Digital Elevation Models and GIS for Watershed Modelling and Flood Prediction – A Case Study of Accra Ghana

D.D. Konadu and C. Fosu

Abstract Geographical Information Systems (GIS) and Digital Elevation Models (DEM) can be used to perform many geospatial and hydrological modelling including drainage and watershed delineation, flood prediction and physical development studies of urban and rural settlements. This paper explores the use of contour data and planimetric features extracted from topographic maps to derive digital elevation models (DEMs) for watershed delineation and flood impact analysis (for emergency preparedness) of part of Accra, Ghana in a GIS environment.

In the study two categories of DEMs were developed with 5 m contour and planimetric topographic data; bare earth DEM and built environment DEM. These derived DEMs were used as terrain inputs for performing spatial analysis and obtaining derivative products. The generated DEMs were used to delineate drainage patterns and watershed of the study area using ArcGIS desktop and its ArcHydro extension tool from Environmental Systems Research Institute (ESRI).

A vector-based approach was used to derive inundation areas at various flood levels. The DEM of built-up areas was used as inputs for determining properties which will be inundated in a flood event and subsequently generating flood inundation maps. The resulting inundation maps show that about 80% areas which have perennially experienced extensive flooding in the city falls within the predicted flood extent. This approach can therefore provide a simplified means of predicting the extent of inundation during flood events for emergency action especially in less developed economies where sophisticated technologies and expertise are hard to come by.

Keywords DEM · GIS · drainage modelling · watershed · flood modelling · ArcGIS · ArcHydro

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1 Introduction

Accra, the administrative and commercial capital of Ghana has serious problems related to urban flooding as in many cities the world over. This situation is highlighted during the rainy season – between the months of May and July each year – when residences in parts of the city experience ankle to knee deep inundations. Daily activities become virtually paralysed and heavy traffic jams crop up due to stagnant water on the streets and other motorable passages in parts of the city. This scenario creates large infrastructure problems for parts of the city and a huge economic loss in production as well as large damages to existing property, goods and even loss of human lives.

Geographic Information System (GIS) has proven to be very resourceful in dealing with many natural disasters in terms of modelling, prediction, damage assessment and evacuation exercises. GIS can assist in all stages of flood disaster management: prediction, preparation, and prevention, mitigation, and post disaster activities especially when it is integrated with Digital Elevation Models. Digital Elevation Models (DEMs) have been proved to be a valuable tool for the topographic parameterisation of hydrological models which are the basis for any flood modelling process. The existence of digital topographic data in the form of contours (Elevation data) and both man-made and natural features presents an affordable source of data for generating DEM and the subsequent use of the derived DEM in hydrological studies. In this paper a vector base GIS and DEM have been used to delineate watershed boundaries and predict areas of possible inundation during a flood event in the city of Accra using ArcGIS 9.0® software package with its ArcHydro® Tool from ESRI.

The main objectives of the study were:

- Develop DEM from digital topographic data
- Delineate watershed and drainage patterns of the study area from the derived DEM
- Model flood extent and areas of possible inundation using vector-base approach from the derived DEM

1.1 The Study Area

The study area, Accra, (Map shown in Fig. 1) is the administrative and commercial capital of Ghana. It is characterized by low relief topography with occasional hill and an average elevation of 20 m above mean sea level. It is bound in the north by the Akwapim ranges from where most of the natural streams that drain the city take their source. 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. Rainfall in this area has two peak periods, from May to August and from October to November, with an annual rainfall ranging from 780 to1,200 mm (Nyarko 2002). It is during these periods that the city experiences serious inundation.

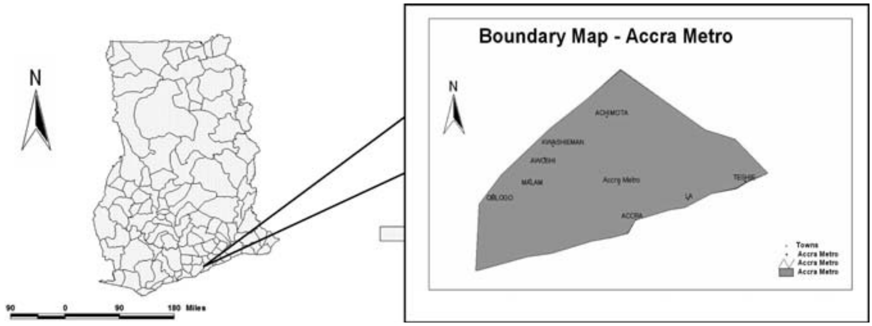


Fig. 1 Map of Accra

2 DEM Data Modelling and Development

A digital elevation model (DEM) is defined as "any digital representation of the continuous variation of relief over space," (Burrough 1986). The preference of data sources and terrain data sampling technique is vital to the quality of the resulting DEM. There are four main methods of data acquisition for the generation of DEMs. These include: Data acquired by space-borne platforms (Satellite Remote Sensing), Air-borne platforms (Photogrammetry and Laser Altimetry), Digitising of contours from already existing topographical maps and Terrestrial Survey techniques (e.g. Spirit levelling, GPS).

2.1 Data Source

In this paper, digital contours and planimetric features (including building footprints, streams, roads etc.) obtained from a 1:2,500 topographic maps of the study have been used. The contours were at an interval of 5 m and had been created from aerial photographs using photogrammetric procedures. This data is very cheap in terms of cost and has an appreciable accuracy. The contours were further interpolated for the generation of the DEM.

2.2 DEM Development

In order to construct a comprehensive DEM it is necessary to establish the topological relations as well as an interpolation model to approximate the surface behaviour (Weibel and Heller 1991). A variety of DEM data structures have being in use over time (Peuker 1978; Mark 1979). However, today, majority of DEMs conform to one

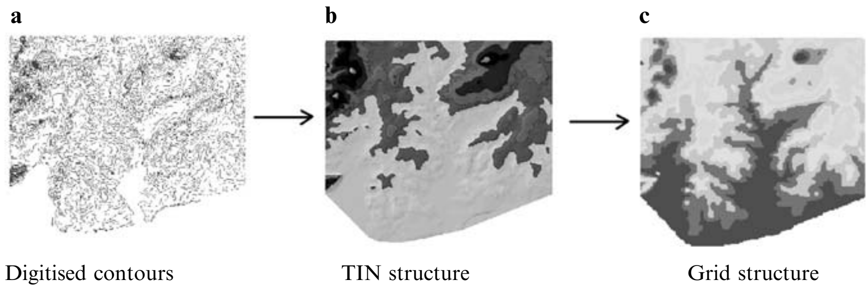


Fig. 2 Various DEM representation

of two data structures: a Triangulated Irregular Network (TIN) (Peuker et al. 1978) or a Regular Grid (or elevation matrix) which is also a format GIS supports (Chen and Kolditz 2005). In hydrologic modelling the first step is to develop this surface.

Watershed and drainage patterns are phenomena which are directly related to the actual ground and must be delineated based on the actual ground elevation so should flood simulation. The digital contours which gives a representation of the bare earth elevation was used as the basis for the creation of a TIN surface in ArcGIS using the 3D Analyst. The output TIN was then converted to a Grid Elevation model. The figure (Fig. 2) above shows the result of the DEM generated from the digital contours covering the study area.

3 Watershed and Drainage Modelling

An effective and proactive means of analyzing any flood event is by determining exactly where water entering a given area will flow; including the general direction and the magnitude of flow. DEMs provide good terrain representation and are the basis for automatic watersheds delineation in GIS technology platforms. The grid DEM generated above has been used for this purpose in this paper.

3.1 Watershed Delineation and Stream Network Generation

Using the ArcHydro Tools, catchment delineation of the watershed and the natural drainage patterns (stream network) of the study area, Accra was generated. Raster analysis is performed to generate data on flow direction, flow accumulation, stream definition, stream segmentation, and watershed delineation. These data are then used to develop a vector representation of catchments and drainage lines (Fig. 3).

4 Flood Simulation

This study has used a vector-based approach in simulating flood extent based on the derived drainage lines, their depth and capacity to hold rainfall run-off. This approach is a very basic flood simulation model which only requires the extents of flood levels, without any information on movement and volume of water. The model uses contours to represent particular flood levels originating from drainage lines. These are selected based on the contours derived from the DEM which have been further interpolated to smaller contour intervals. A catchment has been selected from the delineated watershed of the study area and used as a case study for the simulation. The generalised methods used for the flood simulation follows below.

4.1 Determination of Cross-sections Across Drainage Line

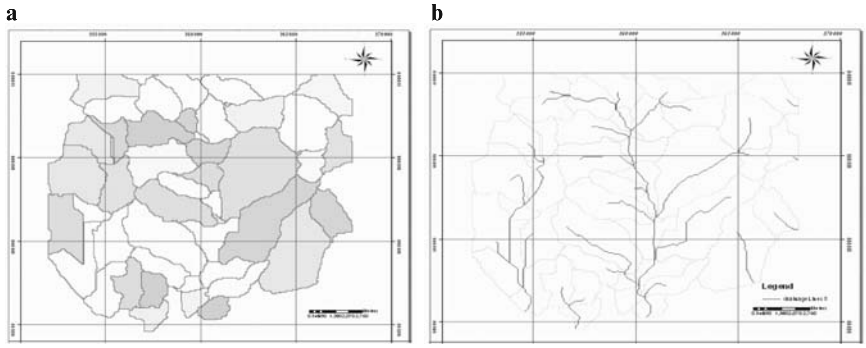
Cross-sections were drawn across the drainage line at locations where there is a sharp change in elevation. The average of the bottom elevation of two successive cross-sections were determined and used to represent the average elevation of the drainage line between them. A total of six cross-sections were determined from the beginning of the drainage line to the end with an average bottom elevation difference between successive cross-sections of about 5 m (See Table 1 below). Fig. 4 shows one of the cross-section positions along the drainage line of the catchment under study.

4.2 Flood Contour Derivation

The mean bottom elevation of consecutive cross-sections determined from the profiles represents the average minimum elevation between the cross-sections above which features in the catchment will be inundated during a flood event, depending on their elevation. With this elevation measure as a guiding factor, 0.5, 1, 1.5 and 2 m were selected as flood water levels. Flood level contours for each of the flood water levels were computed and derived for each of the consecutive cross-sections and then selected from the contours derived at 0.5 m interval and saved as new layers in ArcGIS (Fig. 5). Below is a table showing flood level contours derived from flood water levels for each of the consecutive cross-sections (Table 1).

Table 1 Cross-sections and mean bottom elevation

Cross-section	Bottom elevation	Mean bottom elevation of consecutive cross-section
A-A’	31.5	28.75
B-B’	26.0	24.75
C-C’	23.5	20.50
D-D’	17.5	13.75
E-E’	10.0	7.00
F-F’	4.0	



Catchments

Drainage lines (stream network)

Fig. 3 Maps of delineated catchments and drainage lines of study area (Threshold 500)

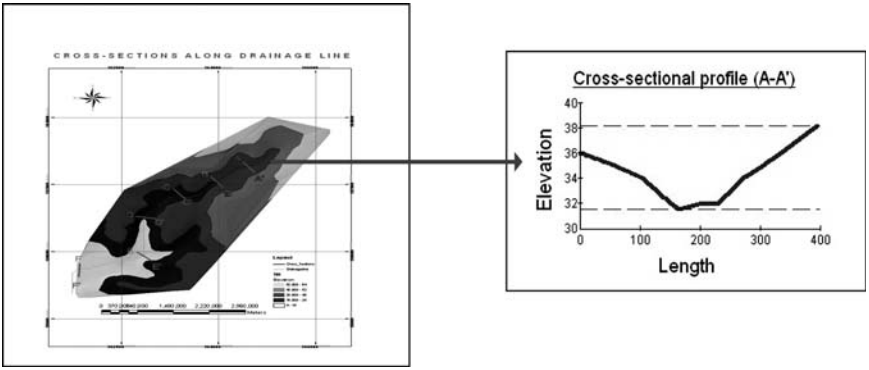


Fig. 4 A cross-section of the drainage line

4.3 Concept Validation and Data Cleaning

The DEM reveals variation in elevation along the drainage line, ranging between 31.5 and 4 m above datum. This suggests that inundations during flood events will vary based on the bottom elevation of the drainage line and that of the adjacent areas. It is therefore rational to section the drainage line with cross-sections and then use the mean bottom elevation between consecutive cross-sections to represent the mean elevation along the drainage line between these cross-sections. The resulting contours represented the flood extents at a given flood level. Many of the areas selected were far and non-adjacent to the drainage line i.e. areas that would not get logically flooded from the drainage line at a given flood level, based on the terrain model and these areas (contour lines) were erased.

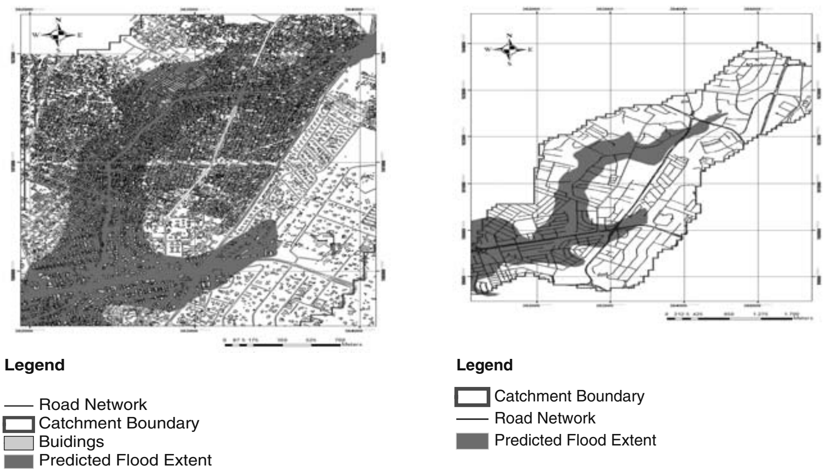


Fig. 5 Maps showing predicted flood extent for 1 m flood water level and properties which may be affected

Table 2 Derived flood level contours

		Flood level contours at specific flood water levels			
Cross-sections	Mean bottom elevation	0.5 m	1.0 m	1.5 m	2.0 m
A-A'/B-B'	**28.75**	29.25	29.75	30.25	30.75
B-B'/C-C'	**24.75**	25.25	25.75	26.25	26.75
C-C'/D-D'	**20.50**	21.0	21.5	22.0	22.5
D-D'/E-E'	**13.75**	14.25	14.75	15.25	15.75
E-E'/F-F'	**7.00**	7.50	8.00	8.50	9.00

5 Results and Analysis of Flood and Map Derivatives

The flood level contours derived for the selected flood water levels indicate areas that face possible inundation in the event of any flood at the specified water levels. The selected flood level contours when converted into polygons and overlaid on the land use and land cover maps of the study area shows elements which would be affected during the event of such flood water levels. In this particular study the major affected elements include residential and commercial establishments, social amenities and other infrastructure such as transportation routes and transit points. This is due to that fact that the area under study is a built up area and hence the land cover will inevitably be constituted of the above mentioned elements.

From the above, the following flood hazard maps have been derived; firstly, general flood hazard maps of a composite land cover/land use showing all elements liable to the predicted floods and secondly maps showing only transportation routes (Roads and streets) that may be affected by the predicted floods. The affected roads give an indication of the traffic congestion that may be experienced on such routes during flood events. This serves as means of managing traffic as well as determining fastest routes for evacuation and rescue operations during flood events. The map derivatives are shown in the figures below.

6 Conclusion

For efficient urban and floodplain and management as well as physical environmental development control and town planning purposes, it is imperative to map various flood prone zones as means for setting development guidelines and instituting emergency response modus operandis. It can therefore be concluded that mapping the extent of flood has overt uses in illustrating the area affected by a particular historical flood or a modeled flood of a given probability of occurrence. Once the possible flood levels have been derived, maps for each flood level can be effortlessly produced with GIS. GIS tools have also shown to have the ability to readily perform different land use based overlay analysis in a planning context, and produce maps of resultant analysis. When overlaid on property or an infrastructure database, it could be analyzed which property or infrastructure is immediately at risk. The visual representations which GIS affords have shown in this case to definitely add value to the results of the numerical modeling for informed planning and hazard management.

It should however be noted that this approach has been used as a prelude to performing hydraulic simulation in a distributed hydrological model for flood modelling in order to assess the type of analysis which can be performed in a vector GIS for flood hazard mapping and planning by disaster management organizations and city authorities with less complexities and cost.

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