International Journal of Engineering and Technology Innovation, vol. 4, no. 2, 2014, pp. 96-106

Prediction of Post-Closure Water Balance for Monolithic Soil Covers at Waste Disposal Sites in the Greater Accra Metropolitan Area of Ghana

Kodwo Beedu Keelson*

Department of Civil Engineering, Kaaf University College, Accra, Ghana.

Received 30 September 2013; received in revised form 26 December 2013; accepted 06 January 2014

Abstract

The Ghana Landfill Guidelines require the provision of a final cover system during landfill closure as a means of minimizing the harmful environmental effects of uncontrolled leachate discharges. However, this technical manual does not provide explicit guidance on the material types or configurations that would be suitable for the different climatic zones in Ghana. The aim of this study was to simulate and predict post-closure landfill cover water balance for waste disposal sites located in the Greater Accra Metropolitan Area using the USGS Thornthwaite monthly water balance computer program. Five different cover soil types were analyzed under using historical climatic data for the metropolis from 1980 to 2001. The maximum annual percolation and evapotranspiration rates for the native soil type were 337 mm and 974 mm respectively. Monthly percolation rates exhibited a seasonal pattern similar to the bimodal precipitation regime whereas monthly evapotranspiration did not. It was also observed that even though soils with a high clay content would be the most suitable option as landfill cover material in the Accra metropolis the maximum thickness of 600 mm recommended in the Ghana Landfill Guidelines do not seem to provide significant reduction in percolation rates into the buried waste mass when the annual rainfall exceeds 700 mm. The findings from this research should provide additional guidance to landfill managers on the specification of cover designs for waste disposal sites with similar climatic conditions.

Keywords: water balance model, landfill cover, landfill closure, waste disposal site, Ghana

1. Introduction

Uncontrolled leachate generation during the rainy season is a perennial problem at most of the abandoned waste disposal sites in the Greater Accra Metropolitan Area (GAMA). This is due to the fact that none of these facilities including the Oblogo and Mallam dumpsites were provided with engineered cover systems to mitigate these leachate flows after dumping operations had ceased there [1]. The Ghana Landfill Guidelines [2] require the provision of a final cover system during closure as a means of minimizing the harmful environmental effects of uncontrolled leachate discharges. However, this manual does not provide explicit guidance on the material types or configurations for landfill covers that would be suitable for the different climatic zones in Ghana.

The design and performance evaluation of several landfill elements depends upon developing a water balance for the landfill. Estimates of maximum and minimum monthly, average and peak daily flows which are obtained from a water balance analysis can be used in the design of leachate collection, transmission, and treatment systems [3-5]. A water balance analysis is also useful in the design of final cover systems [6]. For an existing landfill without a bottom liner, this type of

---

[*] Corresponding author. E-mail address: kodwobeedu@yahoo.com
Tel.: +233-243822223

analysis can determine the suitability of different soil cover systems with respect to reducing leachate generation and minimizing ground water contamination.

Landfill water balance is typically estimated with the aid of computer simulation models. These simulation models compute the difference between precipitation and runoff, evapotranspiration and change in soil moisture storage. This difference or surplus equals percolation, which becomes leachate [3-4]. Modelling can be done for active areas without final cover as well as for closed areas with a final cover. The most widely used approaches for estimating landfill water balance include the USEPA Water Balance Method and the Hydrologic Evaluation of Landfill Performance (HELP) Model. The major difference between these two estimation approaches is that the HELP model simulation uses a much more detailed sequence of calculations which requires daily climatic data. The model also has the ability to analyze water fluxes through the complete vertical profile of a landfill [7]. Computer models which are based on the USEPA water balance method use monthly climatic data and are to a large extent limited to the analyses of water fluxes through the landfill top cover only [8]. It does not also provide peak flow estimates. However, the USEPA water balance method provides a faster method for analysis especially in locations where there is limited site specific data as is usually the case in many developing countries.

The aim of this research study was to simulate and predict post-closure landfill cover water balance for waste disposal sites located in the Greater Accra Metropolitan Area using the USGS Thornthwaite monthly water balance computer program. The importance of this study is that it would provide guidance on the choice of suitable landfill cover material types for waste disposal sites in this particular climatic zone.

2. Study Design

2.1. Description of study area

The Greater Accra Metropolitan Area consists of the Accra Metropolitan Area; Tema Metropolitan Area; Ledzokuku-Krowor Municipal Area; Adentan Municipal Area, Ashaiman Municipal Area; Ga East Municipal Area; Ga West Municipal Area and Ga South Municipal Area. Fig. 1 shows a map of the major waste disposal sites in the Greater Accra Metropolitan Area.

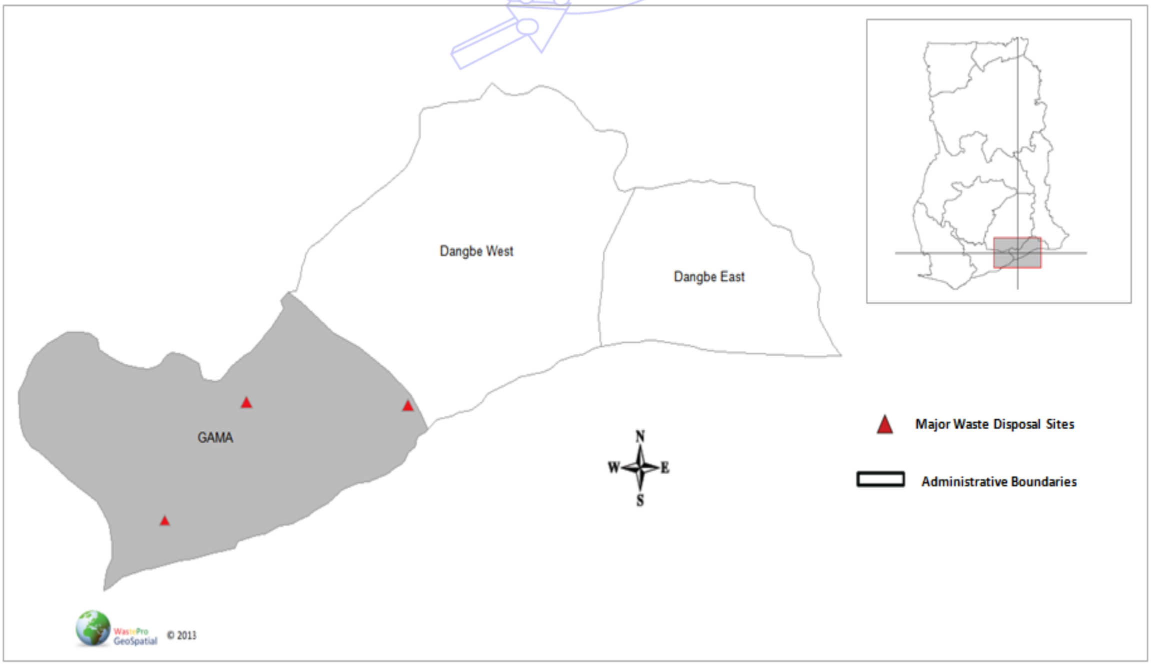


Fig. 1 Location map of waste disposal sites in GAMA

The Greater Accra Metropolitan Area exhibits seasonality in the rainfall distribution, with June being the wettest month, on average, and August the driest. The seasonality in the precipitation patterns is brought about by the movement of the inter-tropical convergence zone (ITCZ). Its northerly advancement during the period from March to June results in pronounced instability, with frequent storms and intense precipitation. A secondary rainy period occurs in between September and November as the ITCZ moves south across the region. Temperatures are high all around the year with daily variations higher than seasonal variations.

The geology of Accra gives rise to generally lateritic soil groups, which are readily erodible, and provide a significant source of sediments. The soils in the metropolitan area can be divided into four main groups: drift materials resulting from deposits by wind-blown erosion; alluvial and marine motted clays of comparatively recent origin derived from underlying shales; residual clays and gravels derived from weathered quartzites, gneiss and schist rocks, and lateritic sandy clay soils derived from weathered Accraian sandstone bedrock formations. These soils belong to the Mamfe-Oyarifa and Densu/Chichewere local series [9] which can be classified as Eutrustox Oxisols [10].

2.2. Theoretical basis for the USEPA water balance method

The theoretical basis and design assumptions for the application of the USEPA water balance estimation method to closed waste disposal sites is outlined in [8]. This estimation procedure considers water which is being routed through a closed waste disposal site as basically consisting of two phases i.e. routing through the soil cover and routing through the compacted solid waste beneath. Fig. 2 presents a schematic of the two phase estimation procedure for water balance analysis of a closed landfill.

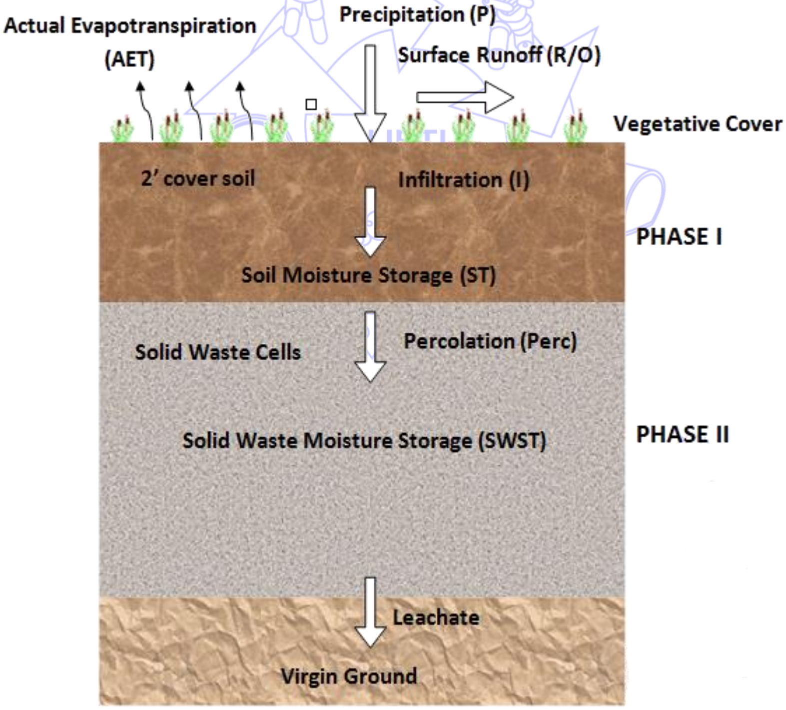


Fig. 2 Two phase water balance estimation procedure for closed landfills

The soil cover is that phase which interfaces directly with the atmosphere and will determine the amount of infiltration into the soil and percolation into the solid waste. The solid waste phase and its attendant moisture storage capacity determine the quantity and time of first appearance of the leachate. The vegetated landfill soil cover is considered as a one dimensional system in order to estimate the percolation of water into the solid waste. The solid waste phase is then analyzed in relation to the percolation amounts from the cover to determine the leachate generation from the landfill.

2.3. Thornthwaite water balance computer program

The Thornthwaite water-balance program is a hydrological model which was developed by the U.S. Geological Survey [11]. This water-balance model analyses the allocation of water among various components of the hydrologic system using a monthly accounting procedure. A schematic of this monthly accounting procedure is depicted in Fig. 3.

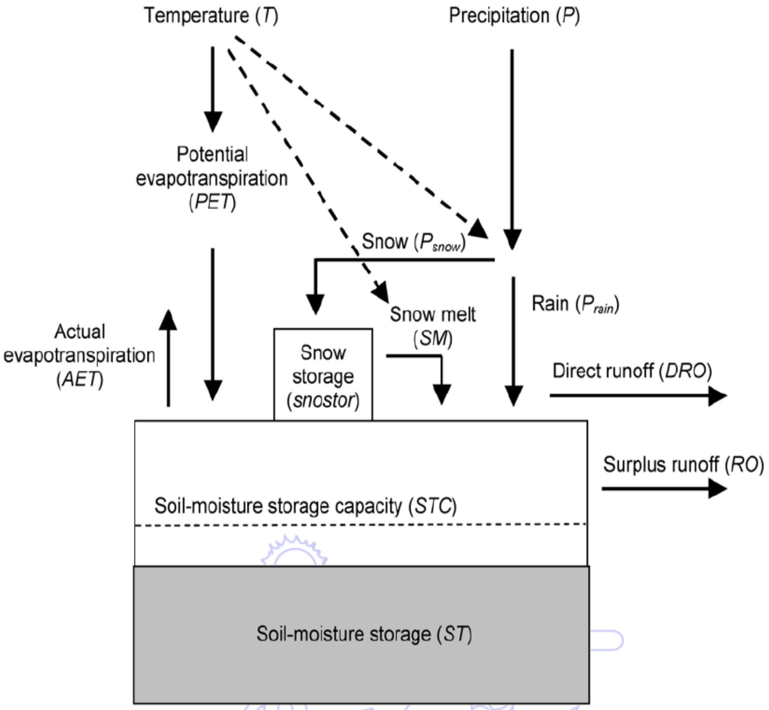
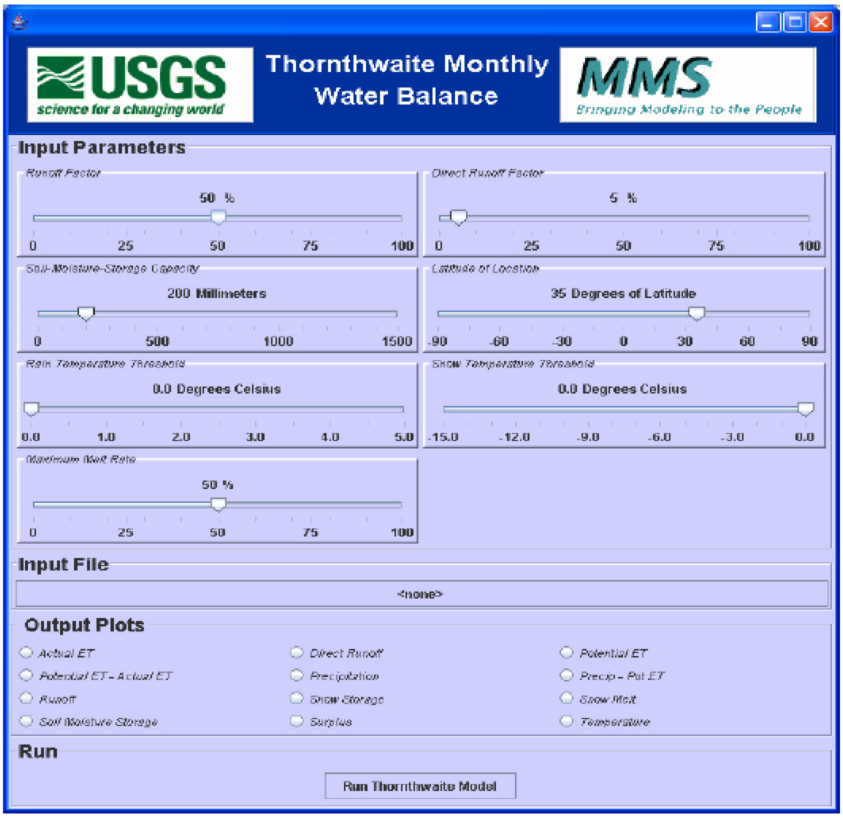


Fig. 3 Schematic of water balance accounting procedure



Runoff Factor: 50 %
Direct Runoff Factor: 5 %
Soil-Moisture-Storage Capacity: 200 Millimeters
Latitude of Location: 35 Degrees of Latitude
Rain Temperature Threshold: 0.0 Degrees Celsius
Snow Temperature Threshold: 0.0 Degrees Celsius
Maximum Melt Rate: 50 %
Input File: <none>

○ Actual ET
○ Potential ET - Actual ET
○ Runoff
○ Soil Moisture Storage
○ Direct Runoff
○ Precipitation
○ Snow Storage
○ Surplus
○ Potential ET
○ Precip - Pot ET
○ Snow Melt
○ Temperature

Fig. 4 Graphical user interface for specifying input and output parameters

The Thornthwaite water balance program requires an input data file that contains a time series of monthly precipitation and monthly temperature. Other input parameters include the runoff factor, direct runoff factor, soil-moisture storage capacity and latitude of the location under consideration. The output parameters simulated by the model includes actual evapotramspiration, potential evapotranspiration, runoff, soil moisture storage and percolation. Actual and potential evapotranspiration are computed by the software using the Harmon equation [12]. Fig. 4 presents a screen image of the graphical user interface for specifying input and output parameters. The simulation results can be generated in a tabular form or as a time series plot.

2.4. *Water balance modelling scenarios*

An input data file containing time series of historic monthly precipitation and temperature for Accra from 1980 to 2001 [13] was used to determine the maximum, mean and minimum percolation and actual evapotranspiration rates. Water balance simulations were initially done for the sandy loam which is assumed to be the native soil type in the study area. The simulations were then repeated for four other soil types including fine sand, silty loam, clay loam and clay. Table 1 presents the hydrologic and location specific data used in the analysis. The soil moisture storage capacities for the various soil types which are shown in Table 2 were computed by multiplying the assumed landfill cover depth of 600 mm [2] with the available water which is the difference between the field capacity and wilting point [8].

Table 1 Hydrologic and location specific data

Parameter	Value	Reference
Runoff factor	50%	[11]
Direct runoff factor	5%	[11]
Latitude of location	5.6	[14]

Table 2 Soil moisture capacities for various soil types

Soil type	Moisture storage capacity (mm)
Fine sand	60
Sandy loam	90
Silty loam	120
Clay loam	150
Clay	180

3. Computer Simulation Results

3.1. *Annual precipitation and Evapotransipration rates*

The estimates for precipitation, actual evapotranspiration and percolation for the sandy loam cover are shown in Fig. 5. There is a good correlation between these three water balance components i.e. peak and low annual values occur at or within the same time periods.

The annual maximum, minimum and average annual estimates for precipitation, percolation and actual evapotranspiration over the 22 year period are presented in Table 3. The annual percolation estimates are between 0–337 mm. whereas the annual evapotranspiration estimates are between 316–974 mm. The average annual estimates for percolation and evapotranspiration are 71.0 mm and 612.5 mm respectively. Generally, the annual percolation rates were zero when precipitation was less than 700 mm.

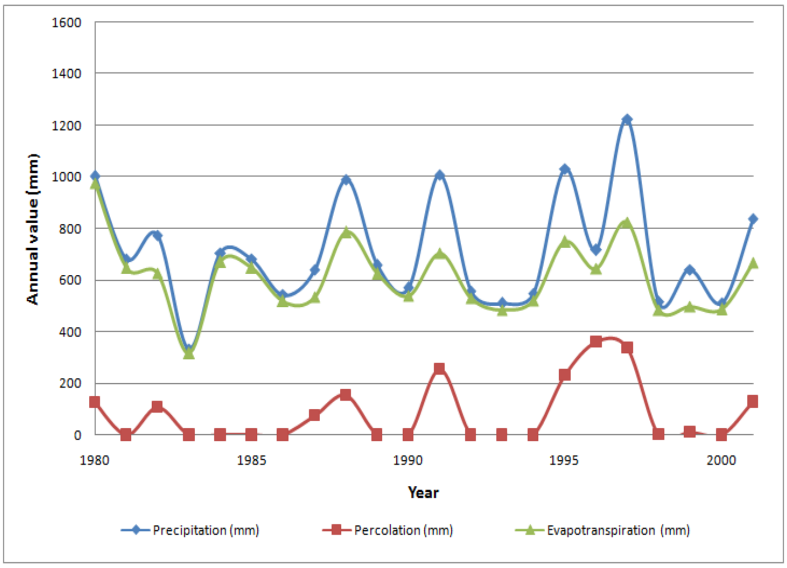


Fig. 5 Annual water balance estimates for sandy loam cover

Table 3 Annual maximum, minimum and average water balance estimates

Parameter	Maximum (mm)	Minimum (mm)	Average (mm)
Precipitation	1223.5	333.1	712.3
Percolation	337.6	0.0	71.0
Actual Evapotranspiration	974.8	316.4	612.5

3.2. *Seasonal and monthly water balance estimates*

Fig. 6 shows the monthly maximum water balance estimates for the sandy loam cover. Monthly percolation estimates exhibit a seasonal pattern similar to the bimodal precipitation regime. There are two peaks which occur in June and September. The maximum and average monthly percolation rates for June and September are 226.6 mm and 73.9 mm respectively. There was no percolation during the dry months of January, February, March, August, November and December which have monthly precipitation values that are usually less than 50 mm.

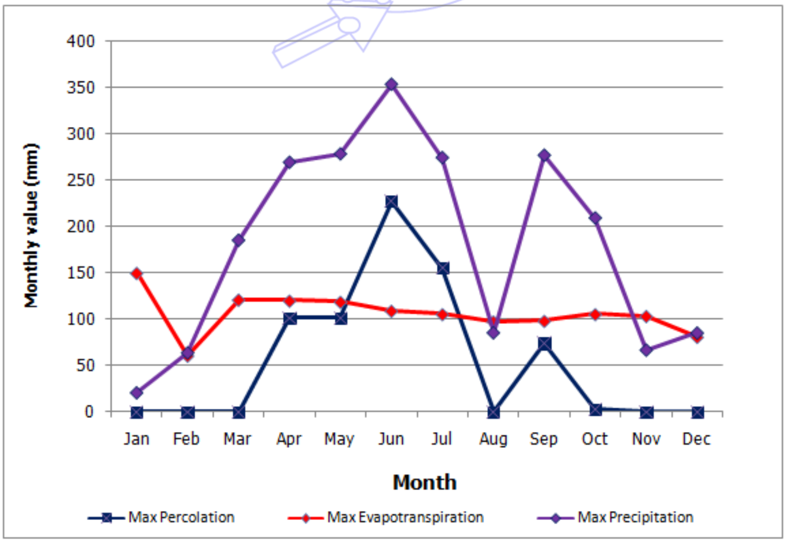


Fig. 6 Monthly maximum water balance estimates for sandy loam

The monthly evapotranspiration estimates do not exhibit a seasonal pattern. This phenomenon is due to the fact that evapotranspiration is to a large extent dependent on monthly temperature which does show a wide variation as precipitation. A peak value of 150 mm is observed in January followed by a sharp drop in February and then a sharp rise in March. The values are fairly stable between April and July and decline gradually during the rest of the year.

3.3. Significance of different soil types on annual water balance estimates

The annual percolation estimates for the different soil types are shown in Fig. 7. It is observed that the highest values were obtained for fine sand while the lowest values were obtained for clay. There was a 58% decrease in average annual percolation for clay compared to loamy sand. Decreases in average annual percolation rates of 44% and 29% were also observed for clay loam and silt loam respectively. An 8% increase was observed for fine sand. The results obtained seem to suggest that percolation is dependent on the sizes of voids in the soil matrix. Larger percolation rates occur in the presence of larger voids which decreases soil moisture retention and vice versa. This explains why sandy loam soil has higher percolation rates in comparison to silty loam. A similar explanation can also be proffered for clay loam having lower percolation rates than sandy loam soil.

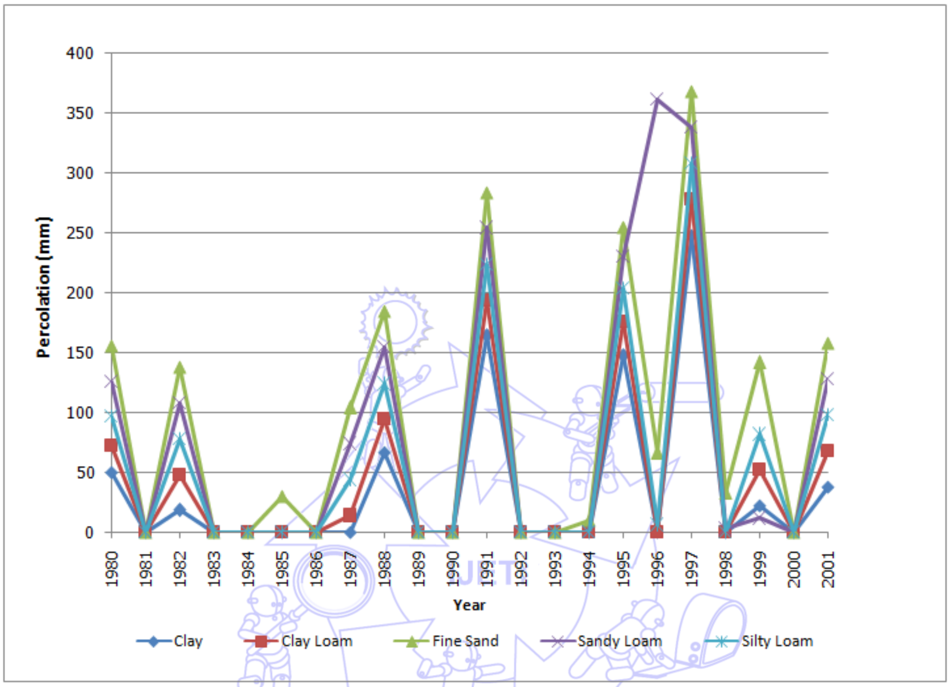


Fig. 7 Annual percolation estimates for different soil type

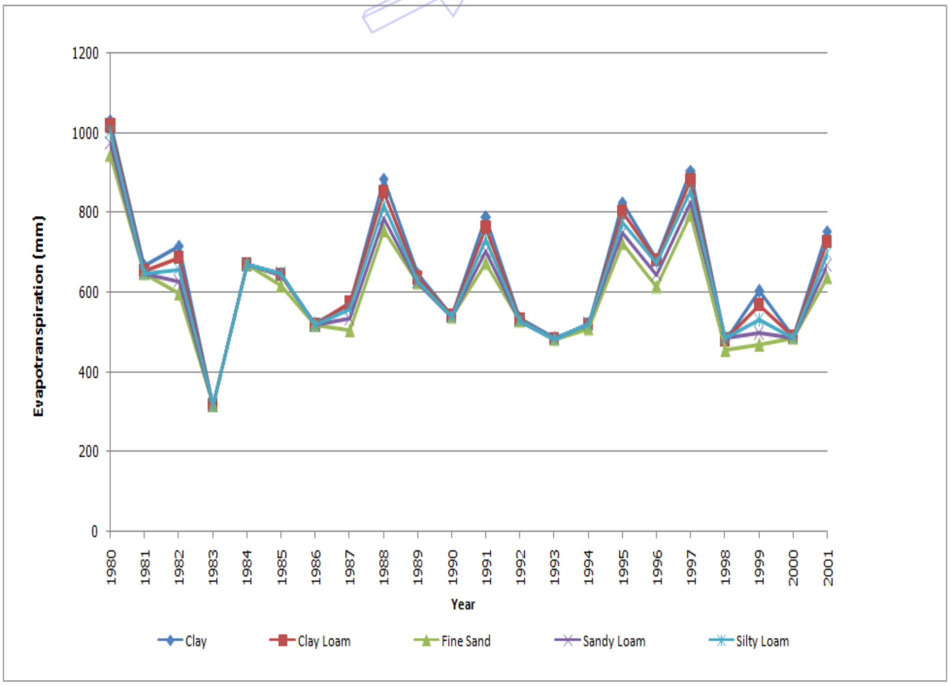


Fig. 8 Annual evapotranspiration estimates for different soil types

With regards to annual evapotranspiration the highest values were obtained for clay whereas the lowest values were obtained for fine sand. Average annual evapotranspiration rates were increased by 6.7% and 4.5% were observed for clay and clay loam respectively compared to sandy loam. There was a 3.1% and 2.5% decrease for fine sand and silty loam respectively. These observations could be most likely due to the fact that clay has higher moisture retention ability and as such more water is readily available for evapotranspiration compared to the other soil types. The annual evapotranspiration estimates for different soil types are shown in Fig. 8.

3.4. Significance of different soil types on seasonal and monthly variation of water balance estimates

The monthly variation of maximum percolation and evapotranspiration are shown in Fig. 9 and Fig. 10 respectively. The order of increasing percolation is as follows: clay, clay loam, silty loam, sandy loam, and fine sand. There was no percolation in the dry months of January, February, March, August, November and December irrespective of the type of cover soil. It can also be seen that the differences in maximum percolation for June for the different soil types is marginal. This may seem to suggest that the 600 mm thick clay cover offers some protection at the onset of the major rainy season and during the minor rainy season; however, it is not effective during very heavy rainfall conditions in comparison with the other soil cover types. It is also observed that monthly percolation exhibits a seasonal pattern of variation similar to the bimodal rainfall regime irrespective of the type of cover soil.

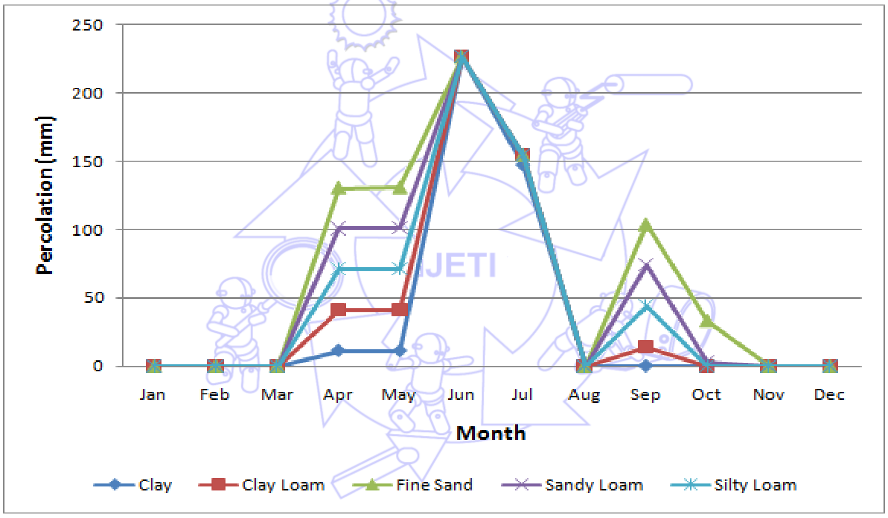


Fig. 9 Monthly maximum percolation for different soil types

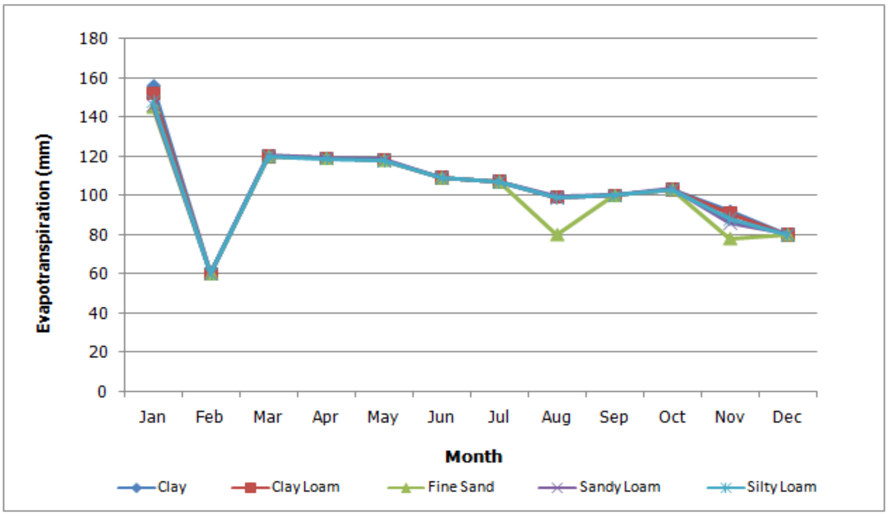


Fig. 10 Monthly maximum evapotranspiration for different soil types

It is observed that there were similar maximum evapotranspiration values for all the different soil types with the exception of January, August and December. No explanation can be provided for this phenomenon beyond the possibility that this may be due to limitations of this particular computer model.

4. Discussion of Results

4.1. Choice of suitable landfill cover for the greater Accra metropolitan area

The principal function of a final cover is to minimize infiltration into the waste and consequently reduce the amount of leachate being generated. Final covers typically consist of a combination of natural soil and synthetic layers [15]. The installation of these types of capping systems is very expensive even in the industrialized countries [16]. In developing countries such as Ghana, the use of monolithic or single layer native soil materials would be a cheaper option provided a specific thickness of the cover can be determined accurately. A monolithic soil cover should typically have a sufficiently deep soil profile so that infiltrated water is stored until removal by evaporative losses from the soil surface and by plant roots at depth in the profile [17]. However, in climatic zones where evapotranspiration rates are relatively low limiting the percolation rates through the use of cover soil layers which have low saturated hydraulic conductivities becomes imperative [18-21].

The Ghana Landfill Guidelines [2] require the provision of a final cover having a thickness of between 400–600 mm. It also requires that this cover should be able to support vegetation which is a major feature of the landfill restoration process. It can be inferred from the simulation results that the use of soils with a high clay content as cover material would be a suitable choice for the Greater Accra Metropolitan Area due to its higher moisture retention capacity and consequently less percolation. However, since moisture retention capacity is also dependent of the soil cover thickness an increase in the cover thickness would result in further reduction in percolation rates. It is significant to note that all the waste disposal sites in the Greater Accra Metropolitan Area have no bottom liners and as such there is a very high risk of groundwater contamination if the landfill cover does not limit the amount of percolation into the waste body below [22].

4.2. Limitations of the Thornthwaite water balance estimation method

It is significant to note that although the Thornthwaite water balance method can be used to conduct a rapid evaluation of landfill water balance components due to the minimal data input requirements it is not very accurate in comparison to other water balance models such as the HELP Model [7]. This is mainly due to the fact that the water balance computation is done using a monthly time step which does not account for daily variations in moisture storage or antecedent conditions. Additionally, only a single soil material layer can be simulated and the effects of landfill vegetation cannot be analyzed.

The inability to simulate vegetation cover means that the Thornthwaite water balance computer program may not be able to consider capillary rise of water from or below the evaporative zone depth [18-20]. These peculiar features seem to suggest that that apart from a comparative assessment of the suitability of different soil cover types and thicknesses the results from the Thornthwaite water balance analysis cannot be used to accurately determine the configuration and dimensions of landfill capping and leachate collection systems.

5. Conclusion and Recommendation

Computer simulations for five different monolithic soil covers were done using historical monthly climatic data for the Greater Accra Metropolitan Area. The maximum annual percolation and evapotranspiration rates for the native soil type were 337 mm and 974 mm respectively. Monthly percolation rates exhibited a seasonal pattern similar to the bimodal precipitation regime whereas monthly evapotranspiration did not. It was observed that soils with higher clay content would be the most suitable material for use as cover material in this geographical or climatic zone, due to the fact that they have higher moisture storage capacity which limits percolation but increases evapotranspiration. However, it was also determined that the recommended maximum cover thickness of 600 mm specified in the Ghana Landfill Guidelines would not ensure a significant reduction in percolation rates at waste disposal sites in the Greater Accra Metropolitan Area when the annual precipitation is in excess of 700 mm.

The inherent limitations of the Thornthwaite water balance computer program does not make it possible to account for different topsoil vegetative conditions and evaporative zone depths. Recommendations for further study should include the study of the combined effects of different topsoil vegetative conditions and evaporative zone depths on evapotranspiration and percolation rates for monolithic soil covers using other peer reviewed water balance models such as EPIC, HYDRUS-2D and UNSAT-H [23].

Acknowledgement

The work for this paper was carried out with technical support from Kspyx HR Consult Ltd/WastePro Software. The author also wishes to thank the Dean and faculty members at the Department of Civil and Geomatic Engineering of Kaaf University College.

References

[1] S. Twumasi-Ankrah, J. Holm and E. Oppong, “Evaluation of landfill cover design options for the Greater Accra Metropolitan Area using the HELP Model,” BSc. Project Thesis, Department of Civil Engineering, Kaaf University College, Ghana, 2012.

[2] Ghana Environmental Protection Agency, “Ghana landfill guidelines,” July 2002.

[3] Washington State Department of Ecology, “Solid Waste Landfill Design Manual,” http://www.access.wa.gov, July 12, 2012.

[4] Ireland EPA, “Landfill Site Design,” http://www.epa.ie, July 6, 2012.

[5] P. Rushbrook and M. Pugh, “Solid waste landfills in low and middle income countries – A technical guide to planning, design and operation,” World Bank Technical Publication 426, Washington D.C., Feb. 1999.

[6] K. Berger, “Water Balance of Capping Systems,” http://www.landfill-technology.info, July 12, 2012.

[7] R. Schroeder, P. Dozier, T. Zappi, B. McEnroe, J. Sjostrom and R. Peyton, “The Hydrologic Evaluation of Landfill Performance (HELP) engineering documentation for version 3,” EPA/600R-64/168b, U.S. Environmental Protection Agency Risk Reduction Laboratory, Cincinnati, Ohio, 1994.

[8] D. Fenn, G. Hanley, and K. DeGeare, “Use of water balance method for predicting leachate generation from waste disposal sites,” Report No. EPA/530/SW-168, http:/nepis.epa.gov, July 5, 2012.

[9] H. Obeng, “Soil classification in Ghana, in: selected economic issues No. 3,” Centre for Policy Analysis, Accra, Ghana, 2000.

[10] United States Department of Agriculture, Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys. 2nd Edition, Agriculture Handbook, no. 436, Washington D.C., U.S.A., 1999.

[11] G. McCabe and S. Markstrom, “A monthly water balance model driven by a graphical user interface,” U.S. Geological Survey Open-File Report 2007-1008, http:/www.usgs.gov, July 2, 2012.

[12] W. Harmon, “Estimating potential evapotranspiration,” Journal of the Hydraulics Division, American Society of Civil Engineers, vol. 87, pp. 107–120, Dec. 1961.

[13] K. Keelson, “The Ghana hydro-database project - IT applications in water resources engineering and management,” 1st GIMPA School of Technology Workshop on Information Technology and Systems, Accra, Ghana, Jan. 31, 2012.

[14] Accra Metropolitan Assembly, “Rehabilitation, closure, bid evaluation, construction supervision and contract management of the Oblogo No.1 and Mallam No.1 dumpsites in Accra,” Draft Design Report, Accra, Ghana, Aug. 2011.

[15] United States Environmental Protection Agency, “Design and Construction of RCRA/CERCLA Final Covers,” EPA/625/4-91/025, http://nepis.epa.gov, July 6, 2012.

[16] United States Department of Energy, “Alternative landfill cover,” Innovative Technology Summary Report, http://ost.em.doe.gov, July 12, 2012.

[17] United States Environmental Protection Agency, “Evapotranspiration Landfill Cover Systems Fact Ssheet,” EPA 542-F-03-015, http://nepis.epa.gov, July 6, 2012.

[18] S. F. Dwyer, “Water balance measurements and computer simulations of landfill covers,” Ph.D. dissertation, University of Mexico, Albuquerque, New Mexico, USA, 2003.

[19] B. A. Gross, “Water balance evaluations for monitored evapotranspirative cover systems at three sites in the semi-arid and arid Southwest USA,” Ph.D. dissertation, University of Texas at Austin, Texas, USA, 2005.

[20] V. L. Hauser, D. M. Gimon, J. V. Bota, T. A. Howell, R. W. Malone and J.R. Williams, “Models for Hydrologic Design of Evapotranspiration Landfill Covers,” http://pubs.acs.org/cgi-bin/art.PDF, July 6, 2012.

[21] W. H. Albright, G. W. Gee, G. V. Wilson and M. J. Fayer, “Alternative cover assessment project Phase 1 Report,” Publication No. 41183, http://www.dri.edu/acap-publications, July 6, 2012.

[22] United States Environmental Protection Agency, “Case Studies on Ground Water and Surface wWater Contamination from Municipal Solid Waste Landfills,” EPA/530-SW-88-040, http://nepis.epa.gov, July 6, 2012.

[23] Interstate Technology and Regulatory Council, “Technical and Regulatory Guidance for Design, Installation, and Monitoring of Alternative Final Landfill Covers,” http://www.itrcweb.org, July 6, 2012.