SPATIAL DEPENDENCY OF BURULI ULCER ON POTENTIAL SURFACE RUNOFF AND POTENTIAL MAXIMUM SOIL WATER RETENTION

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ABSTRACT

Buruli Ulcer (BU) is an endemic prevalent disease in Ghana and other West African countries including: Cote d'Ivoire, Benin and Togo. Despite recent upsurge of research in Buruli Ulcer, the natural reservoir and mode of transmission of Mycobacterium ulcerans (MU) have not yet been determined. However, all major foci are found in wetlands of tropical and subtropical countries. In this study, a landscape spatial hydrological modeling approach based on Potential Maximum Soil Water Retention (PMSWR), Soil Conservation Service Curve Number Grid (SCS CNGrid) and empirical evidence from field research were applied to understand their relationship with BU disease in two districts of Ghana.

Landuse data, Hydrological Soil Groups (HSGs), Landsat images and Digital Elevation Models (DEMs) were used to generate the SCS CNGrid and the PMSWR of the study areas. The results of the SCS CNGrid and PMSWR maps linked BU endemic areas to low to moderate surface runoff potential and high to moderate PMSWR. BU endemic communities in the two districts were also mostly enclaved by galamsey (illegal) mining activities and farms. This study proved that the PMSWR and SCS CNGrid values are important hydrological parameters to determine surface runoff potential and thus delineate BU disease prone areas.

Key words: BU, SCS CNGrid, PMSWR, Potential Surface Runoff, DEM, Ghana

INTRODUCTION

BU is an endemic disease which destroys the skin, underlying tissues, muscles and bones when not treated early. It is caused by MU. The disease has been known in endemic communities in Ghana for years with an overall prevalence rate of 20.7 per 100 000 [1]. But in recent years, cases have increased, prompting renewed interest in BU research especially in parts of West Africa (Cote d'Ivoire, Ghana, Guinea, Liberia, Benin, Burkina Faso and Togo) [2-7]. Despite the renewed research interest in BU disease, the natural reservoir and mode of transmission of MU is still unclear.

However, research has pointed to wetlands of tropical and subtropical areas as potential reservoirs of the MU [3, 7-13]. It is also widely believed that BU disease mostly occurs in people who live and work close to stagnant bodies of water [14].

Additionally, research has shown that new cases of BU have been reported after flood events [5, 7, 13, 15-18]. For example, Bainsdale in Australia, recorded the first case of BU in 1939 after the worst floods in 1935 [19-21]. BU cases were also reported after flood events along the settlements of Sepik and Kumusi Rivers in Papua New Guinea in 1957 [22]. This flooding was in concert with the explosive eruption of Mt. Lamington in 1951 [23, 24].

Case and control studies have linked landscape disturbances to BU disease [16, 25]. Furthermore, surface runoff from landscape disturbances also lead to solubilisation of exposed reactive minerals causing pollution of rivers, streams and soils by sulphuric acid and harmful elements such as arsenic, cadmium and mercury [26, 27].

Pollution of rivers, streams and soils usually occurs when mined materials from uncontrolled and
unscientific mining (e.g. galamsey) activities are exposed to oxygen and water [28]. For example, spatial analysis performed by [9], detected that some 250 cases of BU were within a 1000 m buffer zone around mine sites, compared to 62 cases elsewhere within his study area. Likewise, Kumi-Boateng et al. [29], observed that improper mining methods by galamsey operators and lack of post mining treatment and management further alters the already fragile ecosystem. The gravity of the impact, nonetheless, depends on the techniques used and the size of the Mine [30]. A study by Salvareddy-Aranguren et al. [31], in the Milluni Valley, Bolivia, further revealed that potentially harmful elements (e.g. Cd, Zn, As, Cu, Ni, Pb and Sn) exceeded the recommended World Health Organization (WHO), limits in surface waters downstream of galamsey mining sites.

Duker et al. [9] also linked arsenic levels in soil and illegal gold mining activities with increased BU disease risk in Ghana. Thus, landscape alteration, can lead to increased surface runoff and contamination of surface waters [32-35]. Landscape alteration may also increase the risk of flooding [36-39] as a result of increased surface runoff and subsequently induce the outbreak of BU disease due to contamination of surface waters [9].

Surface runoff, however, varies depending on the nature of the soil and its management [40]. Surface runoff and PMSWR are undoubtedly important to the understanding of BU prevalence. Though, a number of surface runoff models have been developed, the SCS CNGrid method stands-out, produces better results and is well acclaimed [41-47]. The SCS CNGrid considers major surface runoff watershed characteristics such as soil type, landuse, digital elevation models and antecedent moisture conditions (AMCs) to estimate the loss and runoff volume [41, 48, 49], which can be obtained from optical and microwave remotely sensed data.

The fundamental premise of the SCS CNGrid method is that, for a single storm, the ratio of the actual soil retention after runoff begins to the PMSWR is equal to the ratio of direct runoff to available rainfall. This relationship is expressed as [41]

\[ X = \begin{cases} 0 & \ldots \ldots P \leq I_a \\ \frac{(P-I_a)^2}{I_a+S} & \ldots \ldots P > I_a \end{cases} \quad (1) \]

where \( X \) is the actual direct runoff (mm); \( P \) is total precipitation (mm); \( S \) is PMSWR after runoff begins (mm); \( I_a \) is initial abstraction (mm) [41]. To simplify equation one (1), \( I_a \) is fixed at \( I_a = 0.2S \) [41]. Thus, equation one (1) can be expressed as:

\[ X = \begin{cases} 0 & \ldots \ldots P \leq 0.2S \\ \frac{(P-0.2S)^2}{P+0.8S} & \ldots \ldots P > 0.2S \end{cases} \quad (2) \]

The SCS CNGrid is then related to the PMSWR as

\[ S = 25.4 \left( \frac{1000}{\text{CNGrid}} - 10 \right) \quad (3) \quad [41] \]

SCS CNGrid can be found in the Technical Release 55 (TR-55) Table or can be calculated as the composite CNGrid [41]. Equation three (3) shows that the CNGrid decreases as the PMSWR (\( S \)) increases.

The objective of this research therefore is to use the SCS CNGrid model, which thoroughly considers physiographic heterogeneity (e.g. soil, landuse and digital elevation models) and empirical evidence from field research to determine the relationship between surface runoff potential, PMSWR and BU disease.

**MATERIALS AND METHODS**

**Study areas:** The study areas are Amanse West District (AWD) and Upper Denkyira West District (UDWD). These study areas were selected due to their similarities in socio-economic activities (e.g. illegal “galamsey” mining and farming activities) and BU prevalence.

The AWD lies between latitudes 6°07' N and 6°35' N and longitudines 1°42' W and 2°08' W (Fig. 1). The district is bounded by UDWD, Amanse Central district, Bibiani-Anwiaso-Bekwai district, Atwima Mponua district, Atwima Nwabiagya district, Atwima Kwanwoma district and Bekwai Municipal. The district is a tropical rain forest area of about 1 320 km² with an estimated population of 134 331 (2010 Population and Housing Census). It
Fig. 1: Map of Amansie West District

Fig. 2: Map of Upper Denkyira West District
is approximately 60 km southwest of Kumasi, the regional capital of Ashanti. AWD has the highest BU prevalence rate of 150.8 per 100 000 in the country [50-52] and the second highest reported active cases across the country [52]. The main occupation of the people is subsistence farming and small scale “galamsey” mining. The AWD is drained by the Offin and Oda rivers and their tributaries (Fig. 1).

UDWD is the second study area and lies between latitudes 5° 54’ N and 6° 18’ N and longitudes 1° 49’ W and 2° 12’ W of the Greenwich Meridian (Fig. 2). The district is bounded to the south-east by Upper Denkyira East district, Amansea Central district and Obuasi Municipal. Bounded to the south-west are Wassa Amenfi East and Amansea West districts. The district is also bounded to the north-west by Bibiani-Anwiaso-Bekwai and Wassa Amenfi West districts. UDWD covers an area of about 1 700 km² with an estimated population of about 132 864 (2010 Population and Housing Census). While the Central Region has the highest overall prevalence rate of active cases [52], UDWD is among the most endemic districts in the Region and has the third highest prevalence rate of 114.7 per 100 000 nationwide together with Upper Denkyira East District after Asante Akim North district (prevalence rate of 131.5 per 100 000) and Amsesie West district (prevalence rate of 150.8 per 100 000) [52]. Subsistence farming and small scale “galamsey” mining are the main occupation of the people in the district. UDWD is drained by Offin, Dia and Subin rivers as well as their tributaries (Fig. 2).

**Data Acquisition:** Data for the study include; DEMs, Epidemiological data of BU for the two districts, Landuse and Soil data for the two study areas. Landsat images (path 194/rows 056 and 057) were acquired on January 01, 1991, February 01, 2008 and May 31, 2013 for this study. The DEMs were obtained from the Advanced Space borne Thermal Emission and Reflection Radiometer Global Digital Elevation Models (ASTER-GDEM). The Epidemiological data was obtained from the National Buruli Ulcer Control Programme and from field investigation based on clinical case definition of WHO [1, 53]. The Landuse data was acquired from the Centre for Remote Sensing and GIS (CERGIS) at the University of Ghana. The Soil data was also procured from the Soil Research Institute of the Council for Scientific and Industrial Research (CSIR-SRI). The Landsat images were made available by the Earth Resources Observation Systems Data Centre, United States Geological Survey (USGS) and were rectified to the Universal Transverse Mercator projection system.

**Methods Used:** BU disease prone areas were delineated from the study areas using SCS CNGrid and PMSWR maps. The procedure adopted to achieve this objective is summarized in the flow chart as shown in Fig. 3.

**Fig. 3: Flow chart for Generating SCS CNGrid and PMSWR**

**Selecting Soil, Impervious Surface and Vegetation (S-I-V) Fractions**

Composite CNGrid values were computed from S-I-V fraction which was derived from normalized spectral mixture analysis (NSMA) and linear spectral mixture analysis (LSMA). The NSMA was applied to estimate and normalize the percentage of impervious surfaces by modelling a mixed
spectrum as a linear combination of three endmembers: soil, impervious surface and vegetation. The normalization process of NSMA was used to reduce the within-class radiometric variations and therefore facilitate the separation of S-I-V land cover types. Two key steps were employed to perform the NSMA. Firstly, the original Landsat TM/ETM+ images were normalized to reduce within-class radiometric variations using equation four (4) [54].

\[ \bar{R}_i = \frac{R_i}{k} \times 100 \]  \hspace{1cm} (4)

where \( k = \frac{1}{n} \sum_{i=1}^{n} R_i \) and \( \bar{R}_i \) is the normalized reflectance for band \( i \) in a pixel. \( R_i \) is the original reflectance for band \( i \), \( k \) is the most probable reflectance for that pixel and \( n \) is the total number of bands. Secondly, LSMA was applied to calculate the fractions of the three endmembers within the normalized spectra. Clusters of each of the endmembers were identified by visual interpretation of the Landsat images and the feature space images of a principal component transformation. The fraction of S-I-V endmembers in a pixel was derived with a least squares method in which the residual, \( R_i D_i \) is minimized (Equation 5):

\[ R_i = \sum_{a=1}^{b} U_a R_{ia} + R D_i \]  \hspace{1cm} (5)

where \( i = 1, \ldots, m \) (represents number of spectral bands); \( a = 1, \ldots, b \) (represents number of endmembers); \( R_i \) is the normalized spectral reflectance of band \( i \) which contains endmembers; \( U_a \) is the proportion of endmember \( a \) within the pixel; \( R_{ia} \) is the known normalized spectral reflectance of endmember \( a \) within the pixel on band \( i \); and \( R D_i \) is the residual for band \( i \). A constrained least-squares solution is used with the assumption that the following two requirements are satisfied concurrently (Equation 6):

\[ \sum_{a=1}^{b} U_a = 1 \text{ and } 0 \leq U_a \leq 1 \]  \hspace{1cm} (6) [55-60].

### Computing Composite CNGrid Values

To calculate the composite CNGrid values, four steps were used (Fig. 3). The first was to classify vegetation types based on NDVI values and assign initial CNGrid values with reference to TR-55 Table. Secondly, the S-I-V fraction images were extracted from Landsat images of the study areas using the NSMA and LSMA models. Thirdly, hydrological soil groups of the study areas were assigned initial CNGrid values with reference to the TR-55 Table. Finally, the composite CNGrid is calculated as the weighted average of the initial CNGrid values of S-I-V fractions, which were then, keyed into the Look-Up Table for generating the final CNGrid and PMSWR maps of the study areas.

### Processing DEM and Generating SCS CNGrid

The DEM used to create the SCS CNGrid was processed by performing “fill sink”. This was necessary to minimize sinks in the DEM which were due to errors.

In order to generate the SCS CNGrid, the corrected DEMs, reclassified landuse and HSGs were merged. The original landuse data of the study areas were reclassified into four major landuse categories namely: water, medium residential, forest and agricultural. The reclassification was based on Anderson’s land use classification scheme [61] and empirical field evidence (groundtrutthing). The reclassification was to normalize the different categories of the dataset for analyses. The reclassified landuse data were then converted to polygons.

The diverse characteristics of the soil data such as rate of infiltration of the study areas were used to generate the HSGs for all polygons in the study areas. The three HSGs identified in the study areas indicated the amount of infiltration rates as follows [45]: A-soil with high infiltration rates (lowest CNGrid values); B-soil with moderate infiltration rates (moderate runoff values) and C-soil with slow infiltration rates (high runoff values).

The percentage of each soil group in a particular polygon was also calculated. After processing the HSGs, the soil and landuse were then merged to create polygons. A Look-Up Table was also created to contain SCS CNGrid for all landuse and soil groups. The merged HSGs and the landuse data, was converted to polygons to represent the merged HSGs and landuse. Composite SCS CNGrid values for each reclassified landuse were assigned in the Look-Up Table [62]. HEC-GeoHMS, a SCS CNGrid generating tool in ArcGIS was used to
generate the SCS CNGrid maps using the HSG map, the landuse map, the corrected DEM and the Look-Up Table. The PMSWR maps were generated using equation six (6) from the SCS CNGrid.

\[ S = 25.4 \left( \frac{1000}{CNGrid} - 10 \right) \]            ..........(6)

The PMSWR maps are related to the soils and land cover conditions of the study areas through SCS CNGrid, which is dependent on landuse, HSGs and DEMs. The landscape parameters from the SCS CNGrid and PMSWR maps were extracted using kriging method of gridding. Kriging method was chosen because it yielded the best correlation coefficients for all the data sets.

**Hydrological Soil Groups (HSGs):** The HSGs found in the study areas include A, B and C. Soils are classified into HSG’s to indicate the rate of infiltration obtained for soils after prolonged wetting. Group “A” soils have low runoff potential due to high infiltration rates (7.62–11.43 cm/h). Group “B” soils have moderate runoff potential due to moderate infiltration rates (3.81–7.62 cm/h) and group “C” soils have a moderate to high runoff potential due to slow infiltration rates (1.27–3.83 cm/h) [63]. The initial SCS CNGrid values for each HSGs and corresponding landuse classes adopted from the description of HSGs for Ghana [45, 62] are presented in Table 1.

**Table 1: CNGrid Look-Up Table for Landuse and HSGs of Study Area**

<table>
<thead>
<tr>
<th>Landuse Description</th>
<th>Curve Number Grid (CNGrid)</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Medium Residential</td>
<td></td>
<td>57</td>
<td>72</td>
<td>81</td>
</tr>
<tr>
<td>Forest</td>
<td></td>
<td>30</td>
<td>58</td>
<td>71</td>
</tr>
<tr>
<td>Agricultural</td>
<td></td>
<td>67</td>
<td>58</td>
<td>71</td>
</tr>
</tbody>
</table>

(Source: Anon., 1986; McCuen, 1982)

**RESULTS AND DISCUSSION**

HSG “A” leads to low CNGrid values while the HSGs “B” and “C” lead to moderate and moderate to high CNGrid values respectively in the study areas. Maps showing the SCS CNGrid are presented in Fig. 6 to 7b. The SCS CNGrid values ranging from 80-100 have the highest runoff potential while SCS CNGrid values from 30-49.99 and 50-79.99 have low to moderate runoff potentials respectively. The landuse types in the SCS CNGrid values from 30 to 79.99 are mostly forest, agricultural and galamsey activities with HSGs of mainly A and B. The landscape parameters extracted from communities in the two districts and their respective BU cases are shown in Tables 2 and 3 and Fig. 4a to 5b. Correlation coefficients (R) between CNGrid, PMSWR and BU cases were determined to examine their statistical relationships. There was a strong positive correlation between CNGrid and BU cases (R = 0.83) as well as a strong negative correlation between PMSWR and BU cases (R = -0.80) for AWD (Fig. 4a and 4b). Correlation coefficients between CNGrid and BU cases (R = 0.74) as well as PMSWR and BU cases (R = -0.67) for UDWD were also strong (Fig. 5a and 5b). The positive correlation between CNGrid and BU cases link low to moderate potential surface runoff areas to increasing BU cases whilst the negative correlations between PMSWR and BU cases show that, as PMSWR decreases, BU cases increase. BU cases generally decline with CNGrid values of eighty (80) and above. CNGrid values from 80 to 100 represent high surface runoff potential areas.

**Table 2: Landscape Parameters from AWD**

<table>
<thead>
<tr>
<th>Community</th>
<th>CNGrid</th>
<th>PMSWR (mm)</th>
<th>BU Cases 1999 - 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dawusaso</td>
<td>68</td>
<td>119.53</td>
<td>62</td>
</tr>
<tr>
<td>Abore</td>
<td>71</td>
<td>103.75</td>
<td>62</td>
</tr>
<tr>
<td>Aiyem</td>
<td>84</td>
<td>48.38</td>
<td>35</td>
</tr>
<tr>
<td>Tontokrom</td>
<td>78</td>
<td>71.64</td>
<td>121</td>
</tr>
<tr>
<td>Bonsaaso</td>
<td>78</td>
<td>71.64</td>
<td>82</td>
</tr>
<tr>
<td>Akyekyewere</td>
<td>30</td>
<td>592.67</td>
<td>43</td>
</tr>
<tr>
<td>Watreso</td>
<td>30</td>
<td>592.67</td>
<td>45</td>
</tr>
<tr>
<td>Eissenleyem</td>
<td>58</td>
<td>183.93</td>
<td>55</td>
</tr>
<tr>
<td>Agoroyesum</td>
<td>78</td>
<td>71.64</td>
<td>120</td>
</tr>
<tr>
<td>Datano</td>
<td>78</td>
<td>71.64</td>
<td>76</td>
</tr>
</tbody>
</table>
Fig. 4a: CNGrid and BU Cases (1999-2012) Relationships for AWD

Fig. 4b: PMSWR and BU Cases (1999-2012) Relationships for AWD

Table 3: Landscape Parameters from UDWD

<table>
<thead>
<tr>
<th>Community</th>
<th>CNGrid</th>
<th>PMSWR (mm)</th>
<th>BU Cases 1999-2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diaso</td>
<td>79</td>
<td>67.52</td>
<td>47</td>
</tr>
<tr>
<td>Moudaso</td>
<td>67</td>
<td>125.10</td>
<td>30</td>
</tr>
<tr>
<td>Agona</td>
<td>67</td>
<td>125.10</td>
<td>35</td>
</tr>
<tr>
<td>Ntom</td>
<td>67</td>
<td>125.10</td>
<td>41</td>
</tr>
<tr>
<td>Adeade</td>
<td>67</td>
<td>125.10</td>
<td>47</td>
</tr>
<tr>
<td>Subin</td>
<td>67</td>
<td>125.10</td>
<td>42</td>
</tr>
<tr>
<td>Ameyaw</td>
<td>85</td>
<td>44.82</td>
<td>37</td>
</tr>
<tr>
<td>Ampabena</td>
<td>72</td>
<td>98.78</td>
<td>55</td>
</tr>
<tr>
<td>Nyinwonsu</td>
<td>30</td>
<td>592.67</td>
<td>22</td>
</tr>
<tr>
<td>Domenase</td>
<td>30</td>
<td>592.67</td>
<td>22</td>
</tr>
<tr>
<td>Ayanfuri</td>
<td>79</td>
<td>67.52</td>
<td>43</td>
</tr>
<tr>
<td>Nkotumso</td>
<td>55</td>
<td>207.82</td>
<td>30</td>
</tr>
<tr>
<td>Abora</td>
<td>72</td>
<td>98.78</td>
<td>56</td>
</tr>
<tr>
<td>Treposo</td>
<td>72</td>
<td>98.78</td>
<td>56</td>
</tr>
<tr>
<td>Adaboa</td>
<td>30</td>
<td>592.67</td>
<td>23</td>
</tr>
<tr>
<td>Bethlehem</td>
<td>67</td>
<td>125.10</td>
<td>45</td>
</tr>
</tbody>
</table>
Fig. 5a: CNGrid and BU Cases (1999-2012) Relationships for UDWD

Fig. 5b: PMSWR and BU Cases (1999-2012) Relationships for UDWD
Fig. 6: CNGrid Map of AWD

Fig. 7a: CNGrid Map of UDWD
Fig. 7b: CNGrid Map of UDWD

**Potential Maximum Soil Water Retention (PMSWR):** The PMSWR were generated based on the SCS CNGrid Method. The maps of PMSWR for the study areas are shown in Fig. 8 to 9b.
Fig. 8: PMSWR Map of AWD

Fig. 9a: PMSWR Map of UDWD
CONCLUSIONS

This research presents a new approach to delineating BU disease prone areas and will be useful for identifying new areas where humans may be at high risk to the disease. The study observed that BU endemic communities were mostly surrounded by farms and galamsey activities. The endemic communities in the study areas correlated with high to moderate infiltration rates as well as moderate to high PMSWR.

Low to moderate runoff potential areas have SCS CNGrid values which range from 30 to 79.99. The landuse are forest, agricultural and galamsey activities with HSGs of A and B. CNGrid values from 80 to 100 also correlate with high runoff potential areas with landuse of mostly, agricultural and galamsey activities and HSG of mainly C.

Low to moderate surface runoff potential and moderate to high PMSWR of between 67.52 mm - 592.67 mm correlate with BU disease prone areas. This study has demonstrated that PMSWR and SCS CNGrid values are important hydrological parameters for the delineation of BU disease prone areas.

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