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Determination of the Infiltration Parameters for Benin City by the Green-Ampt Methods

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Abstract:

Infiltration for a layered lithology was investigated for a section of Benin city using the Green-Ampt model to determine the infiltration rate, cumulative infiltration and the time of travel of infiltrates from the natural ground to the zone of saturation. The base data for this study include the hydraulic conductivity and porosity of each stratum of the lithology. The depths of each of the stratum were determine from monitored borehole drilling operations. The modified Green Ampt model for layered soil was used to determine relevant infiltration parameters. The results showed that a fairly uniform infiltration rate of 21.9m/year was found for the catchment while the cumulative infiltration was between 5.06 and 14.08m at Iguike and Okhunmwun respectively. The time of travel of the infiltrates from the natural ground to the aquifer level ranges from 2.85 to 7.831years. it can therefore be stated the cumulative infiltration and time of travel differ slightly in the catchment.

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1.0 Introduction

Infiltration entails the penetration of water and other solute particles to a lower membrane caused by gravitation force, adhesion and cohesion mechanism(Cao *et al.*, 2019). This is a critical parameter towards determining the water balance of an aquifer and the general ecosystem (Pitt *et al.*, 2008, Wang and Guo, 2020). The principal parameters upon which infiltration depends include the storm runoff, soil permeability, particle size, bulk density, land use among other considerations (Ibeje and Osuagwu, 2018, Wang and Guo, 2020).

Some of the prominent methods for the determination of infiltration in a location, particularly at shall depths in urban areas include the Green-Ampt method, the Horton methods and the Holtan methods

(Hsu *et al.*, 2002, Haghighi *et al.*, 2010, Becker, 2016, Parnas *et al.*, 2021). The Green-Ampt Model is generally more employed for infiltration computation due to its simplicity and applicability in hydrologic modelling. The initial Green-Ampt model effectively computes the infiltration for homogenous soils where nonuniform soil water content hold sway and in the scenario of unsteady of rainfall. The method assumes the wetting front as an abrupt interface between the wetted and nonwetted material. Liu *et al.* (2008) derived an expression for the Green-Ampt model for layered soils (GALS). The new model is generally referred to as the modified Green-Ampt model and is useful for estimating the average suction (S), infiltration capacity, ponding time and cumulative infiltration for layered lithology that is typical of the Benin city groundwater system.

The study is aimed at determining the infiltration rate, ponding time and cumulative infiltration of Benin city towards accurately determining the water balance parameter for the catchment.

1.1 Modified Green-Ampt Model

The modified Green-Ampt Model can be used to compute the infiltration at each stratum of the soils towards determining the water and solute transport flow as well as groundwater recharged (Chu and Marino, 2005, Ma *et al.*, 2011, Cheik *et al.*, 2019). Figure 1 is a schematic representation of a layered lithology to which the green-Ampt model can be applied.

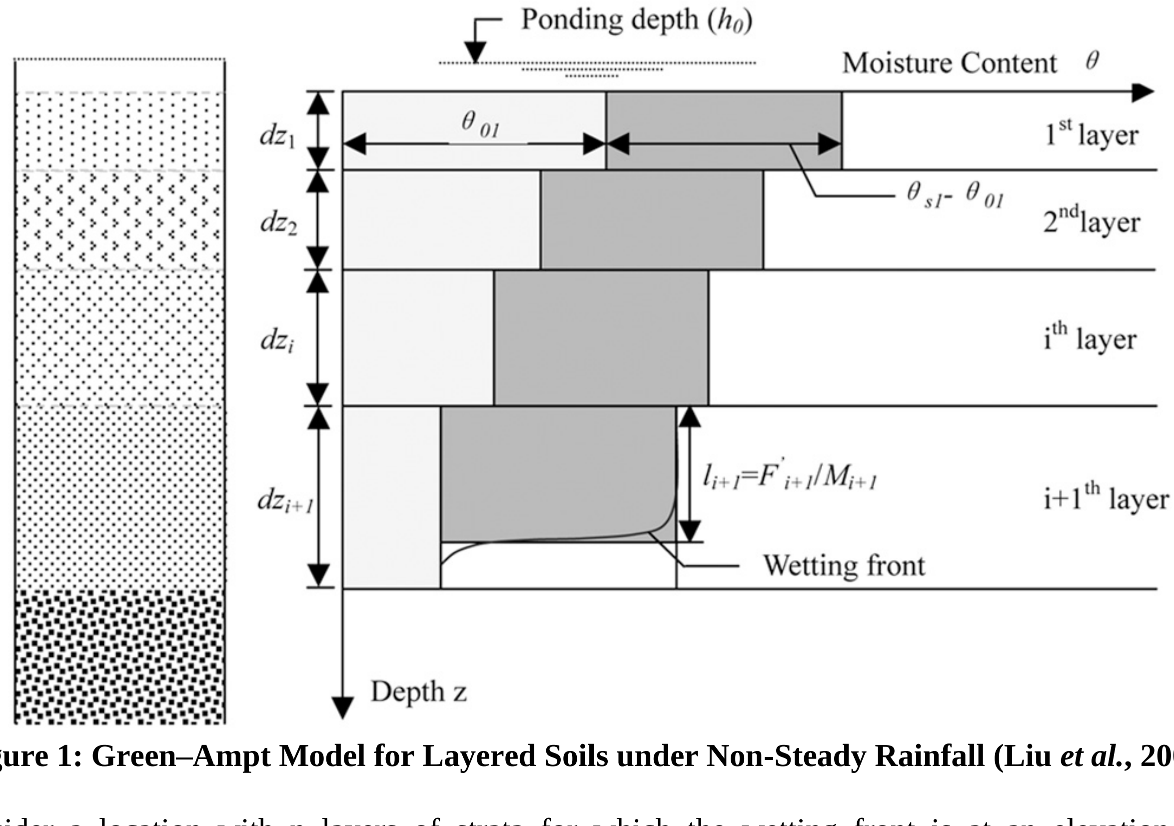


Figure 1: Green–Ampt Model for Layered Soils under Non-Steady Rainfall (Liu *et al.*, 2008).

Consider a location with n layers of strata for which the wetting front is at an elevation of z $(z_{n-1} < z < z_n)$, the infiltration rate (i) and cumulative infiltration (I) is expressed in equations 1 and 2 (Ma *et al.*, 2011).

$$i_{zj} = \frac{z + \Psi_{sn}}{\sum_{j=1}^{n-1} \frac{z_j - z_{j-1}}{k_j} + \frac{z - z_{n-1}}{k_n}} \quad (1)$$

$$I_{zj} = \sum_{j=1}^{n-1} \left(z_j - z_{j-1}\right)\theta_{fj} + \left(z - z_{n-1}\right)\theta_{fn} \quad (2)$$

Where

Z = wetting front (here taken as the water table elevation)

Ψ_{sn} = suction head of the log layer

J = each layer or stratum of the subsurface under consideration

n = number of layers in the subsurface of the location.

K = hydraulic conductivity (m/year)

$\theta_{fj} = \theta_{sj} - \theta_{ij} \Rightarrow 0.7 * \theta_e$ Change of water content of the soil layer

Θ_s = saturated water content of the layer

Θ_i = initial water content of the layer; Θ_{ej} = effective porosity of the layer j

For the layers exceeding the zone of saturation, Θ_{fj} is zero considering that there is no form of infiltration after the wetting zone (z). Other parameters such as the time of travel (t) of water from one layer to the other is given in equation 3. The final travel time to the zone of saturation is the total time of travel at the aquifer level.

$$t_z = t_{z_{n-1}} + \frac{\theta_{fn}}{K_n}\left(z - z_{n-1}\right) + \theta_{fn}\left[\sum_{j=1}^{n-1} z_j \left|\frac{1}{k_j} - \frac{1}{k_{j+1}}\right| - \frac{\Psi_{sn}}{K_n}\right] \ln\left(\frac{z + \Psi_{sn}}{z_{n-1} + \Psi_{sn}}\right) \quad (3)$$

2.0 Materials and Method.

2.1 Description of Study Area

Benin City is one of the ancient cities in Nigeria that is fast expanding and soon-to-be-designated as smart city in Nigeria (Ihimekpen and Ogbeifun, 2017). It is located between longitude $5^0 30'$E and $5^0 48'$E and Latitude $6^0 17'$N and $6^0 24'$N (see Figure 2). The city was decapitated from the former Midwestern region of Nigeria where it held sway since 1963. Benin City is about 250km east of Lagos, 90km from the coastline and the Atlantic Ocean. Studies show that the built-up area is about 60750 hectares and the spatial expansion of about 9% (Balogun and Onokerhoraye, 2017). The metropolis comprises several water bodies such as the Ikpoba River, Ogba River and the Onigie-Ogbovhen river. smaller water bodies such as streams also abound in the metropolis which together with the larger water body can impact infiltration in the catchment(Akpoborie *et al.*, 2012, Edjere *et al.*, 2016, Emeribe *et al.*, 2016, Akpe *et al.*, 2018, Okonofua *et al.*, 2019). Ikpoba river is by far the largest and prominent river in the catchment with a mean annual runoff of 225.18mm (Akujieze, 2004, Onyeobi and Akujieze, 2014, Ikhile, 2016).

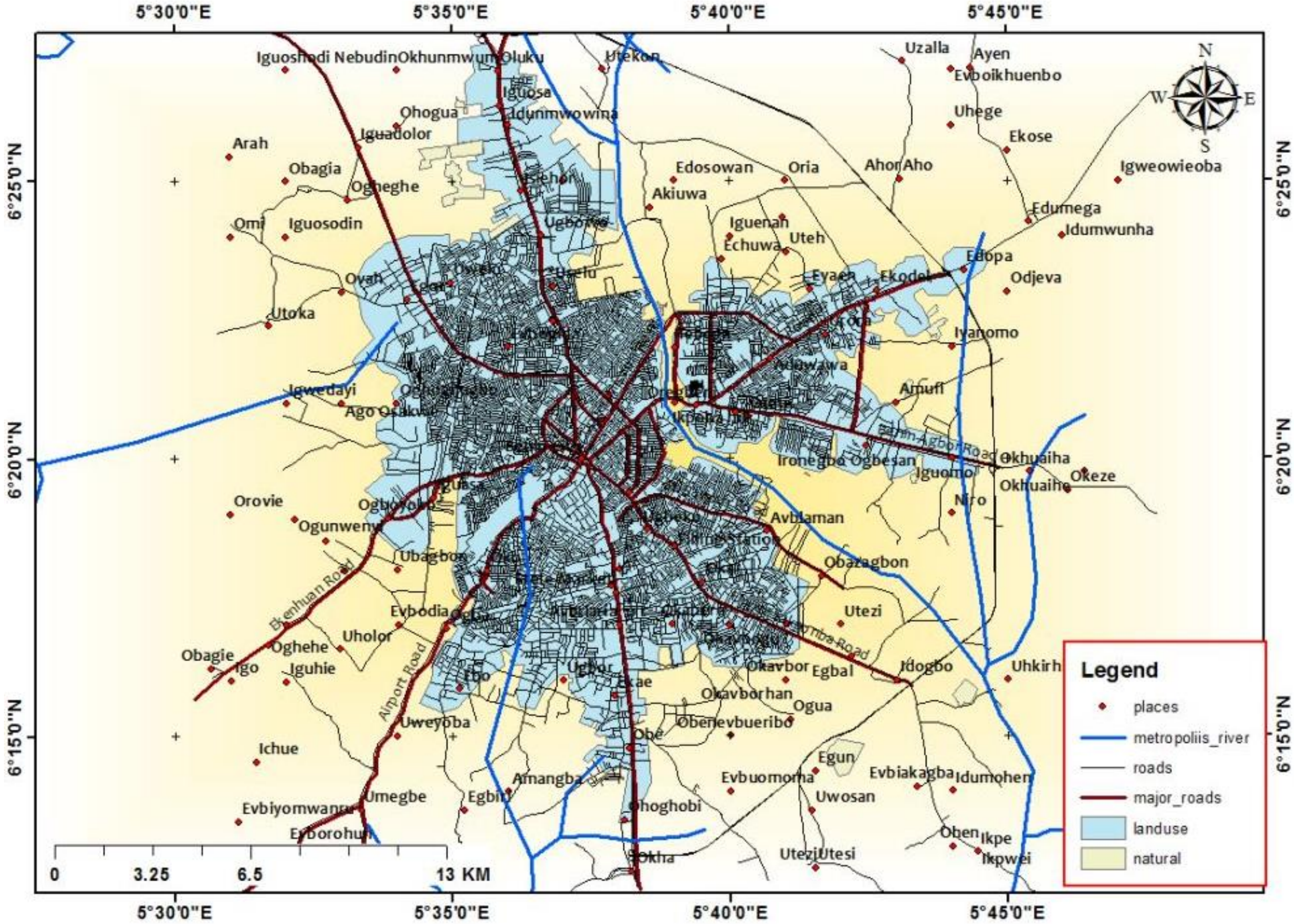


Figure 2: Location Map of Benin City (Ihimekpen *et al.*, 2018)

2.2 Methodology

Borehole log of the aquifer obtained from drillers log and archival data

2.2.1 Borehole Log Determination

Borehole log for the determination of the stratigraphy for the catchment were obtained from local drillers by way of filled questionnaire and monitored drilling operations. Log information were obtained for about 130 locations suitably spread across the catchment for the determination of the lithology of the area up to the aquifer zone. The number of log points were determined from statistical analysis of the total number of locations in the study area with the standard variance as obtained from archival data of the depth to the zone of saturation in the catchment (Ogbeifun, 2022). The period of monitoring was about 18 months.

2.2.2 Determination of the Green-Ampt Parameter.

The chief parameters that characterize the Green-Ampt model are the hydraulic conductivity and the porosity. The procedure for the determination of these parameters are presented in the section below:

2.2.1 Hydraulic Conductivity

The approach to determining the hydraulic conductivity include the use of the regression model of the index parameter or adopting empirical models in soil mechanics. one of the very popular empirical relationship for determining Hydraulic Conductivity from sieve analysis is the Allen Hazen's formula with hydraulic conductivity as a function of the percentage for which 10% particle are finer than this size and is expressed as (Cabalar and Akbulut, 2016)

$$k = 100D_{10}^{2} \qquad (4)$$

where D_{10} is the grain size of 10% fine soil passing the various sieves expressed in cm

Sieve analysis was performed on the log and appropriate percentage fine is applied to the model shown in equation (4)

2.2.2 Porosity of Borehole Log

The porosity of each of the layers of soil forms a typical parameter for the computation of infiltration using the Green-Ampt model. The porosity is defined as the ratio of the total volume of the soil to the total volume of the soil (Garg, 2005). This can be mathematically expressed as

$$\text{Porosity}(n) = \frac{V_v}{V} = \frac{V_a + V_w}{V_a + V_w + V_s} \qquad (5)$$

where

V = Total volume of soil; V_a = Volume of air in the void; V_w = Volume of water in the void;
V_s = Volume of solid in the void;

For this study, the porosity was obtained from the Moisture Content tests for each of the borehole log as outlined below:

a) Ensure oven drying of the borehole samples, to remove all the volume of water from the soil samples i.e. V_w= 0 and $V_v = V_a + 0(V_w = 0) \Rightarrow V_v = V_a$

b) Place the soil into a measuring cylinder or beaker up to 10ml volume. Pour water into the soil content in the container until full saturation. The pouring of water must be accompanied by stirring to remove all air entrapment in the soil. Measure the saturated volume of the soil. $V = V_w (V_w = V_a) + V_s$

c) Measure the difference in volume before and after saturation to obtain the volume of the void V_v $(V_v = V - 10)$

d) Porosity can be calculated thus from the relationship stated in equation 3.88 earlier mentioned.

e) The process is repeated for each layer of the soils comprising the log of the borehole

2.2.3 Other Green-Ampt Parameter

Parameters derived from the hydraulic conductivity and porosity were used to extrapolate other Green-Ampt parameters such Residual Porosity Θ_r, Effective Porosity(Θ_e) and wetted capillary pressure (ψ) from the table of values provided in Rawls *et al.* (1983). Part of the sieve analysis results were applied to carryout soil classifications.

2.4 Application of Geostatistical Tools

Geostatistical procedures were applied to the results of both the borehole log as well as the infiltration computation to account for areas with no field data. This entails the instrumentality of kringing in ARC GIS 10.1 that chooses the optimal unbiased estimate of a parameter for a model domain. Kringing differs from other interpolation methods due to its consideration of the spatial configuration of the parameters as well as provides prediction of the interpolation error, the likes of which include standard deviation and weights of the Kringed values (Ryu *et al.*, 2002). The steps involved in the geostatistical assessment of the processed data to cover the entire catchments are presented in figure 3:

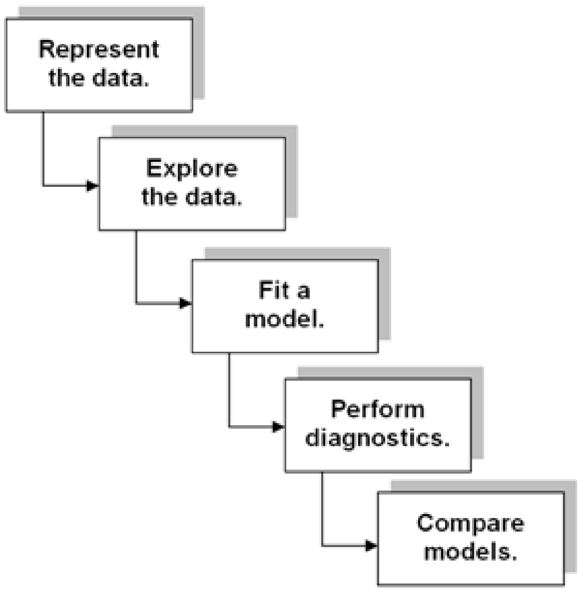


Figure 3: Steps in Geostatistical Assessment of Data

3.0 RESULTS AND DISCUSSION

3.1 Green-Ampt Parameter from Soil Data

The Green-Ampt parameters comprise hydraulic conductivity, effective porosity, suction head (or wetted capillary pressure), total and residual porosities. Particle Size Distribution tests were used to classify the logs into the various geotechnical classes from which their Green-Ampt parameters were derived from Rawls *et al.* (1983) that made use of the Brooks and Corey equation. Table 3.1 shows the various Green-Ampt parameters of the sample logs of the study catchment. For each drilling points, a total of nine (9) logs were obtained which has been presented in a top-to-bottom fashion. The top layer of the aquifer level has been labelled G.

Table 3.1: Green-Ampt Parameters for Infiltration Computation

Label ID	Borehole Log Soil Class	Green-Ampt Parameter (Rawls *et al.*, 1983)				
		n	Θ_r	Θ_e	Ψ x10^{-2} (m)	K (m/yr)
A	Loam	0.463	0.029	0.434	8.890	29.7850
B	SM /Sandy loam/SM	0.453	0.041	0.412	11.010	95.4872
C	SM/Sandy Loam	0.453	0.041	0.412	11.010	95.4872
D	SM/Silt Loam	0.501	0.015	0.486	16.680	56.9419
E	SC-CL/Sandy Clay	0.398	0.068	0.330	21.850	13.1404
F	CH/Clay	0.475	0.090	0.385	31.630	2.6281
G	SW/Sand	0.437	0.020	0.417	4.950	1031.9631
H	Sand-gravel (SW-SP)	0.436	0.015	0.459	4.050	1098.9794
I	GW/Coarse Sand	0.434	0.010	0.500	3.150	1165.9956

Where

n – Total Porosity, Θ_r – Residual Porosity; Θ_e – Effective Porosity; ψ – wetted capillary pressure, k – Hydraulic Conductivity.

3.2 Geostatistical Evaluation of Cumulative Infiltration

For better spatial analysis for the missing location, the infiltration data were subjected to geostatistical analysis using Kringing as the principal tool for finding the actual values of the missing location. The semivariogram of the closest point selection is shown in Figure 4. The prediction statistics indicating te data error and the input parameters from the geostatistical procedure is presented below:

a) Mean -0.002030317424816929
b) Root-Mean-Square: 2.8893255937647577
c) Mean Standardized: -0.0014453210983884537
d) Root-Mean-Square Standardized: 1.4763187590588858
e) Average Standard Error: 1.959104176863842
f) Goodness of Fit: 2.9048
g) Neighbourhood Type: Advance
h) Maximum Neighbours: 1000
i) Minimum Neighbour: 0
j) Sector Type: 1 Sector
k) Major Semi Axis: 8357.248
l) Minor Semi Axis: 8357.248
m) Anisotropy Factor: 1.0

n) Spatial Condition Number Threshold: True
o) Spatial Condition Number Threshold: 6.171978
p) Measurement Error Is 100%
q) Partial Sill: 0.3286358
r) Kringing/Cokringing Algorithm: Gaussian

It is on the above basis that the refined plot of spatial variation of infiltration for the study catchment was plotted. The standard error plot and qqplot of the geosstatistically processed data are shown in Figure 5a. The range of cumulative infiltration and much shorter with higher level of precision of value are shown in figure 5b.

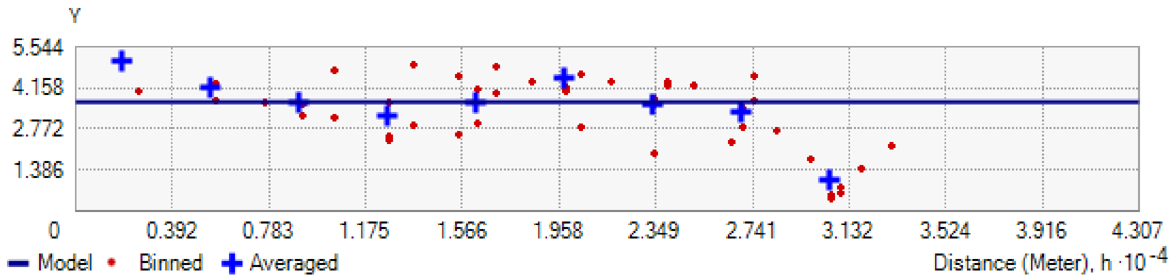
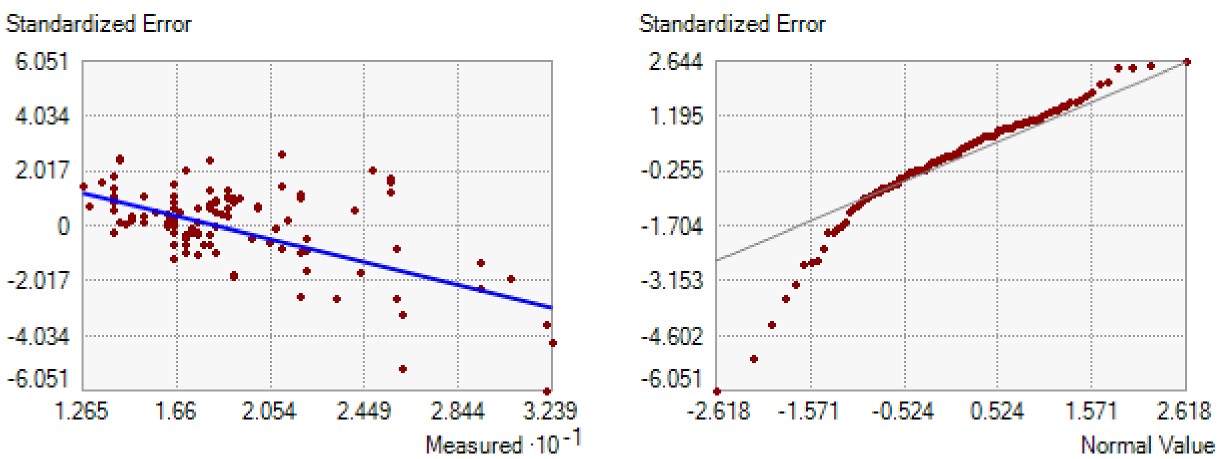


Figure 4: Semivariogram of the Geostastically Analysed Points



(a) (b)

Figure 5: Standardized Error plot (a) and Normal QQplot (b)

3.3 Infiltration Rate

The infiltration rate of the entire catchment reveals strong uniformity despite obvious changes in the depth to the zone of saturation. The infiltration rates were computed for the different layer assuming that no infiltration occurs at the wetting front. The rate of infiltration at the wetting front was found to be approximately in the region of 21.6m/year.

3.4 Cumulative Infiltration

Figure 6 is the Triangular Irregular Network (TIN) plot of spatial variation of infiltration just before the zone of saturation of the study area. This plot shows that the highest value of total infiltration occurs around Oluku and a portion of Isihor along the Ugbowo-Lagos corridor with a value between 14.165 and 32.385m. The lowest values of the cumulative infiltration occurred around Uselu and Ugbowo areas of Egor Local Government Area of the metropolis. Furthermore, Aduwawa has the highest cumulative infiltration within its vicinity with a value of 26.06m while New Era College, with a value of 14.17m is the lowest around its area. Igwedayi has a value of 21.76m while the lowest occurred around Iguike with a value of 11.51m. Etete market and the Okabere areas have extreme values of 13.92m and 17.46m within their vicinity respectively. Areas around **Umegbe** and **Iguenan** have cumulative infiltration between at 12.65m and 21.00m respectively.

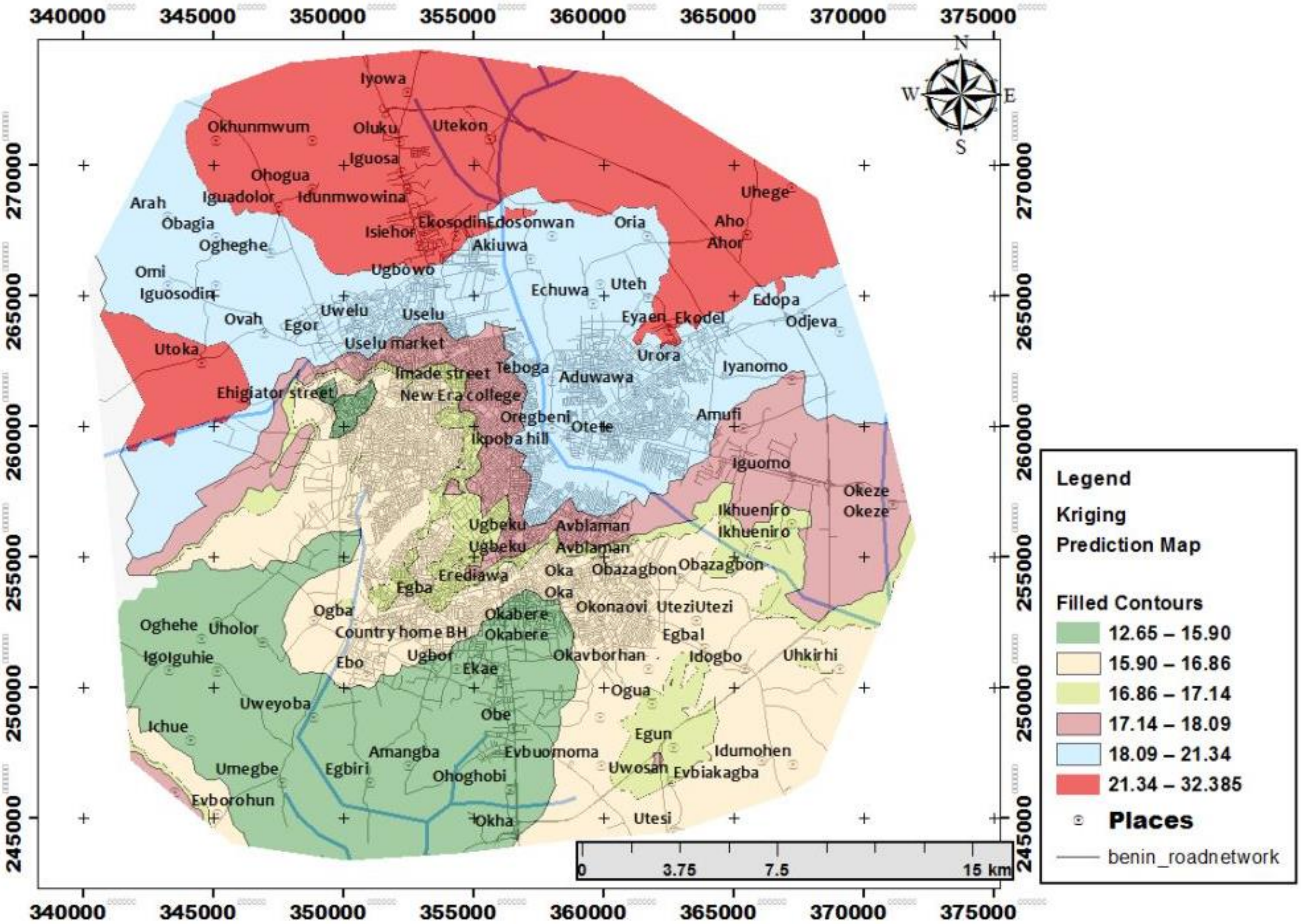


Figure 6: Cumulative infiltration plots of the study of the area.

Travel Time computation

A sample zone comprising locations such as Amangba, Egbiri, Ekae, Obe, Ogheghe, Ohoghobi, Okabere, Uholor, Umegbe and Uweyoba were selected for presentation and shown in Figure 7. It can be seen graphically that Okabere has the longest period of travel of infiltrates of 4.196years to the aquifer zone, followed by Ogheghe with a value of 4.073years for the zone examined. Umegbe followed by Amangba has low travel time of infiltrates reaching the aquifer zone of 3.028years and 3.088 years respectively. For the generality of the study area, the longest travel was found at

Okhunmwun having a value of 7.831year while Aduwawa has the least travel time in the catchment with a value of 2.580 years.

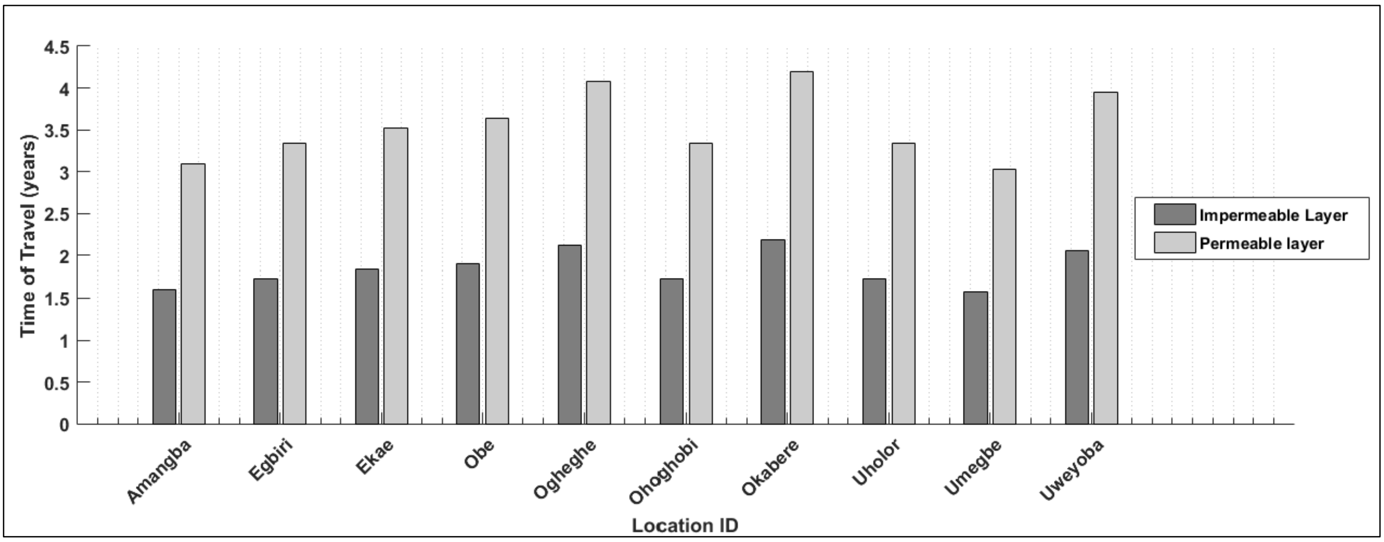


Figure 7: Sample zone travel time using the Green-Ampt Method of infiltration

4.0 Conclusion and Recommendation.

The Modified Green-Ampt model offers a veritable approach to determining the infiltration rates, cumulative infiltration and travel time of infiltrate across layers of soils down to the zone of saturation. In this study, the model was applied to Benin city to determine the aforesaid parameters. This study showed that the infiltration rates for vast number of locations in the catchments were fairly uniform with a value of 21.6m/year irrespective of the transiting lithology. The cumulative infiltration was highest around Utekon, Iyowa with values ranging from 21.34 to 32.4m. The time of travel for the study location ranges from 2.850 to 7.831years.

Given the high rate of expansion of the city, it is recommended that other models are employed to compute the catchment infiltration in order to determine the most optimal value that can be used for infrastructural designs and other modelling endeavours.

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