science & innovation
Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA

HSRC
Human Sciences
Research Council
DCES
Developmental, Capable
& Ethical State

Strengthening disaster risk resilience through enhanced coordination mechanisms at local level in flood hazard prone areas: Case study of KwaZulu-Natal province

Prepared for:

HSRC's DCES

By:

Wilfred Lunga, Moremi Nkosi, Precious Tirivanhu, Thanyani Madzivhandila, Tshegofatso Ramaphakela, Yamkela Majikijela, Alubafi Mathews Fubah, Charles Hongoro

"Whilst the flood duration is short-term in its nature, the impacts are typically long-term and sometimes humans or systems never recover"

Contents

Introduction

Approximately half the world's population has moved into cities and other peri-urban areas. This type of urbanisation is predicted to continue (Bai et al. 2018, Williams et al. 2018). However, accommodation and amenities are generally unplanned or unprepared for the sudden upsurge of humans associated with such rapid urbanisation, and thus posing big challenges concerning the efficient administration of cities, worse so, in the developing world (United Nations Development Programme Report 2018). Under this scenario, the urban poor are not only characterised by low-incomes and overcrowding, but are also confronted with substandard housing and limited or no access to other basic services such as sanitation. They lack secure tenure, face insufficient access to safe water supplies, lack proper sanitation, and the areas lack drainage and solid waste management infrastructure. Healthcare and emergency services are also under pressure. Furthermore, such areas are commonly found in environmentally vulnerable zones, and thus at risk from the effects of climate change (United Nations Development Programme Report 2018). Local authorities are unable to provide affordable housing for the poor. Consequently, over 1 billion people reside in informal settlements globally primarily across Africa, Asia, and South America. These informal settlements are very prevalent and are part of the social and economic fabric in countries such as Brazil, India, Mexico and South Africa. In these regions and countries, informal settlements sprout out around cities, in peripheral areas, and on marginal lands where people are still able to gain access to urban resources such as job opportunities, healthcare services, or education (International Institute for Environment and Development report 2018).

Climate change is accentuating environmental risks through increases in the frequency and the intensity of extreme events including heat waves, floods and storms (United Nations Development Programme Report 2018). Informal settlements have become particularly vulnerable to increased rainfall and flash floods, extended periods of decreased rainfall, and prolonged stages of intense heat or cold, as well as rising sea levels. During the United Nations conference on disaster risk reduction held in Sendai, Japan in 2015, scientists acknowledged a rise in disaster-related losses, impacting economies, social, health, and environmental issues in the short, medium, and long term (Bai et al. 2018). During the last several years, evidence continues to increasingly point to an increase in the cost of disasters, and more specifically attributed to storms and floods. The exposure to flooding seems to be one of the most recurring disasters, and its impacts are compounded by an increase of human density in flood-prone areas (International Institute for Environment and Development Report 2018; Pachauri et al. 2014).

The concentration of elements at risk in such zones can be explained by the attraction of rivers or areas in their proximity because of easy access to water and fertile lands in valley bottoms. For South African cities, historically, planning ensured that buildings were established away from low-lying, and potentially high floods-risk, areas. However, this approach left gaps of unoccupied lands, which lead to a mushrooming of informal settlements. With climate change, these low-lying areas have become death traps during flash floods because they have no proper drainage systems or flood-attenuation infrastructure in place. As a result, social vulnerability is concentrated in these informal settlements. There is a growing prevalence of inadequate infrastructure to cope with the impacts of climate change to protect the populations, particular vulnerable ones living in high-risk areas. Population growth and expansion further exacerbate flood vulnerability for poor communities (Kellens et al. 2013). Poorly built housing units and lack of access to basic services compound the risks further. Subsequently, flood events account for over half of the disaster-related fatalities and about a third of economic losses (Wehn 2015). Sadly, the risk of flooding will further increase with global warming (Hirabayashi et al. 2013). Interestingly, while climate change is occurring at a global scale, the response to climate-induced hazards is typically local, which indicates that the capacity of local governments to address and mitigate against such hazards is vital (Wehn 2015). Local governments need policies and strategies, which lessen the impacts of climate-induced risks on communities (Surminski et al. 2017). This challenge is particularly important when it comes to informal settlements, as not only are these commonly excluded from formal urban planning processes, but often do not have properly structured systems of governance or controls.

Management of flood risk is usually divided into risk assessment and mitigation (Schanze et al., 2006). This distinction considers apart from the hazard itself, its impacts, since the total elimination of risk is not possible. At regional scales, strategies against floods' impact require the identification of high risk areas (Tehrany et al., 2013) in order to provide early warning, facilitate quick responses and decrease the impact of flood events (Kia et al., 2011). Economic pressures may also explain the increase in the density of populations living in flood-prone areas. In Quarry Road informal settlement (located in Durban, KwaZulu-Natal (KZN) Province), inhabitants as well as informal jobs opportunities, are located in flood prone areas and thus exposed to the risk of flooding. This highlights the importance of assessing the exposure of the area to flooding as well as estimating the damage potential.

The devastating floods of 2017, 2019, 2020, 2021, and 2022 in the Southern African Development Cooperation (SADC) region, particularly those affecting Mozambique, South Africa, and Zimbabwe, have highlighted the need for more effective and efficient national flood-forecasting and timely warning systems. The South African Weather Services (SAWS) is a national specialized centre that provides meteorological services and is the national focal point for flood forecasting and flood vigilance in South Africa. Currently, SAWS acknowledges the importance of land exposure and considers that as key factor for flood alerts. However, SAWS advisories are limited to the main rivers and urban centres. For the informal settlements in South Africa, it is just a wait and see approach based on actual rainfall measurements. There is no consideration of exposure to flooding, monitoring or early warning of events leading to a flood, which could assist with mitigating the extent of the hazard's impact level. The SAWS implements a warning method for flash floods using radar rainfall data. Although this method provides information on the magnitude of floods, it does not consider the community's elements at risk around the rivers, streams, and nearby informal settlements. Therefore, whilst it is beneficial for crisis management, it is limited in as far as it not giving information on the actual flood risk.

To improve the effectiveness of the existing systems, there is a need for introducing a combination of early warnings combined to an exposure index, which will be able to assess the risk of flood damage/impact in real-time. This study aimed to present an innovative and easily reproducible method to evaluate exposure to floods over large areas using simple land-use and Synthetic Aperture Radar (SAR) data to design a flood exposure index, which could be easily integrated into the SAWS early warning mechanism. For validation purposes, a case study of KZN related to the floods of the 3rd or 15th January 2022 tested the effectiveness of combining hazard and exposure to assess the risk of flood-related damage. This combination was considered a reliable approach in arriving at an accurate overview of the river areas and settlements most at risk of flash floods damage.

Following the above logic, this report is divided into the following sections. **Part 1** presents the main issues faced in South Africa in terms of flood forecasting. **Part 2** presents an innovative method to assess the exposure to flood; and **Part 3** presents a case study of the Quarry Road informal settlement in Durban, KZN to illustrate the usefulness of an exposure-based warning system, which monitors water levels in rivers, as well as underground water table during the period leading to a flood in order to trigger an early warning when surrounding soils have reached saturation (high water level), a point where there is no longer infiltration taking place but instead additional rainfall received will lead to overflow and flash floods. The final part of the report introduces the need of a post-flood damage database meant for validation purposes and calibrating future model predictions.

Factors associated with floods

Geographically, South Africa is located in a region of the world that is amongst those most vulnerable to climate variability and climate change (IPCC, 2012). Due to its location, South Africa often experiences mid-latitude systems that move towards the east (Bopape et al., 2021), and the cut-off lows associated with this usually result in heavy rainfall and flooding over parts of the country. Flooding can occur when the amount of precipitation in an area exceeds the evaporation rate and infiltration capacity of the soil (Rachelle 2013). Most flood damage occurs as a result of long and intense flood duration associated with events such as prolonged and intense rainfall, cyclones, storms, and tidal surges (Stephen, 2012). Experience has shown that South Africa is ill-prepared for the heavy summer rains that cause flooding in eight of its nine provinces.

Massive rainfall events, failing drainage systems around roads, and ineffective or inadequate infrastructure design all contribute to flooding during heavy rains and have a critical influence on the extent of flooding experienced by informal settlements. Other important factors that may contribute to flooding of informal settlements include (a) overflowing of the rivers; (b) collapsed dams; (c) deforestation; and (d) climate change associated influences on rainfall patterns and rainfall intensity.

Key *issues impacting flood forecasting*

Generally, people most vulnerable to the effects of floods have low incomes, and live in low-lying areas, or valley bottoms such as those in informal settlements and peri-urban zones in Africa, Asia, and Latin America (Satterthwaite, and Bartlett, 2017). Worldwide, informal settlements are home to over a billion people. Therefore, there is a growing recognition of the importance of building resilience to flooding in informal settlements (Lines, and Makau, 2018).

The main challenge is in the geographical locations of such settlements versus the trade-offs for livelihoods and access to opportunities offered by central business districts. Climate change is becoming more evident with historical records showing that destructive floods and cyclones have continued to cause severe damage to infrastructure, properties, crops, livestock, and loss of human lives (Hossain et al., 2012). In recent years, not only has the frequency of floods increased but the severity of these floods has also increased (Naudé et al 2009; Klijn 2009; Shamaoma, Kerle & Alkema 2006; Wisner et al. 2004). If detailed, accurate weather forecasts, and early warning systems are built at the correct scale; and flood information issued and communicated timeously, and actioned upon, then communities can reduce the impact of disaster events.

In South Africa, the responsibility to provide such forecasts is with local municipalities and/or dedicated state-owned entities. Floods such as the one over KZN province in January 2022 continue to cause damages to infrastructure revealing shortcomings in existing early warning systems at the local level. The systems currently in place continuously fail to pick up or locate the start of flood events and often underestimate the extent of damage that may arise as aresult of the flood events. Flood impacts assessments indicate that more needs to be done to increase awareness, and build systems, including disaster preparedness and risk reduction at a catchment area scale. In South Africa, informal settlements including those in KwaZulu-Natal experience scarcity of resources and a lack of coping mechanisms and face poor access to technology (Roberts et al., 2012), which all hamper their response to flood events.

The ability to access a real-time view of affected areas during a flood event is also critical for fast, accurate responses, and to initiate the recovery process. For example, during a flooding event, it is important to be able to visualise quickly the impact of flooding on infrastructure, critical facilities, and to locate people that require emergency rescue services. Water levels and access points can change rapidly, making it imperative to have a real-time view. Satellite imagery is important to developing a bird’s eye view of an unfolding event and to provide information relevant for proactive planning and decision making regarding early warnings and support to be provided to potentially affected areas. However, if flood waters need to be viewed at night or where there is cloud cover as often is the case during storms or precipitation events, optical satellite imagery is of no help since most sensors cannot capture data at night or through clouds (Liang, J., & Liu, D. (2020). SAR data is increasingly popular for monitoring natural disasters due to its ability to capture data at night and through cloud cover, dust, or smoke. SAR can also provide data to fill in the blanks left by optical sensors. Geographic information systems (GIS) is a powerful tool to integrate and analyze data from different sources and map flood risk (Correia et al. 1999). Zerger (2002) highlights the importance of connecting spatial analysis to the real-world during planning and decision making.

In order to assess the spatial distribution of run-off, flood waters, and the average flow over time in river basins, it is important to incorporate parameters such as slope, land use, and soil type in GIS models. Furthermore, it is possible with GIS to link flood vulnerability with important economic activities for specific areas (Van Der Veen and Logtmeijer, 2005). For example, Dewan et al. (2007) developed flood hazard maps in the Dhaka River basin in Bangladesh through GIS by processing data of the historical major flood events and considering the interactive effect of land cover, elevation and geomorphology. For Quarry Road informal settlement in Durban, KZN the starting point is to enhance the process of dealing with floods risk management, (i.e., timeous warning of an impending flood hazard, defining and identifying flood hazard zones where mitigation measures should be taken).

The South African flood vigilance system

In South Africa, meteorological forecasting is SAWS's prerogative. SAWs coordinates provincial meteorological centres (local offices for flood forecasting and warning). This forecast takes the form of "vigilance advisories", which consists of alerting people and disaster management centres about the possible occurrence of floods, storms, high or low temperatures. It enables communities to be prepared and encourages the watchfulness of potential road flooding conditions. The meteorological information is released over television and radio stations. There are four vigilance levels ranging from the colour green corresponding to the absence of imminent danger to the red colour corresponding to a high-level of danger. The goal is to anticipate floods for crisis management purposes. However, elements at risk, progression of floods, and water levels are not reported.

The merits of applying a SAR-based system for flood warning

Modernising flood management requires developing a suite of tools/indices or a network for a flood warning system. The proposed system for flood warning is based on a simple model at a catchment scale of a square kilometre (1 km²) resolution using SAR data, soil moisture, the

Digital Elevation Model (DEM), rainfall, and ground water level information in real time. The system can generate warnings depending on changing conditions, especially rising river flows, rainfall intensity, and rising water table. The water table level is monitored on an on-going basis using SAR data. Historical flood information will also be considered in order to assist with identifying elements at risk. With regards to historic floods, three different levels of warnings can be related to flood return intervals and the second zonation, corresponding to a return period ranging from 10 to 50 years. The final zonation, corresponding to a return period greater than 50 years. The system gives information on low-lying areas in the catchment with a size of 1 – 2 km^2. This small-scale resolution enables greater accuracy in flood warning. The flood warnings will also provide information on the magnitude of the water flow in rivers considering the land use. Equal level warnings would be given for infrastructure (1 – 2 km^2) within informal settlements and urban zones. To make the distinctions between different zones and to compare them to each other, a common index [a generalized exposure index] was developed using weighting of several parameters for the entire region.

Study Site

Durban has a population of 3.6 million, making it the third largest city in South Africa (StatsSA, 2016). About 27.4% of the city's residents live in informal settlements facing key social, economic, and political challenges. The climate is subtropical, humid with warm, wet summers, and mild, dry winters. Studies project an increase in mean annual temperature of between 1.5 ◦C and 2.5 ◦C by 2065, and a further increase of between 3 ◦C and 5 ◦C by 2100. The projected rise in maximum temperature is likely to cause a higher incidence of heat waves and droughts. Mean annual precipitation exceeds 1000 mm per annum, making Durban one of South Africa's wettest cities. Studies project an increase in the total amount of annual precipitation by 500 mm. The Climate Service Centre in Germany has already recorded an increase in intense rainfall, and a decrease in rain-days for Durban. Their observations suggest an increase of storms and high intensity rain events, which could trigger frequent flooding in regions including the Quarry Road informal settlement. The combination of substandard housing, poor services, and increased rainfall intensity will accentuate the flood risk for these settlements.

Quarry Road West informal settlement is representative of many other informal settlements around South Africa and the developing world. It was established in 1984 in the eThekwini Municipality. The informal settlement consists of approximately 550 – 931 households and a population ranging from 1650 – 2400 individuals. The settlement has four municipally provided Community Ablution Blocks containing showers, toilets and wash basins. It is located near the city's residential suburbs, major transport routes and the Central Business District. This location provides opportunities for informal settlers to engage in informal work activities or part time work. Quarry Road West informal settlement is located on the narrow floodplain of the Palmiet River, near an extensive road network (**Figure 3.1**). Although the history of flooding is not well documented, there are various media accounts of the Palmiet River breaking its banks and causing flooding after heavy rainfall events. Many residents in the settlement have migrated from the rural areas of KwaZulu-Natal and the Eastern Cape.

The Integrated Development Planning (IDP) is a legislated process that is designed to be a local initiative to improve planning at the municipality level, including the participation and involvement of those residing in informal settlements. However, in many municipalities the initiative is still in its infancy, and is characterised by a lack of informed policies aimed at addressing spatial and socio-economic legacies of Apartheid, a housing backlog, and limited implementation capacity at the local level further hinders the realisation of equitable, just, accessible spatial development. In South Africa, informal settlements are not adequately incorporated into urban planning, and there are few possibilities for informal settlement communities to involve themselves in the planning process.

Figure 1: Location of the Quarry Road West informal settlement on an insert of a true color composite satellite image. The location of Durban in the southern African context is illustrated in the top left-hand box.

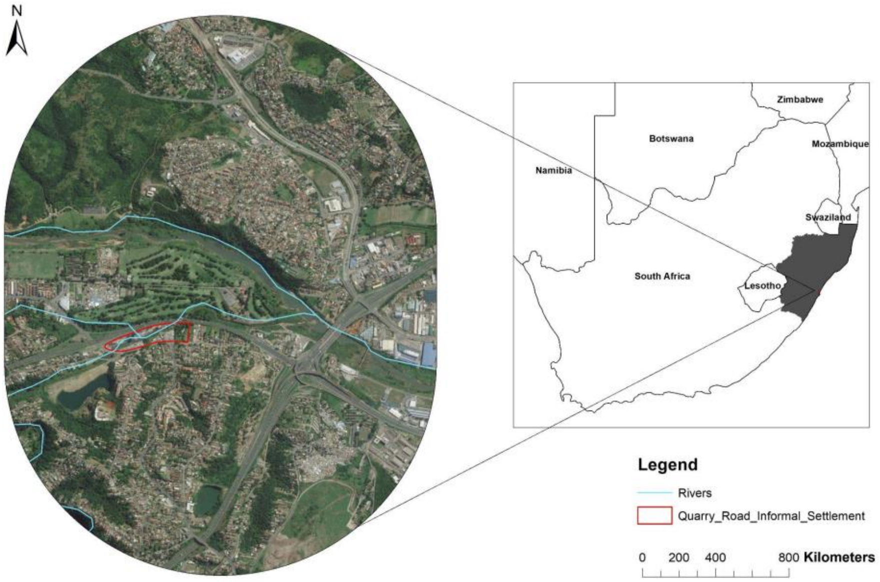
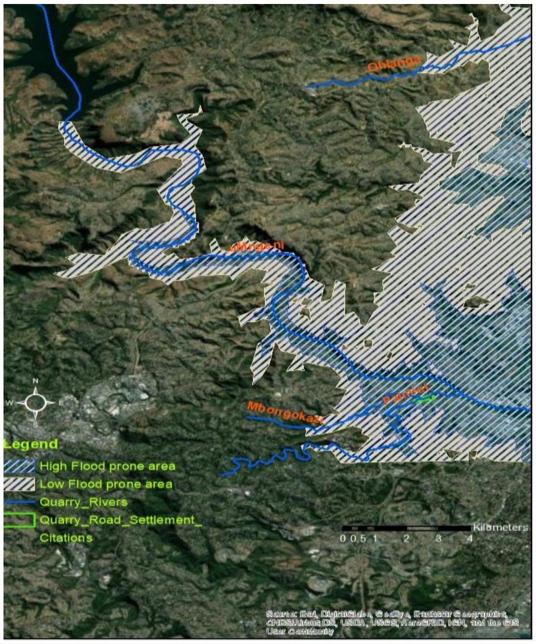


Figure 2: The geographical configuration of Quarry Road West informal settlement in terms of its exposure to floods



Methodology

To accurately map and delineate areas that are under risk of flooding or hazardous areas, the Analytical Hierarchy Process (AHP) method was applied using seven parameters. The parameters included (i) Drainage; (ii) Flow accumulation; (iii) Slope; (iv) Elevation; (v) Water holding capacity; (vi) Geology, land use, land cover, distance from the river, groundwater levels; and (vii) Rainfall factor. Based on the seven selected influential parameters, flood susceptibility mapping was achieved by giving each parameter a weight based on the significance of its influence. However, based on the amount of model input data requirements, it is always appropriate to make use of a high-speed computer capable of handling big data and processing the outputs.

Data sources

Table 1: Different types of data used as the study parameters and their sources

Data type	Source	Link to source
Digital elevation model (DEM)	United States Geological Survey	https://earthexplorer.usgs.gov/

Geological	Council for Geosciences	https://www.geoscience.org.za/index.php/publication/downloadable-material
Soil data	United States Geological Survey	https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en
Groundwater levels	Department of Water Affairs	http://www.dwa.gov.za/Groundwater/NGIS.aspx
Rainfall	Agricultural Research Council	https://www.arc.agric.za/arc-iscw/Pages/Climate-Monitoring-Services.aspx
Sentinel-2 MSI for Moisture index	United States Geological Survey	https://earthexplorer.usgs.gov/
Land use	Department of Water Affairs	https://egis.environment.gov.za/sa_national_land_cover_datasets
Sentinel-1	European Space Agency	https://sentinel.esa.int/web/sentinel/sentinel-data-access

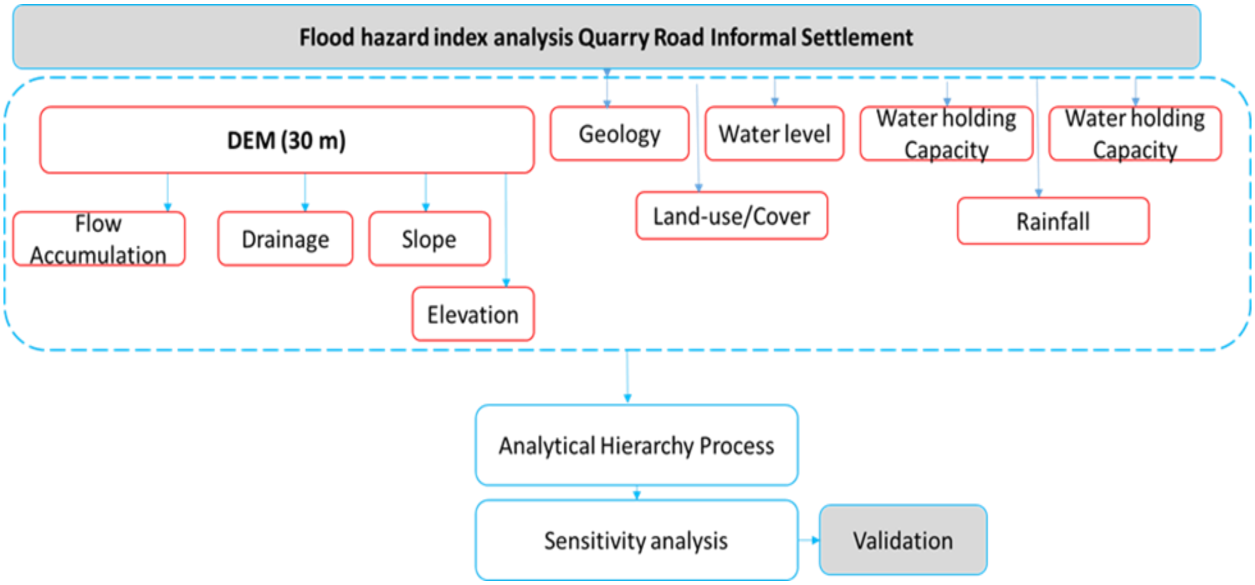
Software and Hardware requirements for the Quarry Road informal settlement flood analysis

The implementation of the techniques, models and processes described in this study of the Quarry Road informal settlement required the following software under Windows 10 Enterprise, 64-bit, CPU: Intel(R) Core (TM) i7-8650U CPU @ 1.90GHz RAM: 16GB GPU: Intel(R) UHD Graphics 620 (Driver: 27.20.100.9416)

1) ArcGIS 10.6.1 and corresponding Spatial Analyst extension (Esri) for all the GIS data preparation work as well as the application of a flood hazard model;
2) The flood hazard toolbox developed to apply the flood hazard modelling protocol;
3) Matlab R2021b (or higher) developed by MathWorks;
4) The programming codes for flood analysis application for disaster risk;
5) S-Plus 10.8 developed by Insightful Corporation, to explore and identify statistically significant parameters and their relative contribution to the spatialization of the precipitations using a stepwise multiple regression; and

6) Remote sensing software, such as SNAP Toolbox, Erdas or Envi to process remote sensing data for flood mapping.

Figure 3. A schematic flow diagram of the parameters and processes used for hazard analysis



Methods employed to obtain the model parameters

(a) Drainage

The drainage pattern was derived from the DEM and slope data. In events of rainfall when the soil is saturated, water uses these drainage lines to flow down where it accumulates resulting in flood occurrence. Therefore, it is crucial to demarcate elements at risk including the built-up area from such drainage zones.

To derive the drainage network of the Quarry Road informal settlement, the deterministic eight-node algorithm (D8) was used. The algorithm based on the DEM grid allocates the flow path or direction by giving every cell in the model a flow link from one cell to another cell based on the steepness direction. The upstream cells are higher than the downstream cells, which enables the drainage network to be defined. Although within the DEM depression cells occur, they confuse the algorithm in selecting the linking cells; to solve the issue of sinks, we used a fill sink tool in the Arc Hydro tool to reduce drainage network errors.

(b) Flow accumulation

Flow accumulation is the most crucial parameter in determining flood risk. Areas with higher flow accumulation values represent high flood potential zones. Water flows from low accumulation pixel values with high energy and concentrates at high flow accumulation values. Flow accumulation was derived using ARC hydro tool, which is a plugin for the ARCGIS software for watershed analysis based on the DEM data. In this study, the following steps have been applied in order to calculate the distance from the flow accumulation path:

1) The flow accumulation layer was derived from SRTM DEM 30m by using the Arc Hydro-tool for flow accumulation function.
2) An algorithm to select the cells that fall within the flood limits was used prior to the use of the reclassify tool on model builder using Python mode.
3) Computing the distance from these four classes separately by using the Euclidean distance function.

(c) Slope

The slope of an area is also an influential variable towards flood occurrences. Flat lying areas are more prone to flooding, flood waters accumulate for long periods in low lying flat areas causing water stagnation, which has detrimental effects on the social lives and the natural environment as a system. The slope map of the Quarry Road informal settlement was generated from the DEM data and classified into five classes depending on the slope degree.

To create the slope layer from the DEM, we used a script in Python that calculates both the slope and aspect. Four dependencies or libraries were used namely: (i) numpy; (ii) matplotlib; (iii) elevation; and (iv) richdem. The elevation library creates access to the elevation information within the 30 meters Shuttle Radar Topography Mission (SRTM) mission DEM, with the Kml polygon defining the Quarry Road informal settlement area coverage. In this step, the boundary assists in clipping every output GeoTIFF (.tiff) raster layer. The rd.TerrainAttribute function was used to derive the slope for each pixel in the DEM.

(d) Elevation

Elevation is a crucial factor in occurrence of floods, flooding and elevation have a contrary relationship with low-lying areas being more prone to flooding while high lying areas allow flow of water down slope. The elevation map of this study area was computed from a 30m digital elevation model with 10m pixels and was re-sampled to 1m, as the area is spatially smaller. The following steps were followed to obtain the elevation map from the DEM:

1) The GeoTIFF raster DEM was read in the ArcGIS environment to display the pixel values at each cell;
2) A fishnet grid was created to cover the resampled DEM;
3) The extract multi values to points tool was used to obtain the elevation values;
4) The XYZ data was then converted to raster format resulting in an elevation map; and
5) Subset area was created for the Quarry road informal settlement.

(e) Water holding capacity

Soil water holding capacity defines a measure of how much water volume a given quantity of soil can hold and permit it to slowly flow through. Different soil types have different capabilities of holding water or releasing water. Some soils allow water to pass through fast while some soils can hold water for a longer period of time. Water holding capacity is another factor that is governed by the soil type; soil type controls the rate at which water infiltrates the ground before flooding occurs. Clay soils have high water holding capacity; when it rains clay soils hold more water than sandy soils, therefore floods are more likely to occur in clay soil than in sandy environments.

Two variables determine how much water volume a given quantity of soil can hold. The variables are texture and the amount of organic matter content available. Soil texture, which defines the amount of particles of varying sizes which include: sand, silt, and clay in a volume of soil. On the other hand, soil organic matter defines the amount of decayed material that originated from plants.

We obtained the soil data that covers the Quarry Road informal settlement from the Harmonized World Soil Database FAO-UNESCO Soil Map of the World (Macfarlane & Yang (2017). The data was clipped using the settlement boundary. The information regarding the soil type in the area was extracted to a single value since the area lies within one soil type. The information was converted using the polygon to raster tool. From the FAO-UNESCO Soil Map of the World (FAO, 1971-1981) the water holding capacity of sand is 0.8"/ft, loamy Sand: 1.2"/ft, clay: 1.35"/ft, silty Clay: 1.60"/ft, fine Sandy Loam: 1.9"/ft and silt Loam: 2.4"/ft. In this situation, the quarry road settlement is made up of mostly sandy soil, it could only mean that it can hold 0.8" per foot.

(f) Geology

The geology of an area is key in determining flood hazards and plays a crucial role towards water recharge and infiltration. Hard igneous rocks have low permeability, which influences surface run off during rain events. Consequently, porous sedimentary rocks have the capability to allow water to pass through reducing surface runoff. The area lies within the shale formation with high water holding capacity. The geological data that covers the Quarry road informal settlement was obtained from the Council for Geosciences South Africa (geoscience.org.za) downloadable material database. The lithological information coinciding with the area boundary was clipped and the geology of the area was derived from this information.

(g) Land use

Land use has a significant effect on flood susceptibility, mostly people fail to follow the right protocols towards the use of land, such as poor farming methods, poor drainage designs and building on unsuitable land parcels such as flood lines. The land-use map was modified from the South African land-use land-cover map of 2020 available on the department of environmental affairs https://egis.environment.gov.za/sa_national_land_cover_datasets. Land use change has, potentially, a very strong effect on floods as humans have heavily modified natural landscapes. Large areas have been deforested or drained, thus either increasing or decreasing antecedent soil moisture and triggering erosion. Hillslopes were modified for agricultural production, thus changing flow paths, flow velocities, and water storage, and consequently flow connectivity and concentration times.

The land-use/land-cover of the area was extracted from the ready classified raster data of the national land cover using the clipping by mask tool in the ARCGIS environment. The land cover map was reclassified to ensure the sub classification of different settlement types found within the quarry road informal settlement.

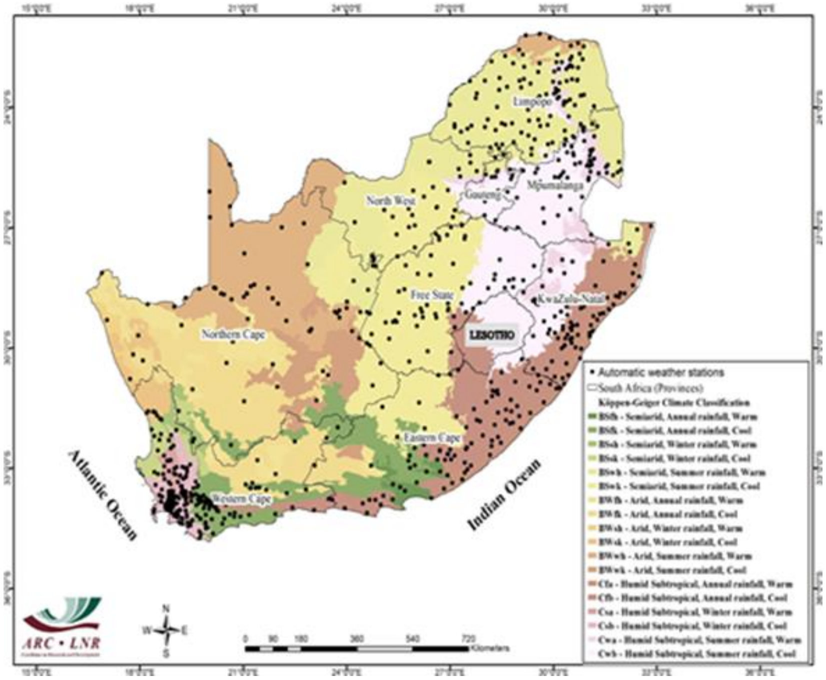
(h) Distance from rivers

The distance from the rivers has a direct link on the chances and extent of flooding because of terrestrial water storages that are highly linked with flood events. The map of this factor was prepared using the Euclidean distance tool and divided into five classes; a 40m buffer was used as per the Macfarlane & Yang (2017) protocol.

(i) Rainfall amount

Rain amount is a key factor that has the greatest effect on flooding, the more it rains, the more water accumulates to a point where soil saturation is reached and then run-off occurs. The spatial distribution of average annual rainfall in the Quarry road informal settlement for the January month was computed based on the geo-statistical approaches on the automatic weather stations data from the Agricultural Research Council throughout, South Africa. Pixels falling within the quarry road settlement were extracted to fit the study objectives.

Figure 4. Spatial distribution of the Agricultural Research Council automatic weather stations



(j) Water levels

Water levels distribution map was computed based on the national ground water archive borehole information that is updated every time from the monitoring wells. The data was acquired from the national groundwater archive website http://www.dwa.gov.za/Groundwater/NGIS.aspx. The site contains the updated groundwater levels found at the national water monitoring locations.

Data modelling exercise

Most flood warning systems do not clearly define the notion of exposure. Further confusion exists with the concepts of risk and vulnerability. Risk is the combination of hazard and element(s) at risk. Elements at risk are defined by both exposure and vulnerability. Hence, risk is a compound function of natural hazards and the number of people characterized by varying degrees of vulnerability who occupy the space and time of exposure to floods. However, exposure is often overlooked or confused with vulnerability. In this study, we defined exposure as the damage potential. Then to assess exposure, we must identify the location and attributes of the elements at risk. The concept of exposure has a spatial dimension as it characterizes whether or not an element will be directly affected by a flood hazard. In order to measure the exposure of a given area, we first have to identify the elements exposed to a flood hazard and then characterize their attributes.

For this study, we selected the elements located in flood-prone areas, then assessed their damage potential considering the nature of their characteristics. For instance, a hospital is by nature more exposed to a flood hazard as opposed to a supermarket. This is because the damage potential to a hospital is higher as the occurrence of a flood would imply the endangering of the patients, the staff, and the capacity of the hospital to fulfil its task.

(a) Identifying the elements at risk

To identify the elements at risk, we first delineated the flood-prone areas. Then, we selected the elements, which a flood can potentially damage. Once those elements were identified, we assigned them with an exposure value.

(b) Delineation of the flood-prone area

The delineation of the flood-prone areas is complicated, more so for large zones. The main issue is that the flood envelope may vary based on the severity of the flood. We mapped this area from a mix of existing data such as municipal boundaries, city boundaries, flood-prone areas and reported data from historical floods. Where there is no data available, the flood-prone areas can be delineated by DEM and applying the geology of the area. We used a classic topographic analysis method and to extract the flood areas from a digital elevation model. Many elements are likely to be damaged during a flood such as infrastructures, buildings, etc. For this work, we chose to take only into account the static elements in the form of land-use.

(c) Selection of the elements at risk

There is a lot of different land-use for Quarry Road informal settlement available. We needed both an easily accessible and complete database. For this purpose, we chose to resort to the land-use data from the ARC–NRE Institute. The data contains vector formats describing the land-use all over KZN. The database contains 10 themes with different subsets under which elements of the same object type (line, point, and polygon) are aggregated. Among those 10 themes, we made a first selection of 5, which are detailed in the table below:

At first, we identified and recorded roads and/railroad networks. Then, identified cultivated lands/vegetable/agricultural crops, and then buildings. Then, we identified a third group, which contains buildings with a special function such as hospitals, schools, or rail stations. Once these elements were sorted, we proceeded to select based on spatial relationships within the flood-prone area layer to obtain the actual set of elements at risk from flooding. Once the elements at risk were identified, the next step was to find a way to aggregate them by zone, to be able to characterize the damage potential of a given area. This way, it was easier to be working on an exposure index to homogeneously areas and assess as well as compare the exposure of different zones.

(d) Implementing an exposure index at the river reach scale

Assessing exposure is the first step to assess potential impacts of floods. The goal was to develop an easily reproducible method to be able to use the index not only on different areas, but also to update it as the land-use changes or in the presence/access to different data. To be able to compare different areas according to their exposure, we had to find a way to aggregate the elements at risk by area. To be able to compare the flood warning levels with land-use data, we needed to supply an exposure index at the same scale.

To that end, we chose to assess an exposure assessment at the river reach scale. In other words, we chose to aggregate the elements at risk by watershed. However, those elements have different natures that we need to take into account as it influences their damage potential. Indeed, to assess the damage potential of the elements at risk, we decided to prioritize them and assign them with a value according to their nature. The method we implemented was meant to enhance the flood warning system intended for crisis managers. The method allows a great flexibility but also requires fine adjustments to be as relevant as possible at the local scale.

To aggregate the elements at risk per watershed, we assigned them with a value according to their ranking in each object type. Then we used a spatial joint with a sum function on the settlement parameters, to aggregate the elements at risk within the settlement in a form of an exposure value per type of elements (network, building and building with special function). Finally, we added up the four types of exposure values to obtain a general exposure value corresponding to the damage potential of flood in the settlement.

Flood Hazard Index

The index was developed in a GIS environment aimed at defining flood hazard areas and providing early risk warning at impending flood hazards within a settlement area focus. However, we also provided target zones outside the Quarry Road informal settlement because of the coarse resolution of our data. The developed model incorporates a multi-criteria analysis. The index aims to assist with the identification of hotspots related to flood risk and allow a comparative analysis between different areas of the settlement. Initially, information from various data sources is fed in the GIS environment. This information is processed in a second phase and along with the definition of the parameters' weights, they result in the flood warning. The warning is the outcome of a sensitivity analysis.

Parameters included in the Flood warning system

The warning system comprises nine criteria–parameters, namely:

i. Flow accumulation (FA);
ii. Rainfall intensity (RI);
iii. Infiltration rate (IR);
iv. Water table level (WTL);
v. Geology (G);
vi. Land use (LU);
vii. Slope (S);
viii. Elevation (E); and
ix. Distance from the drainage network (D).

The selection of these parameters has been theoretically based on their relevance to flood hazards as documented in the literature (Haan et al., 1994). On the other hand, the selected parameters have been proved effective when included in relevant research studies and applications. Input data for each parameter was processed in a GIS environment and the seven parameters are visualized in independent thematic maps. The distance from the rivers was calculated by imposing buffer zones around the drainage network information. Finally, rainfall intensity and water table level was estimated from rainfall measurements and SAR data.

Relative weights of the criteria

The method considers the above hydrogeological, morphological and socio-economic parameters and the weight of each factor determines its role in the result. Thus, a spatial analysis of studied areas evaluates each grid-point on every parameter. Then, according to the local conditions, each grid point is assigned values on a scale between 2 and 10 (rating score). The classes of the flow accumulation, elevation and rainfall intensity were defined using the grading method of natural breaks, which has been used in similar studies (Huan et al., 2012; Kazakis and Voudouris, 2015). The slope classes were defined according to the Demek (1972) classification, whereas the classes of the distance from the drainage network have been defined by processing records of historical floods in the study area. The qualitative parameters of land use and geological formation were classified similarly to previous studies with modifications according to the characteristics of the study site (Kourgialas and Karatzas, 2011; Tehrany et al., 2013; Ouma and Tateishi, 2014). The acquired values are processed in order to calculate the relative significance of each criterion and the corresponding weighting factor (w).

The AHP is a pairwise comparison method to be used on the criteria regarding the objective, which in our case is to monitor the severity of floods occurring again. These pairwise comparisons are carried out for all relevant parameters within an analysis. Once the criteria have been consolidated and classified, the AHP is used to calculate relative weights, importance, or value, of each factor. Once the relative weights are assigned, we then calculate a priority vector, giving us the overall relevance modifier value for each factor, to be used in the GIS calculations. A Consistency Ratio (CR) is then found, in order to measure how consistent the judgements have been relative to large samples of purely random judgements. If the CR is over 0.1, then the judgements should be considered untrustworthy. Each input can be weighted according to its importance or its percent influence. The weight is a relative percentage and the sum of the percent influence weights must equal 100%.

To generate a flood hazard or risk map, three steps were followed, the steps are:

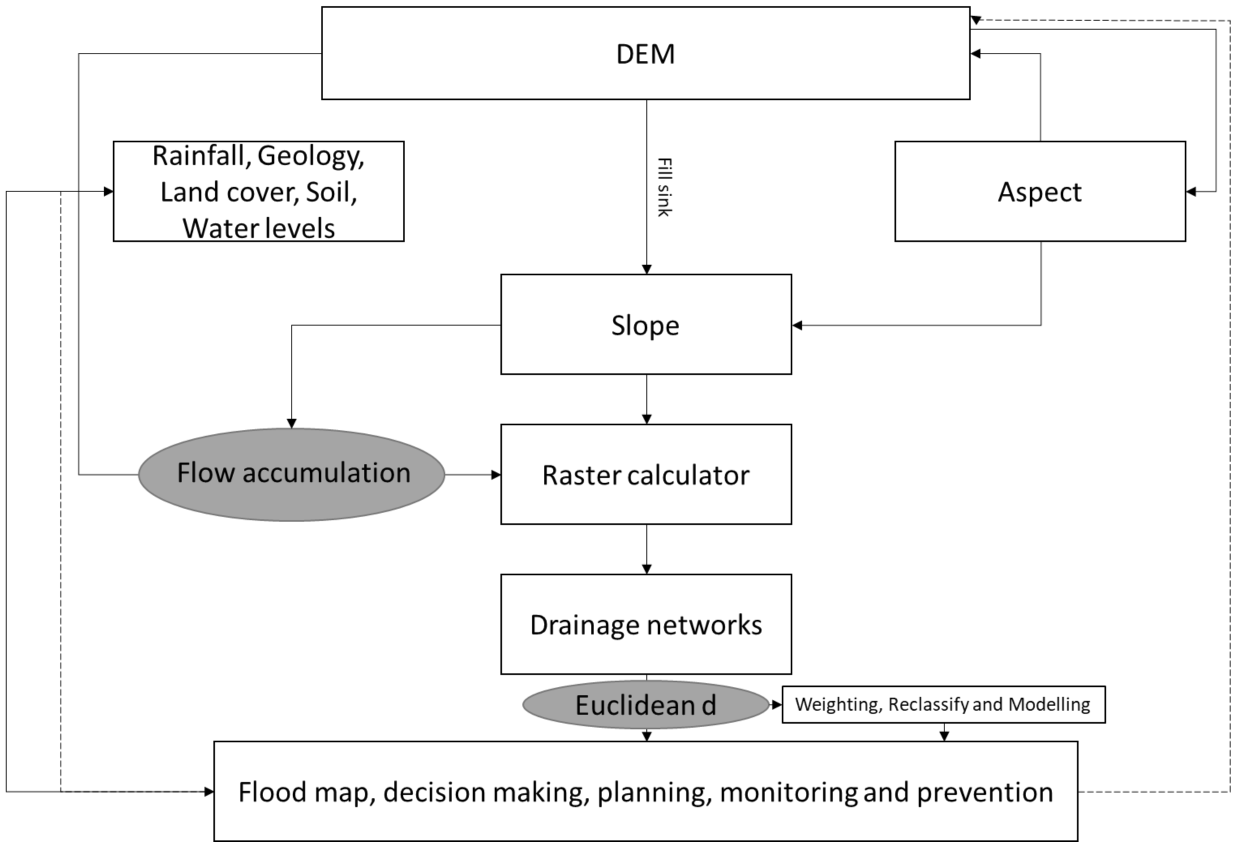
1) **Criteria maps were calibrated:** In this step, all criteria maps derived from various sources were set to one standard coordinate system (UTM 35°South, WGS1984). This allows layers to easily overlay and match cells. Each map has a rank of classes with the

lowest being bad and the highest being good or vice versa depending on the importance.

2) **Combining calibrated criteria layers:** At this step, all layers were combined to produce a hazard flood map showing areas with high risk and locations with low risk. Conditions were set to clearly delineate the hazardous areas.

3) **Masking out the flood zones:** All areas with high flood risk were removed by masking the Quarry Road informal settlement.

Figure 5: Flood risk assessment and management framework



Study Results

Drainage network in Quarry Road Informal; settlement

Figure 6 shows details about the drainage network of the Quarry Road informal settlement besides the main river, which cuts perpendicular to the network. The drainage network has a direct influence towards floods because it drives the run-off water to their zones of accumulation. The drainage network of the Quarry Road informal settlement appears in a radial network pattern, this type of network permits water flow towards a central point, which at this environment runs through the settlement towards the mainstream. The main river and the new network of tributaries cutting through the whole settlement indicate the elevated risk of flooding of the Quarry Road Informal settlement under intense rainfall events. This suggests that geographically, Quarry Road informal settlement is highly predisposed to flooding.

Figure 6: Quarry Road informal settlement drainage lines

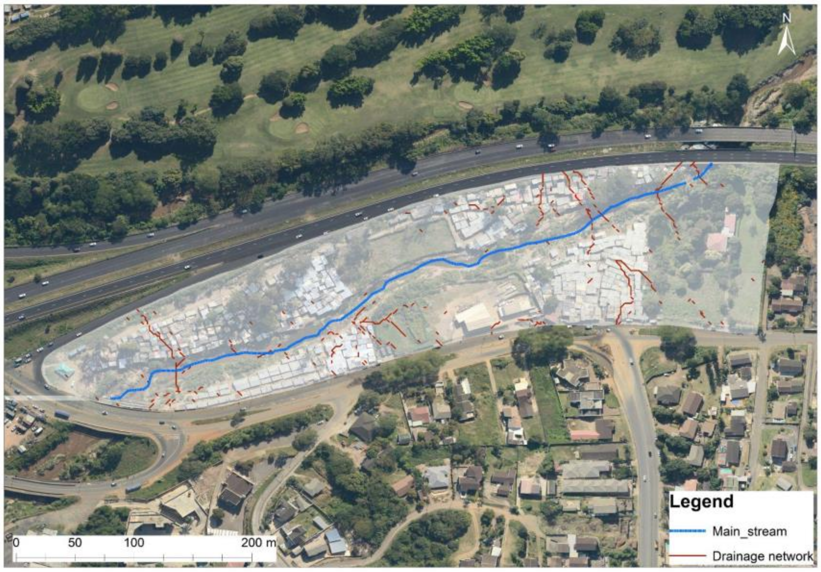


Figure 7 shows the flow accumulation derived from the combination of the DEM and the drainage pattern. Areas with high flow accumulation values are more prone to floods as compared to areas with low flow accumulation. There is a direct link between the drainage network and the flow accumulation in this area. The flow accumulation ranges between 0 and 5097, at the flow accumulation value of 5097 more water accumulates during rainy days, if more

water accumulates floods are prone to occur. Barriers such as blocking the flow of water by building along the drainage flow network promotes run-off water accumulation, as a consequence; any continuity if building along the water paths result in areas being flooded because water doesn’t find its way down stream.

Figure 7. Quarry Road informal settlement flow accumulation

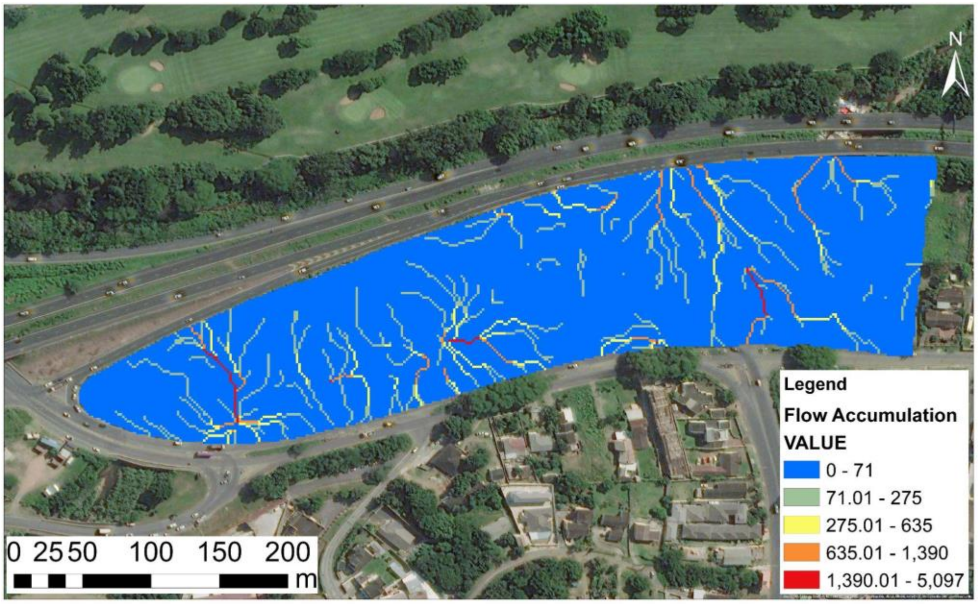


Figure 8 shows the slope of the area derived from the DEM and the flow accumulation; gentle slopes are more prone to flooding since all the run-off accumulates at low lying flat areas (greater than 90% of the total of Quarry Road informal settlement). On the other hand, steep zones trigger run-off rather than water accumulation. Areas that are flatter occur within the Quarry road settlement area making it more prone to flooding as indicated on drainage network description. The slope is however controlled also by different land use of the area as well as natural occurrences such as sedimentation and siltation without.

Figure 8: Quarry Road informal settlement slope

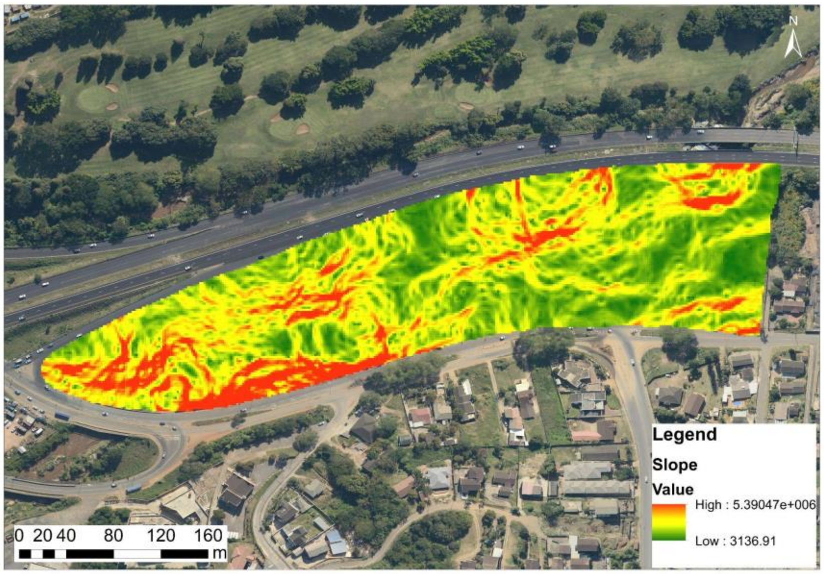


Figure 9 shows the settlement elevation, which is the range between the highest height above sea level and the lowest point of the area. Water flows from a high lying area to the low-lying zones. The highly elevated area experiences less floods or are more likely to experience a lag in flooding compared to the low-lying zones where water accumulates. Figure 4.3 shows that greater than 70% Quarry Road informal settlement is likely to get flooded quickly under intense rainfall events because it occurs in low-lying areas.

Figure 9: Quarry Road informal settlement elevation

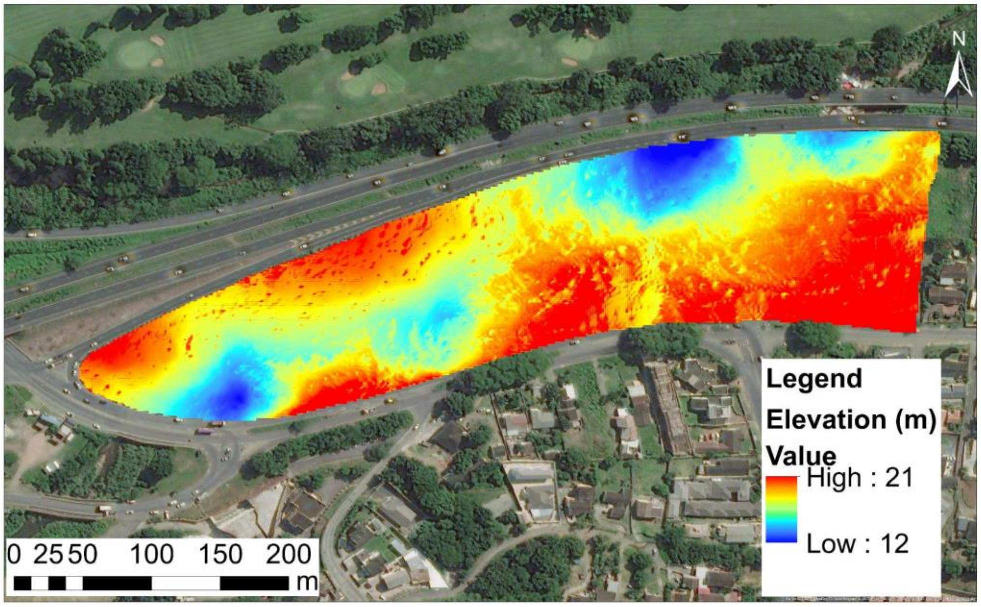
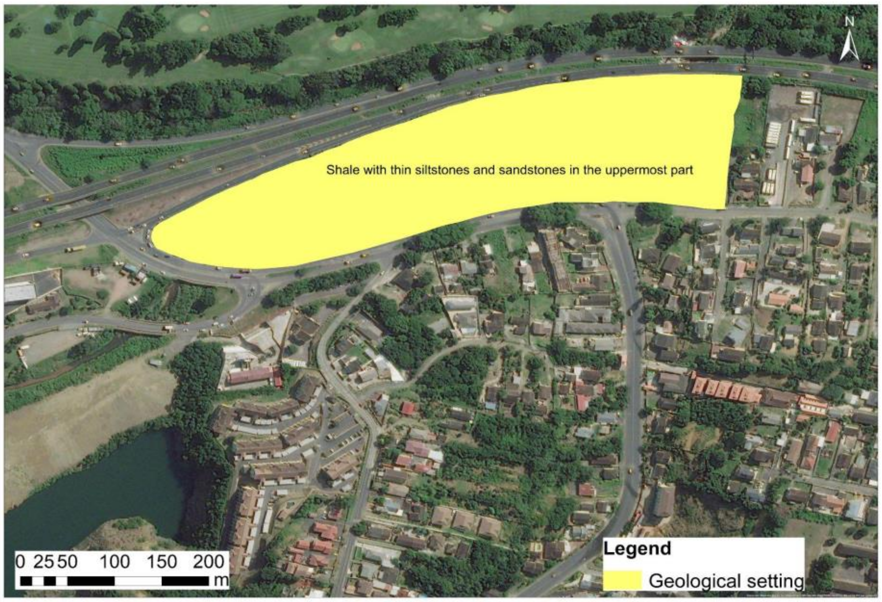


Figure 10 shows the geology of the area. There are no varying lithological units around the settlement, besides a strata of shale that overlays the underlying strata of the area. The geology of the area determines how water moves from one point to another. In the case of the Quarry road informal settlement, the presence of shale which is rich in clay minerals and high compaction influences flooding at a fast rate when it rains as there are less pores to allow water to pass through towards the groundwater level but rather accelerates surface run-off.

Figure 10: Quarry Road informal settlement geology



The dominant land-use type in this area is residential or settlement with less grass and few natural vegetation, with less amount of grass and vegetation. As shown in **Figure 10**, nothing traps the water or absorbs more water in the area leaving it bare to the extent where run-off and flooding becomes easy.

Figure 11: Quarry Road informal settlement land-use/ land-cover

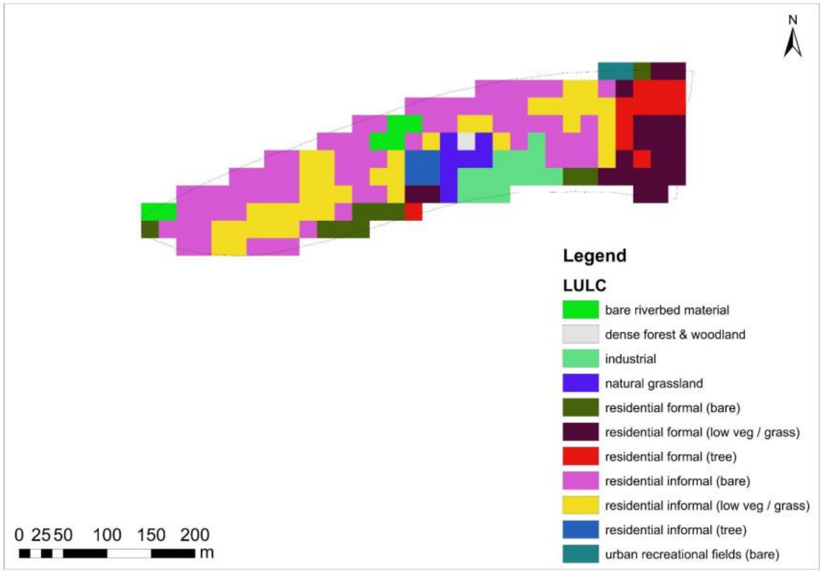

N
Legend
LULC
bare riverbed material
dense forest & woodland
industrial
natural grassland
residential formal (bare)
residential formal (low veg / grass)
residential formal (tree)
residential informal (bare)
residential informal (low veg / grass)
residential informal (tree)
urban recreational fields (bare)
0 25 50 100 150 200
m

Figure 12 shows the monthly average rainfall for the January period. The highest recorded rain amount was 481 mm. Around the Quarry Road informal settlement highlighted by a red polygon on the zoomed in insert (top right of **Figure 11**) high rainfall measurements were recorded. Broadly, the higher rainfall this area receives annually increases the risk of flooding. The risk is even more elevated during the summer period given that approximately over 95% of the rainfall during the three months window (October/November-March).

Figure 12: Quarry Road informal settlement monthly average rainfall

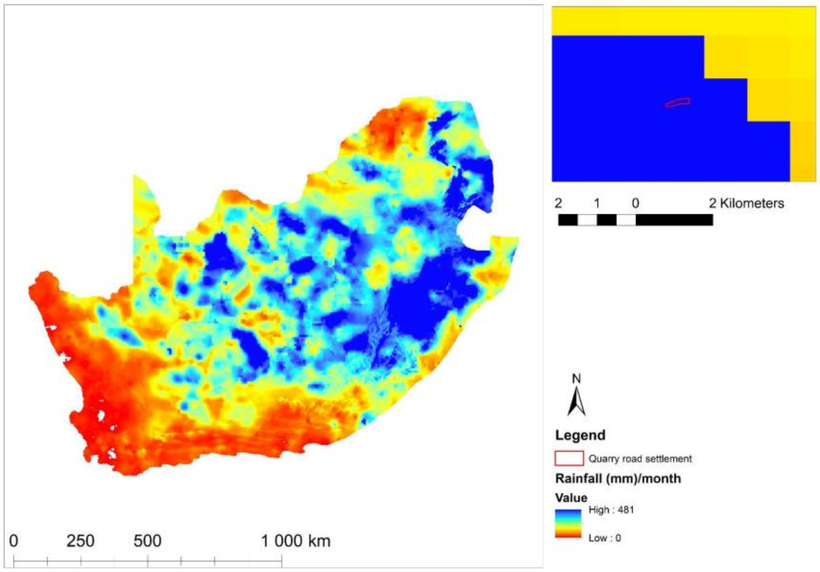


Figure 13 depicts the groundwater levels (m) above sea level measured during the summer season. It is evident that coastal areas have the shortest distance between the earth surface and groundwater levels. The Quarry Road informal settlement lies in a zone where groundwater levels were ranging from 1m to 6m. At such instances the surface soils remain saturated leaving no space for more water accumulation, consequently, flooding is always an omnipresent risk.

Figure 13. Quarry Road informal settlement groundwater levels

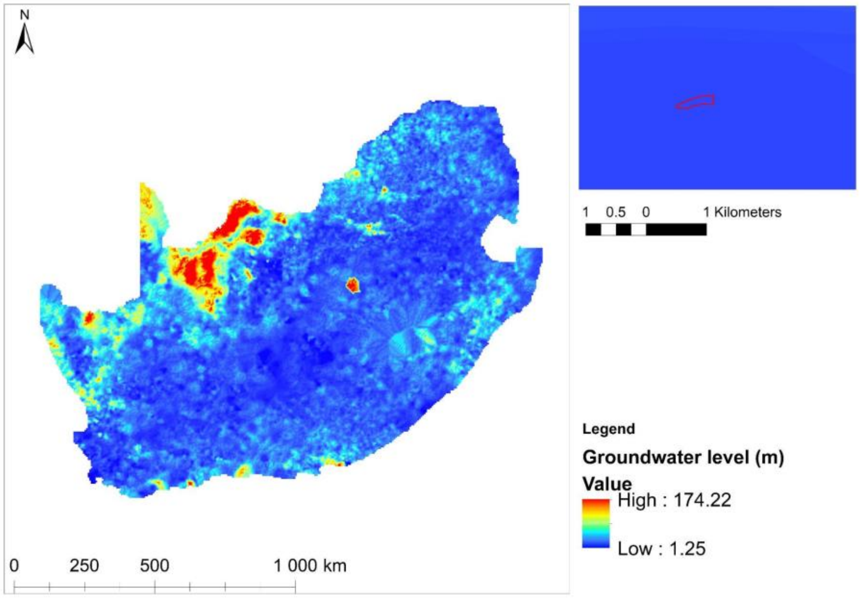


Figure 14 depicts the flood hazard index map, which shows areas that are more prone to floods and areas that are less prone to floods depending on the influence ranking amongst the 7 selected variables.

Figure 14: Quarry Road informal settlement Flood Index map

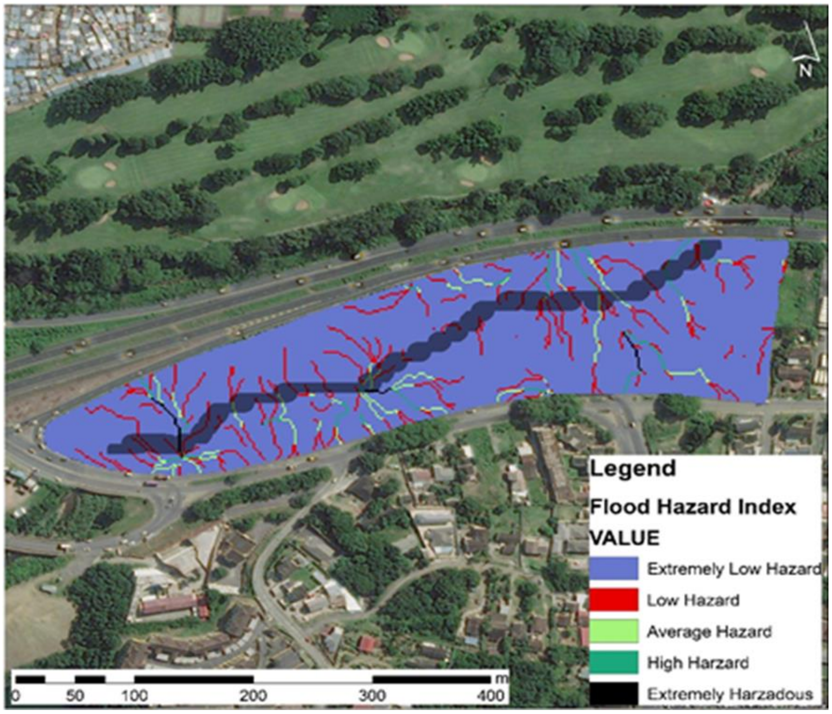


Figure 15 Quarry Road informal settlement Flood hazard vulnerability map

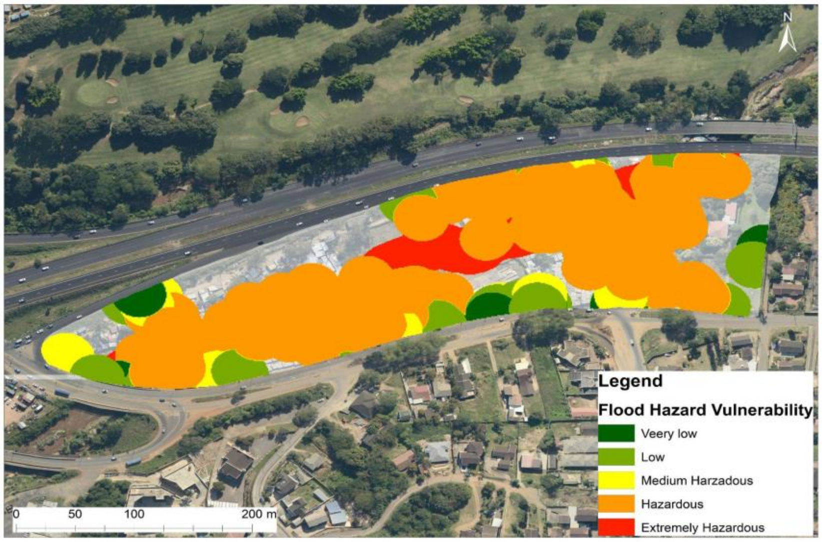
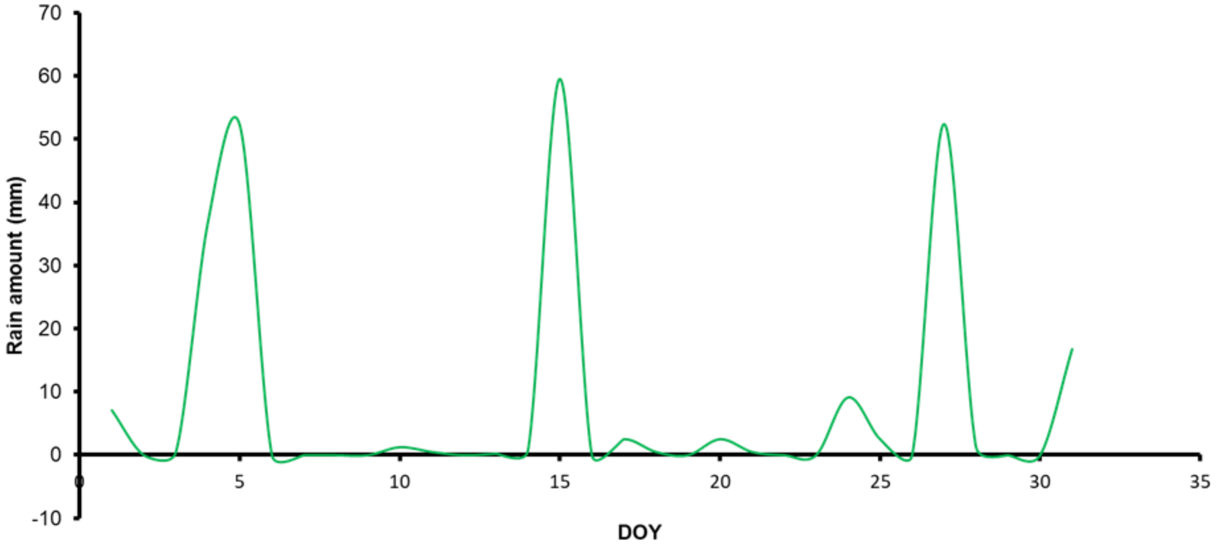


Figure 16 depicts the flood hazard vulnerability map, which shows areas that are more prone to floods and areas that are less prone to floods depending on the influence ranking amongst the 7 selected variables. It appears that more areas within the Quarry Road settlement are vulnerable to flood hazard. The daily amount of rain during the January period is portrayed in figure (15)

below, around the 2nd to the 6th of January the amount of rainfall received was about 55 mm daily while around the 15th January more rain towards 58 mm per day was measured. High rainfall might have been the reason the area was flooded.

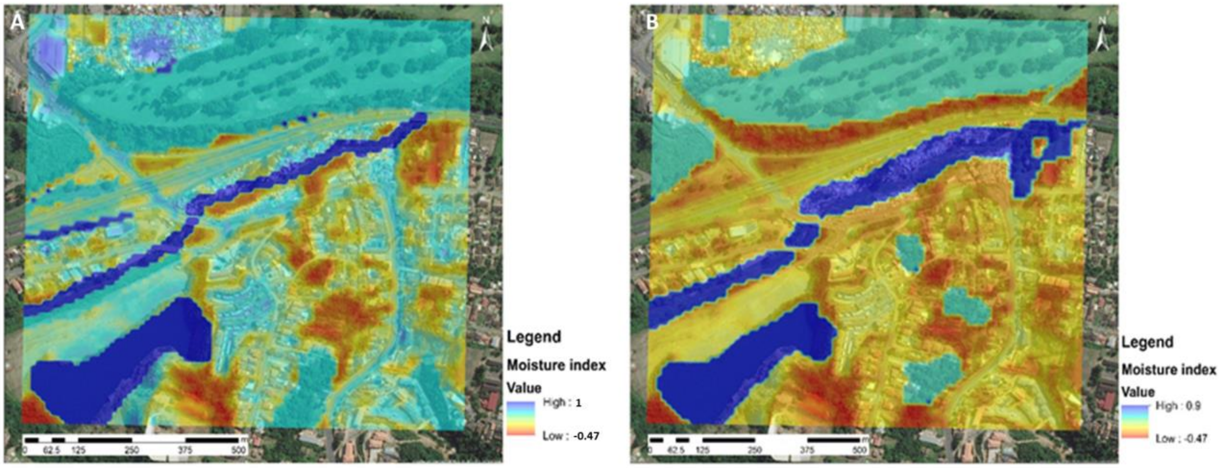
Figure 16: Quarry Road informal settlement-Rainfall in January 2022



Soil water content estimation

Soil moisture index was estimated using sentinel-2 MSI images for the dates before and post flooding at the quarry road informal settlement. The NDWI results from the following equation: Index = (NIR - MIR) / (NIR + MIR) using Sentinel-2 Band 8 (NIR) and Band 12 (MIR). The NDWI is a vegetation index sensitive to the water content of vegetation and is complementary to the NDVI. During the flooding time, soil moisture readings increased around the river extending towards the settlement area where water flowed from the zinc roof joining the stream water.

Figure 17: Depicts soil moisture index (A) prior flooding and (B) post flooding.



Modelling excise results

Table 2 shows the parameters used for flood hazard analysis using the Analytical Hierarchy Process.

Parameter	Flow accumulation	Drainage distance	Elevation	Land use	Rain intensity	Slope	Geology
Flow Accumulation	1	2	2	3	3	5	7
Drainage distance	1/2	1	1	3	3	4	6
Elevation	1/2	1	1	3	3	4	6
Land use	1/3	1/3	1/3	1	2	4	5
Rain intensity	1/3	1/3	1/3	½	1	4	5
Slope	1/3	1/4	¼	¼	¼	1	3
Geology	1/7	1/6	1/6	1/5	1/5	1/3	1

(a) Flow accumulation

According to the initial conjecture and the resulting values indicated in **Table 2**, flow accumulation is the most influential parameter in determination of flood hazard. The accumulated water flow sums the water flowing down-slope into cells of the output raster. High values of accumulated flow indicate areas of concentrated flow, consequently; these are the zones of high flood hazard susceptibility. The flow accumulation values vary in a range between

0–5097 with the higher flow accumulation values occurring in the settlement upper part, midpoint and the lower end downstream.

(b) Distance from drainage network

Besides the areas where the surface water is concentrated, the river-overflows are very important to note when dealing with flood analyses because they are the zones where floods initiate. Moreover, floods emanate from riverbeds expanding towards the surrounding settlement area causing nothing less than damage. The influence of the riverbed in floods decreases as the distance increases away from the bed. As a result, the distance from the drainage network has been assigned a high weight in the study methodology. The classes of this criterion have been defined by processing records of historical floods in the study area. It appears that areas near the river network (D<40 m) are in high flood hazard zones, whereas the effect of this parameter decreases in distances (D>40).

(c) Elevation and slope

Water flows from higher to lower elevations and therefore slope influences the amount of surface runoff and infiltration. Flat areas in low elevation may flood quicker than areas in higher elevation with a steeper slope. For the Quarry Road informal settlement, the high-elevation appears in the outer parts of the settlement and the upper part making the middle of the settlement and downstream to be in high flood hazard risk. For this area, low slope zones and low elevated zones have been assigned the highest rating, as flood prone areas.

Figure 18: Shows the elevation profile across the Quarry Road informal settlement

Measure the distance between multiple points on the ground

Length: 1,691.48 Meters

☑ Show Elevation Profile

☑ Mouse Navigation

Imagery Date: 9/17/2021 lat -29.804125° lon 30.966300° elev 18 m eye alt 870 m

Graph: Min, Avg, Max Elevation: 14, 18, 22 m

Range Totals: Distance: 1.68 km Elev Gain/Loss: 30.5 m, -27 m Max Slope: 12.0%, -12.2% Avg Slope: 3.4%, -3.2%

(d) Land use

Land use influences infiltration rate, slope and the debris flow. Moreover, while forest and grass favour infiltration, built up areas support the overland flow of water than infiltration. A large proportion of the studied area is covered by built up shacks and surrounded by grass, which have been assigned rates equal to 2 and 4.

Figure 19: Shows the land cover/ land use at the Quarry Road informal settlement

(e) Rainfall intensity

Rainfall intensity is expressed using the modified Fournier index (MFI). MFI is the sum of the average monthly rainfall intensity at each rain gauge weather station of the ARC-NRE surrounding the Quarry Road informal settlement. The spatial distribution of the rainfall intensity has been performed considering the allocation of stations in the studied area. Considering their relatively sparse set-up, we used the inverse distance weighting interpolation method, considering that a geo-statistical method would be more appropriate than ordinary kriging/co-kriging (Huang et al., 1998; Hutchinson, 1998). MFI for the whole of South Africa ranges from 0 to 481, with the higher values being part of the Quarry Road informal settlement.

(f) Geology

The geology of flood hazard areas is an important factor based on the utter fact that it may amplify the magnitude of flood events. Permeable formations favour water infiltration, through flow and groundwater flow. On the contrary, impermeable rocks, such as crystalline rock, favours surface runoff. Karst formations can also significantly affect the generation of flash floods (Bonacci et al., 2006). Therefore, shale as a product of loamy and clay materials have been assigned a rate of 8.

(g) Maps' interpolation

The proposed methodology linearly merges the selected parameters, taking into account the relative weights as part of the AHP method. This involves superimposing different thematic maps with different weights in the GIS model builder. From all the weight assigning, buffering and distance calculation, the flood hazard map is created (Figure 4.11), defining 5 classes of flood vulnerability (very low, low, medium, high, and extremely high). Classification is based on the inherent information of the derived, linearly combined data. Thus, the breakpoints in the Datasets are spotted by minimizing the variability inside each class and maximizing the variability among them, in a way like Statistics “Cluster Analysis”. Accordingly, datasets are divided into clusters by setting boundaries where significant changes in data values appear.

Most prone zones are housing areas, with some small-scale subsistence agricultural areas in the mix. Low to moderate prone areas appear mainly at mixed forests and sparsely vegetated areas. Therefore, we propose the FHIS index expressed from Eq. (5) for the assessment of flood hazard areas. The parameters' classes of land use and geology are location dependent and should be adjusted to the local characteristics of each studied area.

Table 3: Parameters applied in the model

Parameters	**Min**	**Max**	**Mean (μ)**	**SD (σ)**
Flow accumulation (F)	6.6	45.9	12.0	3.2
Drainage distance (D)	6.1	50.5	25.6	7.8
Elevation (E)	7.9	51.7	30.4	7.7
Land use (U)	2.2	21.6	7.4	3.4
Rainfall intensity (I)	1.1	16.1	5.0	3.0
Slope (S)	4.3	27.3	15.5	3.9
Geology (G)	0.6	11.6	4.0	2.4

Table 4: Categories of food hazards

Flood hazard	**FHI Area (%)**	**Number of events**	**FHIS Area (%)**	**Number of events**
Very low	20.7	0	13.7	0
Low	29.6	11	23.1	1
Medium	28.7	18	24.5	12
High	18.0	67	26.8	16
Very high	3.0	4	12.0	71

(h) A Remote sensing Perspective

In addition to an early warning system that aims at alerting the public well in advance before the flood event can occur to minimize the risk, mapping the extent of the flooded area is also important for damage assessment and post recovery measures. This exercise requires real-time, or near real-time view. Remote sensing data, particularly SAR products can be useful in this regard. This is because flood events are associated with cloud cover, and SAR sensors can penetrate such weather conditions (Liang & Liu, 2020). For the purpose of this demonstration, two Sentinel-1 IW GRDH (Ground Range Detected in High resolution) data were downloaded from European Space Agency (ESA) Sentinels Scientific Data Hub covering the pre and post flood event (Figure) of the test site. These images had a spatial resolution of about 20 x 5 m with double polarization (VV and VH) (**Table 5**).

Table 5: List of Sentinel-1 images acquired and used for demonstration in this case study.

Mission	Date	Mode	Polarization	Pass	Orbit
S1A	6/12/2021	IW	HV + VV	Ascending	40890
S1A	23/01/2022	IW	HV + VV	Ascending	41590

(i) Image analysis

The two Sentinel-1 images covering the pre and post flood event were pre-processed including orbit file applications to reduce orbital errors, speckle filtering, and geometric distortion using SNAP software (Bioresita et al 2018). The raw amplitude images were then calibrated to a backscatter quantitative use of SAR images (**Figure 20**). The images were further converted from sigma-nought to decibel to allow a more quantitative analysis of the images. Subsequently, Range Doppler Terrain Correction was applied to geocode the images. We applied a thresh-holding technique on the SAR images to delineate and differentiate water pixels and the non-water pixels (Liang & Liu, 2020).

Figure 20: Flowchart showing the overall SAR-based flood delineation method adopted in this demonstration.

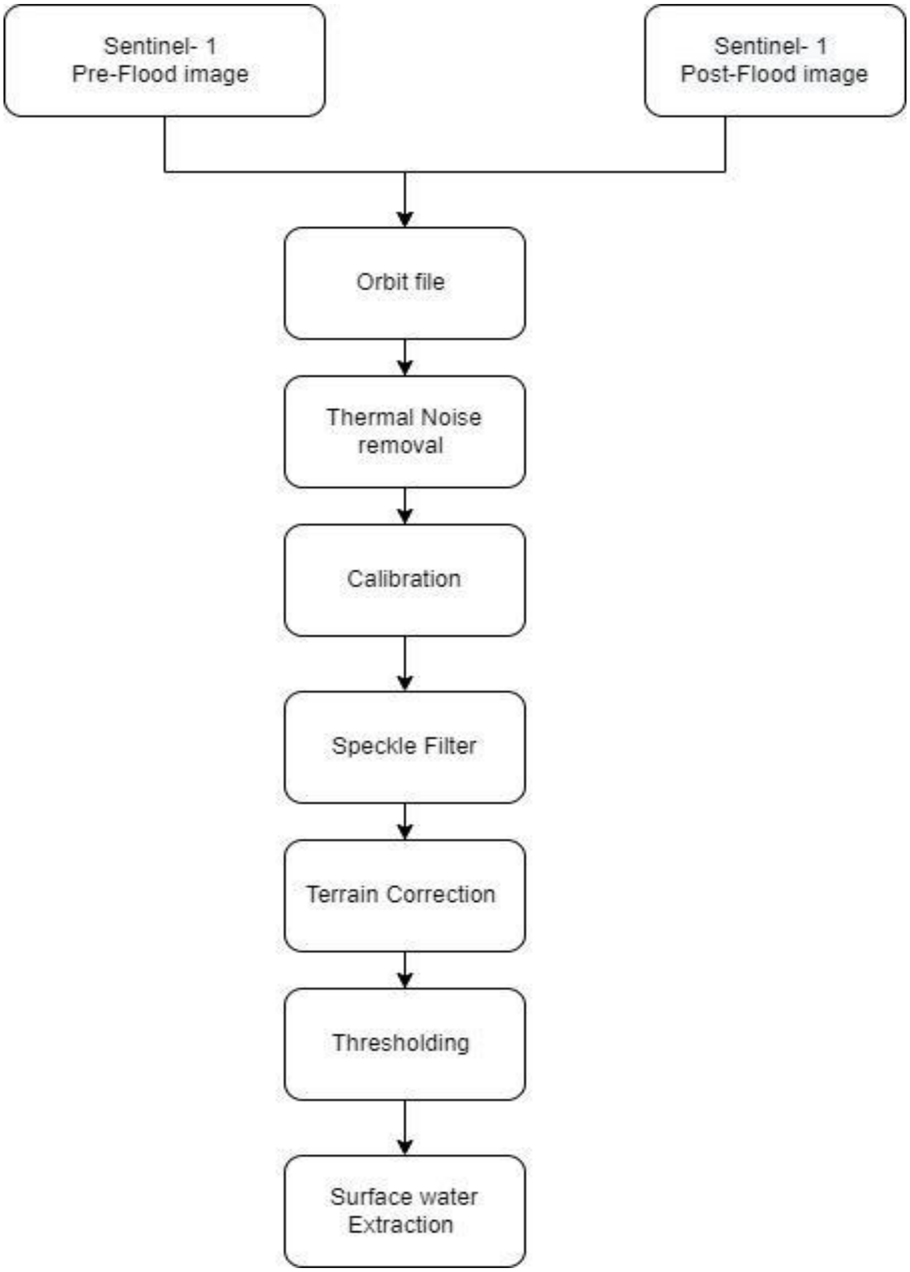

Sentinel- 1
Pre-Flood image
Sentinel- 1
Post-Flood image
Orbit file
Thermal Noise removal
Calibration
Speckle Filter
Terrain Correction
Thresholding
Surface water Extraction

Figure 21: Sentinel-1 image of the test site A) pre-flood event image, B) Post-flood event Image

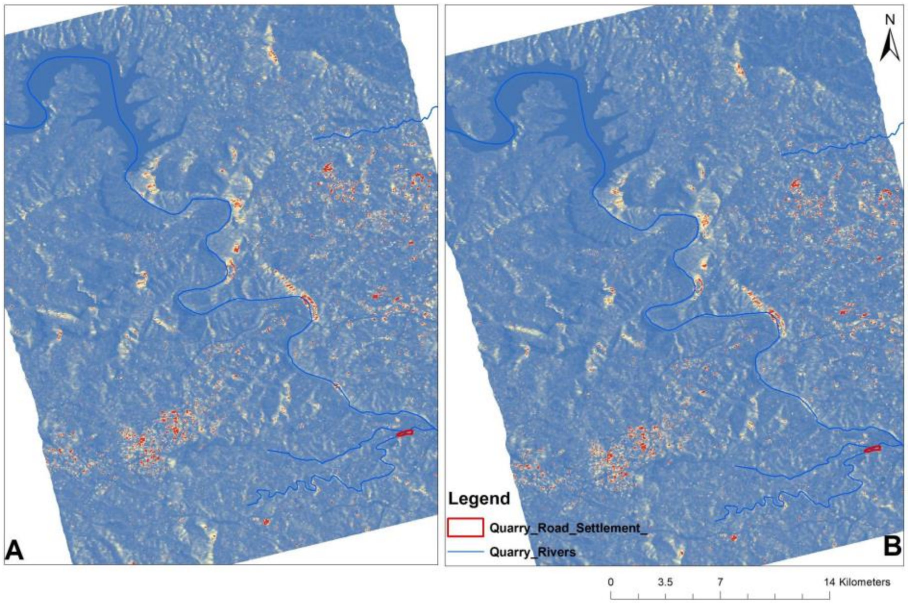
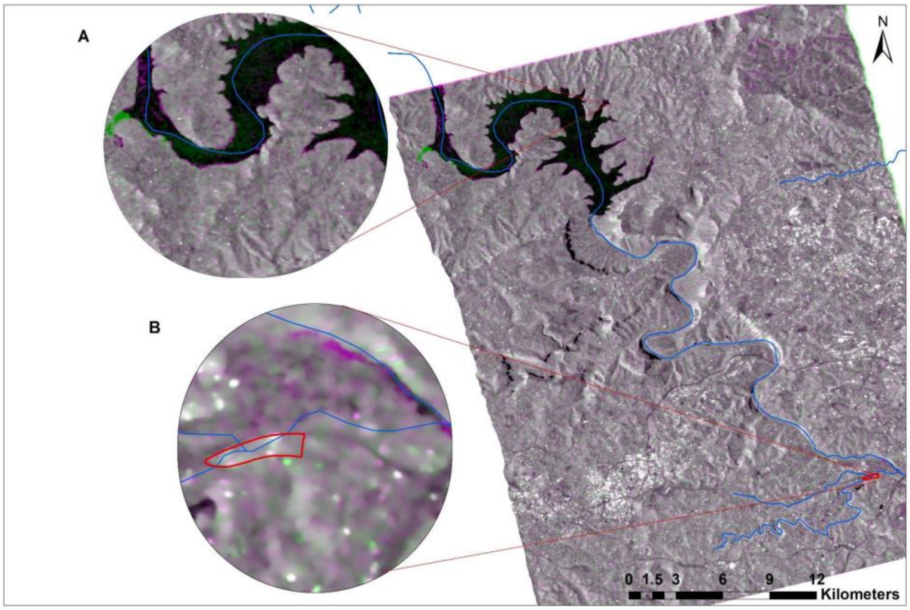


Figure 22: Sentinel-1 band combination (RGB) image of the test site showing difference in surface water areas, with two portions of the site zoomed in.



Using the thresh-holding method, the extracted water map before the flood is shown in **Figure 21 (a)**. In order to show the difference in the water extent, we generated a map for each date (i.e., figure for the pre-flood and **Figure21 (b)** for the post-flood, and lastly, we overlaid the extracted water bodies on top of each other to show the flood extent in **Figure 25**. The results show a small extent of flooded areas are located in the edges of the dam. This method is simple, efficient, and suitable for near-real-time flood extent.

Figure 23: Pre-flood event map derived using the proposed method

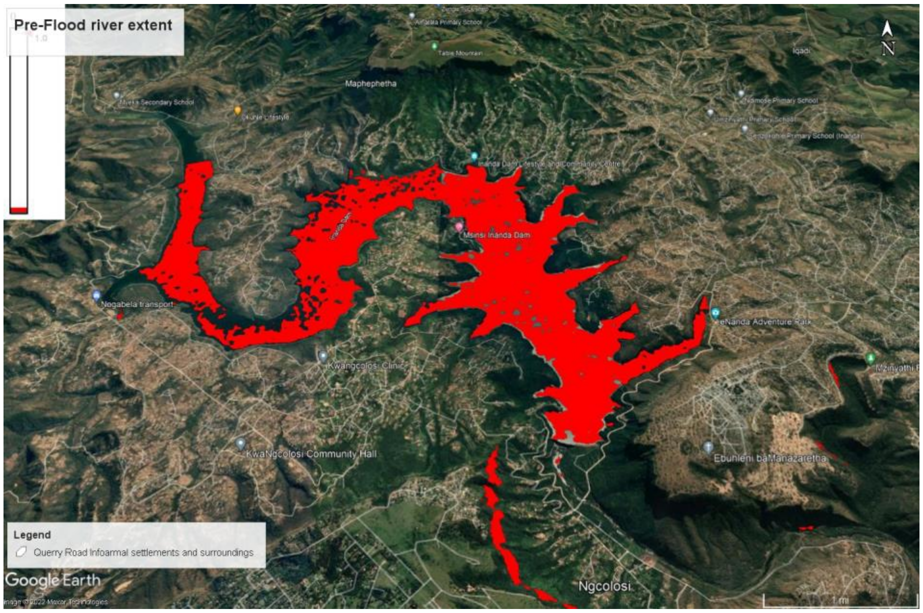
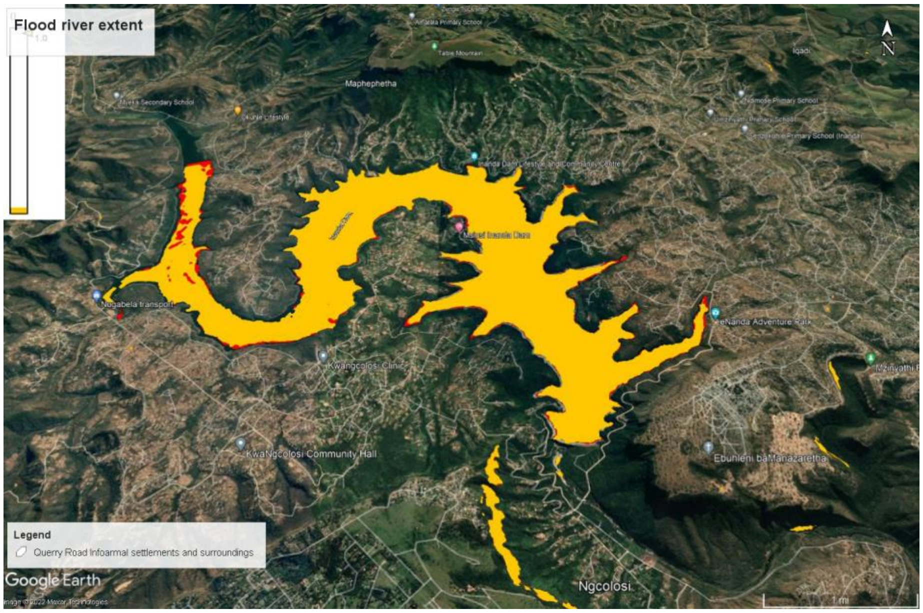


Figure 24: Post-flood event map derived using the proposed method

Figure 25: Flood extent overlay map derived using the proposed method



Discussion

The proposed methodology and the early warning system for the estimation of flood hazard areas can be a useful and practical tool for the mitigation of the devastating impact of floods in South Africa. However, the approach needs to be validated with more SAR data in other areas in the country for wider acceptability and use. The validation and model calibration should also take into account historical flood events, which may lead to refining of the model. In the area under study, the model (approach) has revealed the important contribution of tributaries and rivulets, construction of human dwellings in low-lying areas and absence of proper drainage systems, absence of flood attenuation infrastructure as well as substandard housing units as high risk elements during flood events in Quarry Road informal settlement. The above needs to be integrated in flood prevention and response plans of the area.

In particular, the model indicates that zones around rivers and tributaries that all drain or flow through the lowlands are even more prone to flooding. This claim is especially evident along the river, the tributaries and rivulets, where the model underestimates higher hazards. Specifically, the analysis includes Umgeni River and its surrounding areas in the class of very highly prone areas. A revisit to records of historical flood events should assist in validating this analysis through the recurrent flooding of the Umgeni River. Furthermore, an analysis of historical flood events should classify as highly susceptible areas with a high number of recorded flood events, an additional indication of accuracy.

It is corroborated that geology is the least affecting parameter. Initially, assumptions considered flow accumulation as the dominant parameter. However, the model analysis concluded that elevation, distance from drainage network and slope have a bigger influence in the KZN region. This interpretation is in line with studies elsewhere (Kourgialas and Karatzas 2011). Since rainfall intensity is associated both with the frequency and the amount of precipitation, it is crucial in identifying flood prone areas and therefore has been prioritized in several scientific studies (Ouma and Tateishi, 2014; Tehrany et al., 2014). Indeed, rainfall amount is the precursor to the whole process. This is followed by saturation of the local areas driven by the rising water table. The above finding not only places rainfall at the centre of flood warning in KZN, but also highlights a closer monitoring of the rising water table as an accurate indicator of the timing and start of a flood event.

The modelling exercise has revealed valuable information concerning the contribution or influence of each parameter in the assessment of flood hazard areas via its weight. However, the application of this approach elsewhere in other regions might reveal different weights and influence of each criteria in the estimation of flood hazard areas. The subjectivity of the estimation of the weights is the main drawback of this method. However, a validation of the method using historical floods should easily circumvent the subjectivity of the weighting process. A single-parameter sensitivity analysis should also serve as a validation technique in order to overcome this drawback. Thus, the method can be further modified using different techniques to determine the parameters' weights. It is also important to handle qualitative parameters such as geology and land use according to the specific characteristics of each region.

This report in no way suggests that flood risk management must be exclusively reliant on static visualisations provided from index-based methods. Although these methods appear to be reliable, additional tools are needed to enhance triangulation and reliability of estimations. In urban areas, flood events can be also influenced by human behaviour or operational deficiencies (Cherqui et al., 2015).

A further step is the estimation of the peak discharge and exceedance probability at locations where flood hazard is high/very high. In these areas depth, duration and velocity of flood should also be calculated using historical SAR data covering those flood events. The main advantage of the proposed method is its ability to provide overall assessment of flood hazard areas. In the area under study, it successfully considers the role of infiltration, timing of saturation, human dwellings in low-lying areas, and rivulets or tributaries passing through the region in heightening flood risk hazard. Since the role of the latter in major flood events can be significant, the construction of small dams (e.g., beaver dams) in tributaries can be an effective and sustainable measure with several side-benefits on groundwater recharge and soil erosion (Nyssen et al., 2011). Obviously, parameters can be added or removed according to local hydrogeological, hydrological and morphological characteristics of a region.

Table 6: Model parameters and weights

Parameter	**Class**	**Rating**	**Weight**
Flow accumulation	1390 – 5097 635 – 1390 275-635 71-275 0-71	10 8 6 4 2	3
Distance from the drainage network	<40 >40-100 100-150 150-200 >200	10 8 6 4 2	2.1
Elevation	0–124 124–288 288–476 476–699 699–1440	10 8 6 4 2	2.1
Land use	Urban-wetlands Pastures Agricultural Sparsely vegetated Mixed forest	10 8 6 4 2	1.2
Rainfall intensity	159–193 132–159 108–132 88–108 59–88	10 8 6 4 2	1.0
Slope	0–2 2–5	10 8	0.5

	5–15 15–35 35–60	6 4 2	
Geology	• Crystalline rocks • Sedimentary (Clay) • Neogene sediments • Continental deposits • Alluvial	10 8 6 4 2	0.3

To accurately describe the flood hazard risk prone areas, a number of factors were incorporated into the FHI model. It was observed that factors that had variable influences in modelling the hazard risk of the Quarry Road informal settlement and that some have more influence towards flooding of the area.

Firstly, the geographic location of the area: human dwellings occupy the spaces opposite and along river beds [low-lying zones], without due consideration of the ever present flooding dangers due to river overflows during higher precipitation days. It is evident that there is no clear or defined flood line in the area. This is a high rainfall area receiving in some cases over 1000 mm annually. Furthermore, the settlement is close to the sea and hence the water table is always high thus continues to hold a risk of quick saturation and leading to sudden flood events. The absence /or presence of the not so obvious drainage network indicates that the entire Quarry Road informal settlement lies in an area where the radial network collects water from the high lying areas and flows downwards to the mainstream passing through the informal settlement.

To worsen the situation, there are no structures in place to reduce the speed of flow or divert the water away from the informal settlement. Assessing the geology of the area, the settlement lies on a mud rock (shale), which acts like a confined rock due to its compact structure with very low pore spaces. Any water coming to the settlement will eventually flow as the surface runs off because it cannot infiltrate the ground. The above suggests the danger of floods is ever present during high rainfall events.

When considering land use and land cover, the area is dominated by built up structures with little vegetation and grass. Although water can accumulate in these areas, tree roots have penetrated to better depths linking the surface to the subsurface where water can move from the surface toward the ground water table.

When analysing the groundwater levels in the area, the distance between the water level and the surface runs around 8m. The area is closer to the coast, which keeps the area moist than areas away from the coast. Coastal areas are more prone to flooding as the land gets saturated quickly.

Enabling informal settlements to adapt to climate change impacts must be treated as a priority (Williams et al. 2018). Other researchers working in the Quarry Road informal settlement have highlighted the disconnect between the community and other sectors, with municipal authorities challenged by the priority actions required to enable adaptation to climate change. This compromises responses to flood events. Land-use is known to have a big impact on floods, particularly in urban areas were preventing the sealing off of natural drainage areas and restricting urbanization upstream can alleviate the risk of flooding downstream. Appropriate land-use management is critical to preserve the permeability of soils and to reduce run-off.

Basing flood warning systems strictly on hydrological and meteorological criteria is a major shortcoming in flood risk prevention because any analysis of synoptic conditions that inflict harm on society is pushed to the background. Such an approach does not make a distinction between the least damaging and most severe types of floods, and this constitutes a major problem when it comes to forming a complete picture of flood risk in each area (Cherqui et al., 2015).

Findings from empirical study

The empirical case study employed a qualitative methodology that utilized in-depth interviews with key informants (KIIs) and focus group discussions (FGDs) with the informal settlement community members. Transect walks were also used to observe the physical structures and to establish context of the area. The methodology adopted helped to obtain useful information related to what communities apply as early warning and other measures utilized in mitigating disaster prevalence to ensure effective disaster risk management in their settlement. The sample included government officials working for disaster risk management organizations, local leaders, councillors and ordinary members residing in the informal settlement.

The question on the estimated number of informal settlements in eThekwini Metro revealed that there are close to 300, although this number varies greatly as informal settlements rapidly mushroom in various areas of the city. Most of the informal settlement were of different pockets and sizes and located in different types of areas, but mostly situated in hazard prone environments. Key informants from government departments were of the view that residents of the informal settlements were mostly migrants from their rural homes who come to the city to seek job opportunities and a better life, but end up settling in these hazard prone areas. They also expressed that building shacks is the easiest way to get a shelter and is considered to provide relatively affordable accommodation.

The question on the role of disaster risk management organisations involved in assisting communities deal with the consequences of floods indicated that most the work they do falls in four categories namely:

i. ***Mitigation*** **–** evaluating the hazard postured by a danger and endeavouring to decrease the hazard.
ii. ***Preparedness*** – building up a reaction design in view of the hazard appraisal, preparing reaction staff, masterminding fundamental assets, making courses of action with different stakeholders such as the human settlement, department of social development (DSD), non-profit organisations i.e. Red Cross, private players like checkers the uniformed force and others.
iii. ***Response*** – executing the plans, diminishing the potential for auxiliary harm, and planning for the recovery stage e.g. Gift of the Givers; and
iv. **Recovery** – restoring life emotionally supportive networks, for example, repairing damaged homesteads, damaged infrastructure and provision of lodging, sustenance, and other essentials e.g. Department of Cooperative Governance and Traditional (CoGTA), Department of Human Settlements, etc.

The focus group discussions revealed that most hazards prevalent in informal settlements were fires that happen on a regular basis, storms and floods mostly during the rainy season. Other challenges cited by community members were gender-based violence, the prevalence of diseases (i.e. TB), theft, rape cases and child abuse. One participant said:

> *"It's like a cycle we live with these challenges for by the time we are trying to recover, maybe in a year's time, another incident will happen".*

Observations made during transient walks in the Quarry Road informal settlement showed that the level of vulnerability is huge and probably pervasive. Communities live in unsafe conditions where fires are prevalent, and no one seems to have a clue on how to control and prevent hazards from turning into regular disaster. It was noted that community members' livelihoods were much closer to the informal settlements and coupled with the relatively low cost of rental accommodation and ease of access to transport to and from work, many of the focus group discussion participants indicated that they were not willing to relocate to other places, irrespective of the high risk of floods in the informal settlement. Some of the residents of the shacks built them for the purposes of renting them out. Additionally, some respondents indicated that owners of shacks (landlords) were government officials who benefit from the rentals they charge occupants and when materials for reconstruction are issued. One key informant said:

> *"We do awareness campaign as a disaster management organisation, as part of trying to educate people on these situations. But obviously not everyone takes that seriously or practice and negligence from the children. So basically, it's just an unfortunate cycle that keeps happening."*

On the matter of whether the eThekwini Metro do have early warning system for weather-related disaster risk alerts, key informants and community members related that the eThekwini coastal, storm water and catchment management department has developed a forecasting early warning system that incorporates weather forecasting, flood prediction and coastal modelling. The primary objective of the system is to alert authorities to severe weather to provide them with real-time and spatial information to guide planning, preparedness and decision making. It was also revealed that monitoring gauges installed in various areas of the eThekwini Metro provide authorities with real-time information regarding pending severe weather and possible disaster in high-risk areas such as Quarry Road informal settlement. However, community members in the informal settlements explained that they were not supplied with information on time. Some respondents indicated that they thought the floods were a result of dam flood gates being opened upstream, rather than the result of heavy rains and stormy weather.

Key informants revealed that early warning is still in a developmental stage and requires investments from national government and local authorities to enhance its appropriateness and practicality. Perceptions of experts interviewed showed that flood events happening in the province suggest there is still a long way to improve and further develop the early warning system. The success of developing early warning for disaster risk will rely on improved data sharing between government departments, academia and communities. It was also suggested by the disaster management personnel that for the forecast system to work, metros of the future need significant on the ground support in the form of disaster management teams composed of police, rescue workers, climate data transcribers, volunteers, community support organisations, paramedics and places of shelter.

Conclusion

The main aim of this case study was to develop a methodology that identifies flood prone zones and triggers an early flood warning system applicable in the KZN region of South Africa. This is important for planning, preparedness and decision-making as it creates a roadmap for the required flood mitigation measures.

A system based on the level of the water table as a trigger to an early warning has thus been developed. The method spatially analyses seven parameters, combining the information in the Flood Hazard. The parameters are flow accumulation (F), rainfall intensity (I), geology (G), land use (U), slope (S), elevation (E) and distance from the drainage network (D). The relative importance of each parameter is calculated by an assessment of literature (albeit subjectively) but an assessment of historical flood events and a parameter sensitivity analysis can overcome this drawback. A statistical sensitivity analysis on the values assigned to the different criteria could be easily carried to validate the efficiency and effectiveness of the developed methodology. The application of the methodology and indices in the KZN region has revealed the areas that are most prone to floods. Human dwellings built in or located closest to low-lying areas, tributaries, easily saturated soils, high levels of the water table are pinpointed as those residences that most likely to experience some form of disaster due to their proximity to a flood prone zone.

The methods and techniques used in the study of the Quarry Road informal settlement permits assessing the spatial variability of flood hazard. With the ability to incorporate historical flood events, the method has been designed to provide actionable information to the decision-making process on development and planning, emergency preparedness, and prioritisation of areas with high probability of hazard occurrence or intensity in order to avoid any dramatic disaster. It is important to remember that the GIS and remote sensing applications in this work played a central role in integrating, organizing, processing, modelling, and visualizing the spatial data from multiple sources.

Recommendations

A key conclusion to note from this case study is that Quarry Road informal settlement occupies a very small area, which requires expensive high-resolution images from the satellite perspective in order to capture all the details and changes occurring within the settlement during an impending or already occurring flood event. This requires investment, involvement and support from a wide array of government, the private sector and non-government stakeholders. Hazard managers should give attention to the modelling and prediction of hazards, and in strengthening early warning systems for the early detection of catastrophic events will reduce the potential losses and damage. This research has put forward critical knowledge for understanding flood in the study area and thus it is recommending the non-structural enabling environments for managing combined hazards. The non-structural approach measures should go side-by-side with society's customs and needs to ensure effective hazard management. People should be flexible to change their behaviours to reduce vulnerability and exposure to hazards. A multi-hazard system approach based on simulation, optimization, and multi-objective assessments can help plan for future combined hazard. Future research should study how different provinces and cities in South Africa are preparing to manage multiple future hazards, including the comparative assessment of the strengths and weaknesses of individual provinces and cities’ planning and preparation.

References

Afjal Hossain, M., Reza, I., Rahman, S., & Kayes, I. (2012). Climate change and its impacts on the livelihoods of the vulnerable people in the southwestern coastal zone in Bangladesh. In *Climate change and the sustainable use of water resources* (pp. 237-259). Springer, Berlin, Heidelberg.

Bai, X., Dawson, R.J., Ürge-Vorsatz, D., Delgado, G.C., Salisu Barau, A., Dhakal, S., Dodman, D., Leonardsen, L., Masson-Delmotte, V., Roberts, D.C. and Schultz, S., 2018. Six research priorities for cities and climate change.

Bioresita, F., Puissant, A., Stumpf, A., & Malet, J. P. (2018). A method for automatic and rapid mapping of water surfaces from sentinel-1 imagery. Remote Sensing, 10(2), 217.

Bopape, M.J.M., Cardoso, H., Plant, R.S., Phaduli, E., Chikoore, H., Ndarana, T., Khalau, L. and Rakate, E., 2021. Sensitivity of Tropical Cyclone Idai simulations to cumulus parametrization schemes. Atmosphere, 12(8), p.932.

Bopape, M.J.M., Sebego, E., Ndarana, T., Maseko, B., Netshilema, M., Gijben, M., Landman, S., Phaduli, E., Rambuwani, G., Van Hemert, L. and Mkhwanazi, M., 2021. Evaluating South African Weather Service information on Idai tropical cyclone and KwaZulu-Natal flood events. South African Journal of Science, 117(3-4), pp.1-13.

Cherqui, F., Belmeziti, A., Granger, D., Sourdril, A. and Le Gauffre, P., 2015. Assessing urban potential flooding risk and identifying effective risk-reduction measures. Science of the Total Environment, 514, pp.418-425.

Correia, F.N., Da Silva, F.N. and Ramos, I., 1999. Floodplain management in urban developing areas. Part I. Urban growth scenarios and land-use controls. Water resources management, 13(1), pp.1-21. Demek, J. (Ed.). (1972). *Manual of detailed geomorphological mapping*. Czechoslovak Academy of Sciences.

FAO/UNESCO, 1971-1981. The FAO-UNESCO Soil Map of the World. Legend and 9 volumes. UNESCO, Paris.

Forte, F., Pennetta, L., Strobl, R.O., 2005. Historic records and GIS applications for flood risk analysis in the Salento peninsula (southern Italy). Nat. Hazards Earth Syst. Sci. 5 (6), 833–844. http://dx.doi.org/10.5194/nhess-5-833-2005 (ISSN 1561–8633, 1561–8633).

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H. and Kanae, S., 2013. Global flood risk under climate change. *Nature climate change*, *3*(9), pp.816-821.

Huan, H., Wang, J., & Teng, Y. 2012. Assessment and validation of groundwater vulnerability to nitrate based on a modified DRASTIC model: a case study in Jilin City of northeast China. *Science of the total environment*, *440*, 14-23.

Huang, W. C., & Yang, F. T. 1998. Streamflow estimation using kriging. *Water resources research*, *34*(6), 1599-1608.
IDP/Documents/Final%202014_15%20IDP.pdf (accessed on 25 February 2022).

International Institute for Environment and Development. Available online: https://www.iied.org/ introduction-urban-poverty (accessed on 25 January 2022).

International Institute for Environment and Development. Available online: https://citiesipcc.org/wpcontent/uploads/2018/03/Informality-background-paper-for-IPCC-Cities.pdf (accessed on 25 January 2022).

Intergovernmental Panel on Climate Change. Climate Change 2014: Mitigation of Climate Change (eds Edenhofer, O. et al.) (Cambridge Univ. Press, 2015)

Kazakis, N., Kourgias, I. and Patsialis, T., 2015. Assessment of flood hazard areas at a regional scale using an index-based approach and Analytical Hierarchy Process: Application in Rhodope–Evros region, Greece. Science of the Total Environment, 538, pp.555-563.

Kellens, W., Terpstra, T. and De Maeyer, P., 2013. Perception and communication of flood risks: A systematic review of empirical research. Risk Analysis: An International Journal, 33(1), pp.24-49.

Kia, Masoud Bakhtyari, Pirasteh, Saied, Pradhan, Biswajeet, Mahmud, Ahmad Rodzi,Sulaiman, Wan Nor Azmin, Moradi, Abbas, 2011. An artificial neural network model for flood simulation using GIS: Johor River Basin, Malaysia. Environ. Earth Sci. 67, 251–264. http://dx.doi.org/10.1007/s12665-011-1504-z (ISSN 1866–6280).

Klijn, F., 2009. Flood risk assessment and flood risk management; an introduction and guidance based on experiences and findings of FLOODsite (an EU-funded integrated project). T29-09-01.

Kourgialas, Nektarios N., Karatzas, George P., 2011. Flood management and a GIS modelling method to assess flood-hazard areas: a case study. Hydrol. Sci. J. 56 (2), 212–225. http://dx.doi.org/10.1080/02626667.2011.555836 (ISSN 0262-6667).

Liang, J., & Liu, D. 2020. A local thresholding approach to flood water delineation using Sentinel-1 SAR imagery. ISPRS journal of photogrammetry and remote sensing, 159, 53-62.

Lines, K. and Makau, J., 2018. Taking the long view: 20 years of Muungano wa Wanavijiji, the Kenyan federation of slum dwellers. Environment and Urbanization, 30(2), pp.407-424.

Macfarlane, D., & Bredin, I. 2017. Buffer Zone Guidelines for Rivers, Wetlands and Estuaries Part 1: Technical Manual. *Water Research Commission. WRC Report No. TT*, 715-1.

Munyai, R.B., Chikoore, H., Musyoki, A., Chakwizira, J., Muofhe, T.P., Xulu, N.G. and Manyanya, T.C., 2021. Vulnerability and Adaptation to Flood Hazards in Rural Settlements of Limpopo Province, South Africa. Water, 13(24), p.3490.

Naudé, W., Santos-Paulino, A.U. and McGillivray, M., 2009. Measuring vulnerability: An overview and introduction. Oxford Development Studies, 37(3), pp.183-191.

Nyssen, J., Govaerts, B., Araya, T., Cornelis, W.M., Bauer, H., Haile, M., Sayre, K. and Deckers, J., 2011. The use of the marasha and plough for conservation agriculture in Northern Ethiopia. Agronomy for Sustainable development, 31(2), pp.287-297.

Ouma, Y.O. and Tateishi, R., 2014. Urban flood vulnerability and risk mapping using integrated multi-parametric AHP and GIS: methodological overview and case study assessment. Water, 6(6), pp.1515-1545.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P. and Dubash, N.K., 2014. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change (p. 151).

Rachelle, O., 2013 Surface Water Runoff, Saint Martin, C., Fouchier, C., Javelle, P., Douvinet, J., and Vinet, F., 2006. Assessing the exposure to floods to estimate the risk of flood-related damage in French Mediterranean basins. 3rd European Conference on Flood Risk Management FLOOD risk. pp.04013, ⟨10.1051/e3sconf/20160704013⟩. ⟨hal-01523878⟩

Satterthwaite, D. and Bartlett, S., 2017. The full spectrum of risk in urban centres: changing perceptions, changing priorities. Environment and Urbanization, 29(1), pp.3-14.

Sendai Framework for Disaster Risk Reduction. 2015-2050. Available online: https://www.unisdr.org/we/inform/publications/43291 (accessed on 25 February 2022).

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B. and Teuling, A.J., 2010. Investigating soil moisture–climate interactions in a changing climate: A review. Earth-Science Reviews, 99(3-4), pp.125-161.

Schanze, J., Zeman, E. and Marsalek, J. eds., 2007. Flood risk management: hazards, vulnerability and mitigation measures (Vol. 67). Springer Science & Business Media.

Shamaoma, H., Kerle, N. and Alkema, D., 2006, May. Extraction of flood-modelling related base-data from multi-source remote sensing imagery. In ISPRS mid-term symposium.

Stephen, A., 2011. River systems & causes of flooding. Tulane University, EENS, 2040.

Surminski, S., 2017. 5.1 Prevention and mitigation: avoiding and reducing the new and existing risks.

Tehrany, Mahyat Shafapour, Pradhan, Biswajeet, Jebur, Mustafa Neamah, 2013. Spatial prediction of flood susceptible areas using rule based decision tree (DT) and a novel ensemble bivariate and multivariate statistical models in GIS. J. Hydrol. 504, 69–79. http://dx.doi.org/10.1016/j.jhydrol.2013.09.034 (ISSN 00221694).

United Nations Development Programme. Human development report. 2018. Available online: https://www.undp.org/publications/human-development-report-2004 (accessed on 3 March 2022).

Wehn, U., Rusca, M., Evers, J. and Lanfranchi, V., 2015. Participation in flood risk management and the potential of citizen observatories: A governance analysis. *Environmental Science & Policy*, *48*, pp.225-236.

Williams DS, Máñez Costa M, Celliers L, Sutherland C. Informal Settlements and Flooding: Identifying Strengths and Weaknesses in Local Governance for Water Management. *Water*. 2018; 10(7):871. https://doi.org/10.3390/w10070871

Wisner, B., Blaikie, P., Cannon, T., & Davis, I. 2004. At Risk: Natural Hazards, People's Vulnerability and Disasters. Routledge. (1st ed.). Routledge. https://doi.org/10.4324/9780203974575