Modelling Hydrological Functions using Digital Elevation Model (DEM) and Soil Conservation Service (SCS) Model

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Abstract - The principal advance in GIS hydrological modelling that has occurred during the past several years has been the widespread availability of Digital Elevation Models (DEM) via Internet and CD-ROM and advances in the methods of processing them. Using digital elevation data, different models have been developed over the years that can automatically delineate a watershed and sub-basins (Garbrecht and Martz, 1999).

In this study, the Surface Runoff Quantity was derived using Soil Conservation Service (SCS) Model, developed by the U.S. Soil Conservation Service in 1972. Curve numbers were determined by factors based on land use/cover from classified Enhanced Thematic Mapper (ETM) and soil groups. The results show that the simulated runoff processes are in good agreement with measured runoff, and the accuracy of the simulated runoff was over 75%. This clearly demonstrated that integration of Remote Sensing, GIS and SCS model provided a powerful tool for runoff simulation of small watershed in the Study Area.

Keywords: Digital Elevation Model (DEM); Hydrological Modelling; Watershed Delineation; Soil Conservation Service (SCS) Model; Curve Number (CN).

1. Introduction

Water on our planet can be stored in any one of the following major reservoirs: atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields, and groundwater. Water moves from one reservoir to another by way of processes like evaporation, condensation, precipitation, deposition, runoff, infiltration, sublimation, transpiration, melting, and groundwater flow. The oceans supply most of the evaporated water found in the atmosphere. Of this evaporated water, only 91% of it is returned to the ocean basins by way of precipitation. The remaining 9% is transported to areas over landmasses where climatological factors induce the formation of precipitation. The resulting imbalance between rates of evaporation and precipitation over land and ocean is corrected by runoff and groundwater flow to the oceans. (Hubbart et al, 2010). The identification and determination of the runoff and ground water flow are very crucial to human existence.

Digital Elevation Models (DEMs) are used in water resources projects to identify drainage features such as ridges, valley bottoms, channel networks, surface drainage patterns, and to quantify sub catchment and channel properties such as size, length, and slope (O’Callaghan and Mark, 1984). The accuracy of this topographic information is a function both of the quality and resolution of the DEM, and of the DEM processing algorithms used to extract this information.

A watershed describes an area of land that contains a common set of streams and rivers that all drain into a single larger body of water, such as a larger river, a lake or an ocean. Watershed delineation is one of the most commonly performed activities in hydrologic analysis. Digital Elevation Models (DEMs) provide good terrain representation from which watersheds can be derived automatically using GIS technology. The techniques for automated watershed delineation have been implemented in various GIS systems and custom applications (Garbrecht and Martz, 1999).

The conceptual or computational procedure for numerically simulating the processes that occur in a watershed is generally called hydrological modelling. Hydrologic modelling is commonly used to estimate runoff from a watershed which is one of the most important parameters in any water resources design project. One of the widely used applications of these estimates is to determine the design or flood discharge of a watershed.

As a result of the immense importance of the Ogun River, geologically, biologically, historically and culturally. There is therefore, the need to study the impact of land use and land cover on the hydrologic processes that occur in the watershed of the study area and to simulate the hydrologic processes in order to estimate the runoff used as a watershed for stormwater management and to provide a direction
for utilizing natural water resources effectively and beneficially. This work determines and delineates channel networks, watersheds and sub-catchments. Digital Elevation Model (DEM) of Ogun River (from Ogun State - Lagos Lagoon) was created in order to derive the Surface Runoff Quantity using Soil Conservation Service (SCS) Model and analysis was carried out to determine the effects of hydrologic processes in the watershed of the study area. This approach automatically assists in determining the parameters for the Surface Runoff Quantity and is practically labour-saving method for hydrological applications.

1.1 Study Area

The Ogun River basin is located in Southern Nigeria, bordered geographically by Longitudes and Latitudes 2° 28’E, 6° 26’N and 4° 8’E, 9° 10’N. About 2% of the basin area falls outside Nigeria in the Benin Republic. The land area is about 23,000 km². The relief is generally low, with the gradient in the North-South direction. Ogun River (Fig. 1) took its source from Igaran Hills at an elevation of about 530m above the Mean Sea Level (MSL) and flows directly southwards over a distance of about 480km before it discharges into the Lagos Lagoon. The major tributaries of Ogun River are the Ofiki and Opeki rivers (Berga, 2006).

The geology of the study area can be described as a rock sequence that starts with the Precambrian Basement (Jones and Hockey, 1964); which consists of quartzites and biotite schist, hornblende-biotite, granite and gneisses. Ogun River is a source of domestic water which supports the populations that have settled on either side of the river’s course. It flows into Lagos Lagoon. Lagos Lagoon, a water body in the heart of the Metropolis, cuts across the southern part of the Metropolis linking the Atlantic Ocean (in the west and south) and Lekki Lagoon (in the east). It is about 6,354.708km² in area and 285km in perimeter. The lagoon provides places of abode and recreation, means of livelihood and transport, dumpsite for residential and industrial discharges and a natural shock absorber to balance forces within the natural ecological system. The Lagos Lagoon consists of three main segments: Lagos Harbour, the Metropolitan end and Epe Division (Oyenekan, 1988).

2. Methodology

The method adopted consists of the following:

2.1 Data Sources- The sources of data used for this study are:
1. 1:5000 Topographic Sheets (Nigerian Toposheet Lagos 279SW) of the Study Area acquired from Office of the Surveyor General of the Federation (OSGOF).
3. Satellite images (The Enhanced Thematic Mapper –ETM of 30th January 2000) covering the Study Area were used for land use/land cover mapping and classification.
4. The soil map of the study area

Figure 1. Odo Ogun (Ogun River) (flickr, 2013).
5. Meteorological data including daily and monthly rainfall for the period of 2001-2002 obtained from Nigerian Meteorological Agency (NIMET) in Lagos.

6. The daily runoff volume and runoff process of some typical rainstorms (2001–2002) obtained from hydrology station located at the outlet of the Ogun River Basin.

The workflow chart for delineating the Watersheds is shown in Figure 2a, while Figure 2b shows the workflow chart for the Surface Runoff.

2.2 Data Processing Procedure- the following data processing methods were adopted:

2.2.1 Map Digitization: The topographic maps were converted from analogue to digital in UTM projection. Using ArcGIS 9.2 software, details were extracted as thematic layers.

2.2.2 Creating Digital Elevation Model (DEM): Contours (Fig. 3a) from the vectorized topographical map (1:5000) of the study area were used to generate the Digital Elevation Model [DEM] (Fig. 3b). Slope
map was created from the Digital Elevation Model (DEM) in order to calculate the per cent slope. Classified soil map (Fig. 4), based on its hydrologic groups (HSG Map), was overlaid on the Land use/Land cover map to create Curve Number (CN) map (Downer, Ogden, Niedzialek and Liu, 2006).

2.2.3 Land Use: Land use type was used in the modelling to assist in accessing surface water runoff quantity within the watershed depending on soil type and slope function. Satellite images covering the study area, (The Enhanced Thematic Mapper-ETM of 30th January 2000), were used for land use/land cover mapping and classification (Fig. 5). The satellite data was visually interpreted and its accuracy was determined by ground truthing.

2.2.4 Flow Direction: The direction of flow was determined by finding the direction of steepest descent, or maximum drop, from each cell. This is calculated as:

\[ MD = \left( \frac{\Delta z}{d} \right) \]  

(ArcGIS 9.3 Desktop Help)

where: \( MD \) = Maximum Drop  
\( \Delta z \) = Change in Elevation value  
\( d \) = Distance

2.2.5 Watershed Delineation: Watersheds were delineated from the DEM (Nelson and Arnold, 2010), that was based on the raster of flow direction, to determine contributing area, i.e. flow accumulation (Fig. 6b).

2.2.6 Stream Network Delineation: Stream networks (Hassanuzzaman, 1993) were also delineated from DEM by applying a threshold value to the results of Flow Accumulation (Fig. 10b).

2.2.7 Soil Conservation Service (SCS) Model: The Surface Runoff Quantity was derived using Soil Conservation Service (SCS) Model also known as the Hydrologic Soil Cover Complex Model, developed by the U.S. Soil Conservation Service in 1972. Because of its versatility, the model has been widely used internationally for water resources management, urban storm water modelling and runoff estimation (Band, 1986; Dean, Coates and Ball, 1995; Garbrecht and Martz, 1996; U.S. Department of Agriculture, 1972; New Jersey Stormwater Best Management Practices Manual, 2004). Slope map was very important in using the SCS Model to estimate the runoff.

To create the Curve Number (CN) map, soil Antecedent Moisture Condition (AMC) was considered. The following SCS equations were used to calculate the Surface Runoff:

\[ Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \]  

(Delmar et al, 2005)

where,

\( Q \) = Runoff depth (mm);  
\( P \) = Storm Rainfall (mm);  
\( S \) = Potential maximum retention or infiltration (mm).

For convenience and standardization application of Equation (2), \( S \) is expressed in the form of a dimensionless runoff Curve Number (CN) Equation (3):

\[ S = \frac{1000}{CN} - 10 \]  

(Delmar et al, 2005)

\( CN \) represents the runoff potential of the land cover-soil complex characteristics governed by soil Antecedent Moisture Condition (AMC), soil type, and land use and treatment. Three AMCs were defined as dry, moderate and wet, and denoted as AMC I, AMC II, and AMC III, respectively. CN values range from 0 to 100.

2.2.8 Calculation of Curve Numbers (CN) for Antecedent Moisture Condition (AMC I, AMC II, and AMC III): Calculation of \( CN(\text{I}) \), \( CN(\text{II}) \) and \( CN(\text{III}) \), which are the curve numbers for AMC I, AMC II and AMC III, were carried out. To obtain \( CN(\text{II}) \), which is the composite/area weighted curve number for AMC II, Equation 4 was used:

\[ CN_{\text{II}} = \frac{\sum_{i=1}^{n-1}(CN_i \times A_i)}{\sum_{i=1}^{n} A_i} \]  

(Delmar et al, 2005)

where;

\( CN_i \) = the curve number for each land use-soil group polygon;  
\( A_i \) = the area for each Hydrological Soil-cover complex polygon of sub-watershed;  
\( n \) = the number of Hydrological Soil-cover complex polygons in the Watershed.

AMC II is calculated first because AMC I and AMC III depend on its value.
To adjust the composite/area weighted curve number $CN(\text{I})$ and $CN(\text{III})$, i.e. for the cases of AMC-I and AMC-III respectively, Equations (5) and (6) were used:

**AMC I:**

$$CN_I = \frac{4.2 \times CN_{\text{II}}}{10 - (0.058 \times CN_{\text{II}})} \quad (5)$$

**AMC III:**

$$CN_{\text{III}} = \frac{23 \times CN_{\text{II}}}{10 - (0.13 \times CN_{\text{II}})} \quad (6)$$

where:

- $CN(\text{I})$ - Curve Number for AMC-I (Dry Condition);
- $CN(\text{II})$ - Curve Number for AMC-II (Normal Condition);
- $CN(\text{III})$ - Curve Number for AMC-III (Wet Condition).

Appropriate CN values according to standard tables (United States Department of Agriculture, Soil Conservation Service, 1972) were assigned to each Sub-watershed considering AMC. The maximum
potential retention was calculated using Equation 6. Then the direct runoff values from each sub-watershed were estimated using SCS model for rainfall events. The estimated runoff was then validated by comparing it with the observed runoff for that period (Section 3.2, Table 7).

3.0 Results and Analysis

3.1 Results

The vectorized contour lines (Fig. 3a) from topographic sheets covering Lagos-Ogun River were converted into raster DEM using ArcGIS interpolation, Kriging (Fig. 3b).

The Soil type classification for the Study Area is shown in Figure 4 (where: C, LS and SCL stands for clay, loamy Sandy and Sandy Clay respectively). Similarly, Land-use and Land-cover map of the Study Area is shown in Figure 5.

The extent of each Land-use/Land-cover is shown in Table 1.

Table 1: Showing Areas in km² of the Land-use/Land-cover for the Study Area.

<table>
<thead>
<tr>
<th>Land use/Land cover</th>
<th>Area(km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water bodies</td>
<td>72.15</td>
</tr>
<tr>
<td>Wetlands</td>
<td>31.94</td>
</tr>
<tr>
<td>Forested Land</td>
<td>508.85</td>
</tr>
<tr>
<td>Agricultural land</td>
<td>383.56</td>
</tr>
<tr>
<td>High density area</td>
<td>52.13</td>
</tr>
<tr>
<td>Low density area</td>
<td>304.22</td>
</tr>
</tbody>
</table>

Since watershed is derived from depressionless DEM with a surface that has no sinks, a Filled (i.e. Depressionless) DEM map of the study area was created (Fig. 6a). In order to determine where a landscape drains, it is necessary to determine the direction of flow for each cell in the landscape. The flow direction was computed based on grids that are known to be free of sinks. Every watershed is defined spatially by the geomorphologic property of drainage. Flow accumulation was carried out to compute areas of high flow downward (Fig. 6b).

Once flow accumulation is calculated, it is customary to identify those cells with high flow. Because the study area is small, flow accumulation greater than 500 (threshold value cumulative enough to be 'channelized') was used. A pour point is the point at which water flows out of an area (e.g. a gauge station or a dam), but in this research it is a point in the lowest area that intersects with the river. Figure 7 shows vectorized Stream map overlaid with Pour points.
Stream network was extracted and Stream Ordering was carried out using Strahler technique and four orders were obtained thus assigning numeric order to links of the streams: order 1 is a higher stream that flows into the 2nd order stream until finally empties into 4th order. Figure 8 shows the hierarchy of streams overlaid on the DEM map.

Flow Length determination was carried out in order to calculate the length of the longest flow path within the Lagos-Ogun River basin (Fig. 9). This measure is also often used to determine the time of concentration of a basin, given in Equation 7:

\[
\frac{L}{V} = \Delta T
\]  

where:

(Wilson et al, 2000)

- \( L \) = Flow length
- \( V \) = Flow velocity
- \( \Delta T \) = Lag Time for the basin.

The Sub-watershed map is presented in Figure 10a, while the stream network was overlaid on the sub-watershed map of the Study Area as shown in Figure 10b.
The United States $CN$ values of the different Soil types and Land-use types under Medium Soil Moisture are shown in Table 2.

Table 2: $CN$ values of different Soil types and Land-use types under Medium Soil Moisture (United States Department of Agriculture, Soil Conservation Service, 1972).

<table>
<thead>
<tr>
<th>Land Type</th>
<th>Use</th>
<th>Land Surface Infiltration Category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Wasteland</td>
<td></td>
<td>76</td>
</tr>
<tr>
<td>Tuber Crops</td>
<td></td>
<td>70</td>
</tr>
<tr>
<td>Grapery</td>
<td></td>
<td>64</td>
</tr>
<tr>
<td>Cereal and feed stuff crops</td>
<td></td>
<td>64</td>
</tr>
<tr>
<td>Exuberantly natural grassland</td>
<td></td>
<td>49</td>
</tr>
<tr>
<td>Sparsely natural grassland</td>
<td></td>
<td>68</td>
</tr>
<tr>
<td>Planted grassland</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Exuberant forestland</td>
<td>25</td>
<td>55</td>
</tr>
<tr>
<td>Common forestland</td>
<td>36</td>
<td>60</td>
</tr>
<tr>
<td>Sparse forestland</td>
<td>45</td>
<td>66</td>
</tr>
<tr>
<td>Hard surface (cement surface)</td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

A, B, C, and D are four Hydrologic Soil Groups (HSG), which were used to determine Curve Number ($CN$). These soil groups stand for: Soils in Group A = Well drained, in Group B = Moderately-drained, in Group C = Poorly drained, and in Group D = Very poorly drained. Similarly, the U.S. Antecedent Soil Moisture Condition classifications are shown in Table 3.

Table 3: Types of Antecedent Soil Moisture Condition for SCS model (United States Department of Agriculture, Soil Conservation Service, 1972).

<table>
<thead>
<tr>
<th>Antecedent Moisture Condition</th>
<th>Five-day Antecedent Plant Growth Stage</th>
<th>Rainfall (mm) Other Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMC I (Dry)</td>
<td>&lt; 30</td>
<td>&lt; 15</td>
</tr>
<tr>
<td>AMC II (Moderate)</td>
<td>30-50</td>
<td>15-30</td>
</tr>
<tr>
<td>AMC III (Wet)</td>
<td>&gt; 50</td>
<td>&gt; 30</td>
</tr>
</tbody>
</table>

The extent of each Soil Type Classification based on the Hydrologic Soil Groups (HSG) is shown in Table 4.

Table 4: Showing Soil Type Classification for the Study Area.

<table>
<thead>
<tr>
<th>HSG</th>
<th>Texture</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D (Very poorly drained)</td>
<td>Clay</td>
<td>113,367.40</td>
</tr>
<tr>
<td>C (Poorly drained)</td>
<td>Sandy Clay</td>
<td>7,757.77</td>
</tr>
<tr>
<td>B (Moderately drained)</td>
<td>Loamy Sandy</td>
<td>20,566.00</td>
</tr>
</tbody>
</table>

The study area is in the southern-western part of the country where there is usually abundant rainfall, therefore, there is no Group A (i.e. well drained) type of soil. For the Study Area, the $CN$ values of the
different Land-use/Land-cover classes based on the Antecedent Soil Moisture Condition (AMC) classifications are shown in Table 5.

Table 5: CN values of different Land-use/cover classes in the Watershed for the Study Area.

<table>
<thead>
<tr>
<th>LAND USE/LANDCOVER TYPE</th>
<th>AMC I (Dry)</th>
<th>AMC II (Moderate)</th>
<th>AMC III (Wet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water bodies</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wetlands</td>
<td>82</td>
<td>86</td>
<td>91</td>
</tr>
<tr>
<td>Forested Land</td>
<td>78</td>
<td>83</td>
<td>89</td>
</tr>
<tr>
<td>Agricultural land</td>
<td>84</td>
<td>88</td>
<td>92</td>
</tr>
<tr>
<td>High density area</td>
<td>85</td>
<td>89</td>
<td>94</td>
</tr>
<tr>
<td>Low density area</td>
<td>83</td>
<td>87</td>
<td>93</td>
</tr>
<tr>
<td>Commercial/Industrial area</td>
<td>90</td>
<td>93</td>
<td>96</td>
</tr>
<tr>
<td>Other Built-Up area</td>
<td>90</td>
<td>93</td>
<td>96</td>
</tr>
</tbody>
</table>

Similarly, for the different Sub-Watershed Numbers, their CN values based on the AMCs are shown in Table 6.

Table 6: Part of the CN value of each Sub-Watershed in the Study Area (from AMC I, AMC II, AMC III Models)

<table>
<thead>
<tr>
<th>Sub-watershed Number</th>
<th>Area (km²)</th>
<th>AMC I</th>
<th>AMC II</th>
<th>AMC III</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.36</td>
<td>85</td>
<td>88</td>
<td>93</td>
</tr>
<tr>
<td>2</td>
<td>20.50</td>
<td>84</td>
<td>92</td>
<td>92</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>66</td>
<td>0.86</td>
<td>78</td>
<td>85</td>
<td>91</td>
</tr>
</tbody>
</table>

3.2 Analysis

SCS Model Verification

In order to validate the SCS model output, daily rainfall data of seven selected events in 2001 and 2002 in the watershed were collected and the curve number of the watershed was used for the estimation of runoff and runoff process. The validity and feasibility of the SCS model based on the Geographic Information was verified by comparing the estimated runoff with measured values. Pearson's chi-squared test was used to test for the goodness of fit to establish whether or not the observed data (measured runoff) greatly differs from the theoretical data (estimated runoff) using Equation 8:

\[ \chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i} \] .(7)

where:

- \( \chi^2 \) = Pearson's cumulative test statistic,
- \( O_i \) = an observed frequency,
- \( E_i \) = an expected (theoretical) frequency,
- \( n \) = the number of cells in the table.

Degrees of freedom = (number of columns - 1) x (number of rows - 1).

Results obtained are shown in Table 7.

Table 7. Comparison between Measured and Simulated Values of Runoff Yield by SCS Model in the Watershed.

<table>
<thead>
<tr>
<th>Date</th>
<th>Rainfall Depth (mm)</th>
<th>Observed Runoff Volume (mm)</th>
<th>Estimated Runoff Volume (mm)</th>
<th>Relative Error (%)</th>
<th>Absolute Error (Mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/4/2001</td>
<td>43.9</td>
<td>4.82</td>
<td>5.78</td>
<td>19.9</td>
<td>0.96</td>
</tr>
<tr>
<td>6/4/2001</td>
<td>26.8</td>
<td>2.27</td>
<td>2.57</td>
<td>13.1</td>
<td>0.30</td>
</tr>
<tr>
<td>7/4/2001</td>
<td>23.1</td>
<td>0.88</td>
<td>0.68</td>
<td>22.7</td>
<td>0.20</td>
</tr>
<tr>
<td>1/5/2002</td>
<td>20.6</td>
<td>0.36</td>
<td>0.42</td>
<td>16.7</td>
<td>0.06</td>
</tr>
<tr>
<td>13/5/2002</td>
<td>35.8</td>
<td>3.00</td>
<td>2.65</td>
<td>11.7</td>
<td>0.35</td>
</tr>
<tr>
<td>19/6/2002</td>
<td>25.8</td>
<td>1.20</td>
<td>1.45</td>
<td>20.8</td>
<td>0.25</td>
</tr>
<tr>
<td>27/6/2002</td>
<td>39.1</td>
<td>2.70</td>
<td>2.89</td>
<td>7.03</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Computed \( \chi^2 = 0.022 \), the \( \chi^2 \) from the table = 12.592 at 0.05 level of significance and 6 degrees of freedom. Since 0.022 < 12.592, therefore we accept the null hypothesis i.e. there is no significant difference between the measured and estimated datasets. Also, the absolute errors between the estimated runoff and observed runoff range from 0.06mm to 0.96mm and the relative errors were from 7.03% to 22.7%, which were within the permissible limit. The simulated results of the SCS model were consistent with the actual (practical) situation. Thus, the SCS model could be applied to simulating the runoff process of small watershed.

4.0 Conclusion

This study indicated the spread of watershed and how they function within the environment and ecosystem. Stream network and their distributions, based on their drainage area were determined; Stream order was plotted and Stream length and Pour points for the selected area were computed. The number of rivers
and their corresponding watershed within the study area was determined, sixty six (66) in number. Method for determination of runoff for the watershed using GIS and SCS model was described.

Results obtained showed over 75% accuracy between the measured runoff processes and the simulated runoff. This approach has clearly demonstrated that integration of GIS (DEM) and SCS model provides a powerful tool for runoff simulation of small watershed in the Study Area, and may also be applied in determining other watersheds where digital database is available for planning of various conservation measures.

References: