanding its use, and is launching it as a published open-source software suite, known as LROSE. This provides the ideal opportunity for collaboration between NWU and EOL.

2.2 HIGH-RESOLUTION, REAL-TIME WEATHER RADAR, TIPPING BUCKET RAIN GAUGES, DISDROMETERS AND GENERAL

A weather radar and a network of surface rainfall gauges were installed in the Mooi River catchment as part of WRC Project K5-2751. This project continued to maintain these, as well as to expand the network to include AWSs and a disdrometer. The NWU's Lekwena radar was operated continuously and calibrated annually between 15 September 2017 and 15 May 2019.

This project also saw the development of modems to transmit observations to the central server in real time. The nature of these sites means that many of them do not have GSM network coverage. Three alternative communication networks were tested as part of the project. These include LoRa, Foxnet and Thingstream.

A weather radar is an unparalleled tool, which provides high spatio-temporal data over large areas to study storms and precipitation. The national weather radar network of South Africa is a world-class asset with enormous potential to provide real-time, high-resolution data to varied departments and research facilities. Between 2009 and 2012, the network was upgraded from C-band weather radars to S-band radars. The network includes nine single-polarised S-band radars, one dual-polarised S-band radar, two mobile dual-polarised X-band radars and five C-band radars. In a developing country like South Africa, the operation and maintenance of these radars is a challenge. The national weather radar network is a world-class asset with enormous potential to provide real-time, high-resolution data for various departments and research facilities. It can be used in the commercial sector, assist in providing an early warning system, help manage water resources, initiate research projects and much more. Educating and training people to operate and maintain the radars can be huge challenge.

The NWU acquired an outdated weather radar system in 2013 with the intent to upgrade it to a state-of-the-art research-grade radar. The research project focuses on raising awareness and building much-needed capacity in the weather radar environment using the Design Science Research Framework. The radar system was deployed on a site and operated for several months, after which it underwent a partial re-engineering process to improve its capabilities and reduce many of its known risks. From the data collected, scans of the radar were compared with those of the SAWS's flagship radar in Irene, which showed a strong similarity and could therefore validate the quality and accuracy of the radar.

One of the biggest goals of this project is to provide commercial, research and other organisations with open access to this data in a user-friendly manner. Open data is a tremendous resource that is largely untapped. Many individuals and organisations collect a broad range of different types of data to perform their tasks. Government is particularly significant in this respect, both because of the quantity and centrality of the data it collects, and because most of this data is – by law – public data and could therefore be made open and available for others to use. Groups of people and organisations who can benefit from the availability of open data include the government sector, the agricultural sector, insurance companies and infrastructure development companies. Currently, most forms of climate and weather data are difficult to obtain through user-friendly channels. The NWU's Climatology Research Group (CRG) therefore decided to start this project with the hope that open-access data will not only benefit research, but also improve the quality of data.

Through this development, the CRG aims to provide the scientific community and different sectors with this data in user-friendly ways without any limits to the amount of data that can be downloaded or its availability. The project team is striving to provide data in three ways: firstly, by providing raw data that can be computed using open-source programs such as LROSE, the Weather Research and Forecasting Model (WRF) and TITAN; secondly, by cloud-based processing; and thirdly by providing the user with the final product from which interpretations can be done for decision making. With sufficient funding, the development of a live application programming interface (API) will be possible. This can be used to incorporate data into online portals as part of future developments.

2.3 DEVELOPING LOCAL, AFFORDABLE WEATHER STATIONS FOR USE IN A COMMUNITY RAINFALL OBSERVATION NETWORK

The network of rainfall and weather stations was augmented by developing and deploying modular, commercial, off-the-shelf AWSs. These were based on the 3D-PAWS stations designed by Paul Kucera as part of a World Bank project in Kenya. These stations use 3D printed parts, along with off-the-shelf parts of ANDWA Raspberry Pi's Linux minicomputers as loggers and modems. The technology was transferred as part of this project. The total cost of one of these stations can be developed for a fraction of the cost of commercial AWSs. The stations are also highly modular, and each component can be replaced individually. A central server was set up to receive data from these stations.

The Mooi River rain gauge network consisted of 15 TBRs over an area of 3,294 km^2 for this project. This area was chosen due to its proximity to the SAWS's radars, the NWU's Lekwena radar and surrounding agricultural land and built-up areas. The catchment is situated at an average elevation of about 1,500 m above sea level. Sections with the highest gradient are found in the eastern areas where the catchment meets the escarpment of the Witwatersrand. The eastern parts of the catchment are the most populated parts of the catchment. It is also in these parts that flash flooding occurs the most due to the steep topographical gradient.

The main economic activities in the Mooi River network are agriculture and gold mining. Knowing the climate and rainfall variability of the Mooi River catchment is of great importance to these two industries. Therefore, it was decided that a rainfall monitoring network in this area would offer a great deal of information to these two industries. All the rain gauges in the western and northern parts of the catchment are located on commercial farms that practice dryland farming. Rainfall is of critical importance to these farmers as their livelihood depends on it. The other rain gauges in the catchment are all placed in urban areas where flash flooding regularly occurs during large convective storms. This network provides a good understanding of the spatial and temporal variability of rainfall over the catchment. This helps immensely with the calibration of weather radar data.

2.4 COMMUNICATING PRECIPITATION OBSERVATIONS TO INTERESTED COMMUNITIES USING APPROPRIATE TECHNOLOGIES

Rainfall data has wide application across many different stakeholders. Institutions like the Agricultural Research Council (ARC) and SAWS typically have networks and the capacity to use these datasets. However, many users are currently excluded from benefitting from real-time access to rainfall observations. As part of this project, data from rain gauges, weather radar and satellites was made available to interested communities and students. In order to effectively use this data, it must be communicated in the appropriate context. Consultation with individuals from different communities will help to develop precipitation products that are both understandable and useful to these communities.

2.5 SOCIODEMOGRAPHIC PROFILE OF THE PEOPLE WHO WERE INTERVIEWED

Mixed-method research methodologies using open-ended questionnaires were used in this project. The sample consisted of 18 males and 12 females, which is a slightly more unbalanced gender profile than found by Silver (2012). This inconsistency may partly be ascribed to the wish of some interviewees to be questioned with their significant others. Figure 5.1 illustrates the different age groups of the interviewees, which ranged from 30 to 55 years. Some 30% of the interviewees were categorised in the 40- to 45-year age group, whereas 20% were between 45 and 50 years old. In terms of education status, most of the individuals were found to be educated, of which 43% had a bachelor's degree and 27% had an honours degree. The minority had a diploma, as depicted in Figure 5.2. This could mainly be attributed to the smaller sample size and the fact that the focus group contained people who fell within the middle income bracket. Silver and Conrad (2010) found that, in their research, out of 130 individuals, 40% had a post-secondary diploma, 27% had some sort of education, 16% had completed Grade 12, and only 8% had graduate degrees.

The residential areas from which the participants derived were rather diverse, and included suburbs such as Benoni, Boksburg, Johannesburg, Kempton Park, Krugersdorp, Midrand, Randburg, Randfontein, Roodepoort, Rosebank, Sandton and Soweto. Of the individuals that were interviewed, some mentioned having lived in Gauteng for more than five years, whereas other participants have lived in the province for most of their lives. The participants' monthly household income ranged from R10,000 to R30,000, with an average of R15,000. Some 44% of the interviewees earned a monthly income of between R15,000 and R20,000, followed by between R20,000 and R25,000 per month. In contrast, Silver (2015) found, in his research, that the annual income of respondents ranged from less than \$20 000 to more than \$150 000, with an average income of \$70 000. When converted to ZAR, the monthly income of these participants if they were living in Canada, would range between R17,600 and R13,2700.

2.6 DATA MANAGEMENT

The focus of this project is to provide real-time data to stakeholders. The amount of data generated is significant. Data products can reach up to 1 Gb per day. The CRG was therefore forced to implement a solid data management plan to ensure the availability and reliability of data.

The CRG currently collects data from a variety of sources for research purposes. An overview of the workflow is shown in Figure 4.13. The NWU's Lekwena C-Band radar is in the process of becoming fully operational, while the Mooi River rain gauge network has been deployed and is up and running. Along with these operational instruments, the NWU actively runs its own Global Forecasting System (GFS) and WRF models. All the data is used by students and researchers to understand various land system interactions and processes. The following chapter describes the current scientific tools and data management systems in use by the CRG.

2.6.1 Re-analysis data

The CRG currently has several servers running on the NWU's network (see Chapter 4). Bongani is currently used as a backup solution for radar data and configuration files. The second local server is the dedicated Titan 5 radar host. The Titan network links to Gaia, which is used as a web host to provide the radar data to the public. The CRG also has access to the North-West University High Performance Cluster (NWU-HPC), a 32-core Linux server maintained by the NWU. The NWU-HPC runs low-resolution weather simulations using WRF and tests compiling and run-time options for various climate models. The CRG also has access to the NCAR's Yellowstone supercomputer for high-resolution modelling.

2.6.2 Radar data

The radar data is stored on both the Radar 1 and Radar 2 servers at NWU. It is further transferred to an online Dropbox cloud-storage account. All students have access to an allocated Dropbox account where they are required to store all data collected as part of their research. Dropbox has been found to be the best cloud-based solution as it has Linux, Windows and Apple Mac clients. Data stored and managed through this cloud-based solution is essential in case of system failure or theft.

2.6.3 Satellite data

Satellite data for the study area is being served through the project website. These products will be further integrated into the project website over the next year.

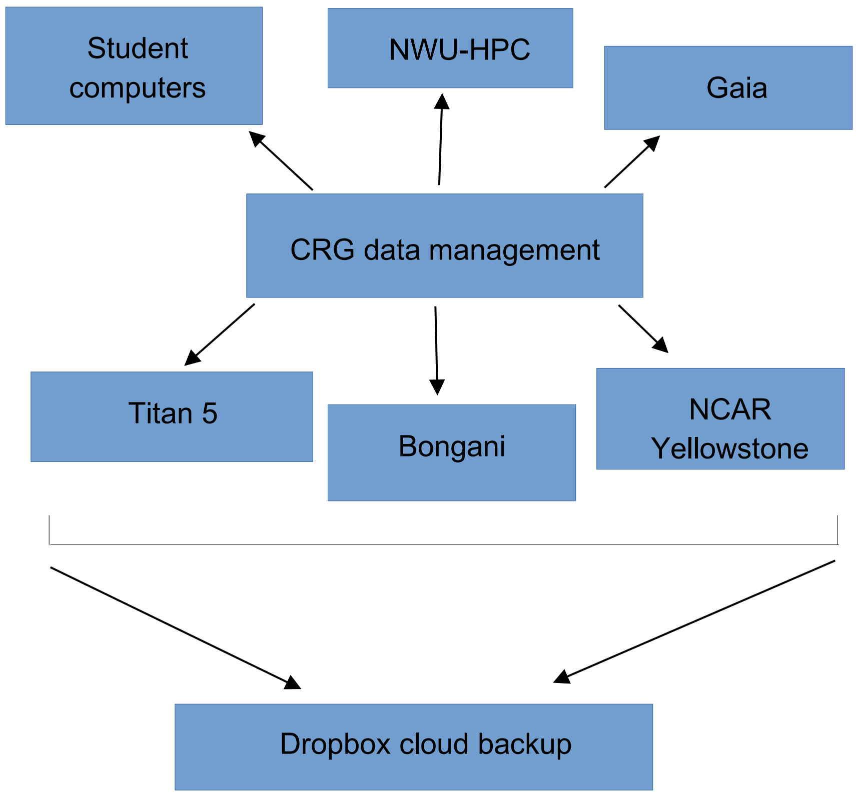

Figure 2.1: The diagram indicates the current workflow related to the NWU CRG data management strategy. The data management starts on local computers assigned to all students, technicians and researchers. The CRG has several local servers on which data is then stored and managed for access across the project team, including Bongani and Drobox. The radar data collected feeds directly to two dedicated servers: Titan 5 and Gaia. Gaia also hosts the radar visualisation that is shown on the website.

2.6.4 Observational data

A network of rain gauges is being fitted with modems to provide real-time access to rainfall and other weather parameters. These datasets are also served through the website.

2.6.5 Data visualisation

Visualising data products is important for the user-friendly interpretation and spatio-temporal representation of data. Currently, the GFS's model data is visualised every day to provide a 48-hour forecast to users who access the website (www.lekwenaradar.com). Further development is in place to provide real-time analysis of rainfall trends data in the Mooi River catchment through the deployment of LoRa and Foxnet networks. The radar products are continually being improved for the web interface.

2.6.6 Cloud storage

For data backup, a 2 TB Dropbox cloud solution was acquired. Dropbox is only used for the backup of data in case of server failure. All students have access to an allocated Dropbox account where they are required to store all data collected as part of their research. Dropbox has been found to be the best cloud-based solution as it has Linux, Windows and Apple Mac clients. Data stored and managed through this cloud solution is key in the case of system failure or theft.

CHAPTER 3: HIGH-RESOLUTION RAINFALL OBSERVATIONS

South Africa has world-class infrastructure to observe weather phenomena (Figure 3.1). The measurement of precipitation is of key significance in relation to weather, climate and the hydrological cycle (Mekis et al., 2018). Precipitation is commonly defined as any H_2O vapour product that is deposited onto the earth from the atmosphere (snow, rain, drizzle, sleet or hail). In this section, South African rainfall measuring instruments, their data processing procedures, and their limitations will be discussed.

3.1 SURFACE OBSERVATIONS WITH RAIN GAUGES

More than half of semi-arid South Africa receives less than 500 mm of rainfall on average per annum. A large proportion of this rainfall results from convective storms, which lead to the formation of rain fields with high variability in space and time (Terblanche et al., 2001). The rainfall monitoring station network in South Africa is quite extensive (94 stations) with a long record of data (1921 to the present) (Kruger and Nxumalo, 2017) (Figure 3.2). Roy and Rouault (2013) investigated data for hourly rainfall from more stations (141 stations), but after quality control, only considered data from 102 stations for analysis. Information regarding the temporal rainfall structure in these stations can be acquired through the utilisation of rain gauges (Pegram and Clothier, 2001). The tipping bucket system is the most commonly used type of rain gauge in South Africa (Sen Roy and Rouault, 2013). In this system, rain is measured at an open top and funnelled to a tipping bucket below. The tipping bucket incrementally measures rain of 0.2 mm, 0.5 mm and 1 mm.

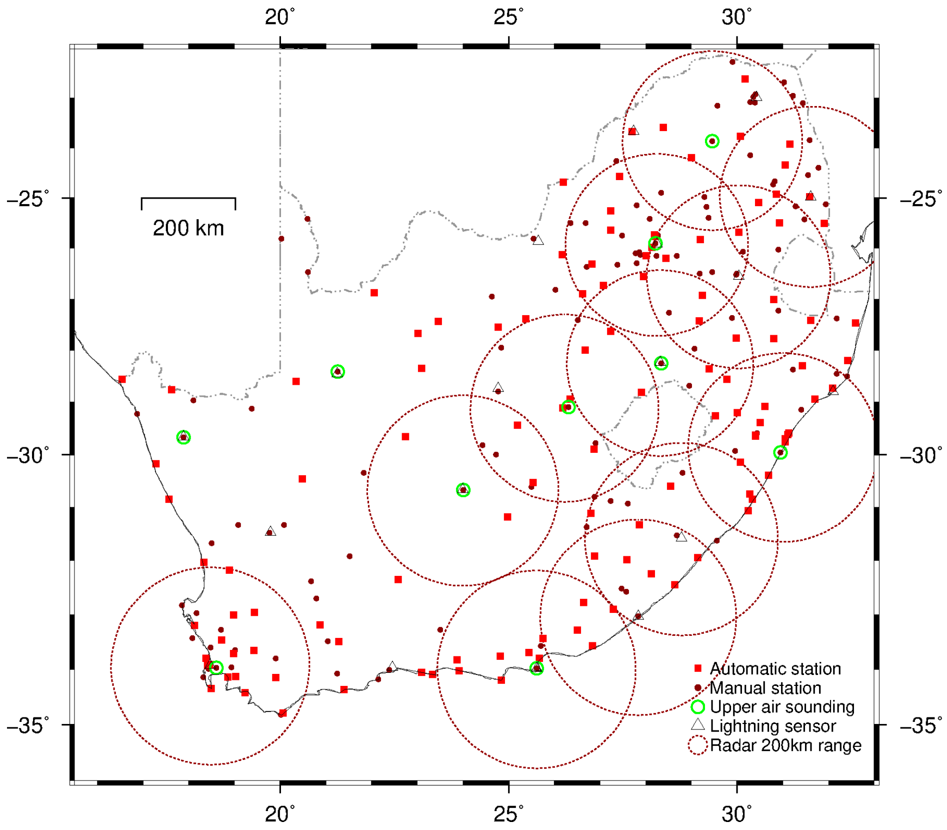

Figure 3.1: The available infrastructure to observe weather phenomena over South Africa

Figure 3.2: The South African precipitation monitoring network as considered and investigated by Kruger and Nxumalo (2017)

Tipping buckets utilised in the SAWS's stations incrementally measure 0.2 mm of rain per tip. On the western coast of the country, rain gauges with attached fog catchers have been used in fog water harvesting studies (Olivier, 2002).

This is because this region mostly receives less than 250 mm of rain per annum, making it one of the country's most arid regions. The rainfall stations cover 94 rainfall-reporting districts and are illustrated in Figure 3.3 (Kruger and Nxumalo, 2017). These rainfall districts can be further categorised into eight climatic regions (Figure 3.4), determined by SAWS (Rouault and Richard, 2003). The mean monthly precipitation for these eight regions from 1921 to 2001 is illustrated in Figure 3.5.

Historically, South African rain gauge measurements have been used in numerous applications. Although the amount of active rain gauges has been decreasing gradually at an alarming rate over the years (Terblanche et al., 2001; Sawunyama and Hughes, 2008), the instrument is still used in a wide array of applications today.

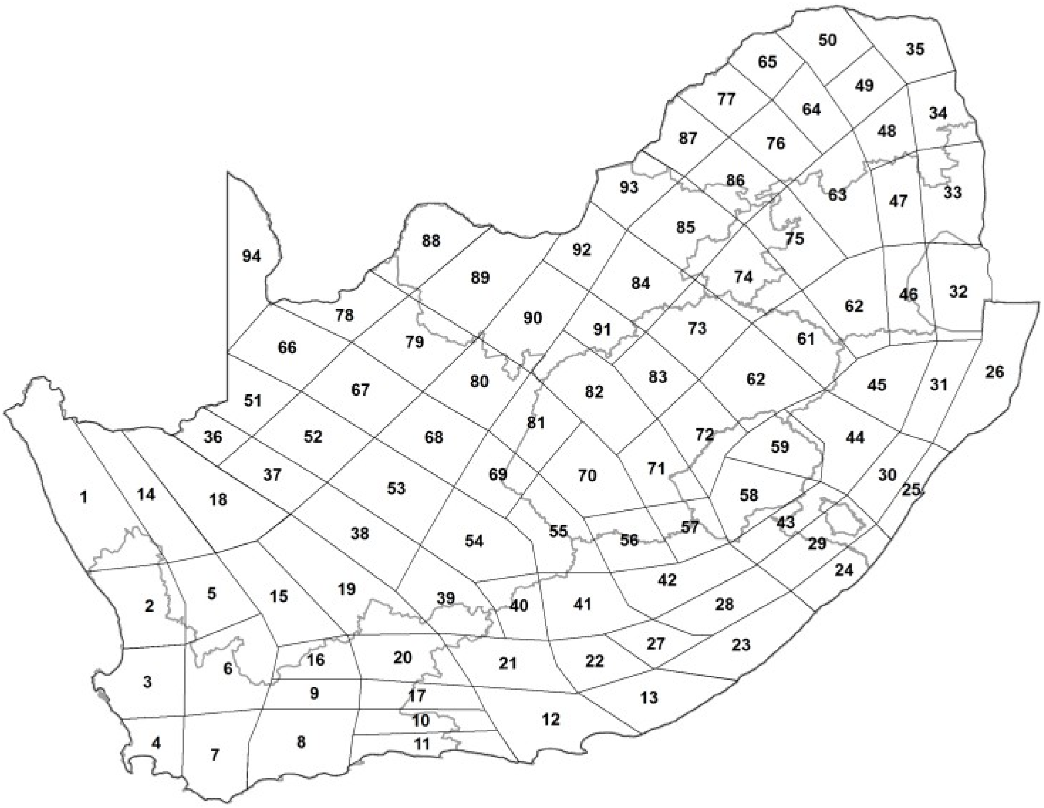

Figure 3.3: Rainfall regions identified by Kruger and Nxumalo (2017)

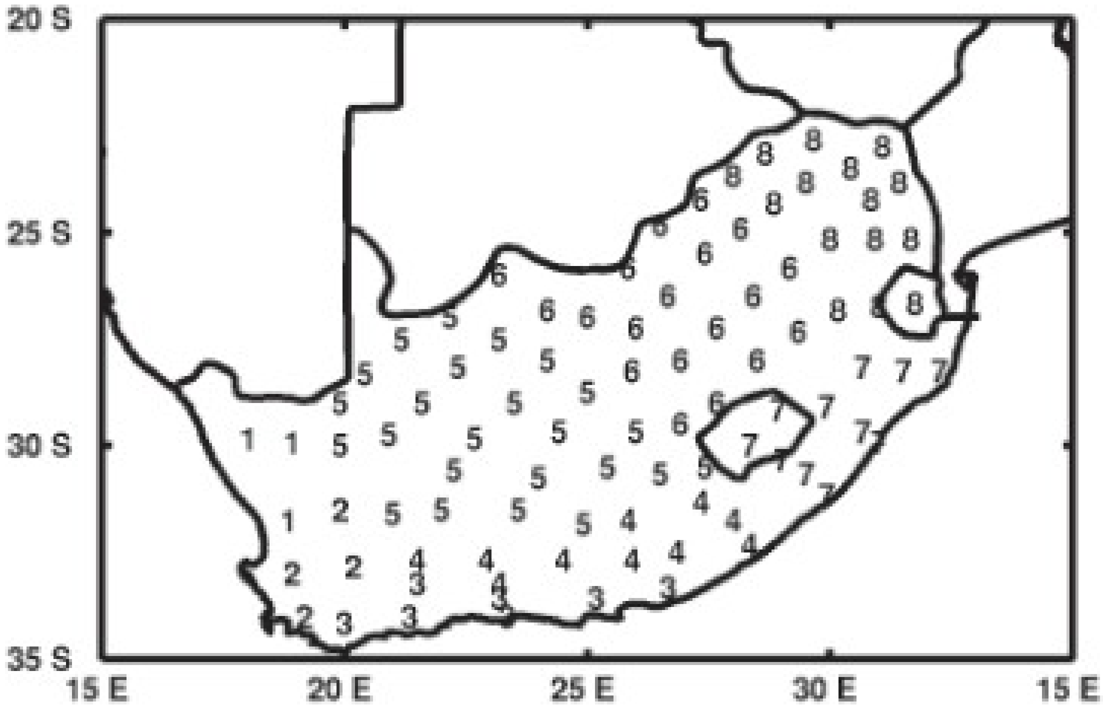

Figure 3.4: The eight climatic regions of South Africa as determined by the SAWS through a cluster analysis of rainfall (Rouault and Richard, 2003)

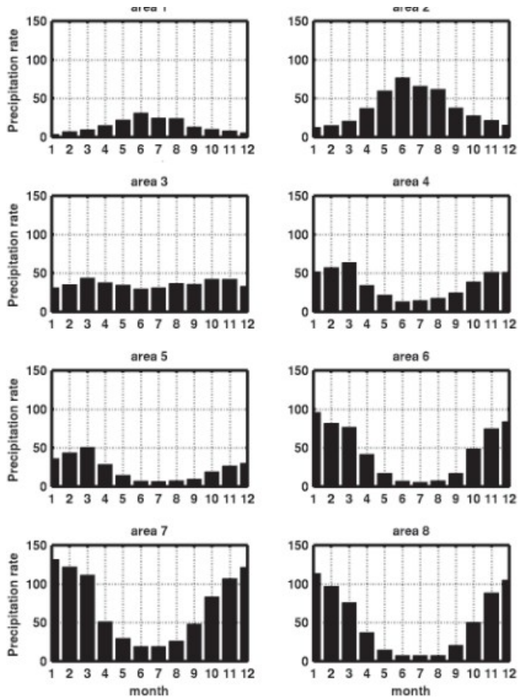

Figure 3.5: Mean monthly precipitation for the eight climatic regions of South Africa (Rouault and Richards, 2003)

3.1.1 Variability and classification

Schulze (1980) manually extracted rain gauge data from charts of certain stations and used it to determine the kinetic energy distribution of rainfall in the country. Scott and Lesch (1996) used these measurements to investigate the effect of afforestation on water yields in a catchment. Daily rain gauge data was used by Pegram and Seed (1998) to categorise the types of rainfall experienced throughout the day over a certain area. Rain gauge measurements have also been used to differentiate between rain and fog days on the West Coast (Olivier, 2002) and over the Northern Cape (Olivier and De Rautenbach, 2002). Owolawi (2011) used gauge measurements to evaluate the probability density of rainfall rate and to map the estimation of rain attenuation. Sen Roy and Rouault (2013) analysed hourly rain gauge data from 102 stations to investigate extreme events of precipitation and determine their spatial variation and seasonality. Recently, Kruger and Nxumalo (2017) also used rain gauge measurements to study the historical trends of rainfall in the country.

3.1.2 Applications in modelling

Pegram and Seed (1998) modelled types of rainfall – established in the first objective of their study – in order to determine rain days and non-rain days for a specific year. Jewitt and Schulze (1999) used rain gauge measurements to verify the use of the Agricultural Catchments Research Unit (ACRU) model in modelling the hydrology of forests. A sensitivity analysis was conducted on the TOPograhic Kinematic APproximation and Integration (TOPKAPI) model where rain gauge measurements was one of the parameters considered (Vischel et al., 2008; Sinclair and Pegram, 2013) to determine whether the model may be applicable for estimations in catchments without any gauges, and also to compare estimates modelled by TOPKAPI and those derived from the European Remote Sensing satellite (Vischel et al., 2008). Rain gauge data has also been used to verify the Conformal-Cubic Atmospheric Model (CCAM), the Unified Model (UM) and the National Centres for Environmental Protection Medium-range Forecast (NCEP-MRF) model forecasts of rain in the uMngeni catchment (Ghile and Schulze, 2010) and the Soil and Water Assessment Tool (SWAT) has been used to model streamflow (Govender and Everson, 2005).

In conjunction with remote-sensing meteorological data, surface-based rain gauge data has been used to develop a geographic information system (GIS) framework to estimate precipitation (Ghile and Schulze, 2008). Rainfall data was used by Bardossy and Pegram (2015) to correct measurements made by pluviometers. Daily rainfall measurements were used by Smithers and Schulze (2003) to assess design rainfalls in catchments. Rain gauge data has also been used to investigate the applicability of fuzzy rule-based circulation patterns in describing and modelling regimes of rainfall and ocean waves (Bardossy et al., 2015).

3.1.3 Use of the WRC rain gauge database

Rain gauge measurements from the WRC's database (Lynch, 2003) have been used to investigate the relationships between the El Niño Southern Oscillation (ENSO), the Antarctic Oscillation and the Madden-Julian Oscillation (Pohl et al., 2010), as well as the relationship between ENSO and South African winter rainfall (Philippon et al., 2011). They have also been used to evaluate the effectiveness of the ACRU model to represent reality by comparing modelling results to those observed (Warburton et al., 2010), to conduct a cluster analysis of outgoing long-wave radiation on a daily basis (Fauchereau et), to investigate patterns of daily rainfall during the heart of the rainy season (Cretat et al., 2012), and as part of a joint analysis with other parameters. Rainfall measurements from this database were also used to investigate the response of the normalised difference vegetation index to rain and two other memory effects (Richard et al., 2008). Pohl et al. (2009) used measurements from this database to investigate the convective variability of the austral summer over the country and to evaluate the model outputs of annual and diurnal rainfall cycles from the weather research and forecasting model (Pohl et al., 2014).

3.1.4 Spatial and temporal variability

Few studies have been done where the South African spatial and temporal variability in rain gauge measurements are reported. This may be due to the rain gauges' inability to capture rainfall variations in space (Wesson and Pegram, 2006).

A previous South African study found that the coastal areas located southeast and west of the country are particularly prone to extreme events of precipitation in summer – an inverse pattern was observed for winter where the high-altitude interior is more prone to these events (Sen Roy and Rouault, 2013). Furthermore, results obtained in a study by Owalawi (2011) conveyed that the Western Cape receives most of its rain in winter, while the rest of South Africa generally gets most of its rain in summer.

3.2 SATELLITE OBSERVATIONS OF RAINFALL

Data obtained from rain gauges, although considered to have the most precise point source information on rainfall, lacks the ability to accurately represent spatial coverages of systems (Pegram et al., 2004). Radar, on the other hand, deals superbly with spatial coverage, but is inadequate in South Africa. This inadequacy signalled a need to come up with alternative platforms to address these limitations, such as the use of satellite observations. In this section, light will be shed on studies that have been done on satellite observations in South Africa. Very few studies have, however, been conducted in this regard.

Pegram et al. (2004) mapped daily rainfall using observations made by rain gauges, radar and satellite. They studied images obtained from the METEOSAT-7 satellite derived from three spectral bands (visible, IR H20-vapour and thermal IR). Not long ago, De Coning and Poolman (2011) used METEOSAT second-generation data to investigate the applicability of the hydro estimator in estimating rainfall. In recent years, thunderstorm nowcasting based on satellite data has become more readily available, due to spatial and temporal coverages.

Zinner et al. (2013) employed the METEOSAT Spinning Enhanced Visible and InfraRed Imager (SEVIRI) to validate thunderstorm lightning network data in Europe and South Africa due to its spatial and temporal scales. METEOSAT data allows for the observation of different stages of storm development using the same sensor. A METEOSAT SEVIRI takes 12.5 minutes to complete a full scan between 75° N and 75° S. Zinner et al. (2013) differentiated between METEOSAT storm detection and lightning network data. This was validated using the Cb-Thunderstorm Tracking and Monitoring (TRAM) to identify thunderstorms against lightning data over six months in South Africa and Europe. The validation process was done by evaluating the probability of detection (POD) and false alarm rate (FAR) for different spatial requirements and lightning intensity classes.

3.3 WEATHER RADAR OBSERVATIONS OF RAINFALL

Remote-sensing instruments like radar provide the opportunity to observe large areas with a minimal infrastructure footprint. In the past, millions of dollars have been invested in building radar capacity in Africa. However, this has been mostly unsuccessful, since Africa presents certain challenges that are not always considered. This section will evaluate the use of weather radar in South Africa as an example of the challenges that are faced. South Africa has a long history in weather radars as it was at the forefront of radar development and use in the early 1940s. In more recent years, SAWS invested roughly $20 million in upgrading and expanding its radar network with high-quality radars from Gematronik (now Selex ES). These included ten S-band radars, one of which is a research-grade, dual-polarised unit situated in Bethlehem, and two mobile X-band research radars, giving a total of 16 radars. Even with all the experience gathered over the years and investing millions of dollars, SAWS is plagued by technical problems. A drastic shift towards commercial operation, enforced by legislation and dwindling funding, has severely limited capacity and resources dedicated to the national weather radar network.

Due to the lack of technical expertise and funding, a recent study by SAWS has shown that only 54.3% of the radar data collected for the last 12 months is available. Some of the radars, such as the dual-polarised radar in Bethlehem, are not calibrated to standard, causing the data to be unusable. The SAWS also has 230 AWSs, 130 automatic rainfall stations (ARSs) and 24 lightning detection sensors (LDS) with similar data availability to that of the radar network.

This is just one case study of the most advanced radar network in Africa that struggles to keep its radars operational. Another example of two countries with the same scenario is Mozambique and Botswana, both with good radars that are not operational. Nevertheless, it is crucial for Africa that weather radars are deployed throughout the continent, but it has to be done in a more effective manner. According to the Southern African Development Community (SADC), one of its highest priorities is the strengthening of observation networks, including the expansion of radar networks.

Keeping the complications of a radar network in mind, NWU is working towards building capacity in radar meteorological research and engineering through innovative methods. In 2014, NWU acquired an outdated WSR74C EEC weather radar from Cotulla, Texas, with the purpose of re-engineering the radar to research standard dual polarisation. The re-engineering process consists of upgrading the original radar to dual polarisation using off-the-shelf components that are locally available where possible. This method will help keep the upgrade costs to a minimum and provide much-needed technical skills to understand, maintain and expand the radar network. Since most of the components will be locally sourced, it will keep the maintenance costs and radar downtime to a minimum.

One of the first and most important steps in the re-engineering process is to conduct a thorough risk assessment on the radar system. It is imperative that all the risks associated with a radar system are known before installing a radar. The risk assessment includes topics such as the re-engineering process, overall cost, infrastructure, the communication network, maintenance and the feasibility of the project.

The assessment strongly focuses on the re-engineering process to better understand why it is difficult to maintain a radar network in Africa or other developing countries. An example of one risk assessment is the risk of each internal component, its probability to fail and the cause and effect on the system. Knowing which components have a higher risk value allows the technician to focus on lowering that specific component's value and so the entire system's risk.

Figure 3.6: The NWU's Lekwena radar situated outside Potchefstroom

CHAPTER 4: TECHNOLOGIES TO FACILITATE REAL-TIME RAINFALL OBSERVATIONS

This project currently collects data from a variety of sources. The NWU's Lekwena C-band radar is in the process of becoming fully operational, while the Mooi River rain gauge network has been deployed and is up and running. Along with these operational instruments, NWU actively builds products using GFS and WRF models. All the data is used by students and researchers to understand various land system interactions and processes. In order to provide real-time access to the NWU's Lekwena radar data, a number of tasks were performed. These are outlined in the following sections.

4.1 AFFORDABLE, LOW-POWER LOGGERS FOR IOT OBSERVATIONS

The continued decline in the number of surface-based automatic and manual weather stations, both locally and globally, is problematic. The low cost of off-the-shelf electronics to augment these observations is making this more viable. Even though these low-cost sensors do not currently reach the reliability, precision or repeatability of traditional equipment, they have seen large improvements in recent years. One of the objectives of this project was to explore and develop technologies to make use of new IoT opportunities, as has been reported in other fields (Coetzee and Kotze, 2018).

A logger that met these requirements was developed in collaboration with Electronic Systems Development (ESD) and is discussed in the following sections. Firstly, an overview of the various IoT communication networks under consideration is given. The one limitation that IoT networks have is the trade-off between power and bandwidth. This technology implies a limited number of transmissions and the limited size of data packages. This design facilitates single observations or control endpoints with users.

4.1.1 IoT communication networks

One of the fundamental ideas around IoT is small sensors that can operate independently for long periods of time. A communication network that can facilitate a large number of transmitters is needed. Three emerging networks are considered in this project: LoRa, Sigfox and ThingStream.

LoRa

The LoRa network is a spread spectrum modulation network that provides a long-range, low-power wireless network for IoT. A global community has defined protocols to facilitate this technology as a general-purpose wide area network (WAN). This community is called the LoRa Alliance. The typical architecture can be seen in Figure 4.1. The different components include the following:

- *End nodes*: These include the sensors deployed to measure weather parameters in this application.
- *Gateway*: Network towers that send and receive data from the end nodes.
- *Network server*: The back-end that handles the communication between the gateway and the application server.
- *Application server*: The server that provides the end user with access to the data.

Users can set up this infrastructure themselves, or they can use one or more components from the community. The most prevalent implementation of this solution is provided by The Things Network (TTN) (https://www.thethingsnetwork.org). If any gateways from other users are available, end nodes will use them for communication. If no gateways are available, users can set up their own gateways and connect to the TTN network server. The TTN provides a free service for application servers to communicate with end nodes.

One of the main advantages of LoRa is the fact that the user can extend the coverage as needed. There is also no cost for data transmission. The full cost of using LoRa, therefore, includes the modems and the deployment of gateways. The transmissions work on a near-line-of-site basis. The coverage of a single gateway is therefore dependent on the site and topography of the area. Figure 4.2 shows a gateway that was deployed as part of this project. It was procured from TTN and coupled to a GSM modem. Data from end nodes is accessed through the application server back-end provided by TTN. A theoretical maximum data rate of 27 kbps is possible. However, gateways are shared and, in order to allow thousands of end nodes, bandwidth is kept between 11 bps and 11 kbps. It is still considered to be the IoT network that offers the largest amount of data transfer.

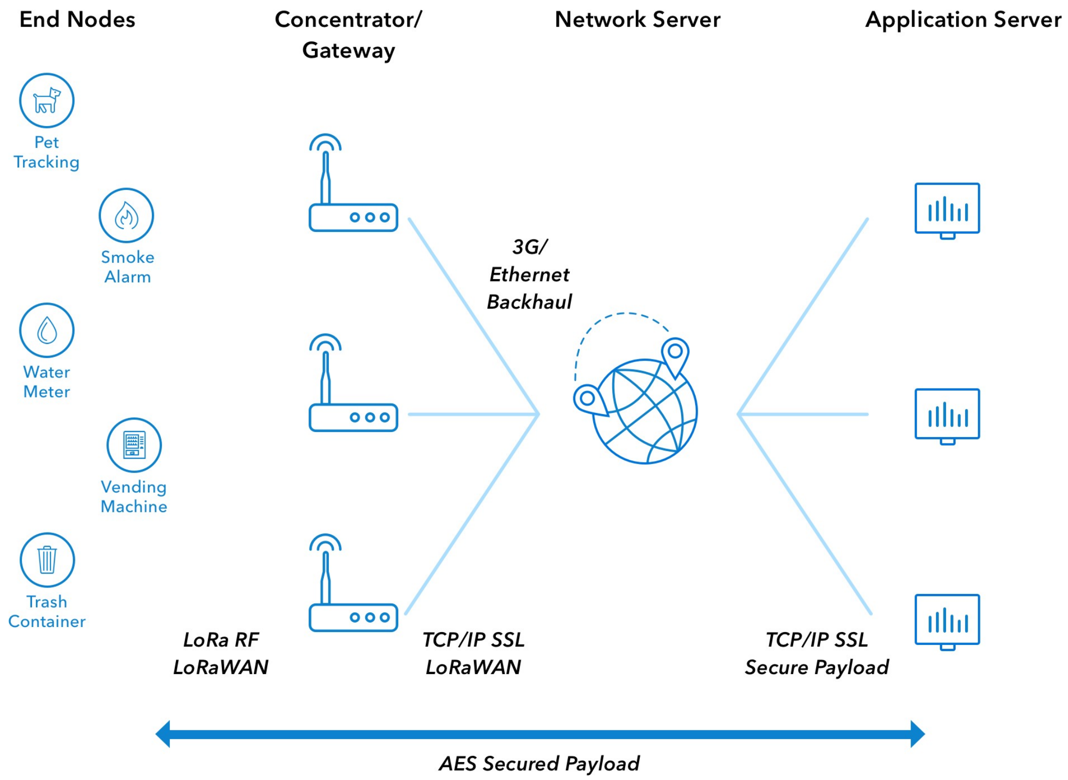

Figure 4.1: The architecture of a LoRa WAN application (https://www.thethingsnetwork.org)

Sigfox

Sigfox is a French global operator that is rolling out a one-hop star topology network similar to LoRa. It uses a wide-reaching signal that can pass through solid objects. Sigfox currently covers more than 4 million km^2 in more than 60 countries, including South Africa. The national coverage is already extensive (Figure 4.3) with claims of more than 83% coverage, especially over the project area of the Highveld (Figure 4.4).

Figure 4.2: A LORA gateway that creates a network working on near-line-of-sight and covers an area of approximately 60 km in radius, depending on the topography.

Sigfox is therefore a commercial network where users pay for access to the infrastructure through a modest subscription fee. The subscription for one SIM card is approximately R320 per year as of 2019. Data from the end nodes is accessed through the application server back-end that is provided by Sigfox. The messages are limited to the total number and size per day. A total of 12 bytes is allowed for uploads and 8 bytes for downloads. For this project, the maximum downlink plan was used (140 messages per day).

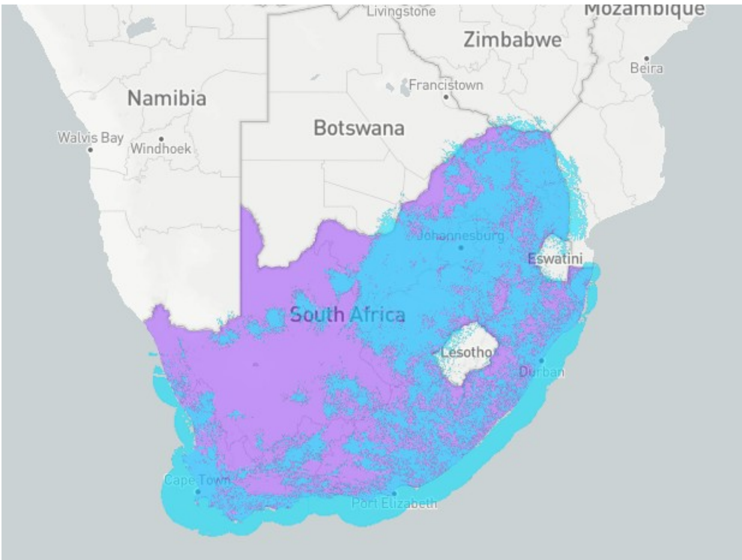

Figure 4.3: The coverage of the Sigfox network over South Africa (https://www. sigfox.com/en/coverage). The blue shows areas that are covered and the purple shows areas that are planned to be covered.

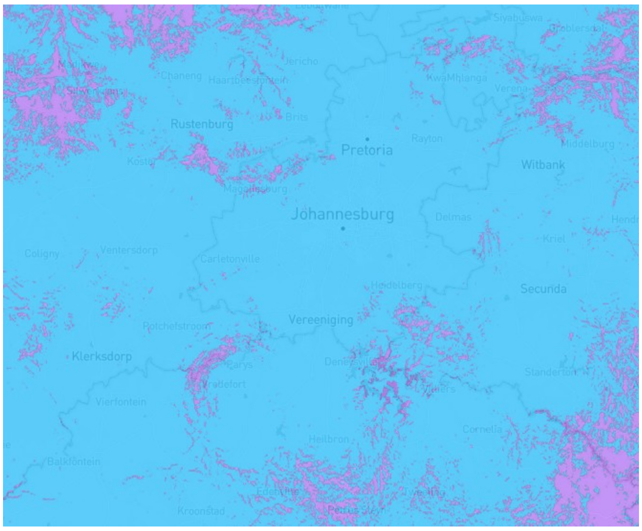

Figure 4.4: The coverage of the Sigfox network over the project area (https://www. sigfox.com/en/coverage). The blue shows areas that are covered and the purple shows areas that are planned to be covered.

ThingStream

ThingStream is also a commercial service, such as those provided by LoRa and SigFox, which can handle a large number of end nodes and which operates on relatively low power transmissions. Its unique feature is that it leverages existing cellular infrastructure. It manages to harness the benefits of the established footprint by using unstructured supplementary service data (USSD) messaging protocols. It therefore provides similar services at very competitive pricing. ThingStream supports a payload of up to 160 bytes of data. This amounts to around 182 characters. A service of $1 per device for 5,000 messages per month was used.

4.1.2 Comparing IoT networks

A simple technological comparison of the different connectivity options is possible (Table 4.1). However, each of the three technologies presented unique advantages. The LoRa network provided flexible data rates, the ability to extend the network to remote areas not covered by other technologies, and very low operational expenditure. It would be ideal for remote areas, or when deploying a very high number of end nodes in small areas. Using a few gateways with no operating costs makes LoRa ideal for these scenarios.

The benefit of SigFox is mostly its ease of use. Each node requires a SIM card with a Sigfox subscription. Once activated, data is generally just pushed through to the back-end. Good coverage over most of the populated areas of South Africa makes SigFox a suitable, reliable option. Along with LoRa, this option also provides the lowest power footprint and nodes can operate for long periods off small batteries with very small solar panels.

ThingStream has the advantage of using existing cellular infrastructure for communication. It therefore provides the most complete coverage of South Africa. The technology also works seamlessly across borders. The operational expenditure was cheaper than SigFox. ThingStream therefore makes sense for a large number of end nodes across South Africa.

The diversity of the connectivity options motivated a logging solution that could be used for any of the networks.

Table 4.1: Comparing the IoT connectivity options evaluated in this project

	Coverage	Capital expenditure	Operational expenditure
LoRa	Depends on gateway	Moderate	Almost zero
SigFox	83% coverage	Low	Low
ThingStream	>90% coverage	Low	Lower

4.1.3 The ESD L151M Data Logger

The logging device forms the heart of the observation system. During a previous project, WRC Project K5-2751, a low-cost logger was developed that could acquire data from rain gauges, as well as other devices. The resulting hardware requires large batteries and solar panels to operate independently. The key to harnessing the potential of IoT is to develop hardware with a very small power footprint. The design specifications for loggers to use in an IoT environment therefore include the following factors:

- Low power consumption
- Interfaces to IoT communication networks like a long-range, low-power wireless protocol (LoRa), SigFox or ThingStream
- Interfaces to commonly used communication protocols used by meteorological equipment, including RS-232, SDI-12, analogue, TTL UART and digital counters

The result is the ESD L151M logger (Figure 4.5), which uses an STM32L151 low-power Arm Cortex M3 MCU 32 MHz. It boasts an onboard real-time clock with backup battery. It is programmed using a three-wire ST-LINK2 pod or a TTY COM port (COM1).

The logger boasts the following specifications:

- RS232 port
- Secondary RS232 or RS422/485 port
- TTL UART
- SDI-12 port
- 12C port for connection to sensors, optional relay or GPIO expansion board
- SPI port for connection to external devices such as an analogue-to-digital board
- 3-12 VDC power supply
- 5-12 VDC at 3 Amp output supply to power probes
- XBEE socket for compliant radio modems
- Micro SD storage card
- Size of 78 x 78 mm

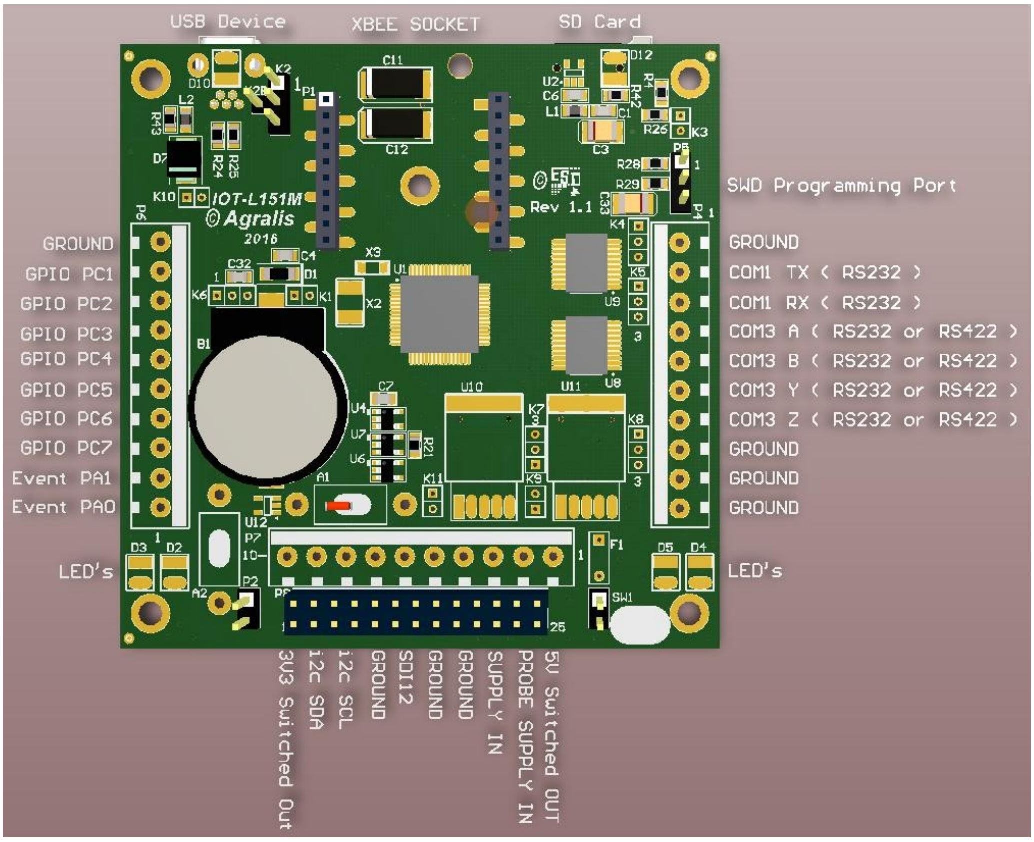

Figure 4.5: The ESD L151M logger design

One of the main features of the board is its ability to go into sleep mode. This reduces power consumption to approximately 300 micro Amperes. An event, such as a trigger from a TBR or a timer, can then wake up the board. This takes about eight seconds. Specifications that allow for this kind of power management include the following:

- Micro SD card
- 3V supply
- RS232 chips
- RS485 and SDI-12 circuit
- External power output
- XBEE socket

This allows the logger to optimise power usage based on the particular application. The current firmware implementation allows for the RTC chip-to-periodic-alarm function to wake the unit up in increments of 1 minute (from one per minute to one per 24 hours). Several configuration parameters determine what action the logger should perform and when it should write data to the SD card or send data to the external modem. Any external modem that supports a serial RS232 port can be used. The modem can be an RF link with XBEE or UHF radio, or a 3G or GPRS unit.

The following peripherals can be accommodated: There are five USARTS on the STM32; the USARTS are allocated as follows: COM1 is used as an RS232 COM port on the 10-header plug P4. This port can be used as a debug port and as a general communications port. On the standard software, this port has been configured at 115200 Baud and is used for configuration of some of the parameters with a terminal emulator program running on an attached laptop or PC. Debug information is also output on this port. The COM2 is connected to the XBEE socket for a FoxBee or other XBEE-compliant wireless modem. The COM3 is used as an RS232 or RS422 port, which is connected to the 10-header plug P4. The COM4 is unused on the standard configuration, but can be used as a TTL UART port on expansion port header P8. The COM5 is used to connect to external probes via SDI12. The default Baud rate for SDI-12 must be fixed to 1200 Baud.

The STM32 chip has several GPIO ports onboard that can be configured as analogue to digital (ADC) inputs. The default ADC ports on the PCB are PC0 to PC7. These ADC inputs are limited to a range of 0 to 3.3 V. The ADC resolution is 12 bits. An ADC0 is used for the battery monitor. A PC7 can be used as an ADC input or a high-speed counter input.

The I2C interface can be used to connect to a variety of I2C sensors and devices. The I2C is multi-drop, therefore only two wires are used for communication with the sensors that are all connected to the port.

The SPI interface is a high-speed synchronous port that is used for connecting to external devices such as additional ADC chips on an expansion board.

The STM32 has an internal RTC, but this is not implemented on the design. An external RTC is used. The external RTC is battery backed with a small on-board lithium battery. The external RTC is used to wake the unit up at user-defined intervals in increments of 1 minute.

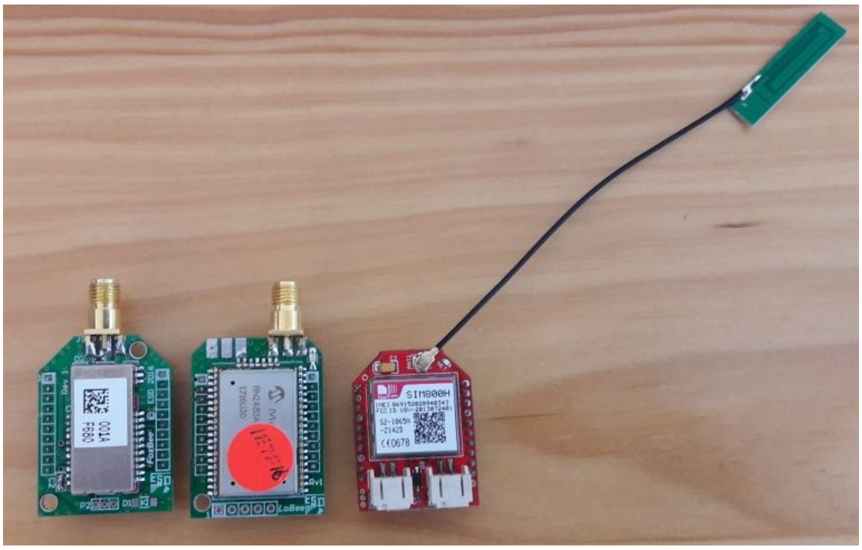

Figure 4.6: The different communication modules developed. The one on the left is for the SigFox network, the one in the middle is for the LoRa network and the one on the right is a GSM modem that could be used for GPRS or ThingStream.

One event counter input is implemented on the logger. This input can be used to wake the unit up to count an event from an external unit such as a rainfall tipping bucket. The event rate has been tested to 10 per second. The event input channel is software de-bounced.

The three XBEE modems are shown in Figure 4.6. The LoRa and SigFox XBEE modules were developed as part of this project. ThingStream uses a standard GSM modem.

The logger with a SigFox XBEE modem is seen in Figure 4.7. These were built into waterproof boxes and fitted with a small power unit that contains an 18650 li-on rechargeable battery and a small power station. These are capable of running the logger until the battery fails and can even provide additional power for instruments like the WXT530 Vaisala multi-sensor or soil moisture sensors (Figure 4.8).

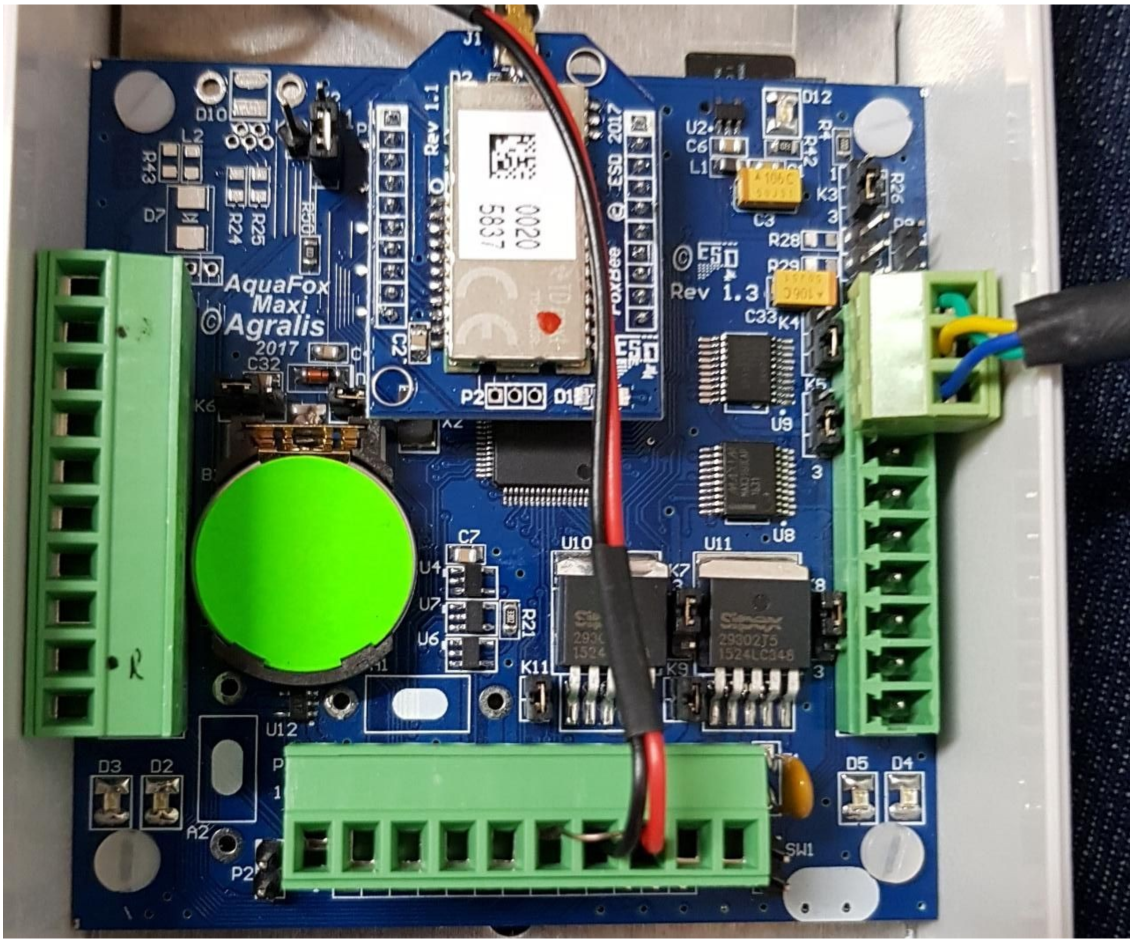

Figure 4.7: The low-cost logger developed for the project

The loggers were evaluated extensively with a range of different sensor configurations (see Figure 4.9, Figure 4.10 and Figure 4.11).

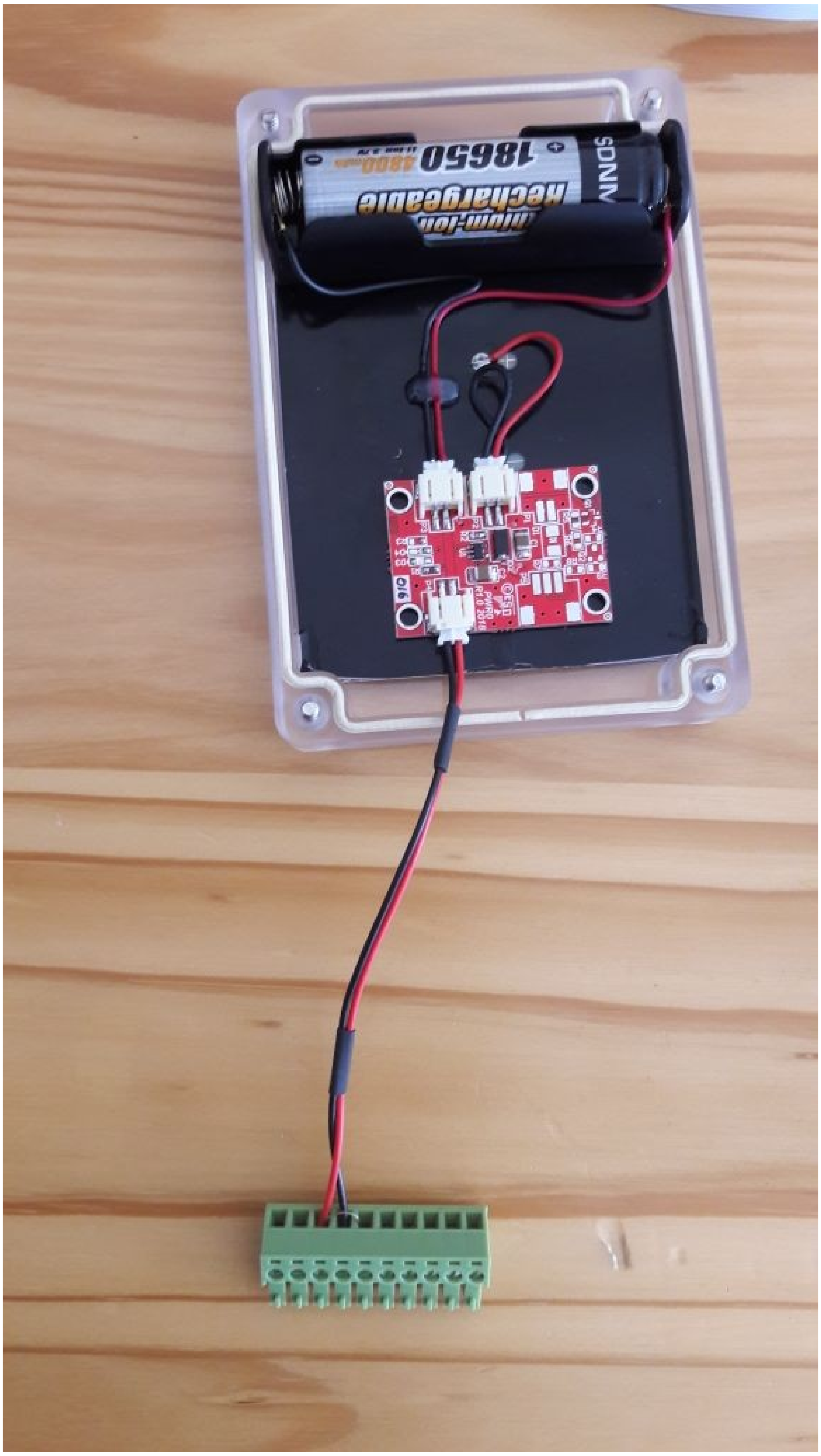

Figure 4.8: The low-cost logger power module that features a rechargeable battery and a small solar panel

Figure 4.9: The lowest-cost logger, modem and low-cost rain gauge developed for the project. This combination costs approximately R5,000.

Figure 4.10: The logger, modem and low-cost weather station developed for the project. This combination costs approximately R8,000.

Figure 4.11: The logger, modem and mid-range weather station developed for the project. This combination uses the Vaisala Multisensor WXT530. The combination costs approximately R50,000.

4.2 THE NWU'S LEKWENA RADAR

The Lekwena radar was operated as part of this project for 354 days between November 2017 and April 2019.

4.2.1 A microwave link between the radar and the NWU

The radar is situated on a fairly remote site. The setting is determined by the need of the radar to observe the atmosphere from an unobstructed vantage point. A microwave link was installed to network the radar with the NWU. There is not a direct line of sight between the radar and the NWU, so a repeater was needed to provide the microwave link. Three potential sites were identified. The best site turned out to be the Tiger Brand silos (Figure 4.12). The first radio link that was tried consisted of four antennas: one at NWU, one at the radar and two on the silos. The longest distance between any two antennas is between the silos and the radar. This distance is approximately 10 km.

The data link provided by this set of radios was not adequate to facilitate real-time transfer of the raw data files. The size of these data files varies according to the weather from 100 Mb during calm conditions to 800 Mb during stormy days. The radios therefore had to be upgraded to Radwin 5000 to provide a link speed around 25 Mbps over 10 km. These radios were installed and configured, and the relay site was changed to a sector antenna. The latency of the current data link is shown with a transcript of a ping from the server at NWU (Radar 2) to the server at the radar (Radar 1). The flow of data through the network is shown in Figure 4.13.

Figure 4.12: The first radio link established between the radar and NWU. The photograph on the left shows the antennae on the silos and the photograph on the right shows the antennae on the radar.

4.2.2 A server to generate radar products

Data is transferred to NWU in real time using the Titan DsDistFile process of the LROSE software. A server (Radar 2) accepts the data that is being pushed by the radar server (Radar 1). This is an eight-core Intel i7 computer with 2 Tb disk space (Table 4.2). It runs Ubuntu 16.04 and has the latest version of the LROSE suite. It receives data in real time from the radar site (Radar 1) and creates the static web images. It then sends these images to the web server (Gaia) and also serves the raw radar data to the data server (Bongani).

Table 4.2: The technical specifications of the Radar 2 server

Variable	Property
Processor	Intel(R)Core(TM)i7-4770K CPU@3.50 GHz
Number of CPUs	8
CPU cache	8192 KB
Hard drive size	2 Tb

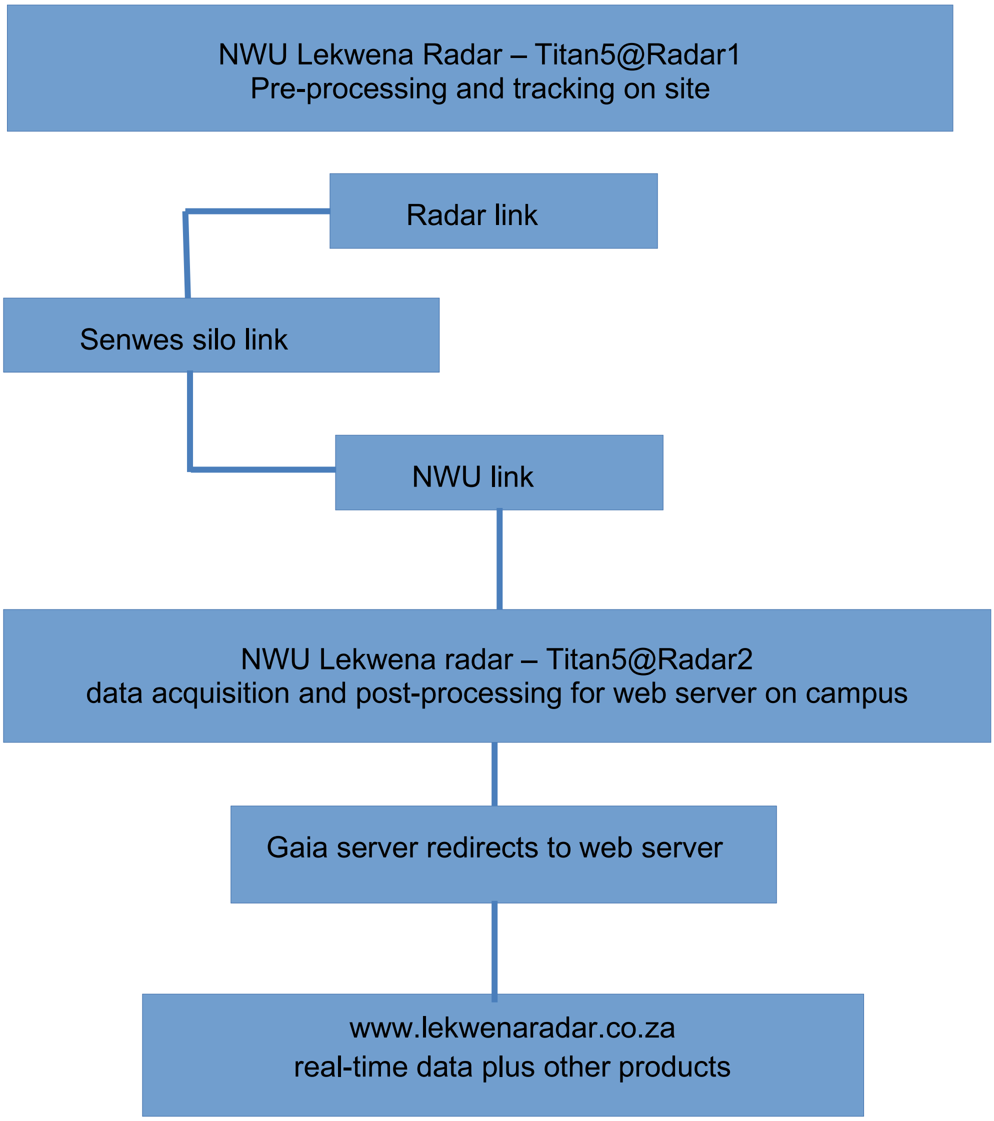

Figure 4.13: The workflow of the NWU's Lekwena radar from the radar to the web-based service driven by students

4.2.3 A server to provide radar products for websites

The server that hosts the radar products is known as Gaia. It is a 4 Intel(R) Xeon (TM) CPU Linux server (Table 4.3). It runs Ubuntu 16.04 LTS and is used as a basic web server to host the static and dynamic radar images and text data files.

Table 4.3: The technical specifications of the Gaia server

Variable	Property
IP	http://143.160.8.22/
Processor	Intel(R)Xeon(TM) CPU@3.00 GHz
Number of CPUs	4
CPU cache	2048 KB
Hard drive size	80 Gb

4.3 A SERVER TO PROVIDE ACCESS TO RAW RADAR DATA

Bongani is a 48 Intel(R) Xeon(R) CPU Linux server (Table 4.4). Bongani has been used in the past for operational WRF simulations. Currently, Bongani is used as a backup solution for radar data and configuration files. It furthers runs an instance of the LROSE software and can serve the raw data to any other LROSE instance. It also provides a full service for the data to be accessed over the internet using the Jazz application (see Section 4.3.1).

Table 4.4: The technical specifications of Bongani

Variable	Property
IP	143.160.8.21
Processor	Intel(R)Xeon(R) CPU E7540@2.00 GHz
Number of CPUs	48
CPU cache	18432 KB
Hard drive size	1 Tb

4.3.1 A Java application to view raw data in real-time

The Jazz Java application is designed and supported by NCAR. The application is described on its website: http://www.ral.ucar.edu/projects/jazz/. It is designed as a display system for MDV-format data and is therefore ideal to provide quick access to the three-dimensional raw data from the NWU's Lekwena radar (Figure 4.14).

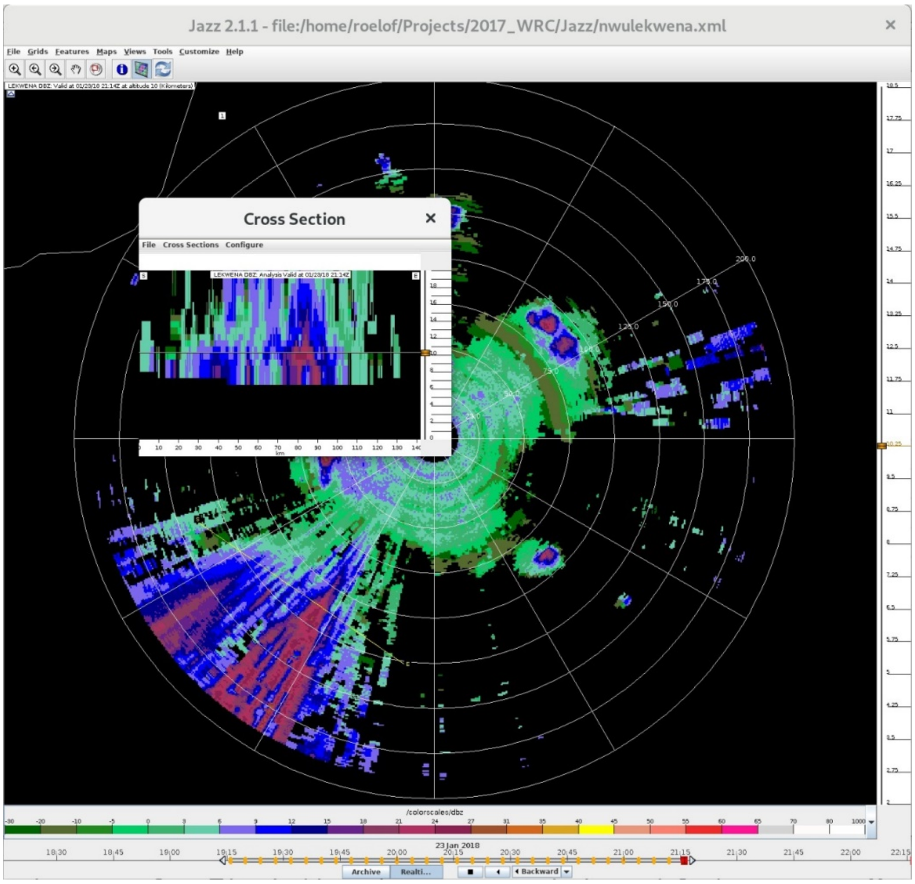

Figure 4.14: The first radio link established between the radar and NWU

The most important parameters of the Jazz XML configuration file are shown below:

<Jazz>

<Layer vis="on" type="MDV" name="LEKWENA DBZ" location="mdvp:://143.160.8.21::mdv/radar/cartLaKwena" field="DBZ" render="grid" colorscale="http://rap.ucar.edu/colorscales/dbz.colors" menuGroup="nwu_short" />

<MenuGroup name="nwu_short" label="NWU short range" parentGroup="GRIDS_MENU" />

<Time mode="real-time" start="-45mins" end="+15mins" interval="4mins" update="5mins" timeZone="UTC" />

<Animation delay="75" dwell="3000" />

<Altitude dataDrivenProperties="true" default="2.4" />

<View projection="Flat" originLon="27.16770" originLat="-26.61886" rotation="0" />

<Window width="900" height="900" xOrigin="0" yOrigin="0"

backgroundColor="black"/>

</Jazz>

4.3.2 LROSE

The LROSE encompasses the TITAN software, and has taken open source radar software to a new level, incorporating open standards such as CfRadial and NetCDF, providing a suite of dual-polarisation software modules. Such software is essential for effective radar research, since it allows students and other researchers to concentrate on the science rather than data handling. It is not distributed through a GitHub repository (https://nsf-lrose.github.io/). The LROSE continues to support the legacy system. The old TITAN approach is shown in Figure 4.15. Radar beam data is passed through a fast message queue step, which is situated between the data ingest and the Cartesian transformation (Dsr2Vol). Different data formats are then handled through different applications that all write data to the standard queue.

The new LROSE approach introduces the Radx applications. It is suited to handling data in polar coordinates as opposed to the legacy TITAN applications that all operated on Cartesian volumes. Additionally, Radx can translate many of the radar formats into a much more widely used NetCDF format, called CfRadial (Figure 4.17). The new LROSE application can also be seamlessly integrated with the legacy applications. The merging of multiple radars can be done as in Figure 4.18.

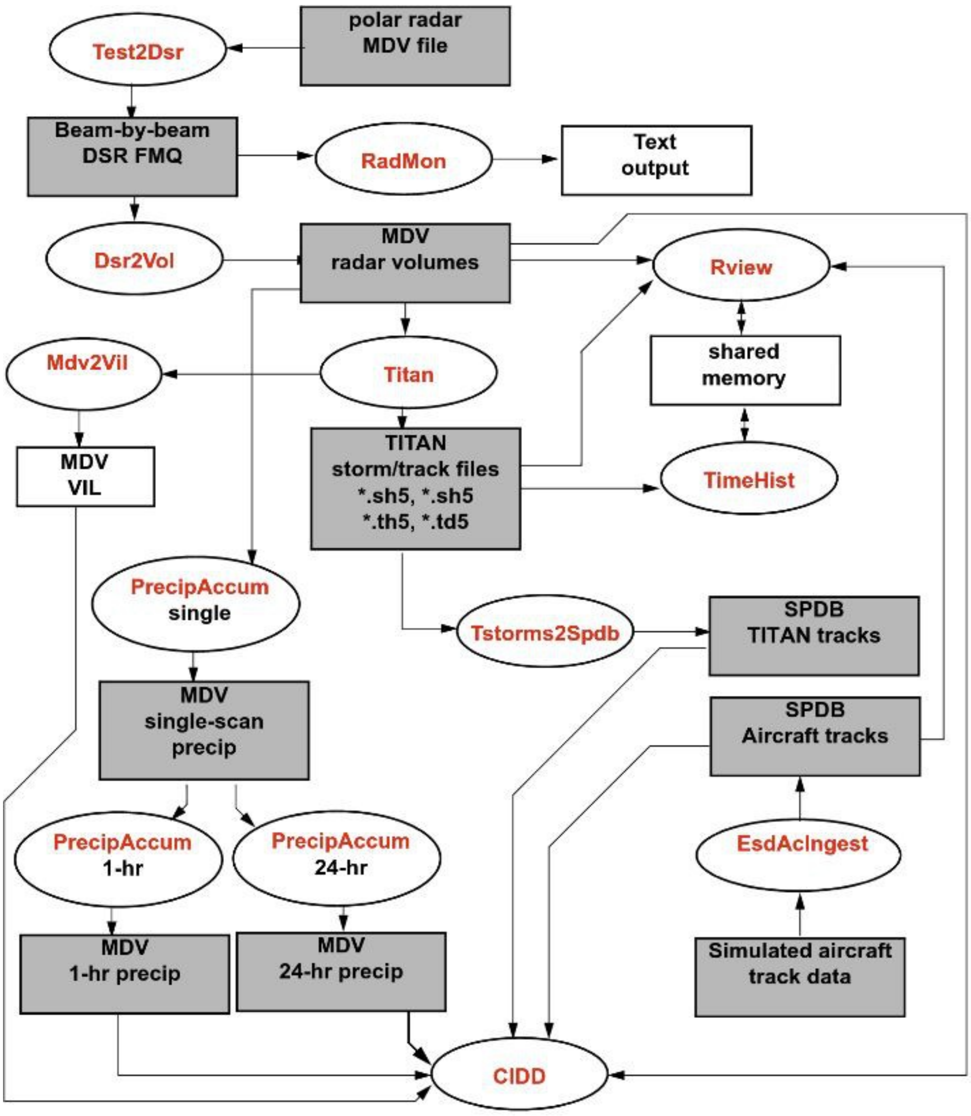

Figure 4.15: The legacy processes used in a typical TITAN application

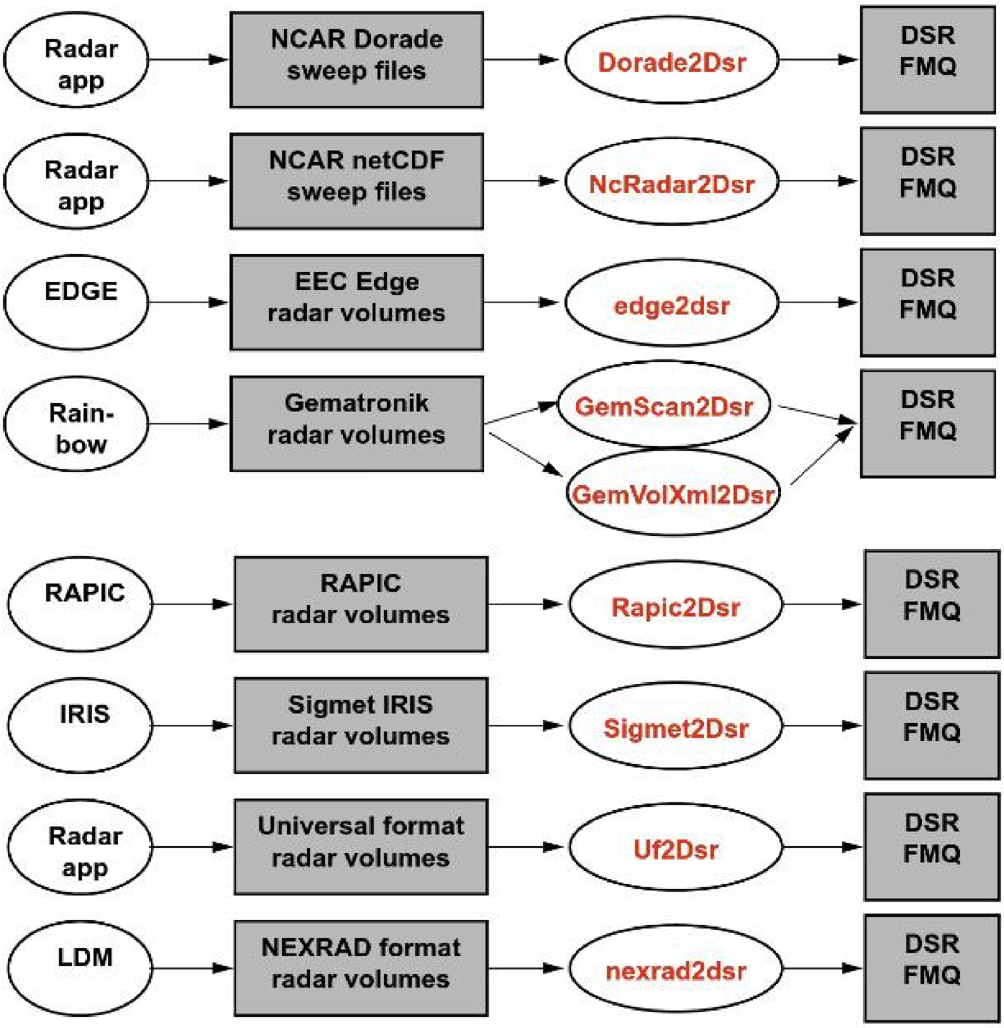

Figure 4.16: The legacy ingests processes used in a typical TITAN application

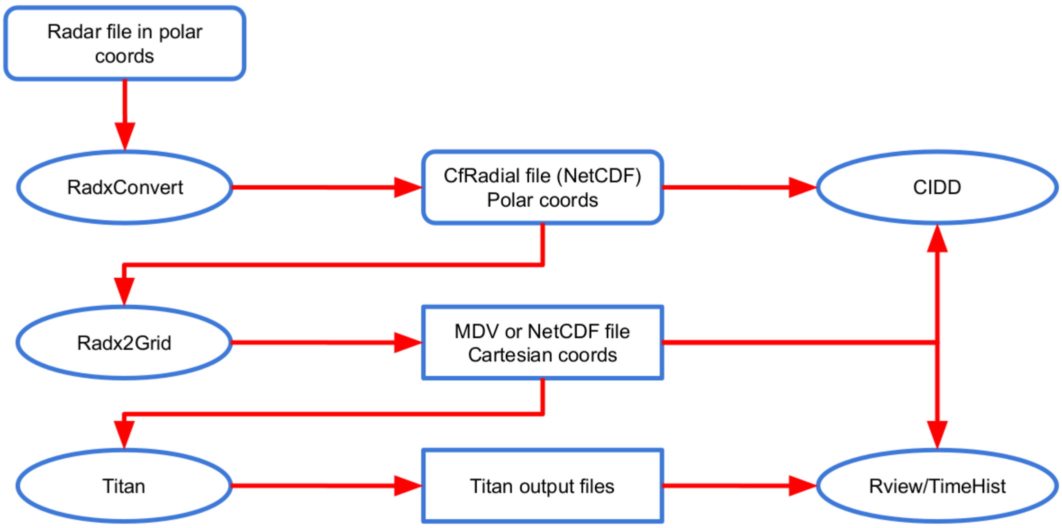

Figure 4.17: The legacy processes used in a typical TITAN application

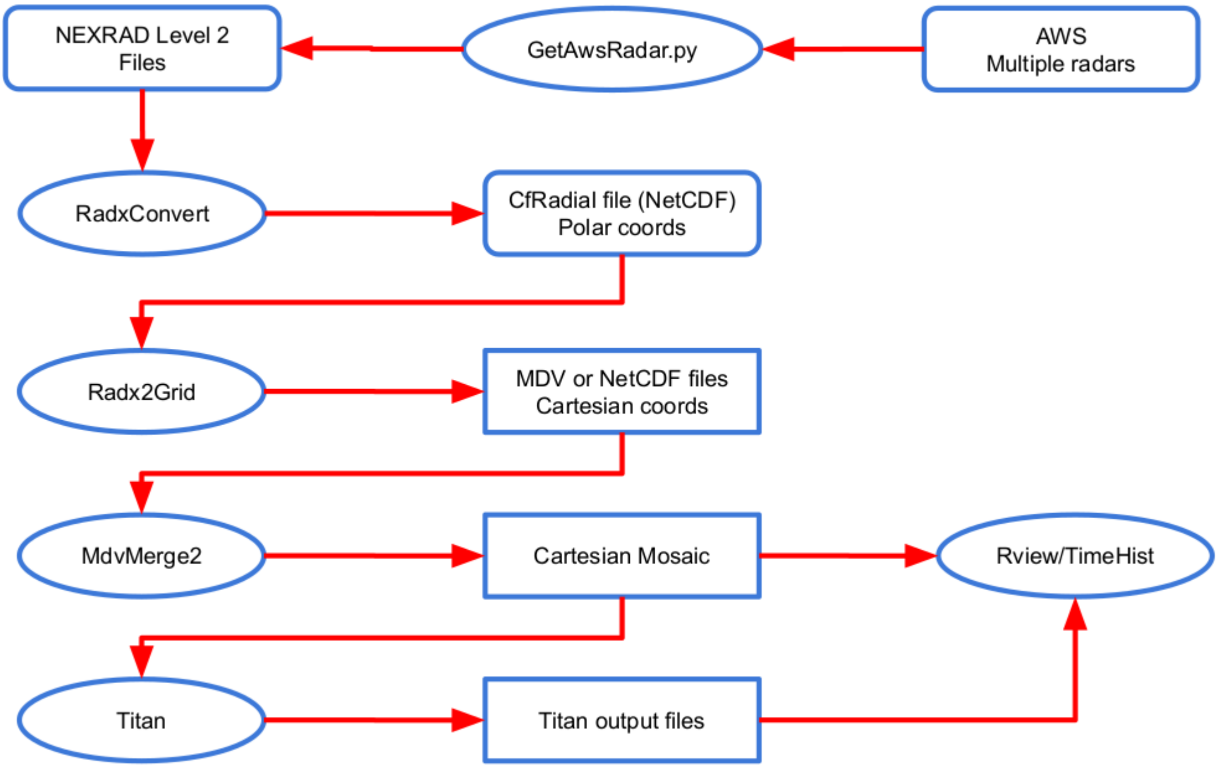

Figure 4.18: The LROSE process flow, merging different radars

4.4 A WEBSITE TO SERVE PRODUCTS IN REAL-TIME

A website was set up to deliver products to stakeholders in real time. To use and deploy a website on the world wide web, a domain has to be bought and registered from a third party. The current registered domain is www.lekwenaradar.co.za. After a domain has been registered, a developer can build a website according to the needs of the organisation. The nature of the website and the living laboratory is to empower and teach students. Graduate students were directly involved in the development of www.lekwenaradar.co.za.

A GitHub account was set up to facilitate version control of code related to data analysis and visualisation, and to host the website. A website is in development to improve the visibility of completed projects. Currently, the GFS models, satellite products and the Lekwena radar output are shown on the website. The website aims to be a simple, efficient platform for scientists to view and download data from any research entity without any concern for affiliation. Students will be encouraged to learn interactively from the web platform by viewing real-time weather, satellite and forecast data.

The website www.lekwenaradar.co.za was deployed using Jekyll and GitHub. Jekyll allows websites to be built locally for testing before deployment (Figure 4.19, Figure 4.20, Figure 4.21 and Figure 4.22). A strategic decision was made to keep the website static. This facilitates a reliable and easily manageable website through GitHub. Students had to learn basic HTML and Markdown to develop the website. A dedicated Linux server was acquired for this purpose. The server is similar to the Radar 2 server discussed in Section 4.2.2.

Technology has become cheaper and more accessible than ever before. A range of low-cost sensors has created exciting opportunities to make measurements at a fraction of the cost of previous generations. One of the objectives of this project is to develop local, low-cost solutions to observe weather and specifically precipitation. A network of these sensors can be used to bias-correct and evaluate the radar rainfall estimates.

One of the key functions of an observation network is communication. Having access to real-time, or near real-time observations enables a range of new applications. This is also a key component of the low-cost solutions being explored by this project.

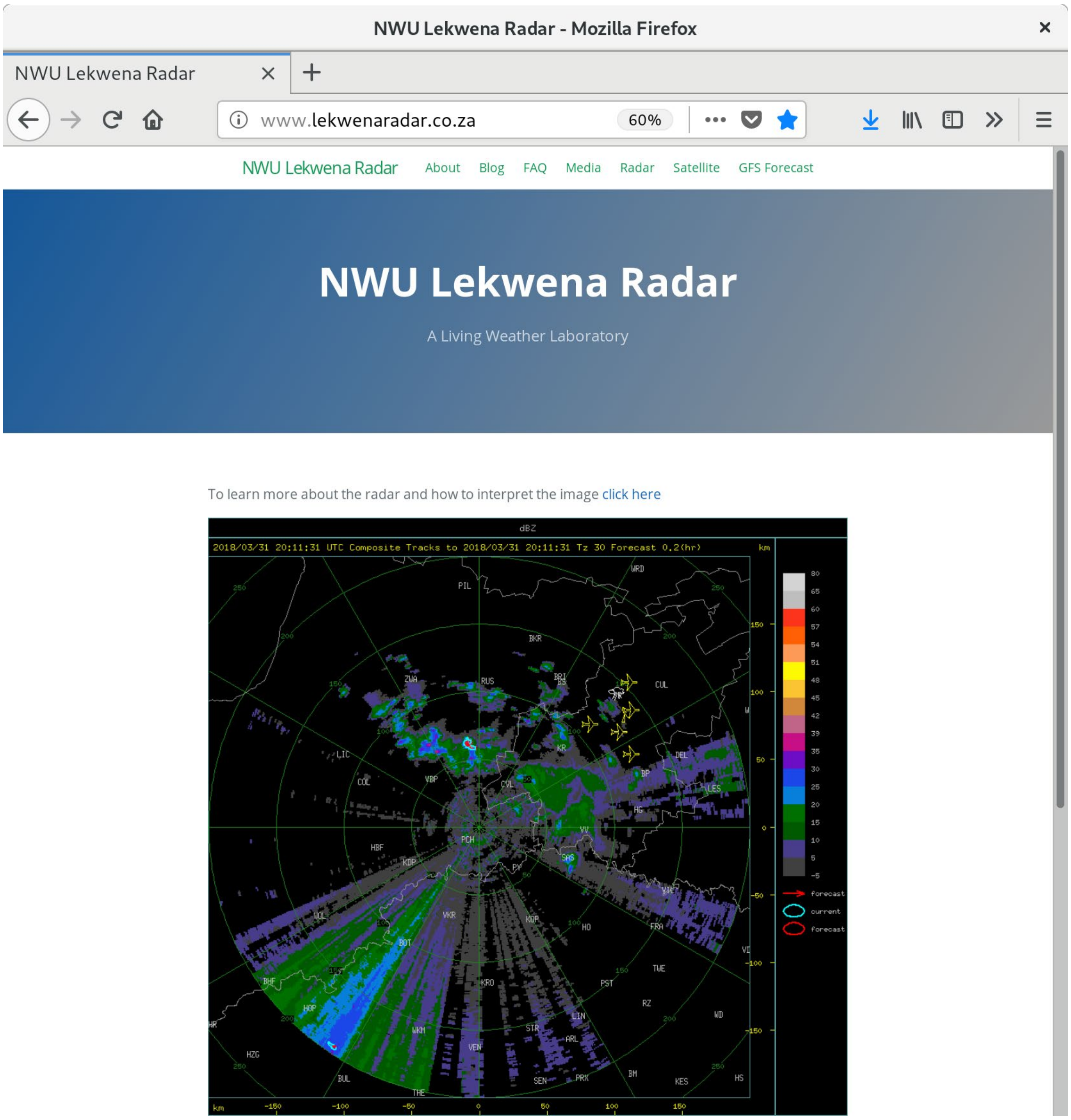

Figure 4.19: The http://lekwenaradar.co.za website showing radar data

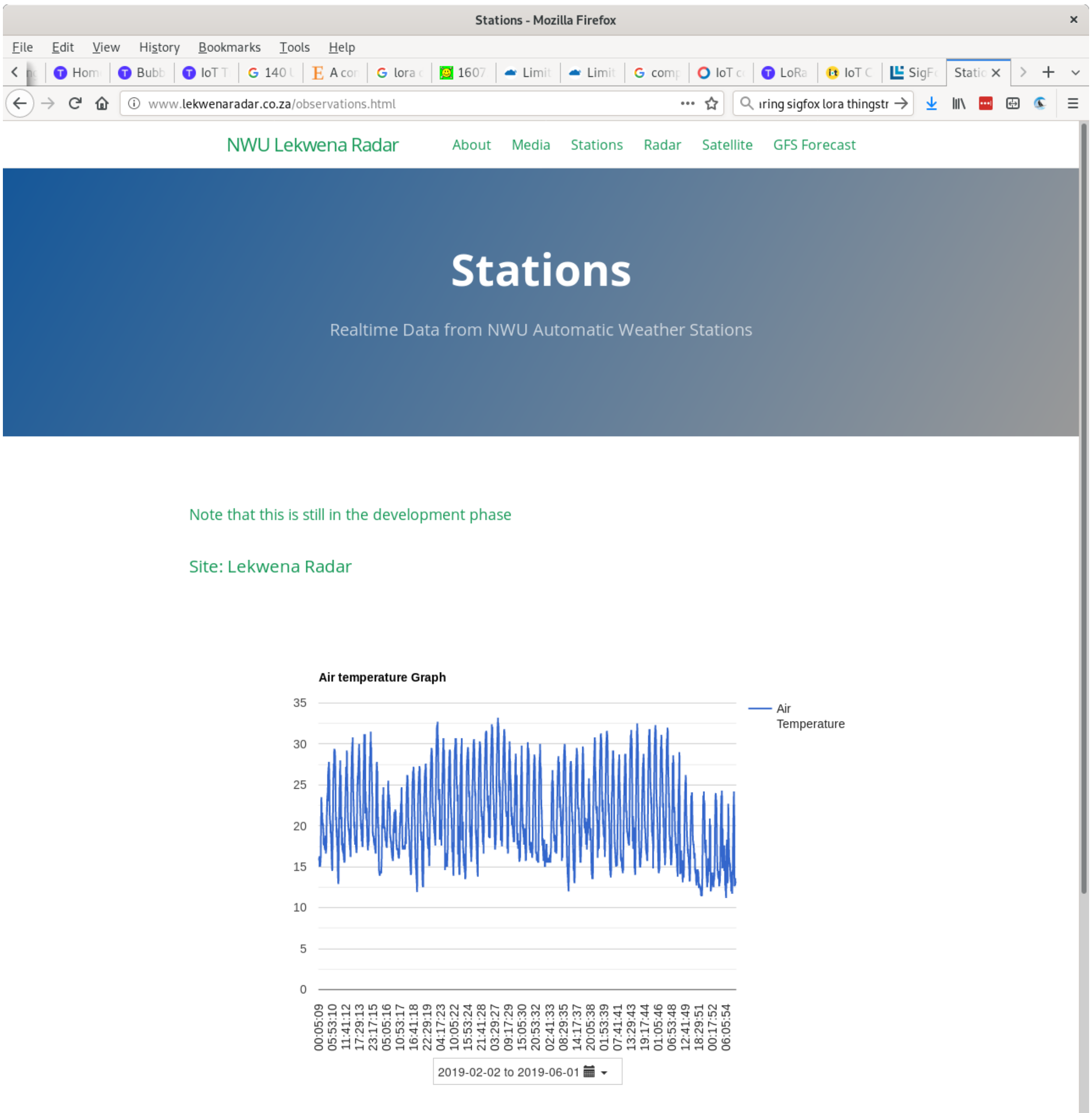

Figure 4.20: The http://lekwenaradar.co.za website showing data from an automatic weather station

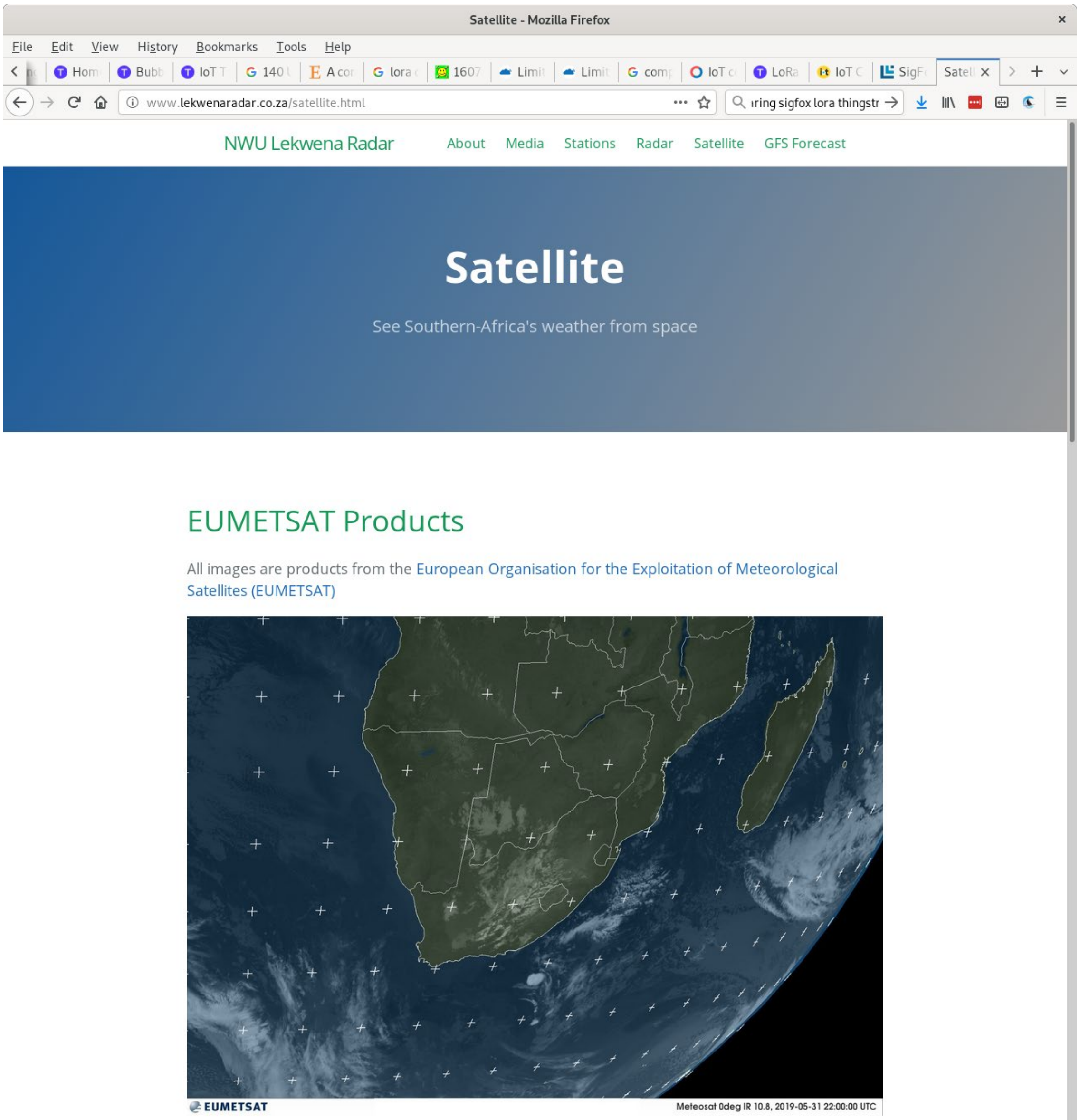

Figure 4.21: The http://lekwenaradar.co.za website showing satellite data

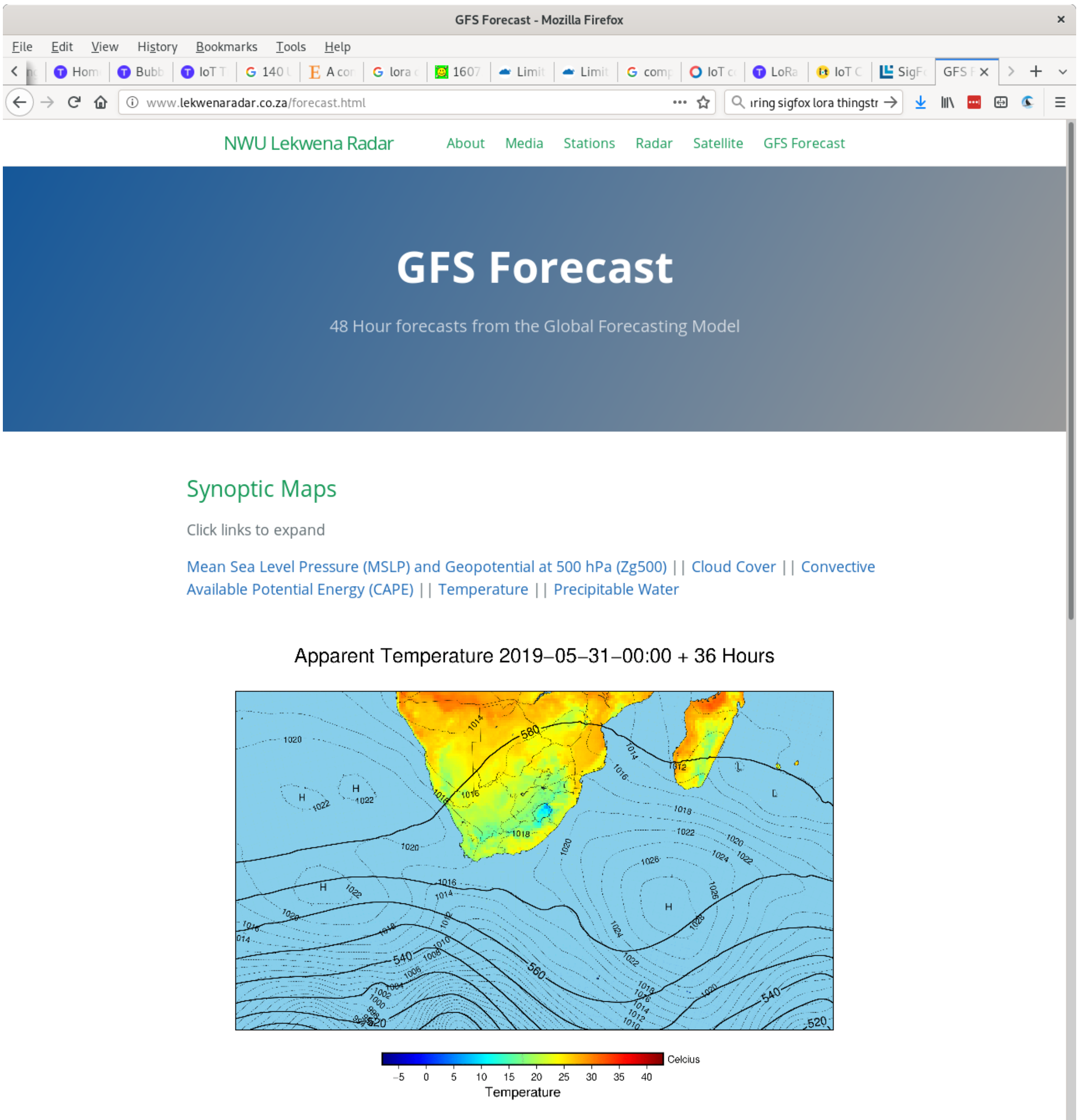

Figure 4.22: The http://lekwenaradar.co.za website showing a synoptic analysis from GFS numerical model output

CHAPTER 5: COMMUNICATING REAL-TIME OBSERVATIONS

Individuals are socially vulnerable to severe weather. Their vulnerability is determined by different factors, such as the timing of storms, public reaction, socio-economic status and past experience of a severe weather event in both a broader social context and a personal context. These factors may have an effect on people's decision-making for the duration of these events. Communicating information to different communities is therefore not a trivial task. This is why the issuing of forecasts of severe weather to the public is governed by legislation (RSA, 2001; RSA, 2014).

Socio-economic status may significantly influence an individual's vulnerability to hailstorms in several ways, both indirectly and directly. Individuals in low-income households are expected to be in informal settlements. Low-income homes are extremely susceptible to even the weakest storm winds and do not have any protective measures during severe weather events (Sutter and Simmons, 2010). Previous studies have shown that people in low-income areas are 10 times more vulnerable to experience severe damages than people in middle-income areas (Daley et al., 2005; Schmidlin et al., 2009). The economic status of a person or family may also influence the technology through which they have frequent internet access. It has been well recognised that communication devices (e.g. television, radio, cell phones, as well as computers with internet access) play a major part in the distribution of warning information before and during severe thunderstorm events (Hammer and Schmidlin, 2002; Comstock and Mallonee, 2005; Sherman-Morris, 2010). Finally, the economic status of an individual may influence the type and range of protective actions taken against severe hail events. For example, individuals within a higher income bracket can afford the latest technologies that would help in taking precautionary measures, such as cell phone weather applications, personal storm shelters and motor vehicles.

Hence, the aim of hail nowcasts is to issue accurate and timely information that can be used by end-users, particularly insurance companies. The duty and responsibility of SAWS is to create and disseminate several weather products such as daily forecasts and severe watches and warnings effectively. Meteorologists employ challenging monitoring infrastructure that comprises of radars, satellites and surface weather stations that can aid in creating weather products. Despite the considerable amount of research conducted on the different facets of weather meteorology, which includes verification, accuracy and implementation, fewer studies have been done on the public's perception of severe weather events (Doswell, 2003). There is an increase in literature that indicates how people react to extreme weather warnings (Wong and Yan, 2002; Silver and Conrad, 2010).

5.1 SOCIODEMOGRAPHIC PROFILE OF THE PEOPLE WHO WERE INTERVIEWED

This sample consisted of 18 males and 12 females, which is a slightly more unbalanced gender profile than that found by Silver (2015). The inconsistency may partly be ascribed to the wish of some interviewees to be questioned with their significant others. Figure 5.1 illustrates the different age groups of the interviewees, ranging from 30 to 55 years. Some 30% of the interviewees were categorised in the 40- to 45-year age group, whereas 20% were 45 to 50 years old. In terms of educational status, most of the individuals were found to be educated, of which 43% of the participants had a bachelor's degree and 27% had honours degrees. The minority had a diploma, as depicted in Figure 5.2. This could mainly be attributed to the smaller size and the fact that the focus group contained people who fell in the middle income bracket. Silver and Conrad (2010) found that, in their research, out of 130 individuals, 40% had a post-secondary diploma, 27% had some sort of education, 16% had completed Grade 12, and only 8% had graduate degrees.

The residential areas from which the participants derived were rather diverse and included suburbs such as Benoni, Boksburg, Johannesburg, Kempton Park, Krugersdorp, Midrand, Randburg, Randfontein, Roodepoort, Rosebank, Sandton and Soweto. Of the individuals that were interviewed, some mentioned having lived in Gauteng for more than five years, whereas other participants have lived in the province for most of their lives. The participants' monthly household income ranged from R10,000 to R30,000, with an average of R15,000. Some 44% of the interviewees earned a monthly income of between R15,000 and R20,000, followed by between R20,000 and R25,000 per month, as shown in Figure 5.3.

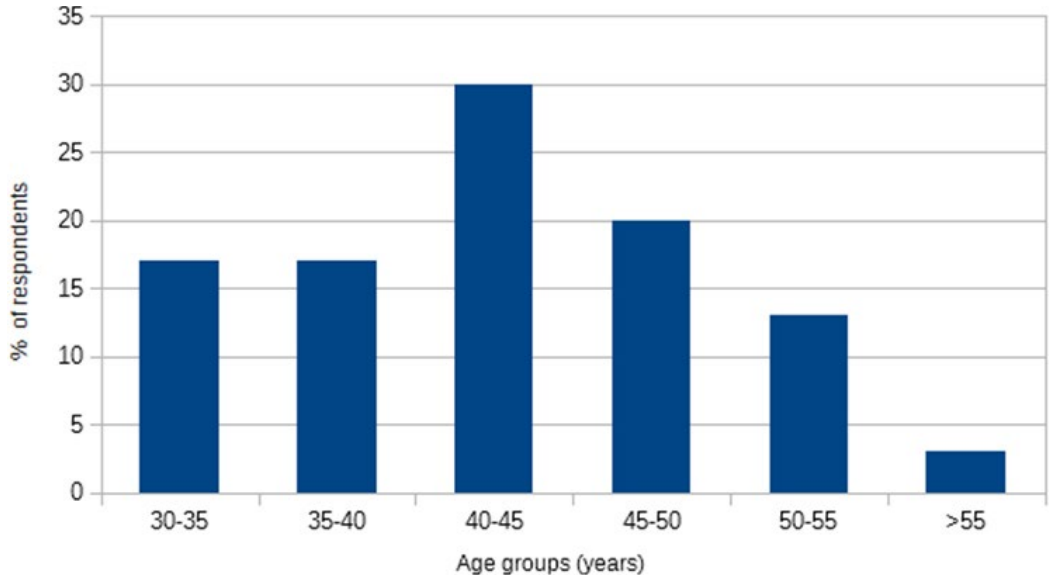

Figure 5.1: The age of the respondents. The question was posed as: "How old are you?"

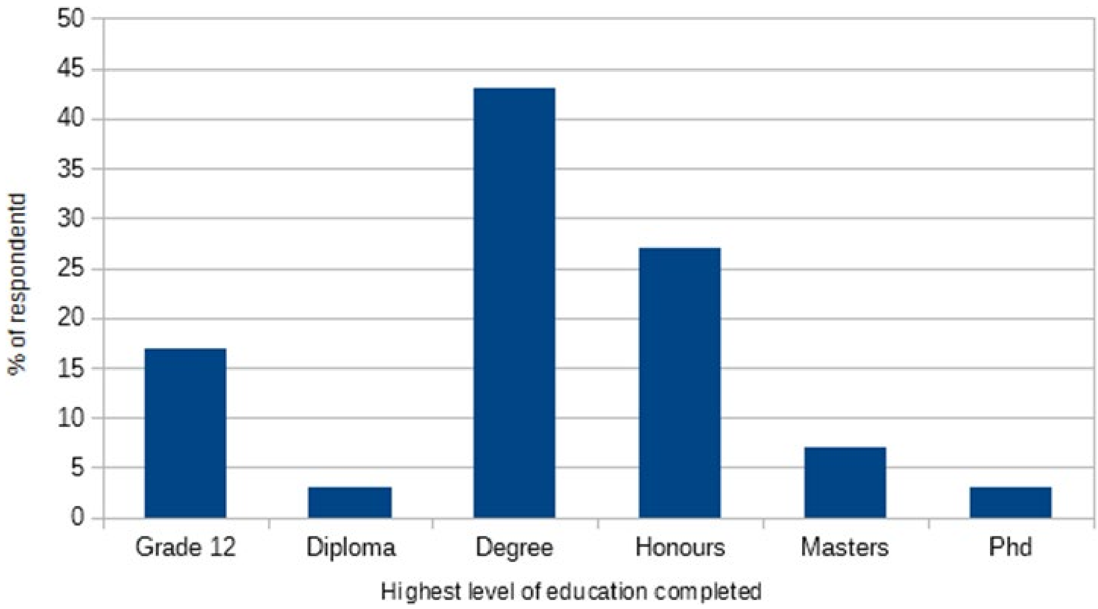

Figure 5.2: The level of education of the respondents. The question was posed as: "What is your highest level of education?"

In contrast, the (2015) found, in his research, that the annual income for respondents ranged from less than $20,000 to more than $150 000, with an average income of $70 000. When converted to ZAR, the monthly income for these participants if they were living in Canada would range between R17,600 and R13,2700, with an average salary of R61,600. This may be due to Canada being a developed country with a low unemployment rate. Another reason could be that the Canadian dollar is strong compared to ZAR. As expected, the racial composition was dominated by Africans (47%), followed by White participants (30%). The minority of respondents were Coloured (17%) and Indian (6%).

The comparison of the sociodemographic profile of this study with the South African national census can be found in Table 5.1.

Table 5.1: Sociodemographic profile of the interview sample (n = 30) in comparison to the national census statistics

Characteristic	This study	Census (2016)
Age (years)	40–45	21.7
Median education	University degree	Secondary education
Total household income (R)	R15,000–R20,000	R8,400
Race	Black African	Black African

The national census of 2016 was compared to the demographic results of this study. The small sample size should be taken into account when generalising the results of this study to the census. The sociodemographic characteristics vary significantly from the census. These differences may be explained as follows:

Most of the participants were referred by interviewees, which explains why more male participants were interviewed. Secondly, the interviewees were mainly from the working class, employed either part-time or full-time and between 40 and 45 years old, which further explains why the majority of the participants had obtained a bachelor's degree and earned more than R15,000 a month. This is much higher than the average income in South Africa. Statistics South Africa reported that 72,6% of South African households get their total income from work, and the typical household income is R100,246 per annum (Christopher, 2014). Finally, not surprisingly, the dominant race in this sample was African, which constitutes the majority of the South African census 2016 population.

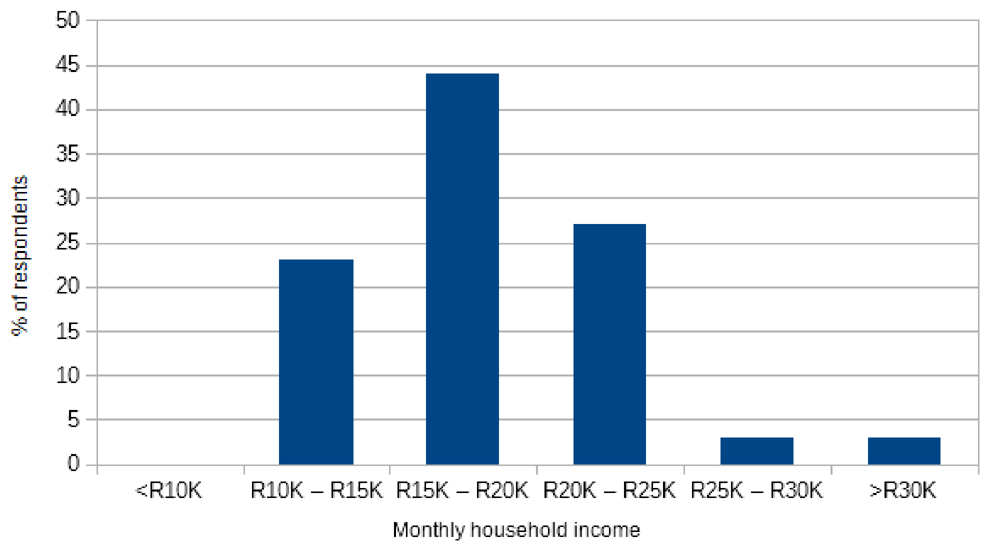

Figure 5.3: Respondents' monthly household income

5.2 PARTICIPANT PROFILES

To understand the diverse range of hail perceptions, as well as the experiences stated by the interviewees, two of the respondents were selected for a detailed analysis. These interviewees were selected since they are illustrative of the sample size, both in their perceptions of hail and their sociodemographic characteristics.

5.2.1 Participant A

Participant A is a 45-year old college graduate who has resided in Krugersdorp since she was a toddler. Participant A describes herself as not really being concerned about the weather. She would only look at weather forecasts if there was a purpose (e.g. a special occasion or a function). She had very limited knowledge of the different forecasts published by SAWS. After experiencing hail twice, she became concerned of these chaotic hail events. Participant A had incurred severe damages to her vehicles as well as to her house. She described the experience as “bad and scary” and thought that her roof was going to collapse due to the amount of hail that hit the roof.

The estimated loss to her personal assets was ±R15,000. Since this horrible experience, she had become more aware of these types of severe storms. She preferred receiving hail nowcasts three hours in advance in order to take precautionary steps such as securing her vehicles and ensuring the safety of her children. Participant A further mentioned that receiving hail nowcasts would help her to save money and would aid her in preparing for the storm. Most importantly, it would empower her to keep her children safe. Upon being asked if she would pay a fee to receive hail nowcasts from SAWS, her reply was as follows:

> *Yes, because you know sometimes the cell phone app says there is heavy rain but on some social networks they just say rain. So, it’s very hard to decide upon. Also, the fee should be reasonable (laughs) because we are working people with family.*

5.2.2 Participant B

Participant B is a 50-year old man who has worked and lived in Midrand for more than five years. In his personal life, he does not make a habit of checking the weather. However, he passively attains weather forecasts from different sources such as the radio or television. He was not really interested in hailstorms until a few years ago when he experienced the most brutal storm that he had ever seen. Upon being asked if he had experienced any damages, his response was as follows:

> *I got stranded in the flood on my way home and my second car was blasted by these big balls of ice. My car’s windscreen was broken as well as the back window. The car was left with minor dents here and there with paint being slightly removed. When going home my car was drenched in water because of the flood.*

The estimated loss to his personal assets amounted to ±R10,000. He has become concerned about hailstorms as it can be very costly. He preferred receiving hail nowcasts approximately two hours in advance, so that he could make preparations, and it would give him time to warn others. Additionally, he added that receiving hail nowcasts would enable him to be prepared for the predicted storm by being able to avoid traffic and possible floods. Thus, to him these nowcasts play a vital role in the sense that it can save lives and money. Upon being asked if he would pay a fee to receive hail nowcasts from SAWS, his reply was as follows:

> *Oh yes, if it means my family will be safe from this storm then it is worth it. Oh, and damages will be minimised.*

5.2.3 Comparison of the two profiles

Participant A and Participant B are representative of the perceptions and experiences frequently mentioned by interviewees. They obtained weather forecasts. However, they had no concern for severe storms such as hail. They both then experienced severe hailstorms and tried to take some sort of action without knowing that SAWS had issued a warning. Both had incurred losses to their vehicles and/or property. Participant A opted to receive hail nowcasts at least three hours before a storm, whereas Participant B was comfortable with a two-hour warning. Their reasons for needing hail nowcasts were quite similar as they both mentioned it would help them save money as well as to take precautionary steps.

5.3 THEMATIC ANALYSIS

5.3.1 General weather knowledge

Interviewees were asked how often they consulted weather forecasts. As depicted in Figure 5.4, 67% of the respondents checked forecasts and identified themselves as “weather enthusiasts”. People watch the weather for different reasons, which will be discussed in the following section. Nonetheless, 33% of the interviewees mentioned that they occasionally or never consulted weather forecasts. Silver and Conrad (2010) found that 58% of individuals in their study reported consulting weather forecasts, while 14% seldom did. Similarly, Silver (2015) found that the majority of interviewees in his study considered themselves to be “weather smart”.

Furthermore, 75% of the interviewees reported receiving general weather forecasts in the mornings. This is consistent with the results reported in the following section, which shows that several participants used forecasts to decide what to wear or to plan their daily activities. Lazo et al. (2009) had similar findings in their study in which more than 70% of the individuals they interviewed accessed forecasts in the morning. A common reason is because people use forecasts to plan their daily activities. Some 10% of the interviewees mentioned that they obtained forecasts during the evening so they could plan for the next day, for example in deciding what to wear or for special occasions such as weddings, funerals or outdoor events.

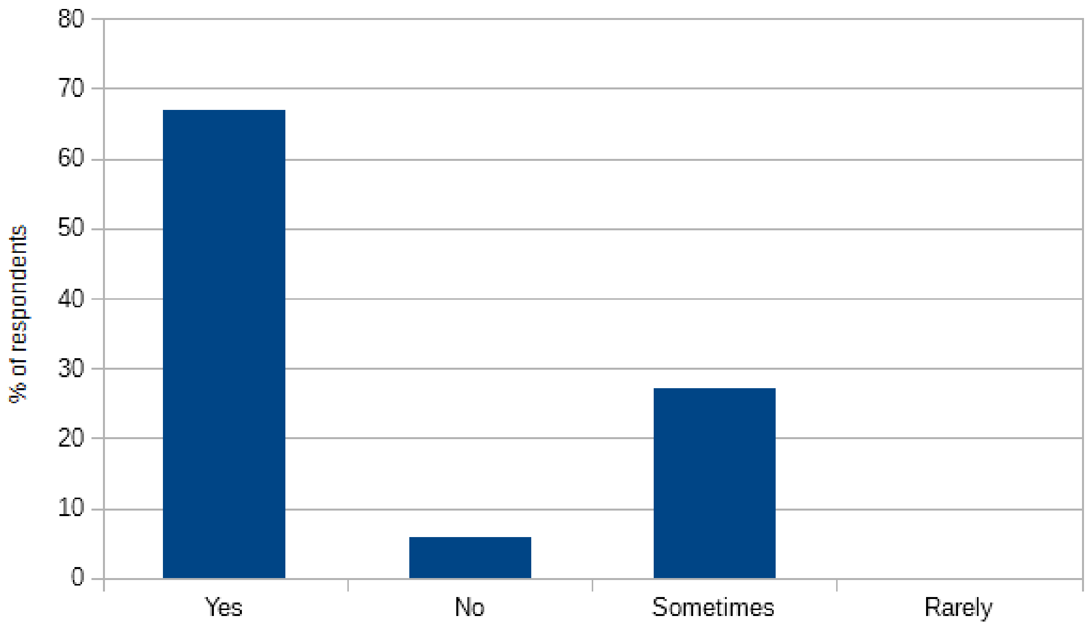

Figure 5.4: Interviewees were asked how often they watched weather forecasts

Interestingly, Lazo et al. (2009) found that 91% of participants in their study indicated that they received forecasts from 19:00 to midnight. This may be due to a bigger population sample that was interviewed compared to the small sample of 30 individuals in this study. A previous study that was undertaken on the public perception of weather forecasts in the USA found that 72% of the participants followed weather forecasts (Lazo et al., 2009). These respondents checked forecasts more often than the interviewees in this study. The difference between the study done by Lazo et al. (2009) and this study is that Lazo et al. (2009) studied individual perceptions of general weather forecasts, whereas this study focused on the perceptions of individuals to hailstorm forecasts. Another reason for the difference may be the way the interviews were conducted. Lazo et al. (2009) conducted online interviews with a target group, whereas personal interviews were conducted in this study. Nevertheless, a past study showed that the public has a habit of checking the weather more frequently if a severe storm, such as a tornado, has been forecast (Zhang et al., 2007). For example, warnings from the weather service of possible hail in the morning could be beneficial to end-users in that they could take the necessary precautionary measures and be well prepared.

These findings are consistent with the results obtained by Silver and Conrad (2010). Lazo et al. (2009) found that more than 70% of their respondents obtained forecasts from television and radio as common sources. Furthermore, they found that newspapers and internet web pages were the least common sources used. Sliver and Conrad (2010) reported that 98% of the Canadian respondents obtained weather forecasts from media sources such as Television Weather Network, the local news, radio and Environment Canada. Another study conducted by Sliver (2015) also found that the average weather consumers tended to consult their radio or television station for weather forecasts. From the above findings, it is clear that television is a dominant source that people use for weather forecasts. Most of the participants followed weather forecasts for pragmatic reasons, such as deciding what to wear, to prepare for social activities or to do laundry. Figure 5.5 illustrates that 53% of the interviewees only consulted weather forecasts when deciding what to wear the next day, 22% mentioned that they used weather forecasts for general activities such as sports or hikes, and 18% obtained forecasts for special occasions or functions, doing laundry or washing their vehicles. Only 4% mentioned that they followed forecasts to see what the day will be like. Lazo et al. (2009) found similar findings, whereby the majority of respondents consulted weather forecasts for dressing and general activities.

5.3.2 Damages caused by hailstorms

Out of the 30 interviews conducted, 83% of the interviewees mentioned that they had experienced mild to severe hail damage to either their homes or vehicles. Some 17% reported not having any sort of damage. The majority of participants stated that their cars had taken most of the beating from hail events, for example, dents, broken or cracked windows and – in extreme cases – their cars were stuck in a flood on their way home. Some reported damages to their property with ceilings completely destroyed by water or windows being shattered and broken.

Most of the interviewees described their experiences as “chaotic, horrifying, scary or dreadful”. Participant C (47 years old) explained:

> *Because of the clogged drains, water started to seep under the doors and a portion of the living room was soaked with water. The pool was flooded, tree branches were inside the pool and the leisure area was completely damaged with electrical equipment destroyed. My vehicle got damaged through the big balls of ice. Windows were broken. I was fortunate the other vehicle was in the garage. I’m scared as it’s that time of the year again where we can expect such violent storms.*

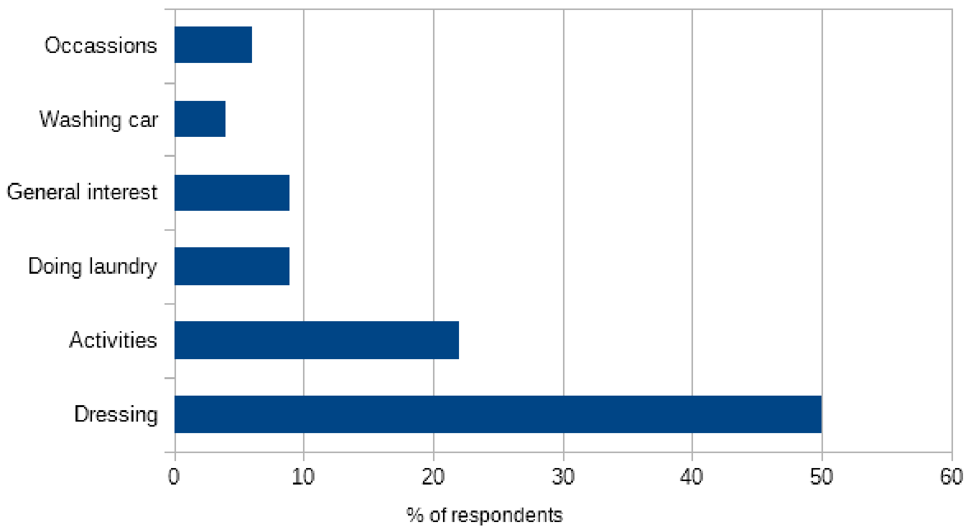

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Figure 5.5 Interviewees were asked why they followed the weather forecast

The majority of respondents mentioned that they had incurred damages of R10,000 to R15,000, followed by 26% who had incurred damages between R15,000 and R20 000 (Figure 5.6). Some 16% of the interviewees reported that they had incurred damages up to R5,000, while 13% indicated no losses.

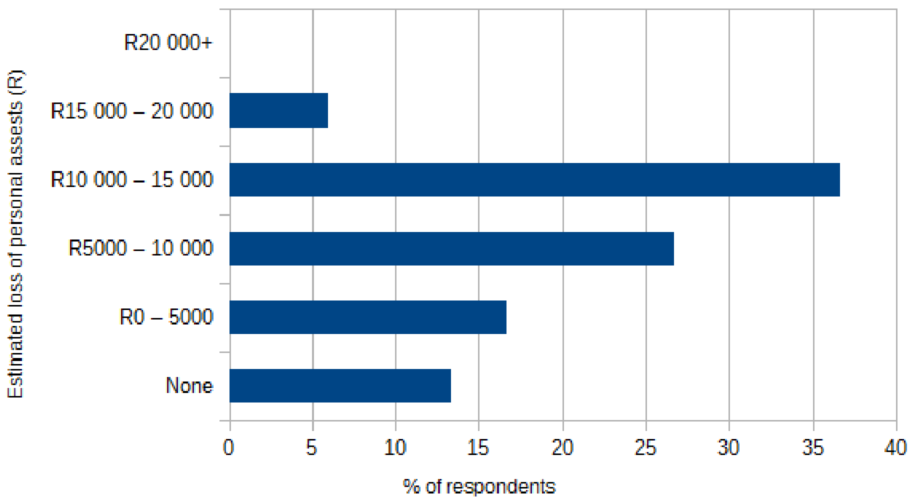

Figure 5.6: Interviewees were asked what their estimated loss of personal assets was

Few interviewees had an overall understanding of the difference between a hail warning and a hail watch. Most of the participants stated that a hail watch was not as serious as a hail warning, and a warning was more serious and severe.

Participant C (35 years old) mentioned the following:

> *Uhmmm, I think a hail watch is just to pay attention and be on the lookout or aware that there might be some hail or hail passing by. And a warning is severe for example hail is predicted so be careful.*

The minority of the interviewees were able to explain both terms. Furthermore, several participants did not know that SAWS issues potential hail warnings. In addition, most of the interviewees mentioned that they are somewhat acquainted with severe weather patterns that are associated with hail, especially on the Highveld.

Participant D (45 years old) mentioned the following:

> *You know I always knew we could get a storm on a hot summer's day, and then suddenly around 15:00 you get to see dark clouds build up. Then I knew we might get hail or just a heavy storm.*

5.3.3 The best ways to warn people about hailstorms

This section serves as a motivation to SAWS to offer a variety of communication platforms to end-users. Interviewees were asked how they obtained weather forecasts (Figure 5.7). Most of the participants obtained weather forecasts from television channels. Some 38% followed weather forecasts by cell phone weather applications such as Accuweather, 23% used radio stations and 8% used the internet to access forecasts. Only 2% of the interviewees reported that they get forecasts from their friends or family.

Interviewees were asked what they considered the best ways for SAWS to warn them about severe hail events (Figure 5.8). Although they had various and different suggestions (e.g. television, radio, social media networks such as Facebook or Twitter, the SAWS website or through SMS), 42% of the respondents said that an SMS would be the most preferred means of communication. Another 34% explained that they preferred social networks, while 14% preferred media platforms such as television or radio. Similarly, Silver (2015) found that most people agreed that they preferred receiving a text message to relay weather information.

As mentioned by Participant E (50 years old):

> *Phew I haven't thought about it. But I think the best way is to send an SMS. Because not all of us might have internet access at that time. So, SMS will be a good way.*

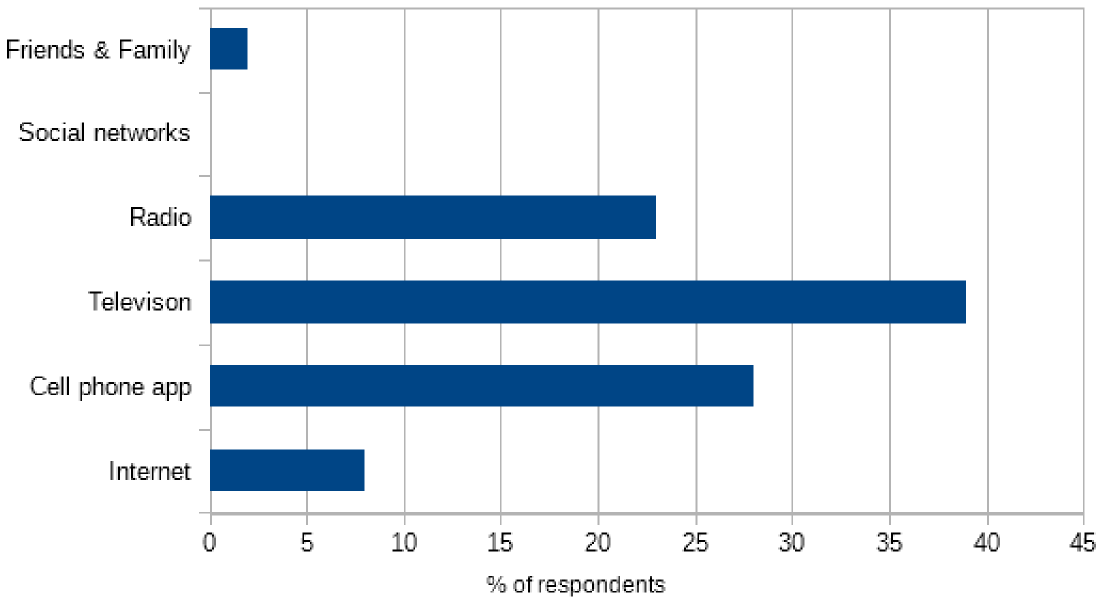

Figure 5.7: The interviewees were asked how they obtain weather forecasts

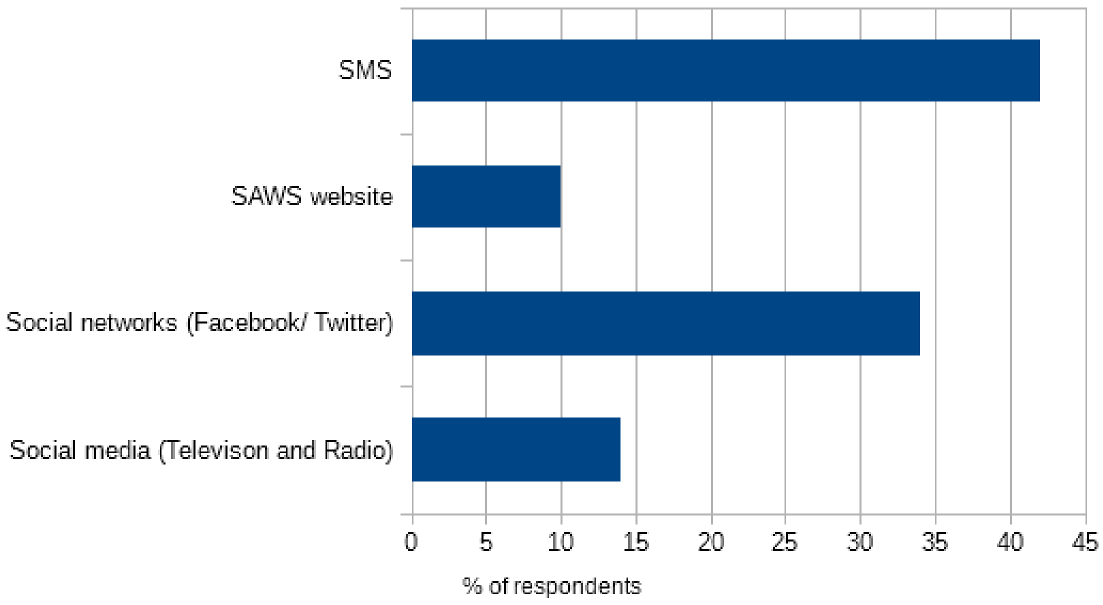

Figure 5.8: The interviewees were asked about the best ways for SAWS to warn them about severe hail events

Hail warning communication process

Interviewees were asked if they were concerned about hailstorms. Some 87% mentioned that they were worried and concerned due to the amount of potential damage, and 13% were not really concerned about hail events. Previous research showed that individuals had access to hail forecasts and warnings via various sources (Lazo and Chestnut 2002; Demuth et al., 2011). This could be because some people have more access to forecasts than others. For example, an individual who has a cell phone is more likely to receive constant hail warnings than an individual who relies on television for information on approaching hailstorms. Out of the 30 interviews that were conducted, 57% of the interviewees mentioned that they received hail warnings, whereas 30% said that they sometimes received warnings, followed by 13% who said that they never get warnings. Furthermore, interviewees were asked how they received warnings. This is illustrated in Figure 5.9. Some 26% of the interviewees indicated that their insurance companies send out messages regarding hailstorms. Some 24% mentioned that they usually received warnings on social networks such as Facebook (through weather groups and sometimes through the SAWS's page). The minority of the participants indicated that they obtained warnings from media platforms such as television (the news channel) or the radio. The other interviewees said that they get warnings from their colleagues at work or through family and friends. Interestingly, 7% of participants did not receive any form of warning, whereas no one received warnings via SMS or through the SAWS's website. One significant finding was that some participants mentioned that they were not aware of the website operated by SAWS.

5.3.4 Lead time of forecasts

The ideal prediction lead time is seen to vary among diverse people. Some individuals may simply need minutes to look for suitable shelter (Ewald and Guyer, 2002). However, previous studies suggest that longer lead times are not always interpreted as a minor risk, as illustrated by death rates (Simmons and Sutter, 2008; Simmons and Sutter, 2009). A longer lead time may not be as effective due to the sense of preparedness, as well as skill, which could end in a decrease in apparent risk (Doswell, 1999). This may cause people to be less driven to take proper precautionary action.

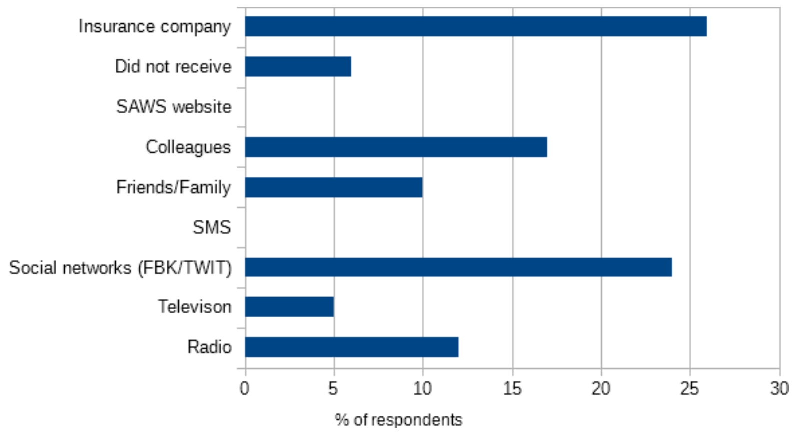

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Figure 5.9: Interviewees were asked how they received warnings

Hail warning lead times were integrated into the interview. This section answers the fourth research question: What is the ideal time for receiving hail warnings?

Interviewees were asked at which time intervals they would prefer to receive hail warnings (Figure 5.10). Some 61% of the respondents reported that they would prefer up to two hours' advance warning, whereas 23% preferred three to five hours' warning because they needed time to prepare for the hailstorm. These key findings are comparable to previous research (Ewald and Guyer, 2002). Simmons and Sutter (2008) similarly indicated that "longer lead times might not increase fatality statistics". Some 10% of the interviewees reported that five hours would be ideal so that they could alert others and take precautionary actions, while 6% preferred to receive hail warnings one day in advance. Interestingly, Simmons and Sutter (2008) found that as warnings in advance increase, morbidity drops in a linear manner.

The study of Simmons and Sutter (2008) on tornado victims showed that lead times longer than 15 minutes did not reduce mortalities or damages associated with severe events without warnings. Previous studies show that a longer lead time did not significantly contribute to an individual's confidence in severe warnings, particularly if the time is related to uncertainty about the intensity of tornadoes (Doswell 1999; Ewald and Guyer, 2002). Individuals may associate a longer lead time with false alarms because the hailstorm event might not even have occurred after the warning. Assuming that the false alarm is above 70% and the individual has little awareness with longer lead times, this is a practical response (Simmons and Sutter, 2006). Hoekstra et al. (2011) supported this and reported that 85% of the individuals in their study showed more confidence in forecasts with shorter lead times, whereas an individual's certainty decreased gradually with longer lead times. A possible reason might be the respondent's uncertainty in longer lead times (Figure 5.10). Two respondents were asked at which time intervals they would prefer to receive hail warnings. The majority of participants explained that receiving hail nowcasts or warnings was important as it would help them save costs that resulted from damages.

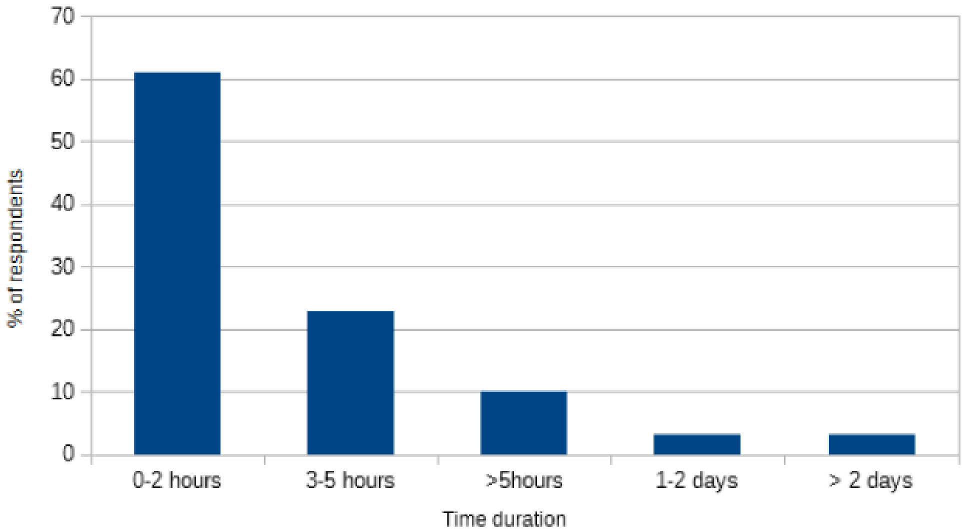

Figure 5.10: Interviewees were asked at which time intervals they would prefer to receive hail warnings

Age similarly was an imperative basis in hail lead times. Generally, the ideal time declined with age (over 50 years) and differs from the results of Hoekstra et al. (2011). A probable reason for this finding is that older people tend be more vulnerable to severe hail events and need more time to prepare. Interviewees who had experienced hailstorms preferred shorter lead times (up to two hours in advance), compared to those who had had no hail experience. Thus, participants who had hailstorm experience could base their evaluation on how much time was needed to respond to warnings on these events, whereas those with no experience, could not. Two of the interviewees responded as follows:

Participant F (41 years old) said:

> *That's interesting, because you see, I would like to receive hail warnings early, like a day before, when chances are high because of heavy winds within the next hour or so. So, ideally, it would be great to receive it like one to two days before.*

Participant G (36 years old) said:

> *I would prefer if we could get the warnings two hours or less in advance so I still have time to take precautionary steps. Like warn my kids at school, make sure the pool is covered or my cars are parked under a sheltered spot.*

5.3.5 False alarms

Previously, it was perceived that excessive warning decreases the general public's readiness to respond to severe weather warnings (Barnes et al, 2007). Breznitz (1984) conducted experiments to study individuals' reactions to recurring false alarms and found that false alarms reduced participants' readiness to respond. However, in contrast, studies have shown that individuals may have a high acceptance of false alarms. Janis (1962) found that false alarms may not reduce an individual's willingness to take precautionary measures in weather warnings and can create a level of awareness if there is a reason for the warning. Janis (1962) further accentuated that the tendency to follow warnings is affected by an increase in the understanding of susceptibility to the severe weather event.

These results were substantiated by Dow and Cutter (1998) in their study of the behaviour of residents in North Carolina who had experienced a false alarm for a forecast hurricane. Dow and Cutter (1998) found that the false alarm did not have an impact on the residents and assisted them in making changes in their pre-emptive protective actions. These results were corroborated with the findings in this study, where the majority of the respondents reported to being over-warned with false alarms rather than under-warned with accurate warnings.

Interviewees were asked if they would prefer to be over-warned with false alarms or under-warned about accurate hail forecasts (Figure 5.11). From the 30 interviews that were conducted, 70% of the respondents reported that they would rather be over-warned of hailstorms even if it was a false alarm. Some 30% of the interviewees added that they would rather be under-warned of hail events, which, however, should be accurate. Additionally, individuals who had a higher false alarm rate held less trust in weather warnings and were less likely to take precautionary measures (Ripberger et al., 2015).

A laboratory study (LeClerc and Joslyn 2015) was conducted showing that the “cry-wolf” effect is real in specific situations. It was found that low and high false alarm rates led to substandard decision making. However, lowering the false alarm rate somewhat did not significantly affect compliance. Most of the individuals in the interview mentioned that they would not mind the false alarms and over-warning because it would assist them in taking precautionary measures. Interestingly, Schultz et al. (2010) found that most of the participants in their study were not too worried about the “cry-wolf” effect. Over-warned weather events, such as heavy rainfall and hail, were perceived to be close calls by the public. These occurrences may not necessarily increase the false alarm rate, but may serve as an educational learning experience (Barnes et al., 2007). Two of the interviewees mentioned the following:

Participant A (45 years old) said:

> *Hahaha, from the experiences I had I would rather be over-warned so if there is actually a hailstorm then I’m prepared and covered.*

Participant H (38 years old) said:

> *You know, I get tired of these false hailstorms because it eventually gets boring so I prefer to be under-warned but then the forecasts must be accurate.*

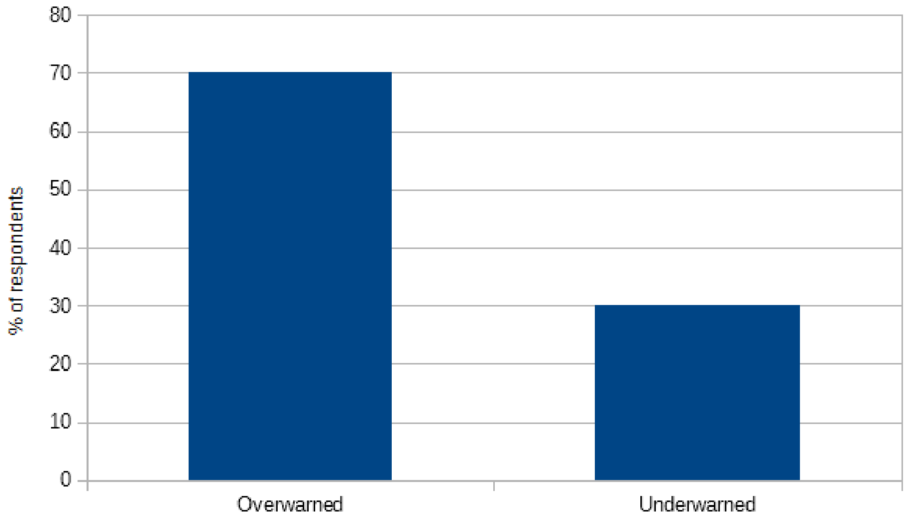

Figure 5.11: Interviewees were asked if they would prefer to be over-warned with false alarms or under-warned with accurate hail forecasts

From the answer given by Participant A, it was evident that the false alarms did not particularly bother her because of the experiences she had faced. Furthermore, Participant H mentioned that false alarms may be monotonous, but he preferred to be under-warned with accurate forecasts.

5.3.6 Perceived benefits of nowcasts

It must be noted that this chapter is based on the challenges experienced by SAWS; notably, not being able to nowcast hailstorms due to the high costs, not having enough specialists in the field and a lack of motivation. The results of this chapter serve as a motivation for SAWS to do nowcasting on a daily basis.

The majority of the interviewees expressed how hail warnings and nowcasts may aid them in the short-term recovery process. Some 80% of the interviewees explained they would save money, and that being prepared for hail events would bring them relief. They further explained that they could protect their properties and vehicles from hail damage by receiving timeous hail warnings. Some 60% of the respondents added that lives could be saved by alerting their loved ones about hail events and further loss and damage could be prevented. Some interviewees agreed that receiving warnings would surely cut down on the recovery process time.

Participant I (41 years old) said:

> *Well, you know, receiving hail warnings in time before a storm would help a lot, especially from damages to my valuables and loss of money from these damages. Also, after these storms, the cities especially are flooded, and we are stuck in the flood or traffic, so these warnings I think it will also help regarding flooding measures.*

Interviewees were further asked if they value hail nowcasts, and 95% of them responded positively. Reasons for valuing nowcasts varied from individual to individual. However, the majority of interviewees explained that receiving hail nowcasts would help them save and cut down on unnecessary costs such as a broken car window. Some 25% of the respondents added that it would assist in keeping their family and children safe from these disastrous storms. Most of the participants reported that by receiving nowcasts they would be able to prepare, for example by parking their cars under a covered parking or by alerting others who might not be aware of the eminent hailstorm. Hence, damages will be minimised and fewer lives would be lost compared to not receiving any hail nowcasts. Interestingly, a few interviewees mentioned that it could help city officials by making sure that the drainage systems are well maintained, thus reducing floods caused by severe storms.

Participant J (48 years old) reported that:

> *As I mentioned, it will help me save a lot, also to keep my kids safe as they are in school at times or at home. It will also help me to be prepared and I won’t have to worry about my car or home being damaged. I mean it can really hit your pockets for nights if you are not warned or aware.*

Lastly, interviewees were asked if they would be willing to pay a fee to receive hail nowcasts directly from SAWS, as depicted in Figure 5-12. Some 30% of the respondents were willing to pay for this service. Not surprisingly, 43% were also only willing to pay if it was affordable. The majority of interviewees reported that they would pay a small fee rather than suffer damages worth thousands of rands. Furthermore, they also mentioned that by receiving nowcasts or forecasts from SAWS, it would help them to trust the source because receiving warnings from various sources with different information was confusing. Some 10% of the interviewees were not sure about receiving nowcasts from SAWS. Finally, 17% of the respondents were not willing to pay a fee because their insurance company warned them of coming hailstorms.

Participant A (45 years old) said:

> *Yes, because you know, sometimes the cell phone app says there is heavy rain but on some social networks they just say rain. So, it's very hard to decide. Also, the fee should be reasonable (laughs) because we are working people with a family.*

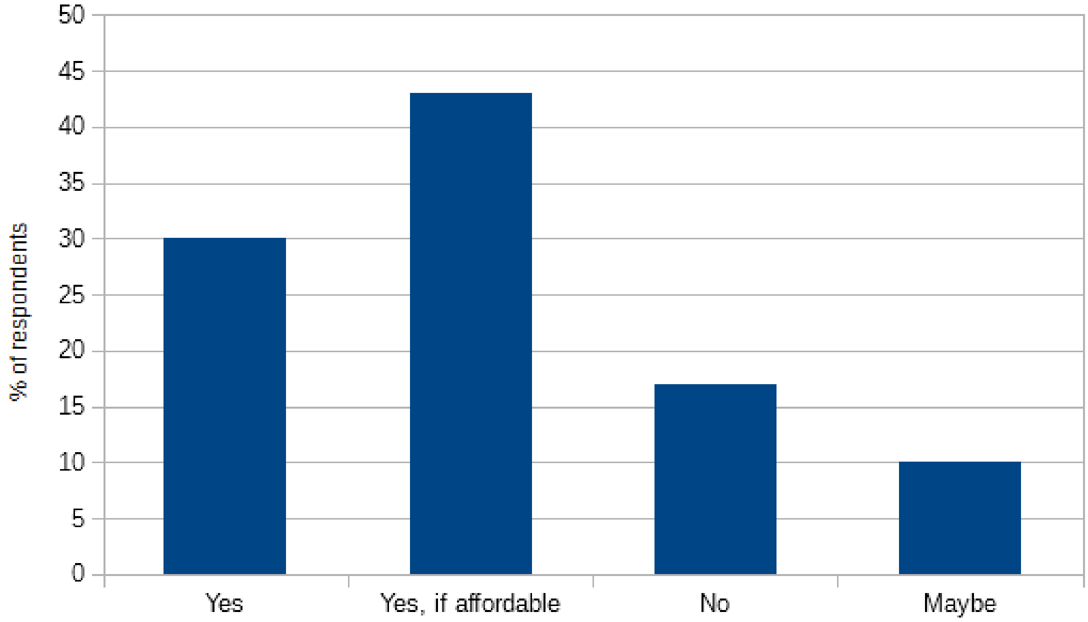

Figure 5.12: Interviewees were asked if they were willing to pay a fee to receive hail nowcasts directly from SAWS

5.3.7 Evaluating the performance of the automatic Titan nowcasting algorithm

Since SAWS generally depends on the automatic TITAN algorithm, an evaluation was performed to test its utility. Very little data exists that can be used to evaluate radar estimates of hail. The only potential strategy was to compare days where hail was widely reported in the media with days where no such reports were available. A total of 315 days of storm data was available. This spanned three years. During that time, six severe hail days were reported for Gauteng. The performance of this, using a similar setup that was reported by SAWS, was done for this period.

The data is described in Table 5.2. The algorithm observed all but one of the severe hail days. The biggest problem was that it predicted hail on 78 of the 315 days when it was not observed. While it is possible that some hail did occur on these days and was just not reported, it still translates into a very high false alarm rate. The evaluation is shown in Figure 5.13.

Table 5.2: The performance of the TITAN algorithm over 315 storm days

Hail forecast	Hail observed	No hail observed
Yes	5	78
No	1	231

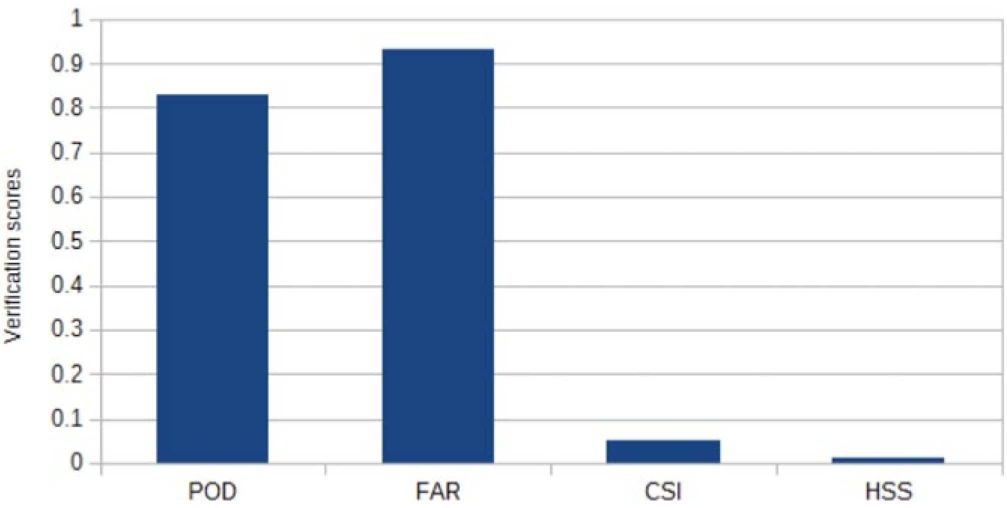

Figure 5.13: The performance of the TITAN algorithm on 315 days versus hail storms reported in the media

5.4 SUMMARY

The findings yielded valuable insight into why and how individuals used hail forecasts. As expected, the majority of the interviewees checked forecasts and identified themselves as “weather enthusiasts”. This finding was reliable compared with the findings of previous studies. Most of the participants retrieved weather forecasts during the mornings. This was found to be consistent with the results of this study, which showed that several participants use forecasts to decide what to wear or for daily activities. Moreover, most of the respondents obtained weather forecasts from mass media platforms such as television and the radio. The majority of these participants consulted weather forecasts for pragmatic reasons, such as deciding what to wear. Some 83% of the interviewees reported mild to severe damages to either their homes or their vehicles. Some 42% of the respondents stated that an SMS would be the most preferred means of communication in sending out warnings, followed by social media networks.

The majority of the interviewees were concerned about hailstorms due to the amount of damage it could cause. Furthermore, more than half of the interviewees added that they received hail warnings via SMS from their insurance companies. Not surprisingly, most of the participants preferred receiving hail warnings as soon as possible. These results were compared to other previous studies. Out of the 30 interviews that were conducted, 70% of the respondents reported that they would rather be over-warned of hailstorms, even if it is a false alarm. This result was consistent with the study conducted by Ripberger et al., (2015). Some 80% of the interviewees explained that they would save money, and that being prepared for hail events would be a relief to them. It is evident that the majority of interviewees valued hail warnings. Their reasons for valuing warnings varied from individual to individual. The majority of these interviewees explained that hail nowcasts could help them save money and cut on unnecessary expenses such as damaged vehicles and properties. Nowcasts would also assist them in ensuring the safety of their loved ones. A few interviewees mentioned that it could help city officials make sure that the drainage systems were well maintained, which would reduce floods caused by severe storms. As expected, most of the interviewees were willing to pay a fee to receive hail nowcasts directly from SAWS, but only if it was affordable. Finally, 17% of the respondents were not willing to pay a fee because they already received weather warnings from their insurance companies.

It should be noted that this chapter is based on one of the challenges experienced by SAWS, i.e. not being able to nowcast hailstorms due to it being expensive, there not being enough specialists in the field and lack of motivation. The results of this chapter could therefore serve as motivation for SAWS to do nowcasting regularly.

CHAPTER 6: CAPACITY BUILDING AND THE COMMUNICATION OF RESULTS

One of the main justifications for this project is building capacity in precipitation observation science to ensure the sustainability of this infrastructure in South Africa. Activities that were pursued in order to achieve this aim included the training of students, international collaboration and the presentation of a national weather radar workshop.

6.1 BUILDING CAPACITY IN STUDENTS

This project provides the opportunity to expose students to a living laboratory. The infrastructure that was established closely matches that used by SAWS and other institutions.

6.1.1 High school students through the SETH Programme

As part of the NWU's Science, Engineering, Technology and Health (SETH) Programme, high school students visited the institution on four separate occasions during the project. The project team, including all students involved, hosted these students and showed them the different technologies presented in this report. A formal programme was also developed that will be run annually from 2019 (Figure 6.1).

6.1.2 Undergraduate students at NWU

Undergraduate students are exposed to radar and weather observations through a course at second- and third-year level. Online tutorials on radar, satellite and precipitation science, developed by the COMET® Programme of the Universities Corporation for Atmospheric Research (UCAR), play an important role in this initiative. Students have to complete ten of these tutorials. At third-year level, students have to perform a research project in groups. A tutorial is being developed to train third-year students on the basics of weather radar. This will be delivered to students between 18 July and 21 October 2020.

Figure 6.1: Interactions with Grade 8 pupils as part of the project

6.1.3 Honours students at NWU

An honours module has been developed at NWU that introduces students to earth observation. As part of this module, students get to work with radar, weather stations and rain gauges. Through this project, students get hands-on experience with radar and other observational technologies. Two of the students also focused the research component of their honours programme on the infrastructure developed through this project (See Table 6.1).

Table 6.1: Honours students who participated in the project

Student	Student no	Year
Lindiwe Khumalo	25395904	2019
Dlangamandla Moletsane	27770826	2019
Nzuzo Shongwe	28311108	2019
Lerato Tshisi	27032175	2019
Leandri Wessels	27227715	2019
Prince Chidhindi	25267108	2018
Michael Cloete	26062232	2018
Desiree´ Coen	25886584	2018
Sue-Nique Davies	25945009	2018
Orlinda Mafika	26918676	2018
Tlhomaro Marebane	29570433	2018
Marizanne Minnaar	26125226	2018
Chante Cronje	25184954	2017
Laurike De Beer	24927945	2017
Francois Du Plessis	25050524	2017
Ketshepaone Modise	24362565	2017
Janette Murray	25060384	2017
Scott Van Eeden	24232246	2017
Ilán Van Staden	24976482	2017
Pierre Venter	25417312	2017

** Names in bold italics completed research projects related to the project.*

6.1.4 Master's and PhD students at NWU

This project helped fund three MSc students and partially funded two PhD students (Table 6.2).

Table 6.2: Students for the period 2017–2019

Student	Affiliation	Role
Runyararo Matandirotya	NWU	PhD student
Jaun van Loggerenberg	NWU	PhD student
Henno Havenga	NWU	MSc student
Francois du Plessis	NWU	MSc student
Nisa Ayob	NWU	MSc student

6.2 INTERNATIONAL COLLABORATION

Strong ties were forged with a number of international organisations and institutes as part of this project. This includes NCAR, the National Oceanic and Atmospheric Administration (NOAA) and Global Learning and Observation to Benefit the Environment (GLOBE). Delegates visited South Africa in May 2017 and again in April 2018.

A meeting was held on 15 May 2017 to coordinate potential collaboration between the project team, SAWS and GLOBE. Dr Paul Kucera and Dr Martin Steinson are the principal investigators in a project called 3D-PAWS.

The aim of this project is to build capacity at national weather services by providing them with low-cost sensors and 3D printed weather stations. Workshops are held to teach participants to build their own weather stations. This technology has been transferred to the project team and the first 3D-PAWS stations are almost ready to be deployed. A second visit by Dr Kucera in March 2018 further strengthened international collaboration. During this meeting, the upcoming 3D-PAWS workshop in September 2018 was planned.

Table 6.3: Project team for the period 2017–2019

Person	Affiliation
Roelof Burger	NWU
Paul Kucera	NCAR
Martin Steinson	NOAA
Mark Brettenny	GLOBE
Jongikhaya Witi	SAWS
Mahlako Lemekoane	SAWS
Johan Stander	SAWS

6.2.1 Radar workshop between 30 July 2018 and 3 August 2018

A radar workshop is planned as part of the project. The workshop is being organised in coordination with SAWS. Participants from other universities will also be invited.

6.3 METED TUTORIALS

One of the challenges of this project is to ensure that the infrastructure and capacity developed at NWU benefits students and researchers at all institutes of higher learning. One potential vehicle is online resources for the South African community in the form of the project website and meted tutorials.

The project team has made contact with members of the UCAR's COMET® Programme, which currently hosts online training material for atmospheric science. The potential to include region-specific content in the existing modules was discussed. While the existing online tutorials already provide a great resource for meteorology and climatology students, most of the content is based on examples from other parts of the world. The goal of locally relevant education would make this online resource more applicable for South African universities, as well as SAWS. The team is exploring the potential of coordinating this effort.

6.4 LAUNCH OF THE LEKWENA RADAR

A media launch of the NWU's Lekwena radar was held on 30 March 2018. All stakeholders, including WRC, SAWS, Aon-Benfield, Senwes and the top management of NWU, were invited to the event. The programme director was Mr Dhesigen Naidoo, CEO of the WRC. The agenda was as follows:

Table 6.4: Agenda for the media event held on 30 March 2018

09:00	Registration and tea	
10:00	Introduction and welcome address	Vice-Chancellor: NWU
10:10	Department of Environment Affairs Ministerial Address	Dr Edna Molewa
10:30	Video of the project	
10:35	Climate data and water resources management	Deputy Director-General: Department of Water and Sanitation

10:45	SA Radar Network and climate data	Mr Jerry Lengoasa
11:00	Data in climate and water research	Dr Stanley Liphadzi
11:15	Overview of radar research at NWU	Dr Roelof Burger
11:30	Launch of the project	
12:00	Closure and vote of thanks	Prof Refilwe Phaswana-Mafuya
12:10	Lunch	

Figure 6.2: The Minister and the team during the media launch

6.5 THE 2019 NRF NATIONAL SCIENCE WEEK

The project team collaborated with the NWU's science centre to host 25 schools and approximately 1,500 learners on the NWU campus during the 2019 National Research Foundation (NRF) National Science Week between 29 July and 2 August 2019 (Figure 6.3). The theme for the 2019 National Science Week was "The harsh realities of climate change". Brochures were developed (Figure 6.4) and shared during the week.

The project team mobilised approximately 45 students to assist with 12 different activities. School learners arrived at 09:00 each day and stayed on campus until about 15:00. During this time, they alternated between the different activities.

The following activities were presented:

- *Rainfall trends over North West:* Students were shown graphs of how rainfall varies over time. The potential impact of climate change and the implications of climate variability were discussed. Students then built rain gauges from household objects.
- *Temperature trends over North West:* Students were shown graphs of how temperatures vary over time. The potential impact of climate change was discussed. Students then built basic thermometers from household items.
- *Air pollution and climate change:* Students were taken to NWU's atmospheric laboratories, where they discussed how air pollution is measured and the implications for South Africa.
- *Disaster risk reduction:* Students were taken to a computer laboratory and played a game that illustrated the concepts of disaster risk and resilience.
- *Geospatial information systems:* The concept of GIS was explained to the students and they were shown how it could be used by doing an exercise to map the retreat of glaciers.
- *Waste management:* Students discussed waste generation and management. They then played a game trying to minimise waste.
- *Environmental law:* Students were shown the inside of a mock court. They discussed the importance of law in the context of environmental protection.
- *Frogs:* Students were entertained by Mrs Frog and the importance of biodiversity was discussed. They had the opportunity to handle live frogs.
- *Aquatic ecosystems:* Students did multiple activities where they discussed the importance of water and our dependence on a healthy aquatic environment. These included visiting the NWU's aquatic laboratory, handling live fish, painting a picture on the laboratory wall and taking pictures.
- *The NWU's science centre:* Students spent time in the science centre exploring the different experiments.
- *Career advice:* The NWU's Marketing Department gave career advice to students.

Another component of the National Science Week was public lectures. Six public lectures were held, some of these by students on the project team. Students were also given brochures to share with the public in the province. At least 800 signatures of public participants were obtained. These activities were filmed and a video showing the events during the National Science Week is available.

Figure 6.3: A collage from the NRF's National Science Week activities during 2019

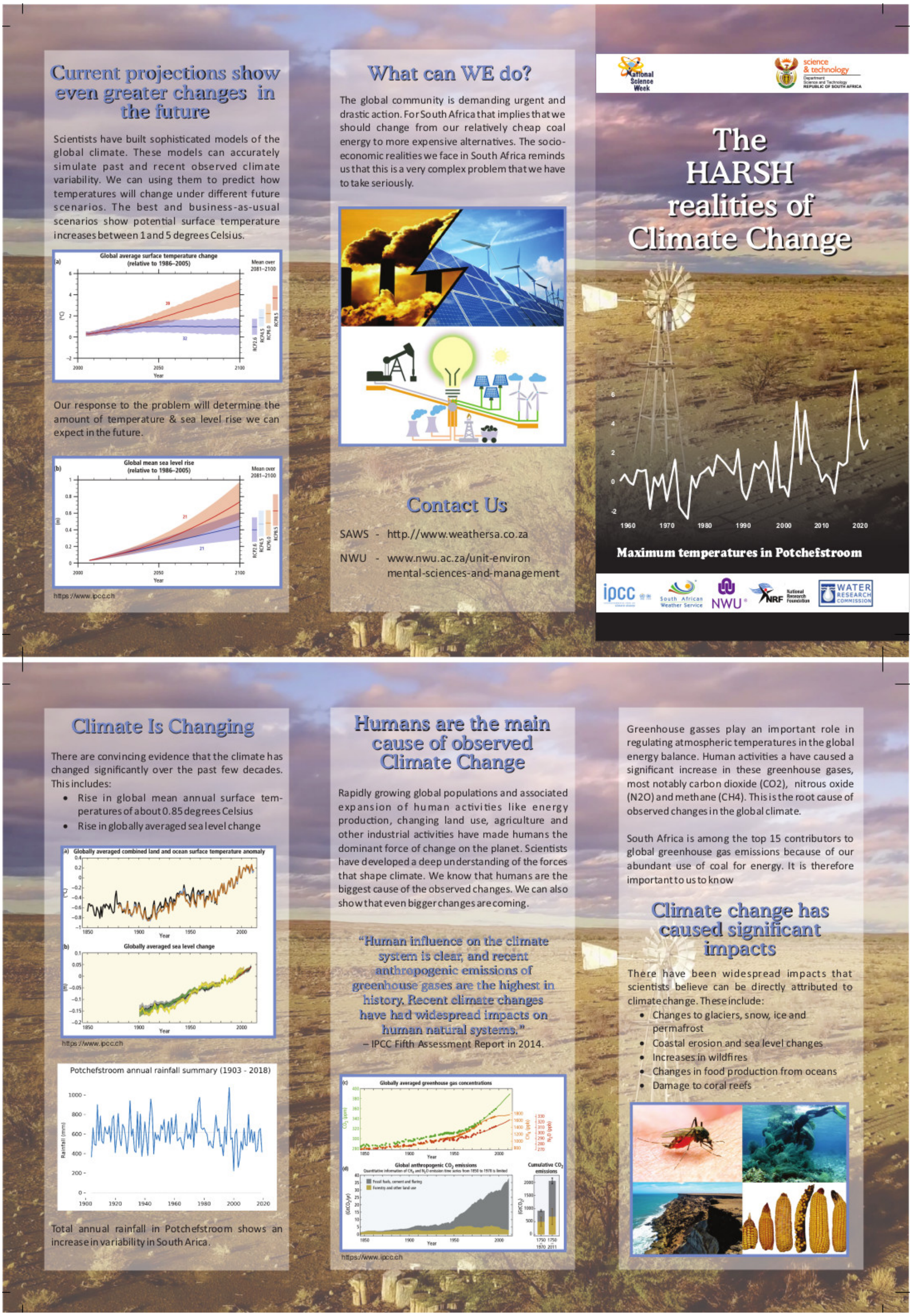

Figure 6.4: The brochure for the NRF's National Science Week

6.6 PROMOTIONAL VIDEO OF THE PROJECT

A professional video was made to promote the project. This was loaded onto YouTube (https://www.youtube.com/watch?v=57KKY4zxU88&t=111s) and is also accessible through the project website.

Figure 6.5: A frame from the project video

6.7 A WEBSITE TO DELIVER PRODUCTS IN REAL TIME

A website was set up to deliver products to stakeholders in real time. To use and deploy a website on the world wide web, a domain had to be bought and registered from a third party. The current registered domain is www.lekwenaradar.co.za. Once the domain has been registered, a developer can build a website according to the needs of the organisation. The nature of the website and the living laboratory is aimed at empowering and teaching both undergraduate and postgraduate students to be directly involved in the development of the website.

A GitHub account was set up to facilitate version control of code related to data analysis and visualisation, and to host the website. A website is in development to improve the visibility of the completed projects. The GFS models, satellite products and the Lekwena radar output are currently shown on the website. The website aims to be a simple, efficient platform for scientists from any research entity to view and download data without any concern for affiliation. Students will be encouraged to learn interactively from the web platform by viewing real-time weather, satellite and forecast data.

The website was deployed using Jekyll and GitHub. Jekyll allows websites to be built locally for testing before deployment (Figure 6.6). A strategic decision was made to keep the website static. This allows for a reliable and easily manageable website through GitHub. Students had to learn basic HTML and Markdown to develop the website. A dedicated Linux server was acquired for this purpose. The server is similar to the Radar 2 server discussed in Section 4.2.2.

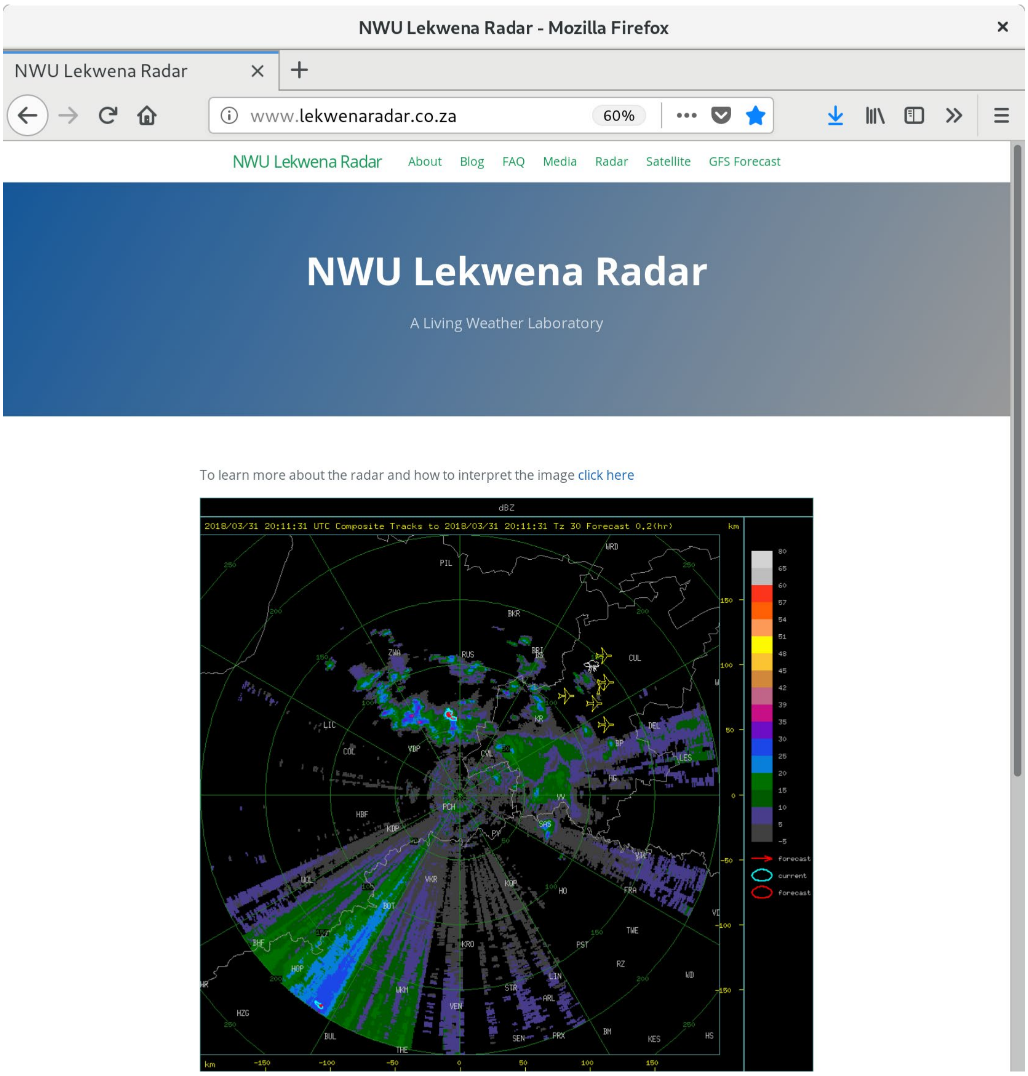

Figure 6.6: The http://lekwenaradar.co.za website

6.7.1 Re-analysis data

The CRG currently has several servers running on the NWU's network (see Chapter 4). Currently, Bongani is used as a backup solution for radar data and configuration files. The second local server is the Titan 5 dedicated radar host. The Titan network links to Gaia and is used as a web host to provide the radar data to the public. The CGR also has access to the NWU-HPC, a 32-core Linux server maintained by NWU. The NWU-HPC is used for running low-resolution weather simulations using WRF and testing compiling and run-time options for various climate models. The CRG also has access to the NCAR's Yellowstone supercomputer for high-resolution modelling.

6.7.2 Radar data

The radar data is stored on both the Radar 1 and Radar 2 servers. It is further transferred to an online Dropbox cloud-storage account. All students have access to an allocated Dropbox account where they are required to store all data collected as part of their research. Dropbox has been found to be the best cloud-based solution as it has Linux, Windows and Apple Mac clients. Data stored and managed through this cloud-based solution is key in the case of system failure or theft.

6.7.3 Satellite data

Satellite data for the study area is being delivered through the project website. These products will be further integrated into the project website over the next year.

6.7.4 Observational data

A network of rain gauges is being fitted with modems to provide real-time access to rainfall and other weather parameters. These datasets are also delivered through the website.

6.8 RESEARCH OUTPUTS

6.8.1 Conference proceedings

- BURGER RP (2018) Potential new technologies to assist cost-effective evaluation of seeding. Improving thunderstorm identification and tracking to support weather modification projects. Annual Weather Modification Association meeting in Estes Park, Colorado, USA, 24–27 April 2018.
- HISCUTT F, BURGER RP and KUCERA P (2018) Low cost loggers for rainfall measurements. Annual Weather Modification Association Meeting in Estes Park, Colorado, USA, 24–27 April 2018.
- AYOB N, BURGER RP and PIKETH SJ (2018) Perceived benefits of hail nowcasts over the Gauteng Highveld. SASAS Annual Conference 2018, Ballito, South Africa, 20–21 September 2018.
- HAVENGA H, BURGER RP and PIKETH SJ (2018) The trends thermodynamic indices over Irene, Gauteng. SASAS Annual Conference 2018, Ballito, South Africa, 20–21 September 2018.
- MATANDIROTYA NR, CILLIERS DP, BURGER RP and PIKETH SJ (2017) Characterising heat loss in low-income houses, Kwazamokuhle, Mpumalanga, South Africa. National Association for Clean Air Annual Conference, Sandton, South Africa, 4–6 October 2017.
- HAVENGA H, BURGER RP and PIKETH SJ (2019) Exploring unintended anthropogenic impacts on severe weather over the South African Highveld. Geophysical Research Abstracts **21**, EGU General Assembly 2019, Vienna, Austria, 7–12 April 2019.
- AXISA D, DeFELICE T, BAUMGARDNER D, BURGER RP, THROCKMORTON J and FREW E (2019) Developing an autonomous cloud seeding system for rainfall enhancement. Geophysical Research Abstracts **21**, EGU General Assembly 2019, Vienna, Austria, 7–12 April 2019.

6.8.2 Graduates

- Nisa Ayob, 2019, MSc, Hail nowcasting over the South African Highveld. Student no. 23799110
- Henno Havenga, 2018, MSc, Characterising hail over the South African Highveld. Student no. 22743529
- Edward Serumaga-Zake, MSc, The impact of rainfall variability on subsistence farmers in the North West province, South Africa. Student no. 17096464
- Newton Matandirotya, PhD, Exploring thermal insulation and energy use in low-income households on the South African Highveld. Student no. 29806062

6.8.3 Present students

- Jaun van Loggerenberg, PhD. Student no. 21714355
- Francois Du Plessis, MSc. Student no. 25050524

CHAPTER 7: CONCLUSIONS

Progress has been made towards the stated objectives. Seven students are directly involved in the project, with a further 10 honours students being exposed to the science and technology through workshops and hands-on experience in 2017, and six honours students in 2018. One of the 2017 students has joined the project and two of the 2018 honours students are doing their research projects on this project.

This report focuses on the work performed to ensure real-time access to the data generated during this project. The overall aim of this project is to build national capacity to ensure the sustainable use of the national observation weather infrastructure. The project team believes that a facility that provides real-time access to universities and other stakeholders can play an important role in bringing together a community to foster and enhance capacity building around the observation of weather in South Africa.

The observational infrastructure of this project includes the NWU's Lekwena radar, a network of rain gauges and a few AWSs. As part of this component, a microwave link was set up to network the radar with the NWU. Derived products are delivered on a website (http://www.lekwenaradar.co.za). Real-time access to the full four-dimensional radar dataset is provided by an LROSE server that makes it possible for anyone to explore the data using the Jazz Java application. Stakeholders can also be provided with the data in real time using an LROSE server. All other data is available through the project website. This is the first time that access to these datasets is provided at this level in South Africa.

Efforts continue to increase the reliability of the network to ensure continued operation. Interference from unlicensed Wi-Fi networks remains a problem and deteriorates the rainfall products from the network. Discussions with the Independent Communications Authority of South Africa (ICASA) continue to find a solution to this problem. The loggers are being deployed in the rain gauge network. The next report will document this and other work performed on the project. A report detailing the progress on the other objectives is the next deliverable. It is expected to be completed by mid-April 2018.

7.1 PROJECT OUTCOMES

A summary of the project outcomes includes the following:

- Capacity building
- A programme to expose high school students to precipitation observation technologies
- Undergraduate and postgraduate programmes to give students hands-on training on the same technologies used by SAWS and ARC
- Postgraduate student participation
- Training workshops for SADC participants
- Technologies for real-time observations
- A low-cost, low-power data logger
- Updated radar software
- A website to communicate real-time data
- High-resolution, real-time weather observations for capacity building
- Real-time radar observations from the Lekwena radar
- Real-time weather observations
- An assessment of the public perception of nowcasting
- An initial indication that a need for nowcasting products exists
- The inclusion of SMS and social media as the best technologies for nowcasts
- An indication that people are willing to pay for nowcasts

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