South African Journal of Geomatics, Vol. 1, No. 1, January 2012

Using Multi-criteria Evaluation and GIS for Flood Risk Analysis in Informal Settlements of Cape Town: The Case of Graveyard Pond

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Abstract

Rural-urban migrations have contributed to the steady increase in the population of Cape Town. Many of the migrants have settled in informal settlements because they cannot afford to rent or buy decent housing. Many of these settlements are however located on marginal and often poorly drained land. Consequently, most of these settlements are prone to flooding after prolonged rainfall. Current flood risk management techniques implemented by the authorities of the Cape Town City Council (CTCC) are not designed to support informal settlements. In fact, owing to a lack of information about the levels of flood risk within the individual settlements, either the CTCC has often been uninvolved or it has implemented inappropriate remedies within such settlements. This study sought to investigate a methodology that the CTCC could use to improve flood risk assessment.

Using a case study of an informal settlement in Cape Town, this study proposed a methodology of integration of community-based information into a Geographic Information System (GIS) that can be used by the CTCC for risk assessment. In addition, this research demonstrated the use of a participatory multi-criteria evaluation (MCE) for risk assessment. A questionnaire was used to collect community-based information. The shack outlines of the informal settlement were digitized using CTCC aerial imagery. The questionnaires were captured using spreadsheets and linked to the corresponding shacks in the GIS. Risk weights were subsequently calculated using pairwise comparisons for each household, based on their responses to the questionnaires. The risk weights were then mapped in the GIS to show the spatial disparities in risk.

Keywords: Informal settlements. Flood risk management. Multi-criteria Evaluation. GIS. Participation. Risk weights.

1. Introduction

1.1 Background

In the period between 1996 and 2005, floods have had devastating effects on the continents of Africa, Asia, and the Americas (Satterthwaite *et al.*, 2007). It is reported that, during that period, there were 290 flood-disasters in Africa alone, which left 8,183 people dead and 23 million people affected, and which caused economic losses of $1.9 billion (ibid). Similarly, 472 flood-disasters in Asia over the same period killed 42,570 people and affected 1.3 billion people, and were responsible for economic losses estimated at $129 billion (*ibid.*). It is also worth mentioning that floods were the most frequent natural disaster in Africa and the most common in Asia during that time period (*ibid.*). Magrin *et al* (2007) recounted that the incidence of disasters related to weather have increased 2.4 times between 1970 and 2005, and more increases are expected in the future. Studies on the changing weather patterns in South Africa predict increased intensity of high rainfall events (Mason *et al,* 1999). Incidentally, Satterthwaite *et al* (2007) reported that climate change has the potential to increase flooding risks in cities because of rising sea levels and storm surges, as well as heavier and prolonged rainfall and increased river flows.

Satterthwaite *et al.* (2007) postulated that inadequate solid-waste management and drain maintenance can lead to clogged drains, which in turn leads to localized flooding even with light rainfall. However, for most urban environments, properly maintained infrastructure such as road drains and channels are adequate to prevent flooding. Unfortunately, owing to high rural-urban migrations, there has been a growth of informal settlements in cities across the world. The migrants are often too poor to afford proper housing in the serviced parts of the city and therefore settle on risk prone land (Barry & Rüther, 2005; SDI, 2009).

In a local context, according to the 2007 Cape Town City Council (CTCC) census report, there were approximately 109,000 families living in informal settlements in Cape Town (City of Cape Town, 2008a). A number of reports point out the extensive effect of flooding in many of these informal settlements. For instance, the CTCC conducted a study in three informal settlements, namely Joe Slovo, Sweet Home and Nonqubela K-Section in Khayelitsha. The study reported that 83% of the residents had been affected by flooding (City of Cape Town, 2005). Bouchard *et al* (2007) reported that, during the winter month of July 2007, heavy rainfall resulted in flooding that affected 8,000 households, comprising 38,000 residents, in the informal settlements of Khayelitsha and Philippi. All the aforementioned studies demonstrate the significant impact of flooding on informal settlements across Cape Town and the consequent need for an efficient flood management policy in such areas. Meyer *et al.* (2009) identified the two main components of flood risk management as flood risk assessment and flood risk mitigation. This paper will present a novel way of carrying out risk assessment in informal settlements.

1.2 Assessing Risk

A widely accepted description of risk was offered by Crichton (1999) and cited by Kelman (2003: 7) as follows:

"Risk is the probability of a loss, and this depends on three elements, hazard, vulnerability and exposure". Hence, the following equation was put forward:

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \quad [1]$$

Based on this description, Crichton (1999) postulated that if any of these three elements in risk increases or decreases, then risk increases or decreases respectively; an opinion shared by Cardona (2004). Cardona (2004) also suggested that hazard and vulnerability cannot exist independently of each other. Hence any changes in hazard and/or vulnerability will influence the extent of the risk. Furthermore, Cardona (2004) pointed out that since hazards cannot be modified; efforts aimed at reducing risk to a hazard can only be focussed on reducing vulnerability of the exposed communities or environments to that hazard.

From Equation 1, it may appear that reducing exposure would also reduce risk. Nevertheless, a different argument was offered by Wilde (1994), Etkin (1999) and Kelman (2001), as cited in Kelman (2003). They subscribed to the theory of risk homeostasis, which basically states that individuals, communities and societies maintain a constant level of risk, irrespective of external influences (Kelman, 2003). For instance, reducing exposure to a hazard will cause behaviour that inadvertently reduces preparedness in relation to the hazard and consequently increases vulnerability. They subsequently contended that external measures do little to influence overall risk in the long term. Instead, Kelman (2003) agreed with Lewis (1999) that, since vulnerability assesses the processes at work between hazard and risk, and since it is applicable to any hazard, targeting vulnerability will reduce overall risk to an acceptable level.

Drawing from the arguments of Wilde (1994), Etkin (1999), Kelman (2001), Cardona (2004), Crichton (1999) and UN DHA (1992), vulnerability has a strong bearing on the magnitude of risk. Consequently, studies into the level of vulnerability of an environment or community to a particular hazard will invariably provide insight into the magnitude of risk of the environment or the community to that hazard. This research therefore adopted vulnerability as an indicator of risk.

Kumpulainen (2006) stated that vulnerability could be viewed as a state of conditions and processes resulting from physical, social, economic and environmental factors that increase the liability of a community with regard to the impact of hazards. Consequently, Kumpulainen (2006) adopted the following notation for vulnerability:

$$\text{Regional Vulnerability} = \text{Damage potential} + \text{Coping capacity} \qquad [2]$$

Turner *et al* (2003) stated that holistic studies on vulnerability which are meant to have an input in decision making should include among others:

- A study of all the hazards affecting the system (community or environment);
- How the system gets exposed to the hazard; and
- The coping capacity of the system.

This study was therefore focused on assessing these prescribed indicators in an informal settlement in Cape Town. Variations in these indicators will invariably result in variations in vulnerability. For instance, if a household in an informal settlement was exposed to more hazards than another, it would have a higher level of vulnerability than the other. Similarly, variations in the forms of exposure of the households to the same hazard will cause variations in levels of vulnerability. Hence, an assessment of relative vulnerability of a household of interest to another household requires the consideration and comparison of the criteria prescribed by Turner *et al* (2003) in those particular households.

1.3 Multi-criteria Evaluation

Multi Criteria Evaluation (MCE) is used to analyse a series of alternatives or objectives with a view to ranking them from the most preferable to the least preferable using a structured approach. The end result of MCE is often a set of weights linked to the various alternatives. The weights indicate the preference of the alternatives relative to each other. They may also be seen as the perceived advantage or disadvantage when changing from one alternative to another. The choice of methodologies for the calculation of these weights varies from text to text. Several authors (Stewart & Scott, 1995; Joubert *et al* 1997; Jankowski *et al* 2001; Ayalew & Yamagishi, 2005; Yahaya & Abdalla, 2010; Kourgialas & Karatzas, 2011) have used the methods highlighted by Malczewski (1999) when calculating weights in MCE. Table 1 summarises the attributes of the various MCE methods presented by Malczewski (1999).

Table 1 Table showing comparisons of method. Source: Malczewski (1999: 190)

METHODS IN MCE				
Feature	***Ranking***	***Rating***	***Pairwise Comparison***	***Trade-off analysis***
Number of judgements	n	n	$n(n-1)/2$	n
Response scale	Ordinal	Interval	Ratio	Interval
Hierarchichal	Possible	Possible	Yes	Yes
Underlying theory	None	None	Statistical / Heuristic	Axiomatic/ deductive
Ease of use	Very easy	Very easy	Easy	Difficult
Trustworthiness	Low	High	High	Medium
Precision	Approximations	Not precise	Quite precise	Quite precise
Software availability	Spreadsheets	Spreadsheets	Expert Choice	Logical Decisions
Application in GIS	Weights can be imported	Weights can be imported	Part of IDRISI	Weights can be imported

A holistic assessment of all the attributes of the various methods reveals that the pairwise comparison method (PCM) and Trade-off analysis method (TAM) are overall the best options. PCM and GIS have been used together by a number of scholars (Guipponi *et al*, 1999; Jankowski *et al,* 2001; Kyem, 2001, 2004; Ayalew & Yamagishi, 2005; Yahaya & Abdalla, 2010) and it was therefore adopted in this study. The MCE methods presented here are by no means exhaustive. For instance, other researchers have employed fuzzy methods (Jiang & Eastman, 2000; Akter & Simonovic, 2005, 2006) and MACBETH (Bana e Costa *et al*, 2004). Furthermore, a thorough review and classification of refereed journal articles covering spatial multi-criteria decision analysis can be found in Malczewski (2006).

A flood vulnerability study was conducted by Yalcin & Akyurek (2004) in Turkey. The study involved the vulnerability assessment of an area located between the Filyos and Bartin river basins in Northern Turkey. The research focussed on biophysical vulnerability and considered the contribution of annual rainfall, the size of the watershed, the basin slope, the gradient of the primary drainage channel, the drainage density, the land use and the soil types with regard to vulnerability in the river basins. The corresponding weights derived from PCM were found to be 0.26, 0.21, 0.17, 0.16, 0.10, 0.06 and 0.04 respectively. The consistency ratio was found to be 0.042, which showed an acceptable level of consistency in ranking the alternatives. Thereafter, vulnerability maps were created, and the authors were able to locate the most vulnerable areas located between the two rivers.

Yahaya & Abdalla (2010) conducted a similar study into flood vulnerability in the Hadejia-Jama'are River Basin in Nigeria. Their research also focused on biophysical vulnerability, and the researchers analysed the contribution of annual rainfall, the basin's slope, drainage network, land cover and the type of soil to vulnerability in Hadejia-Jama'are. A combination of PCM and ranking methods were used to calculate the weights of these attributes. Each attribute was compared to the others, and the PCM matrices were calculated using the MATLAB software package. After the PCM calculations had been done, the normalized weights were found to be 0.339, 0.255, 0.197, 0.152, and 0.057, for annual rainfall, the drainage network in the river basin, the basin slope, the soil type and land cover respectively. Consequently, the highest contributors to risk vulnerability in the region were found to be annual rainfall, the drainage network in the river basin and the basin slope. A check on the consistency yielded a consistency ratio of 0.0506. Since it was significantly less than 0.1, the authors found the analysis to be reasonably consistent. Yahaya & Abdalla (2010) replicated the methodology used by Yalcin & Akyurek (2004) to link the weights into the raster based GIS data and create vulnerability maps.

The studies reported here show that PCM can be used in conjunction with GIS for risk assessment and mapping. A critique of these studies though, is that the communities around the river basins were never involved in the analysis; hence, the existing risk mitigation efforts were not taken into context when assessing vulnerability. In contrast, this study therefore adopted a participatory approach to MCE. The resulting weights were imported into a GIS environment and mapped to identify disparities in vulnerability.

1.4 Study Area

Graveyard Pond is an informal settlement located in Philippi, a suburb of Cape Town. It lies southwest of the intersection of Sheffield Road and New Eisleben Road. This settlement is particularly prone to flooding because it is located in an area designated as a catchment pond by the CTCC. Imagery from the CTCC captured in 2007 clearly depicts the uninhabited wetter part at the centre of the settlement (Figure 1). This specific area is the lowest part of the settlement and it can stay wet for months on end.

Figure 1. Graveyard Pond, September 2007 (Source: City of Cape Town, 2008)

In contrast, imagery from the CTCC captured in 2009, shows an increase in the number of settlements in Graveyard Pond, especially in the wetter part of the settlement (Figure 2).

Figure 2. Graveyard Pond, March 2009 (Source: City of Cape Town, 2010)

2. Approach

The methodology used to collect the data incorporated the methodologies used by Abbot *et al* (1998), Abbot (2000), Karanja (2010), SDI (2009), Turner *et al* (2003) and Tyler (2011).The data collection consisted of two main parts: capturing the social information from the communities using questionnaires and capturing the spatial information using GIS. Approximately 300 households were interviewed with the help of six community leaders residing in the settlement. The social information was subsequently recorded in a spreadsheet, whereas the spatial information was derived from aerial imagery of Graveyard Pond sourced from the CTCC. Since both the spreadsheet and the GIS had corresponding shack numbers as database identifiers, a spatial join could be carried out in the GIS software to link the questionnaires as attribute data for the corresponding shacks.

Every step of the data collection was done in partnership with the relevant stakeholders. Figure 3 summarises the methodology

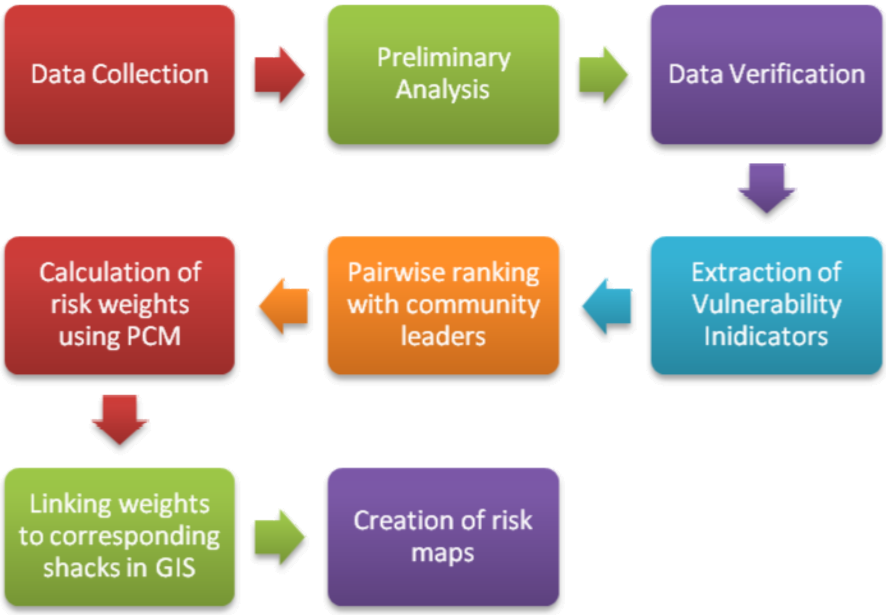

Figure 3. Steps in vulnerability analysis of Graveyard Pond

From the initial maps and community discussions, it emerged that the communities experienced both flooding and fire hazards. However, there were distinct differences in the types of flooding, corresponding mitigation measures, income levels and diseases suffered. Hence these four variations were taken as the main criteria to be used in evaluating vulnerability. Various alternatives of these four criteria were drawn based on the responses to the questionnaires (Table 2). The alternatives were ranked from the best case scenario to the worst case scenario through discussions with the six community leaders. After the ranking had been completed, a pairwise comparison was carried out in order to derive weights for each alternative. The highest weight was allocated to the best case scenario and the lowest weight to the worst case scenario. The weights were then linked to the shacks as attribute data in the GIS, based on the alternative preferred by the corresponding household. Once each household had been allocated a weight, a vulnerability map was created for each criterion in the entire settlement.

Table 2.Vulnerability assessment criteria and the alternatives

CRITERIA	ALTERNATIVES
Exposure to Hazards	• No exposure to hazards • Exposure to fire only • Flooding because of a leaking roof • Flooding caused by rising water • Flooding caused by flash floods • Exposure to both flooding and fire

Methods of Mitigation	• Digging of trenches • Raising of shacks • Use of sandbags • Relocation • Use of concrete floors
Sanitation and Disease	• No incidence of diseases • Running tummy • Respiratory diseases • Rashes • Running tummy and respiratory diseases • Rashes and respiratory diseases; and • All diseases (respiratory diseases, rashes and running tummy)
Income	• Full-time or self-employment • Full-time or self-employment and welfare grants • Part-time employment and welfare grants • Part-time employment • Only welfare grants • No income at all

3. Results

3.1 Exposure to Hazards

Table 3 shows the final relative weights. In this table, the magnitude of the vulnerability is inversely proportional to the magnitude of the associated weight. The weights were allocated to the individual households based on their responses. For instance, if a particular household experienced both fire and floods, a weight of 0.033 was allocated to that household. A map was subsequently created to show the geographical distribution of the vulnerability (Figure 4).

Table 3.Vulnerability weights for hazard exposure

EXPOSURE TO HAZARDS	
Alternatives	**Weights**
No Disaster	0.408
Only Leaking Roof	0.243
Only Fire	0.161
Only Flash Floods	0.097
Only Rising Water	0.057
Flood and Fire	0.033
Sum:	1.000

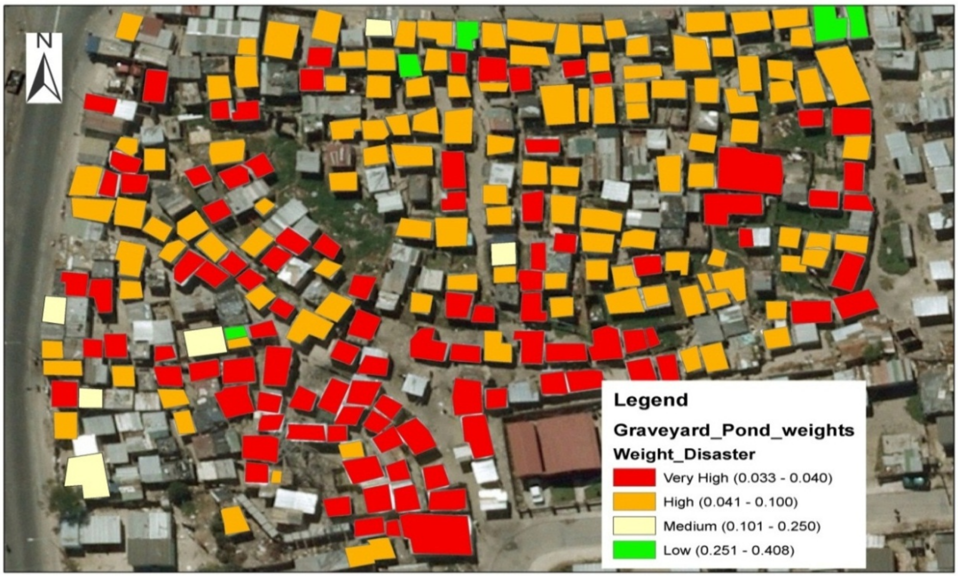

Figure 4. Map showing vulnerability based on type of exposure to a hazard

3.2 Sanitation and Disease

Table 4 shows the final calculated weights. The weights were then allocated to the individual households based on their responses. For instance, if a particular household experienced only coughs and rashes, a weight of 0.046 was allocated to that household. Figure 5 shows the resulting map.

Table 4.Weights for contribution of disease to vulnerability

INCIDENCE OF DISEASES	
Alternatives	**Weights**
No Disease	0.367
Rash	0.224
Running Tummy	0.151
Cough/Flu	0.092
Running Tummy and Rash	0.065
Cough and Rash	0.046
Running Tummy and Cough	0.032
All	0.023
Sum:	1.000

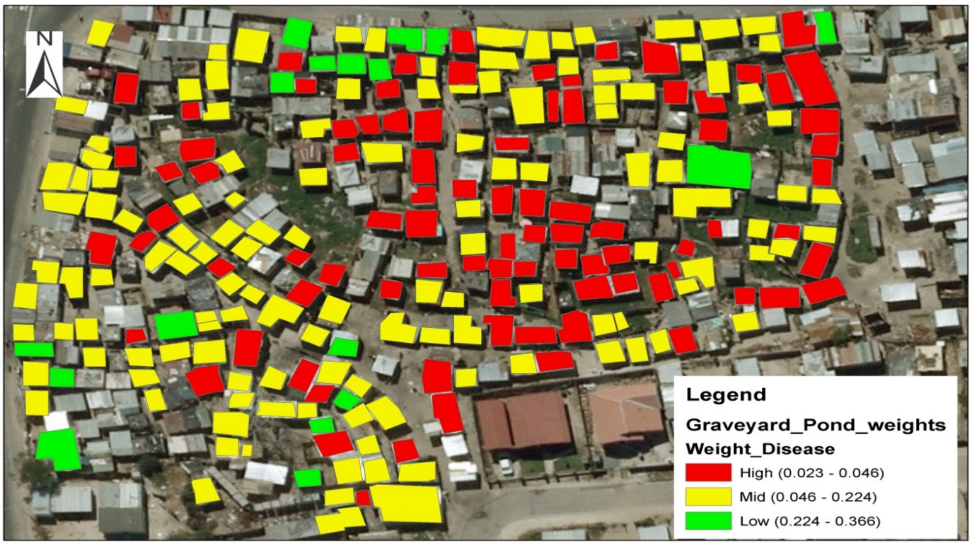

Figure 5. Map showing vulnerability based on prevalence of disease

3.3 Income

Table 5 shows the final weights for the alternatives in income. Figure 6 shows the corresponding map.

Table 5. Calculated weights for sources of income

SOURCES OF INCOME	
Alternatives	**Weights**
Full-time/Self Employment and receiving a Grant	0.381
Full-time Employment	0.274
Part-time Employment and Grant	0.147
Part-time Employment	0.105
Unemployed and receiving a Grant	0.055
Unemployed and not receiving a Grant	0.038
Sum:	1.000

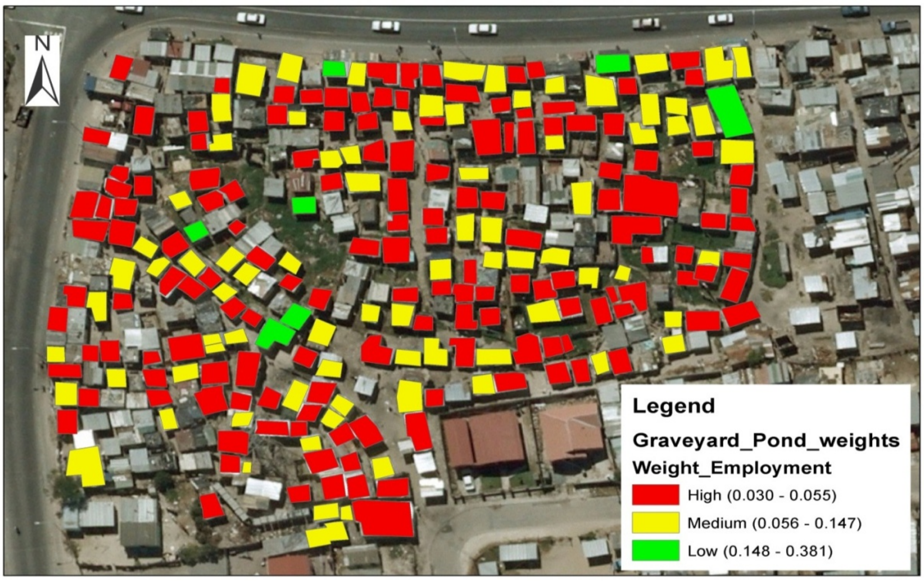

Figure 6. Map showing vulnerability based on type of income

3.4 Methods of Mitigation

Table 6 shows the results of the PCM analysis based on discussions with the community leaders. The mitigation techniques were sequentially ranked based on their efficiency in mitigating the various forms of exposure to flooding. Figure 7 shows the resulting map.

Table 6.Vulnerability weights for methods of mitigation

METHODS OF MITIGATION	
Alternatives	**Weights**
Flash Floods & Dig trenches	0.085
Flash Floods &Raise shacks	0.085
Flash Floods & Sand bags	0.064
Flash Floods &Relocation	0.056
Flash Floods &Concrete floors	0.050
Leaking Roof &Relocation	0.081
Leaking Roof & Sand bags	0.074
Leaking Roof & Raise shacks	0.060
Leaking Roof & Concrete floors	0.060
Leaking Roof & Dig trenches	0.051
Rising Water & Raise shacks	0.069
Rising Water & Concrete floors	0.069
Rising Water & Sand bags	0.060
Rising Water & Relocation	0.087
Rising Water & Dig trenches	0.050
Sum:	1.000

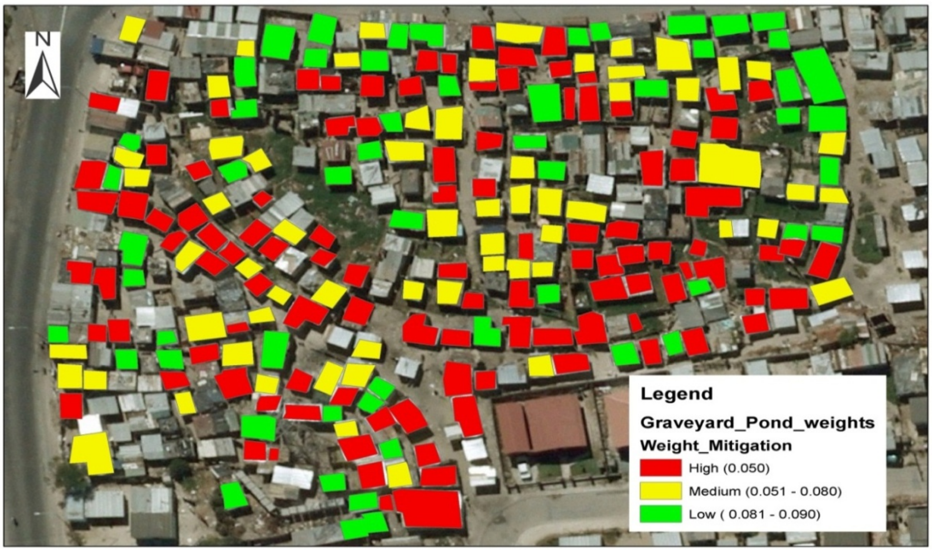

Figure 7. Map showing vulnerability based on methods of mitigation

3.5 Overall Vulnerability

An average weight was calculated for each household to create a holistic value for vulnerability. Figure 8 shows the resulting map. A raster map was also created by interpolating the weights (Figure 9).

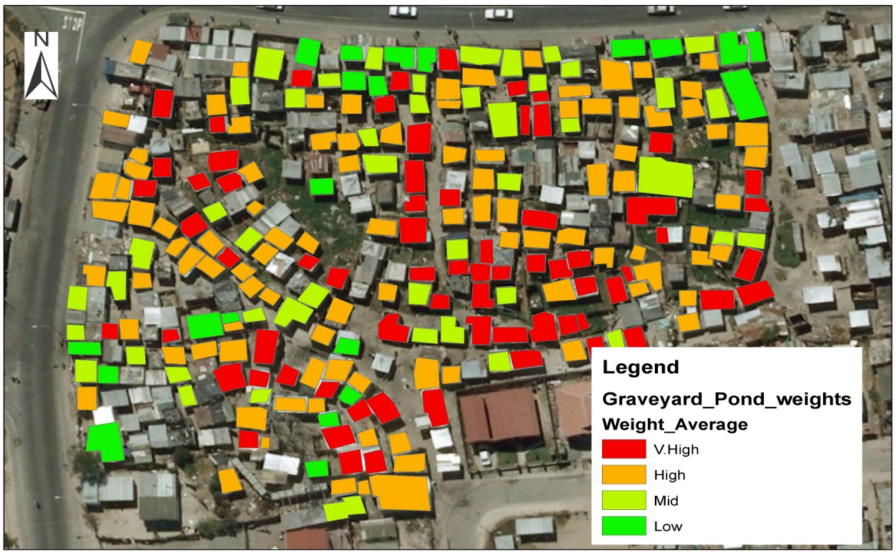

Figure 8. Map showing overall vulnerability

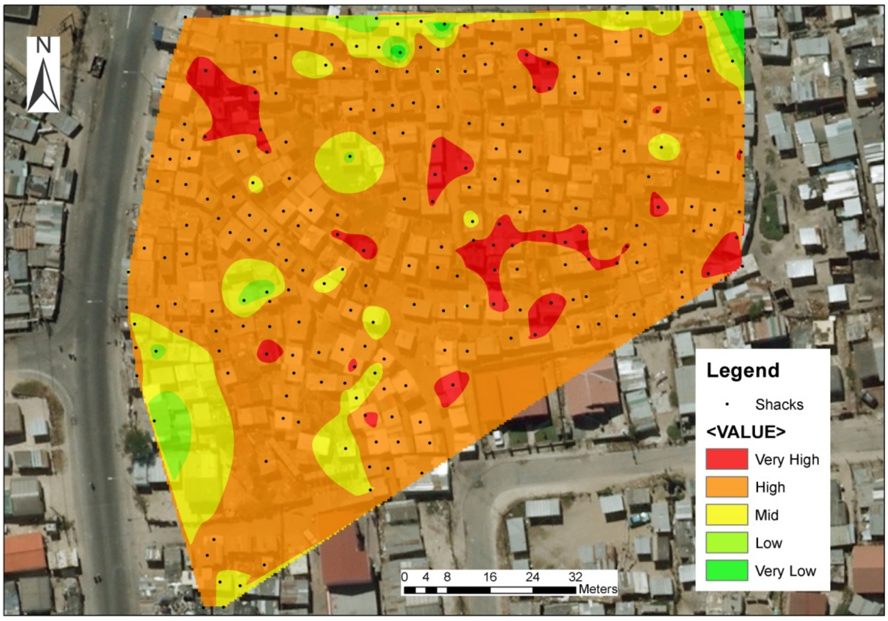

Figure 9. Raster map showing overall vulnerability

An assessment of income showed that most houses have a low income and are therefore unable to protect themselves from flooding (Figure 6). Hence, the low income levels in the households of Graveyard Pond have contributed significantly to their vulnerability. Furthermore, an assessment of the efficiency of the various mitigation methods against the types of flooding showed that various residents got flooded regardless of their efforts at flood mitigation (Figure 7). The majority of the residents with successful mitigation methods were located on the periphery of the settlement, where the residents chose to dig trenches in response to flash floods. The least efficient responses were found to be in the central and southern part of the settlement. Notably, the same areas were also the most vulnerable areas based on exposure (Figure 4) and disease (Figure 5). Therefore, taking all criteria into consideration, the residents of these two areas are highly vulnerable in comparison to the rest (Figures 8 and 9).

4. Conclusions

Multi-criteria Evaluation (MCE) has been at the root of various statistical studies. The MCE methods include, among others, ranking, rating, PCM and TAM (Malczewski, 1999); fuzzy methods (Jiang & Eastman, 2000; Akter & Simonovic, 2005, 2006); and MACBETH (Bana e Costa *et al*, 2004). This study employed PCM because of its simplicity. At any given stage of the MCE, the community leader had to assess between only two alternatives. This made the ranking significantly simpler than assessing all the alternatives at once. By assessing the relative importance of all the alternatives in relation to a particular alternative, the various alternatives were implicitly ranked against each other. Based on the results of this study, a participatory approach to risk assessment in informal settlements is plausible. The participation of the community is essential in estimating risk and identifying dynamics that may be amplifying risk. Pinpointing such dynamics can help identify potential solutions.

The various maps showed that vulnerability and implicitly, risk was not homogeneous across Graveyard Pond. It was found that the central and southern sections of the settlement were most vulnerable based on exposure to both fires and flooding. Furthermore, the majority of the people in the central and southern regions of the settlement were unemployed and dependent on welfare grants. Lastly, waterborne and respiratory diseases were most prevalent in the central regions.

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