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APPLICATION OF A RATIONAL MODEL IN GIS FOR FLOOD RISK ASSESSMENT IN ACCRA, GHANA

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ABSTRACT
Accra has been experiencing periodic flooding that affect properties and lives. The government seeing the dangers involved has commissioned institutions such as Ministry of Works and Housing, Town and Country Planning and City Engineers to identify flood risk zones and adapt measures that will help reduce flood damages. These institutions identify flood risk zones using conventional methods such as watermarks on buildings and reported cases in the news media. Works carried out by these agencies were not able to give details about potential areas that are likely to experience this extreme event. Hence there was the need to find a new method of identifying and mapping of potential flood risk zones. To determine flood risk zones in Accra and its environs a hydrological model (modified rational model) was integrated into the GIS platform, by the arithmetic overlay operation method, using operators such as addition and division. The results show that although the delineated areas experienced a same rainfall intensity of 140.2 mm the flood intensities of these areas could differ. The high flood risk zone covers 35.66 percent of the study area, whiles the low risk zone covers 26.85 percent. The areas that will potentially experience periodic floods with a given input of rainfall are mostly below the 350-meter contour.

KEY WORDS: Flood, Hazard, Mapping, GIS, Integration.

INTRODUCTION

Background
Risk is a factor, element, or course involving danger or can be seen as the possibility of suffering harm or loss (Encarta 99). Risk has become an issue that is being discussed in various fields, in which varied definitions have been given without any discipline claiming authority (Stig, 1996). Studies of risk cover issues like identification and estimation of risk, risk assessment and evaluation, including monitoring and management of risk (Gerrard, 1995).

Renn (1992) classified the concept of risk into seven units namely:
- The actuarial
- The epidemiological (toxicology)
- The engineering (including probabilistic risk assessment)
- The economic (including risk-benefit comparisons)

- The psychological (including psychometric analysis)
- Social theories of risk (sociological and anthropological studies)
- Cultural theories of risk (using grid groups analysis)

According to Stig (1996), three main approaches to risk usage can be identified in the following areas in geography, namely:

- Medical geography (corresponding to epidemiology)
- Applied geography and planning (bearing connections to probabilistic risk analysis)
- The hazard-tradition (with connection to physical geography as well as social theory and cultural theories)

In this study risk is used to imply the probability of human life and properties within the study area to be affected by high rainfall that generates into flood.

Flooding refers the inundation of an area by unexpected rise of water by both dam failure or extreme rainfall duration and intensity in which life and properties in the affected area are under risk. Accra, the capital of Ghana, accommodates major institutions, industries and government Ministries in the country, it also attracts migrants from various parts of the country and the entire world. In recent years, Accra has seen continually erection of concrete structures by private estate developers in areas that experience periodic floods. Between 1955 and 1997, about c300 billion worth of properties has been destroyed, 100 lives have been lost either during the flood period or after the floods and 10,000 people have been displaced from their homes (Adinku, 1994; Gyau-Boaky, 1997). This has prompted the government to setup statutory supervisory agencies such as Ministry of Works and Housing, City Engineers of Accra Metropolitan Assembly and Lands Department and also commissioned consultants (NEDECO, 1962,1967; WATERTECH, 1991) to see to the reduction of the effects of flooding on life and properties.

Consequently it is expected that these government statutory supervisory bodies will limit construction in the areas that continuously experience floods. To identify potential flood risk areas these agencies use methods such as identifying watermarks on structures, media reports and aerial photographic interpretation as shown in Kuma (1996). These methods are inadequate, because there are always new areas that periodically experience floods. Therefore, there is a need to explore new approaches at identifying and mapping flood risk zones that will help in planning and managing the problem. This paper presents the procedure through which the flood risk zone map of Accra was generated.

Study area

The proposed study area is within the Greater Accra and covers approximately about 786.59km^2 (Figure 1.1). It stretches from Botianor to Sakumo, and James Town to Oyarifa. Tema bounds it on the East, on the South by the sea, West by the Weija dam, and North by the Akwapim hills. It lies within the Longitude between 0^o.03 and 0^o.25 West and the Latitude between 5^o.30 and 5^o.53 North.

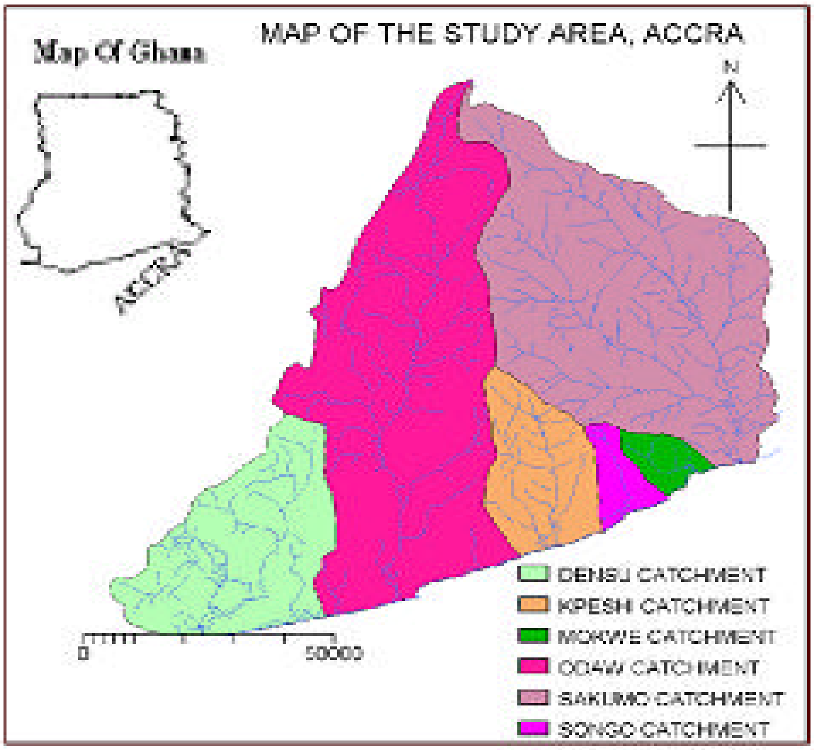

Figure 1.1 Study Area

The area is characterized by lowlands and occasional hills with an average elevation of 20 meters above sea level. The slopes are generally gentle, mostly below 11 percent, except few places such as MaCarhty hills, the television transmitting station near Abokobi and Kwabenya hills, where slopes are above 22 percent. The water table varies between 4.80 meters to 70 meters below the surface at places like Ofankor, Kantamanso and Accra Brewery Limited bottling house in Accra.

Natural streams and valley network and artificial drains drain the area. Most of the streams such as Odaw, Sakumo, Mahahuma, Lador, and Dzorwulu, originate from the Akwapim range. The artificial drainage is mostly built-up structures that enable quick discharge of waste and storm water.

The area falls within the anomalous dry equatorial climate region and experiences double maxima rainfall and a prolonged dry season with occasional dry harmattan condition being experienced. The hottest months are February and March, just before the rainy season, with a monthly mean of temperature 27°C, whilst the coolest months are June and August. During which monthly mean temperature is about 21°C. Rainfall in this area has two peak periods, from May to August and from October to November, with an annual rainfall ranging from 780mm to 1200mm.

There are two major vegetation types within the area, the coastal scrub and grasslands and the mangrove forests. The coastal scrub and grasslands are in patches at certain places with occasional trees such as Nim and Baobab. The mangrove forests are found in the coastal lagoon areas where the soil is waterlogged and salty.

DATA SOURCE AND IDENTIFICATION

Data used for this study were collected mainly from two sources, official and primary sources. Data from official sources were obtained from published information on flood generation factors, such as rainfall, discharge of the various rivers and human activities within the study area compiled and used by specialized organizations such as Water Research Institute, Meteorological Services, Hydro-Division of Ministry of Works and Housing. The data collected from primary source included vegetation characteristics, landuse pattern, channel characteristics (cross section area) and soil characteristics. The methods used to collect these information included, field observations, field measurements and satellite/photographic and topographic map interpretations.

To easily incorporate the data into the proposed geographic information system and hydrological models for analysis, the Terrain Mapping Units (TMU) technique as described in the works of Meijerink (1988), Moore et al (1991) Meijerink et al (1994) and Mitchell (1973) was employed. Using 1997 aerial photographs with a scale of 1:10,000, Thematic Mapper satellite image of 1991 and the 1972 topographic map of scale of 1:50,000, the terrain of the study area was sieved using various cover classes into thematic maps (topography, elevation, slope, land use, and vegetation, drainage channels). Total discharge was calculated using these data collected, the modified rational model and a digital elevation model generated from 1972 contour map of Accra on a scale of 1: 50,000 using ILWIS2.1 software.

MODEL FOR THE STUDY

The modified modeling flow based on the relational rule, was employed for the study as it concerns spatial extent of flood occurrence. A spatial model was adopted because it has the capability of using point data to represent an area in which spatial variability of specific parameters of an area can be integrated to help provide an understanding of interdependence in hydrology (Molenaar, 1998; Este, 1992; Doe III et al., 1996; and Baumgartner & Apfl, 1996). The application of a Geographic Information System Model (GISM) to study hydrological event in its spatial form is therefore appropriate, the reason being that it has the capabilities of incorporating physical and stochastic models for spatial analysis of a phenomenon.

The Geographic Information System Model (Figure 1.2), adapted and modified for this study is the Modeling Flow based on the Relational Rule used by (Meijerink et al., 1994). The model identifies four (4) main stages that could be used for flood risk zoning or assessment.

The first stage involves the generation of various thematic maps of the area of study, using aerial photographs, satellite images, topographic maps and field observation and measurements to check the accuracy of these data.

The second stage involves the incorporation of the thematic data into the Geographic Information System Model (GISM) through digitizing and creation of attribute tables of each theme.

Thirdly, it involves the use of arithmetic overlay operation (addition and division to integrate the hydrological model into the geographic information system model.

The fourth stage deals with the generation of flood risk hazards maps for the Accra area under investigation.

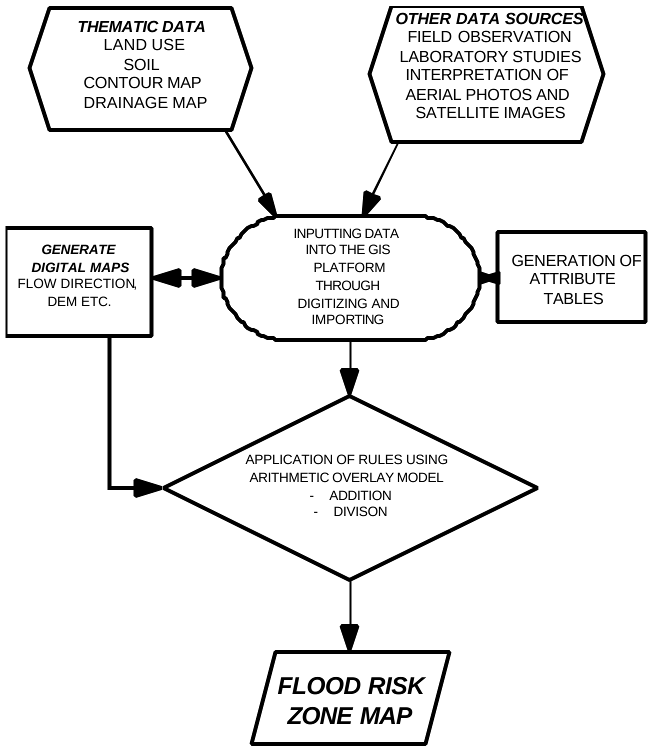

Figure 1.2 MODIFIED MODELING FLOW DIAGRAM FOR RELATIONAL-RULE-BASED FLOOD ASSESSMENT, Source: Meijerink et al. (1994)

FLOOD RISK ZONES DETERMINATION

Bonell & Balek (1993) noted that in traditional hydrologic methods, estimating surface runoff does not always use elevation/height (DEM), because derivation of elevation/height (DEM) information involves laborious operation. Despite that, the possible combination of DEM and discharge maps using an overlay operation method with the geographic information system platform should lead to derivation and the understanding of spatial association between the two which could be used to predict runoff rates and flood risk zones.

Runoff discharge of the study area

The modified rational model Viessman & Lewis, 1996; and Mannaerts, 1996 (equation 1) presented a general step to calculate individual discharge for each section in the entire catchment areas (Table 1.1).

$$\mathbf{Q=0.28*C_s*C*I*A} \qquad (1)$$

Where:

Q= runoff rate [m^3/sec]

C= Runoff Coefficient
C_s= Storage Coefficient
I= Rainfall Intensity [mm/hr]
A= Drainage area [Km^2]

Table: 1.1 Total discharge of section of the Study area

Catchment Name	Area (Km^2)	Runoff coefficient	Storage coefficient	Rainfall (mm)	Discharge M^3/sec
Kpeshie Catchment	62.6	0.7	0.2	140.2	344
Lower Densu	79.4	0.4	0.6	140.2	748.1
Lower Odaw	90.1	0.9	0.2	140.2	636.7
Lower Sakumo	116	0.7	0.4	140.2	1271
Middle High Odaw	18.7	0.7	0.2	140.2	102.8
Middle Odaw	118	0.7	0.2	140.2	650.7
Middle Sakumo	155	0.6	0.5	140.2	1825
Mokwe catchment	13.9	0.7	0.3	140.2	114.6
Songo catchment	16.8	0.8	0.2	140.2	105.5
Upper Densu	24.9	0.6	0.7	140.2	410.5
Upper Odaw	64.5	0.6	0.7	140.2	1063
Upper Sakumo	9.4	0.6	0.7	140.2	155
West Densu	17.3	0.6	0.7	140.2	285.2

Source: Authors Context, 1999

From Table 1.1 the total runoff discharge over the land surface of the study area determines the maximum flood that an area under consideration is likely to experience. Various segments covering the topography (Figure 1.3) produced varied runoff rates. For instance, the Odaw and the Sakumo being the biggest catchments produce a total discharge rate of 1825 m^3/sec and 1271 m^3/sec, respectively, if all the entire catchment contributes to runoff at the same time. However, segments within the catchments also produce varied runoff rates. For instance, the Sakumo catchment presents three different runoff discharge rates of 155 m^3/sec, 1825 m^3/sec and 1271 m^3/sec for the Upper, Middle and the Lower catchment areas, respectively.

As noted in the use of the modified rational model (Table 1.1) the rate of discharge is mostly dependent on rainfall intensity and area. For instance the lower and middle Sakumo with area measurements of 116 km^2 and 155 km^2 presented calculated runoff discharge rates of 1271 m^3/sec and 1825 m^3/sec, respectively. The Kpeshie and Songo catchments, having smaller area measurements of 62.6 km^2, and 16.8 km^2 produce a discharge of 344 m^3 and 105.5 m^3, respectively. However, with the given segment area that is constant over the topography within the catchments, an increase in rainfall will also lead to an increase in the total runoff discharge rate.

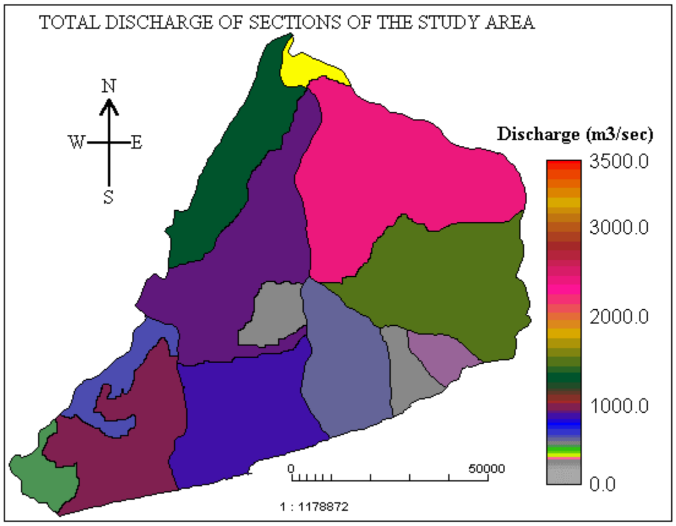

Figure 1.3 Total discharges of sections within the study Area.

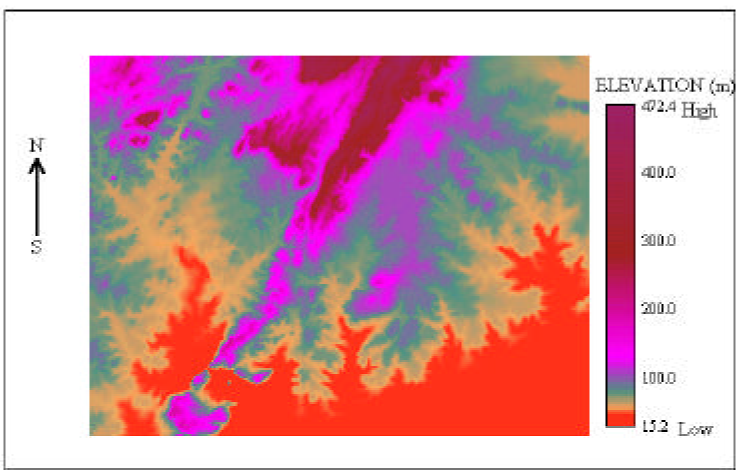

Figure 1.4 Digital Elevation of the Study Area

The modified relational model in risk zone determination

Stages three and four of the modified relational flow models was followed to generate the flood risk map. These are:

- The application of the rule using arithmetic overlay operation, addition and division to help integrate the hydrological model into the geographic information system model.
- The generation of flood risk zone maps for Accra and its environs.

Mode of model integration

Among the various methods of determining runoff, it has been noted that the combination of a physical, deterministic or hybrid model with a digital elevation model within the geographic information system model offers an alternative to these models to give a spatial view of a phenomenon as its end result. To achieve this an arithmetic overlay method was used to combine DEM (Figure 1.4) and discharge map within the geography information system model to identify flood risk areas. Mathematical operators such as addition and division were used in the combination procedure. The essence of using the arithmetic overlay method is that possibilities exist for the derivation and examination of spatial patterns caused by interactions of one map with the other. Secondly, the rule also provided the possibility of restricting areas on the output map according to a binary map that act as a mask.

The arithmetic overlay method used involves two main stages:

1. The first stage involves the determination of runoff within various segments over the landscape.

$$X + Y = Z_{ct} \tag{2}$$

2. The second stage is estimation of values that can be used to infer potential areas that are likely to be in flood with any storm event.

$$\frac{X+Y}{X} = Z_{FRA} \tag{3}$$

Where:
X(m) is the Digital Elevation Model
Y(m^3/Sec) represent total discharge
Z_{ct} (m^3/Sec/m) is the runoff concentration at various elevations
Z_{FRA} is the value for flood risk areas.

Both equations 2 and 3 were used separately to calculate the discharge that each pixel within the segment generated at a given elevation and a weighted pixel indicating areas that fall within the zone that experience flood or not.

Assumptions for using the overlay operation

The application of the arithmetic overlay method (equations 2 and 3) for the study was based on the following assumptions:

1. A steady state condition exists within the variables to be used.
2. The discharge parameter [X] only varies if total rainfall changes.

Runoff Concentration on Elevation

The modified rational method used to calculate discharge gave a general view of the rate at which sections within each catchment area produced runoff with a given rainfall event. To show variability of runoff over the topography, equation (2) was used for the map integration.

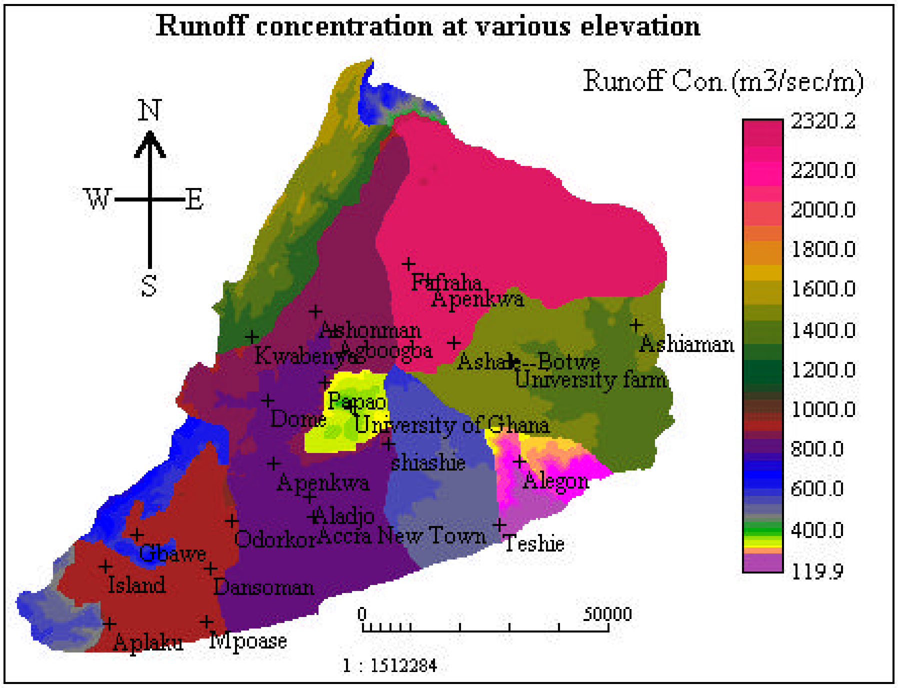

Figure 1.5 Runoff Concentration on elevation

The resultant map (Figure 1.5) showed discharge rate over the topography at varied elevations within Accra and its environs. With a given discharge rate, the catchment runoff concentration value would only vary with elevation. For instance, a discharge value of 155 m^3/sec for Upper Sakumo when combined with an elevation of 1550 meters resulted in a calculated discharge of 1705 m^3/sec/m. Also an elevation of 250 meters will experience a discharge of 405 m^3/Sec/m. Hence, any point within the 155 m^3/sec discharge zone will experience the same runoff rate when they are located on the same elevation. Therefore, the discharge concentration values determined from the arithmetic map overlay decreases as elevation decreases, indicating a slow runoff rate that has the potential of creating a backwater effect and generating flooding.

However, it is noted that no matter the elevation if the area contributing to discharge is large as in the case of the Middle Sakumo, a high runoff concentration is produced as compared with the Upper Sakumo. In other words elevation is not the only determinant of high runoff concentration, but a critical attention should also be paid to the catchment area.

Flood Risk Areas

The runoff concentration map (Figure 1.5) does not show the areas that are liable to flooding, though high elevated areas showed a comparatively higher discharge rates than the low lands.

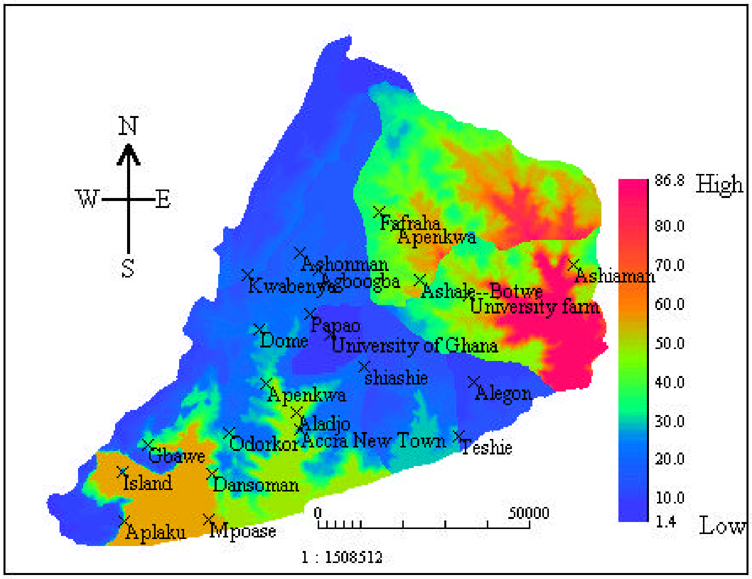

Figure 1.6 Flood risk areas

Using equation (3) for the map combination, it came out those areas within the study area presented different pixel value ranging from low to high. Upon close examination of the map, the areas in an elevation between 350 m and 1550 m had low pixel value between 0 and 20 and the areas in an elevation below 350 m presented high pixel value between 20 and 87. Based on ground truth, areas on a high elevation have low pixel values indicating that they fall within the low flood risk zones. However, areas on a low elevation indicated high pixel values, this falls within locations that experience periodic flooding at a given rainfall event. This confirmed that areas such as Aladjo, Ashiaman and Sakumonu fall within the high pixel values experience destructive floods with high rainfall intensities.

It is important to note that the arithmetic overlay method helped to identify areas even as small as the area within the Densu flood plain (labeled Island) was isolated and assigned the flood risk category that it falls in.

Flood risk zoning

Figure 1.6 show pixel values that can be used to represent the several flood risk areas. These pixel values can be grouped to show a general pattern in the degree of flood intensity of regions that exist within Accra and its environs.

Thus, with a clearly defined domain of: very high, high, moderate, very low and low risk zones, the technique of density slicing made it possible to reclassify the flood risk map. This helped to differentiate between areas that experience different intensity of flood (Figure 1.7).

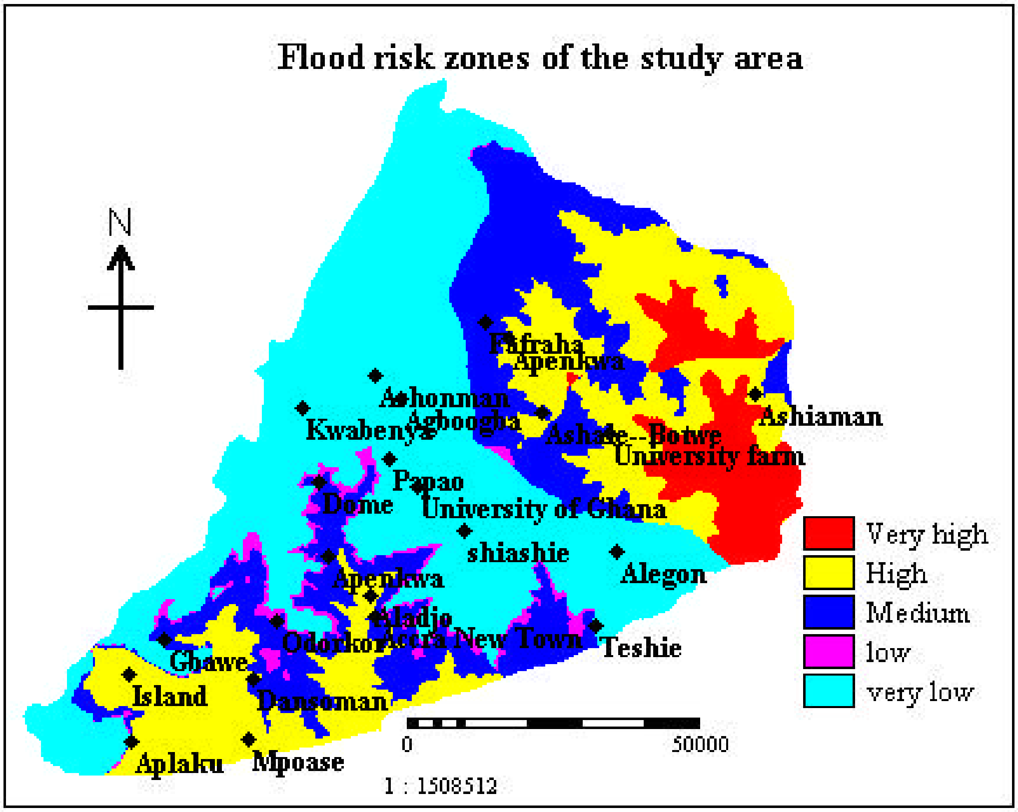

Figure 1.7 Flood risk zones of the study area

Table 1.2 Flood Risk Zone Coverage (Source: Figure 1.7)

Flood Intensities	Area (m^2)	%
Low	2269185000	26.85
Medium	2652485000	31.39
High	3012897500	35.66
Very high	515355000	6.10

Table 1.2 shows areas that fall within the very high flood risk zone covering about 6.09 percent of the study area. However the combination of the very high and high-risk zones constitutes a total of 41.74 percent of the entire study area. Hence, the area coverage of the flood risk zone will expand if the rainfall intensity increases above 140.2 mm/day.

SUMMARY AND CONCLUSION

To determine flood risk zones in Accra and its environs a hydrological model (modified rational model) was integrated into the GIS platform, through the arithmetic overlay operation method using operators such as addition and division. The results show that the delineated areas however experience same rainfall intensity of 140.2 mm yet the flood intensities of these areas differ. For instance, the high flood risk zone covers 35.66 percent of the study area, whiles the low risk zone covers 26.85 percent.

The result of this research showed that areas with a high likelihood of periodic floods for a given input of rainfall are mostly below the 350-meter contour. It was also noted that the flood experienced by an area is mostly dependant on rainfall intensity no matter the catchment area. However other factors such as area, landuse, storage and runoff coefficient were identified as contributory factors to flooding in the study area. It was also observed that about 45 percent of the study areas fall within flood risk zone.

In search for a method to determine flood risk zones, the use of a hydrological model within a geographic information system model is very effective when the appropriate decision rule was defined. It should also be noted that the use of a geographic information model has some difficulties. First, it demands special software and good knowledge in handling the software to enable one analyse the data. Second, data input using the digitizer can be too tedious and therefore prone to mistakes if care is not taken. Lastly, to calibrate hydrological model for easy incorporation into the geographic information system model can be very difficult.

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