A Water Accumulation Flooding Potentiality Index (WAFPI) for rating the risk of flooding– A case study of Mauritius Island

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Abstract

The Water Accumulation Flooding Potentiality Index (WAFPI) is a qualitative risk assessment method based on a factorial scoring system that is aimed at dividing the land into classes that are similar in their susceptibility to flooding due to accumulating water. Such an assessment precedes quantitative flood modeling work, the overall results that are used for planning flood mitigation measures. WAFPI takes the form of an equation with five parameters as input, namely, rainfall amount; topographic slope angle; permeability of geology strata; soil infiltration capacity & land cover imperviousness. The output is a map with indices ranging from 1 to 10, with 1 being the lowest risk and 10 the highest risk of flooding. The assessment has been carried for Mauritius for the rainiest month of February. Results show that the assessment method succeeds in qualitatively evaluating the geospatial potentiality and the geospatial distribution of flooding due to water accumulation.

Keywords: flooding, risk assessment, potentiality mapping, GIS, factorial scoring, Mauritius.

**For correspondences and reprints*

1.0 INTRODUCTION

Mauritius is an island in the Indian Ocean (Figure 1) with a surface area of 1868 km^2 and a population of 1.3 million inhabitants. It is a developing country whose economic development began in the mid-1980s. Since then, there has been a rapid increase in urbanization along with numerous unplanned and improperly built drainage systems, which led to localized flooding problems throughout settlements. In 2001, a study was commissioned by the Water Resources Unit, where 310 flood prone areas were investigated by for the, causes, damages and risks associated with flooding

The primary finding of the study is that flooding problems occur mostly because of anthropogenic causative factors such as lack of drainage facilities, completely blocked drains due to poor maintenance and constructions on marsh and wetlands. The natural causative factors of flooding were studied too, where rainfall and geomorphology were found to be the most important factors. Flooding was found to be more correlated with rainfall intensity than rainfall amount. Antecedent soil water content and the permeability of the geology strata were also found to be influencing factors (WRU & GIBB, 2002).

From reports of Ahmad (2005) and Raynal (2005) the three most common types of flooding are water-flood, sediment-flood and coastal-flood. Water-flood is defined as the overflowing of water onto a normally dry area where it eventually accumulates in areas with low slopes with no or limited escape point. Sediment-flood is the collective name for debris and mud flow. It has been shown by Ahmad (2005) that most areas of Jamaica are affected by sediment-flood rather than water-flood. In the work of Raynal (2005), it is reported that coastal-flood, also commonly known as storm-surge, occurs mostly at river deltas and estuaries; and the conditions that are required for coastal-flood to occur are high river discharge and high sea tide, which are typical of cyclonic events with intense rainfall.

1.1 Location, geology and geomorphology

The study area is Mauritius Island, which is situated between latitudes 19° 58.8’ S and 20° 31.7’ S and longitudes 57° 18.0’ E and 57° 46.5’ E in the Indian Ocean, approximately 800 km east of Madagascar (see the upper left inset of Figure 1). The coastline of nearly 372Km long and the highest peak culminates at 828m above sea level.

The Island is entirely of volcanic origin, except for the coral formations of the reef as well as extents of alluvial deposits at the coast. The geological history and its volcanism has been well documented where for example Sentenac (1964); Saddul (1995); and Proag (1995) described the geology according to a geological chronology starting 10 million years ago and consisting of, the Old Lava Series; the Early Lava Series, the Intermediate Lava Series; and the Late Lava Series (see Figure 2).

According to Saddul (1995) the Island is classified into five geomorphologic domains, which are: 1) the mountain environment which is formed by old lava flows and which forms a discontinuous ring of three mountain ranges; 2) the central plateau that is encircled by the mountain environment; 3) the southern highlands which is in the domain of early lavas; 4) the recent lavas plains that lies below the 200m contour and finally; 5) the coastal environment that is composed of sandy beaches, rocky coastline and coral reefs. The Island has a radial drainage system where the river basins drain outward from the central plateau towards the sea (see Figure 1). The biggest river basin of the island has a surface area of 163 km^2 while the mean river basin surface area is 2.5 km^2.

1.2 Climate, soil and land use

The climate is humid, subtropical and maritime climate due to the island geographical location, small size, lack of extreme elevations and distance to continents. Two seasons predominates over the year, with a warm and rainy season from November to April and the cold and dry season from May to October. The average annual rainfall over a 30 year period is 1990mm, and the wettest month is February whereas the driest month is October (Luk *et al*., 2000; Water Resources Unit, 2003).

The close similarity between parts of the Hawaiian Islands and Mauritius as regard geology, climate, soils and cropping have led to the adoption of a classification system used for the soil survey of Hawaii for Mauritius (Parish & Feillafe, 1965). Two main soil groups exist, which are the mature ferralitic latosols and the immature latosolic soils. The mature latosols originate from highly weathered basaltic lava rock whereas the latosolic soils have minerals that are still in the process of weathering.

Sugarcane covers 50% of the total land and forest and scrub cover 31%. Lakes, reservoirs and roads make up to 3% and the remaining 16% is composed of settlement (Venkatasamy, 1991; Ministry of Agriculture & Natural Resources, 1999).

2.0 Materials and Methods

The aim of this study is to develop a method that makes it possible to divide the lands of the island into regions that are similar in their degree of susceptibility to flooding due to surface water accumulation. An equation that is based on a Geographic Information System (GIS) has thus been developed and it takes as input the five parameters decisive for water accumulation, namely, rainfall level; terrain slope angle; permeability of the geologic strata; soil infiltration capacity and land cover imperviousness, and produces as output a map with indices ranging from 1 to 10 such that 1 is associated with the lowest risk and 10 with a highest risk of flooding due to accumulating water. A GIS approach has been adopted as it permits the manipulation and integration of disparate data sources and the carrying of spatially analysis on the latter to produce new maps and useful statistical results (Burrough, 1986).

2.1 The factorial scoring system

The GIS approach is a weighted factorial scoring system that uses equation 1 with slope; rain; geology; soil and land cover as input.

$$WAFPI = [(RAIN * RAIN\_WGT) + (SLOP * SLOP\_WGT) + (GEOL * GEOL\_WGT) + (SOIL * SOIL\_WGT) + (LCOV * LCOV\_WGT)] \quad (1)$$

Where,

WAFPI	= Water Accumulation Flooding Potentiality Index	
RAIN	= Rainfall Index	$(1 \leq RAIN \leq 10)$
RAIN_WGT	= Rainfall Factor Weight	$(0 < RAIN\_WGT < 1)$
SLOP	= Slope Index	$(1 \leq SLOP \leq 10)$
SLOP_WGT	= Slope Factor Weight	$(0 < SLOP\_WGT < 1)$
GEOL	= Geology Index	$(1 \leq GEOL \leq 10)$
GEOL_WGT	= Geology Factor Weight	$(0 < GEOL\_WGT < 1)$
SOIL	= Soil Index	$(1 \leq SOIL \leq 10)$
SOIL_WGT	= Soil Factor Weight	$(0 < SOIL\_WGT < 1)$
LCOV	= Land Cover Index	$(1 \leq LCOV \leq 10)$
LCOV_WGT	= Land Cover Factor Weight	$(0 < LCOV\_WGT < 1)$

And,

$$RAIN\_WGT + SLOP\_WGT + GEOL\_WGT + SOIL\_WGT + LCOV\_WGT = 1.0 \quad (2)$$

The weighted factorial scoring system works in a standard way: a higher index is given to a class that has a higher potentiality and a lower index is given to a class that has a lower potentiality to water accumulation flooding. Each indexed map is then multiplied with a factor weight. Applying a factor weight has the effect of giving more importance to certain maps than others. For example, if slope is the most determinant factor for WAFPI followed by soil, then slope map is given say 40%, compared to a lower value (say 15%) given to soil map. Thus, the slope map will be multiplied by 0.4 (40%) prior to addition. The values chosen for the factor weights are such that their sum is one so as to satisfy equation 2. The minimum and maximum index is set to 1 and 10 respectively. These conditions result in the WAFPI map having indices ranging from 1 to 10, which permit an easy interpretation of the result.

2.2 Choice for input indices and factor weights

The values that will be contained in the WAFPI map will depend largely on the choice of values for the indices and factor weights. There is no rule of thumb for making this choice but rather a set of procedures that is based on the user own judgments, and experience with the datasets and study area. Since WAFPI is a qualitative assessment, the choice of the indices and factor weights are as the user wishes; and for the present case, a technique that was used to aid in that decision was to check for the occurrence of the flood prone areas from the WRU & GIBB (2002) with the factor maps. Where flood prone area exists, the factor maps are analysed to have a geospatial insight on the conditions that prevails there, such as type of geologic strata, soil type, land cover characteristics, amount of rainfall received and terrain slope angle. The objective of these analyses is to see if correlations exist between the flood prone areas and the factor map classes.

2.3 Sources of input factor maps

The geology map used for the study (see Figure 2) has been produced by digitising the 1:200,000 geology map of Willaime *et al*. (1983b). The slope map used (see Figure 3) was derived from a 25x25m Digital Elevation Model (DEM), the latter that was produced by interpolating OS & GOM (1991) 1:25,000 10m contours. The rainfall map used is for the month of February (see Figure 4) and has been produced using 195 station data points averaged over the period 1961-1990 and interpolated using the robust method, kriging (see Oliver & Webster (1990) for discussions on kriging) . The soil map has been produced by digitising the 1:100,000 soil map of DOS and MSIRI (1962). The land cover map has been produced by digitising the OS & GOM (1991) 1:25,000 map series of the island. 253 out of the 353 flood prone areas that was assessed by the WRU & GIBB (2002) was digitised into point data using the 1:25,000 and 1:5,000 streets maps of the Island, the latter that were obtained in digital format from cartographic section of the Ministry of Housing and Lands. The digitizing error during that process is on the order of 5-10m. Not all of the 353 point data were digitized due to lack of detailed street names. The 253 sites successfully digitized are shown in Figure 5.

2. 4 Processing the inputs and running the equation

After the paper maps are digitized into vector maps, the class of each digitized map is given its index and the new indexed map is then converted into a raster map. Raster is the format that is used for map algebra – that is to run equation 1. During conversion of the vector maps into raster maps, a cell size is chosen based on the scale of the original paper map. For example a 1:100,000 map is given a cell size of 100x100m during rasterization. Maps already in raster format (such as slope and rainfall) are simply reclassified to their corresponding indices, where for example the slope class 0–1 degree is directly converted to its index of 10. After all the rasters have been produced, equation 1 is run using the map algebra function of the GIS package.

3.0 Results and discussion

3.1. Intersection of the flood prone areas with the factor maps and values chosen for input indices

3.1.1. Rainfall and slope

Intersection of the flood prone areas with the rainfall map reveals no correlation. For February, the minimum rainfall is 125mm and the maximum is 500mm. For the flood prone areas, the minimum is 132mm with a maximum of 498mm. Thus flooding does not always occur on grounds that receive high rainfall only. This confirms the finding of the WRU & GIBB (2002) which states that flooding is more correlated with rainfall intensity than monthly rainfall amount. However, it is assumed in this work that with an increase in amount of rainfall received, there is an increase in the potentiality for surface water accumulation. As such the indices assigned to the rainfall map are increased with an increase in amount of rainfall.

Intersection of the flood prone areas with the slope map reveals a correlation where it is observed that flood prone areas are existent mostly on slope below 3 degrees. The most obvious reason for this is because all the flood prone areas are located in settlements, i.e., in urban areas, in built-up areas and in villages, and the latter are most often present on low slopes. The maximum slope for the island is 80 degrees and the maximum slope for the flood prone areas is 14 degrees. Water accumulation predominates when slope is the lowest and as such the indices assigned are decreased with an increase in slope.

The indices assigned for rainfall and slope are as shown in Table 1 and the weight for rainfall (RAIN_WGT) has been set to 0.20 while the weight for slope (SLOP_WGT) has been set to 0.30. This is so because a correlation was found to exist between slope angle and flood prone areas whereas little correlation was found to exist between rainfall and flood prone areas, but still theoretically it is assumed that water accumulation potentiality is higher when monthly rainfall amount is higher. Thus, on a relative scale, the factor for slope is set higher (0.30) than for rainfall (0.20), which is 1.5 times more.

3.1.2. Geology

No correlation turned up from the intersection of flood prone areas with the geology map. Like for rainfall and slope, it all depends on the geographical location of flood prone areas that are themselves restrained mostly to settlement, and the latter is found on particular geological classes, such as late lavas which make up most of the none-steep terrain. According to Giorgi *et al*. (1998), for Mauritius the permeability of the geology strata decreases with an increase in the age of the strata. Thus the indices chosen are increased with an increase in the age of the geology strata as shown in Table 1. The weight for geology (GEOL_WGT) has been set to 0.10, a value which is 3 times less than for slope and 2 times less than for rainfall.

3.1.3. Soil and land cover

A little correlation was observed from the intersection of the soil map with the flood prone areas. It is observed that the latosolic soils support most of the flood prone areas. This can be explained by the impermeability and low infiltration rate of this particular major soil group. Another reason is because settlement is in some places restrained to the non-fertile immature soils which are not used for agricultural practices. Some other soils such as the grey hydromorphic and the low humic gleys are almost nil in the intersection result because they are particularly unsuitable for settlement and as such no construction are normally made there. By considering the percentage porosity and infiltration rates from Balaghee (2001) and Kremer (2000) respectively, the indices chosen for each soil group are as shown in Table 2. The Weight for soil (SOIL_WGT) has been set to 0.20, a value higher than for geology but lower than slope because the soil factor which is found above the geologic stratum is more decisive for water accumulation than the latter, but still less decisive than slope.

The flood prone areas were also intersected with the land cover and as expected the entire flood prone areas are found in urban areas. Table 3 shows the indices applied to each of the land cover classes, where the indices applied are based on the imperviousness of the land cover class. The weight for land cover (LCOV_WGT) has been set to 0.20, a value which is the same as for soil for same reasons mentioned just before.

3.2 The WAFPI map

Figure 6 shows the WAFPI map. The indices has a modal value is 6.0. The WAFPI map was also intersected with the flood prone areas and the distribution of the observed values are as shown in Figure 7 where it is seen that the 253 flood prone areas have a mean of 7.43 and standard deviation of 0.86 and where more than 75% of the 253 flood prone areas has an index greater than 0.60 (60%). The highest values of the WAFPI map are found on the central plateau, the region in the center of the island and shown Figure 1. The central plateau is characterized as follows: rainfall amount is high (see Figure 4); the slope is mostly from 1° to 3° (see Figure 3); and the soil consists mostly of clayey and immature latosolic soils. More than 90 out the 310 flood prone areas come from this central plateau. This demonstrates the capability of the WAFPI method to indicate regions that are prone to flooding. Another flat area is the northern plains (see Figure 1 and Figure 3) but not many flood prone areas are found there because although the terrain slope is low, the rainfall amount received is not high (see Figure 4) and the river basins boundaries are not well defined (see the river basins in Figure 1).

3.3 Result interpretation

Concerning the interpretation of the resulting indices themselves, a user can interpret an index of 7 as being a high potentiality while another user can interpret the same index of 7 as being a moderate potentiality. This should not a problem as long as the user is basing his or her interpretation on a relative scale, i.e. interpreting the indexes relative to each other. Adopting a relative scale for result interpretation means to adhere to the logic that for the WAFPI map, an index of 9 will always be a higher potentiality than an index of 8 whereby doing so ensuring integrity in result interpretation. Additionally, graphical techniques can be used to aid in result interpretation, where color coding schemes can be used for viewing the indices on the map. Also, grouping techniques can be used, whereby the indices can be grouped into common classes, like 5 – 6, 7 – 8,… etc in order to facilitate color coding and/or to facilitate interpretation of a group as a qualitative statement like low, moderate, high, very high, etc.

3.4 Data input, processing and resulting accuracy

The resulting WAFPI map is in raster format with a cell size of 25x25m, the minimum of the input raster cell sizes. A smaller cell size such as 10x10m for the result could have been achieved through resampling but this wouldn't have produced a more accurate result because the minimum of the input cell size was initially 25x25m (Burrough, 1986). The more accurate the data inputs are, the more accurate will be the final output. A geology map at a scale of 1:50,000 (from Geolab-Burgeap *et al*., 1999) can be used to substitute for the geology map of 1:200,000 (from Willaime *et al*., 1983b). A soil map at a scale of 1:50,000 (from Willaime *et al*., 1983a) can be used to substitute for the soil map of 1:100,000 (from DOS & MSIRI, 1962). But before, these maps need be put in the desired GIS format, which was not done in this study due to time and resources constraints.

Moreover, having a larger scale map for topographic contours would have been a big advantage. According to Nathire (2003), large scale 2m digital contour maps at 1:2,500 are being produced at the Cartographic Section of The Ministry of Housing and Lands. Till now only a small part of the island has been completed, and when the work will be done, then finer resolution slope map (such as 5x5m) can be produced using these 2m contours. Better resolution DEM (and thus slope map) can be produced using radar interferometry and stereo-photogrammetry techniques while land cover map can be more accurately produced using methods of classification for the most recent optical and/or radar polarimateric remote sensing images (Jensen, 1996; Bamler & Hartl, 1998; Cloude & Papathanassiou, 1998; Lillesand & Kieffer, 2000).

3.5 Where and when to use the method

The method can be applied in any country provided that inputs are available. The minimum of five inputs (rainfall amount; slope angle; geologic stratum; soil type and land cover) provides comprehensive results. Consequently, with lesser inputs, the result will get less accurate and with additional inputs such as drainage density and underground water regime for example, the result will get more accurate. The method can also be particularly applied in African and developing countries where data availability is low, but still where the basic data of rainfall amount, topographic contours, soil type, geologic stratum map and land cover data can be found. The prerequisite for the data inputs is that they will need to be digitally processed to share the same cartographic projection, and then the indices will need to be adjusted to represent the conditions that exist over the area.

The WAFPI is a simple method that can be very useful and relevant in the process of assessing flooding impact. For example planners can use it to identify the flooding impact in the instance forested areas would be converted into agricultural lands. Another example is to assess the impact of climate change on flooding. The Intergovernmental Panel on Climate Change (IPCC) is projecting with high confidence that in the course of this century drought-affected areas will likely increase in extent and heavy precipitation events, which are very likely to increase in frequency, will augment flood risk (IPCC, 2007). In that context the WAFPI method can be used to produce flooding risk maps for this change by analysing different scenarios such as an increase in number of intense rainfall coupled with a decrease in land cover protection due to desertification. That would be done in WAFPI by increasing the indices of the rainfall map and modifying some of the indices of the land cover map where for example the index of shrubs can be changed into that for barren land. After these changes are done, then the equation can be run.

Furthermore, before planning flooding mitigation measures it would be useful if the qualitative assessment produced by the WAFPI method can be transformed into quantitative statements like: how much, for how long and when will flooding occur. A quantitative assessment involves modeling works using physically-based models and the WAFPI can provide a quick screening assessment before undertaking the longer quantitative modeling work.

4.0 Conclusion

WAFPI is a method for calculating the potentiality of flooding due to water accumulation. It takes the form of an equation that is based on a factorial indexing and which relates water accumulation flooding potentiality index to slope, rain, geology, soil and land cover. The tool required to run the equation is a GIS and the produced WAFPI map indicates areas that are potentially at risk to accumulating water during water-flood. The lowest and highest indices (1 & 10) correspond to the lowest and highest potentiality respectively. The WAFPI method can be easily applied to any country because its data requirement is not high and its only assumption is that the indices need to be adjusted for the conditions that prevail in the area where it will be applied. Judging from the results of this work, it is concluded that the WAFPI assessment method is very effective in qualitatively assessing the geospatial potentiality and geospatial distribution of flooding due to water accumulation and this in a cost and time effective manner, and meantime producing results that can be used for future detailed quantitative flood modeling works.

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Index	Slope (degrees)	Rainfall (mm)	Geological Classes
10	0 – 1	480 - 500	Old Lavas_10
9	1 – 3	443 - 480	Early Lavas_9
8	3 – 5	406 - 443	Intermediate Lavas_8
7	5 – 8	372 - 406	Intermediate Lavas_7
6	8 – 12	340 - 372	Intermediate Lavas_6
5	12 – 15	311 - 340	Late Lavas_5
4	15 – 20	282 - 311	Late Lavas_4
3	20 – 30	250 - 282	Late Lavas_3
2	30 – 45	216 - 250	Late Lavas_2
1	45 - 80	125 - 216	Sandy Coasts

Table 1 *Indices assigned to rainfall, slope & geology classes*

Soil Groups	Index
Dark Magnesium Clays, Ground Water Laterite, Grey Hydromorphic Soils, Lithosols, Mountain Slope Complexes, Low Humic Gleys	10
Latosolic Red Prairie Soils, Latosolic Brown Forest Soil	7

Low Humic Latosols	6
Humic Latosols and Humic, Ferruginous Latosols	5
Alluvial Soils	2
Regosols	1

Table 2 *Soil groups and indices assigned*

Land Cover Class	Index
Urban, Built-Up, Settlements and Rocks	10
Swamps, Marshes, Wetlands, Backwater , Water bodies, Lakes and Reservoirs	10
Agricultural fields and Plantations (Sugar, Tea, Crops, Palms, Coconuts, etc)	6
Barren Lands	7
Shrubs, Sparse Vegetation, Grass, Graze lands and Pasture	3
Forested areas (natural or planted)	2
Sandy areas	1

Table 3 *Land cover classes and indices assigned*

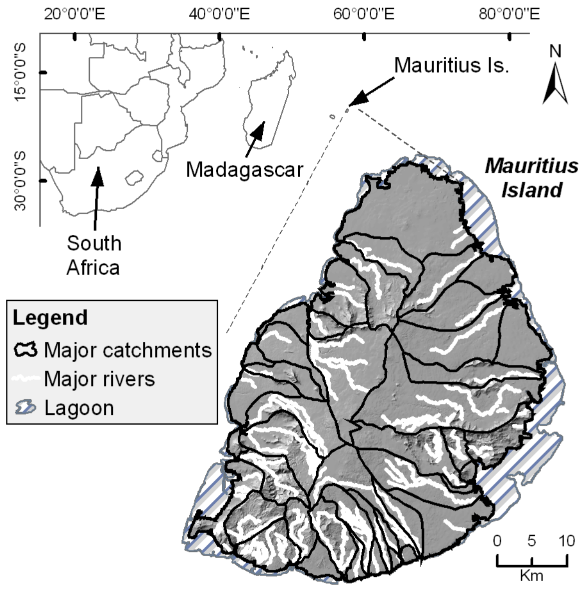

Figure 1 *Location map. Upper left shows the location map of Mauritius in the Indian Ocean. Main Figure is a DEM hillshade overlaid with major catchments of the Island.*

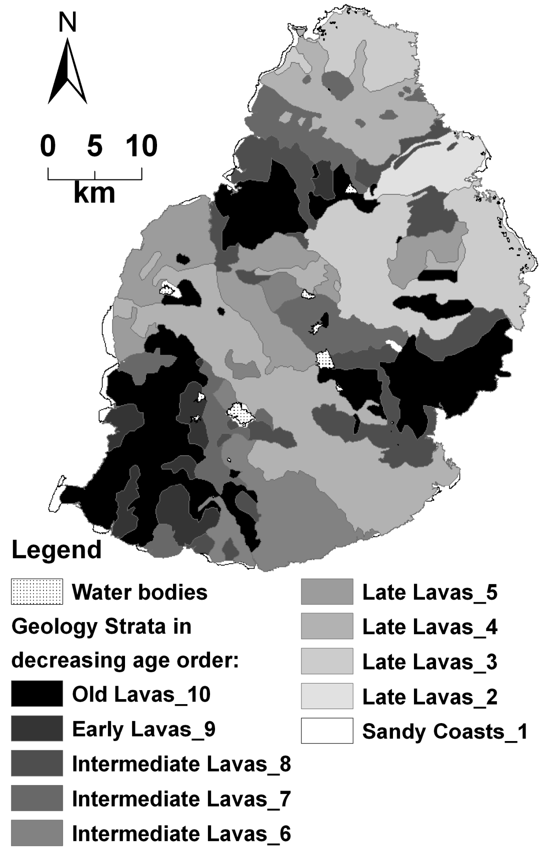

Figure 2 *Geology map showing chronological order (after Willaime et al., 1983b)*

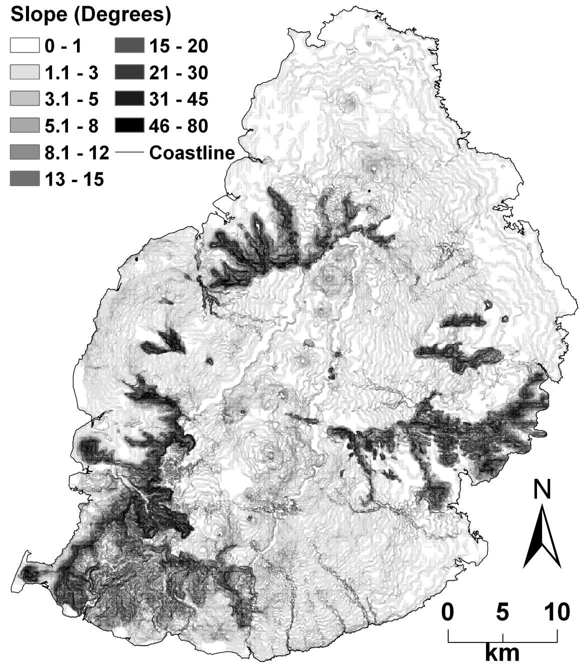

Figure 3 *Slope map*

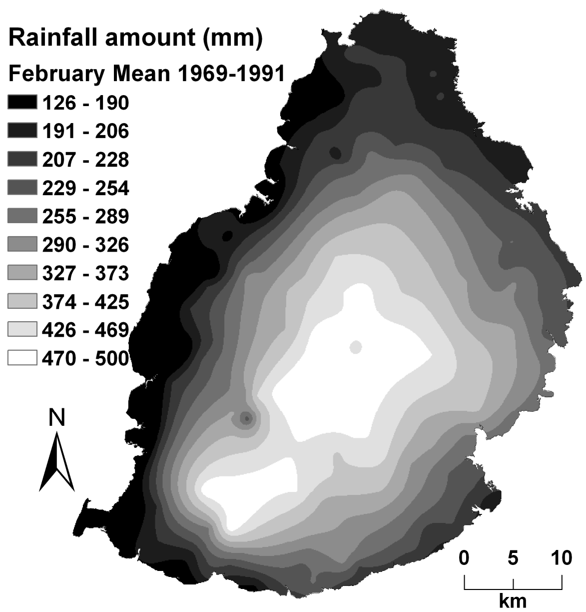

Figure 4 *Rainfall depth for February*

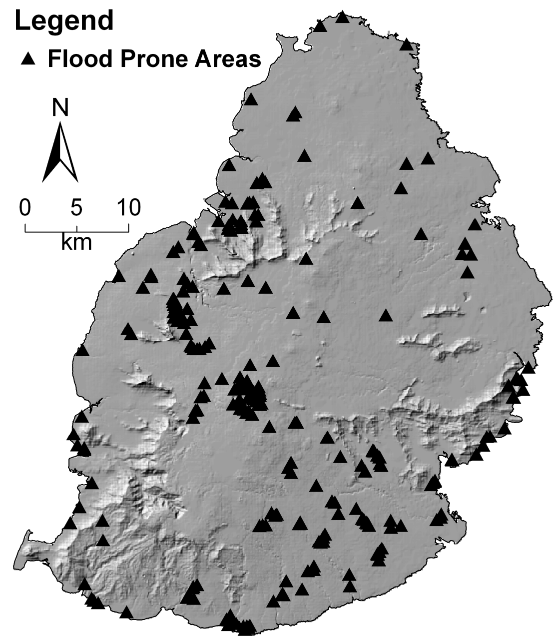

Figure 5 *The 253 out of the 350 flood prone areas that were assessed by the WRU & GIBB (2002).*

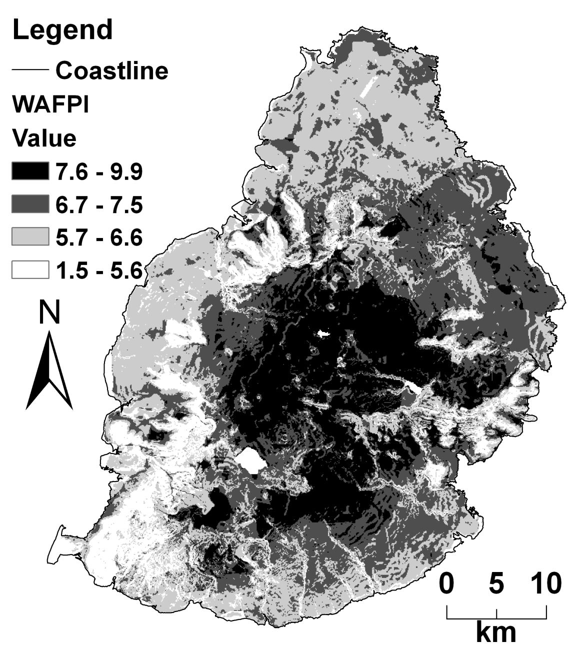

Figure 6 *WAFPI map for the month of February.*

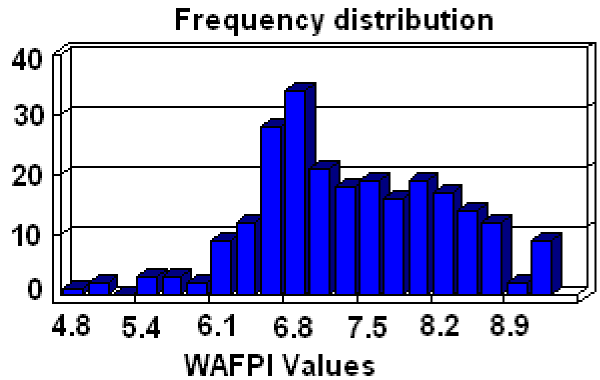

***Figure** 7 Frequency distribution of the WAFPI values for the 253 flood prone areas*