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Evaluation of Landfill Cover Design Options for Waste Disposal Sites in the Coastal Regions of Ghana

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Abstract

Uncontrolled leachate generation from operational and closed waste disposal sites is a major environmental concern in the coastal regions of Ghana which have abundant surface water and groundwater resources. The Ghana Landfill Guidelines requires the provision of a final cover or capping system as part of a final closure plan for waste disposal sites in the country as a means of minimizing the harmful environmental effects of these emissions. However, this technical manual does not provide explicit guidance on the material types or configuration for landfill covers that would be suitable for the different climatic conditions in the country. Four landfill cover options which are based on the USEPA RCRA-type and evapotranspirative landfill cover design specifications were evaluated with the aid of the HELP computer program to determine their suitability for waste disposal sites located in the Western, Central and Greater Accra regions. The RCRA Subtitle C cover which yielded flux rates of less than 0.001 mm/yr was found to be suitable for the specific climatic conditions. The RCRA Subtitle D cover was determined to be unsuitable due to the production of very large flux rates in excess of 200 mm/yr. The results for the anisotropic barrier and capillary barrier covers were inconclusive. Recommendations for further study include a longer simulation period as well the study of the combined effects of different topsoil vegetative conditions and evaporative zone depths on the landfill water balance. The use of other water balance models such as EPIC, HYDRUS-2D and UNSAT-H for the evaluation of the evapotranspirative landfill cover design options should also be considered.

Keywords: leachate, groundwater, landfill cover, waste disposal, Ghana, HELP Model

1. Introduction

Landfill leachate is defined as the liquid that has percolated through solid waste and has extracted dissolved or suspended materials [1]. Leachate is generated either from external water or from within the waste mass. The external water sources include precipitation, surface water run-on and ground water interflow. Leachate needs to be controlled in a landfill for the following reasons [2-3]: to reduce the potential for seepage out of the landfill through the sides or the base either by exploiting weaknesses in the liner or by flow through its matrix; to prevent liquid levels rising to such an extent that they can spill over and cause uncontrolled pollution to ditches, drains, watercourses etc.; to influence the processes leading to the formation of landfill gas, chemical and biological stabilization of the landfill; to minimize the interaction between the leachate and the liner; and in the case of above ground landfill, to ensure the stability of the waste. Uncontrolled leachate generation is a major environmental concern in the coastal regions of Ghana namely the Western, Central, Greater Accra and Volta Regions which have abundant surface water and groundwater resources. Research studies on some abandoned

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dumpsites in the Greater Accra Region [4-6] show that leachate samples have significant concentrations of dissolved organics, inorganic macro components, heavy metals and xenobiotic compounds.

The Ghana Landfill Guidelines [7] require the provision of leachate management systems and procedures at all metropolitan, urban and rural landfills in the country. This ranges from recirculation of untreated leachate to the construction of site infrastructure for the collection, treatment and disposal of leachate for waste disposal facilities which are in operation. The Ghana Landfill Guidelines also requires the provision of a final cover system as part of a final closure plan for decommissioned waste disposal sites. However, this technical manual does not provide explicit guidance on the material types or configurations for landfill covers that would be suitable for the different climatic conditions at various locations in the country. In recent times, the Accra Metropolitan Assembly has awarded a contract for the remediation and closure of a number of abandoned waste disposal sites in the metropolis including the Oblogo No.1, Mallam SCC and Mallam Main dumpsites. Most of the other major waste disposal sites in the coastal regions including the Abloradjei, Saba, Axim, Agona Swedru, Nkamfua, Mfoum and Sofokrom dumpsites are fast approaching their capacity and would require that the appropriate landfill capping systems are put in place.

This aim of this research study was to undertake a comparative assessment of various landfill cover design options which could be used to control leachate flows from decommissioned waste disposal sites in the coastal regions of Ghana. It involved the prediction of annual, monthly and daily water balance estimates for different landfill profiles using the HELP computer program. The effect of using different types of topsoil material was also examined. Some concluding thoughts are then put forward on the choice of capping systems in order to minimize the impact of leachate flows from closed waste disposal sites after their useful design life.

2. Study Design

2.1 Description of Study Area

The coastal regions considered during this study were the Greater Accra, Central and Western regions. Fig. 1 shows a location map of these coastal areas. Fig. 2 shows the current conditions at some disposal sites in these coastal areas.

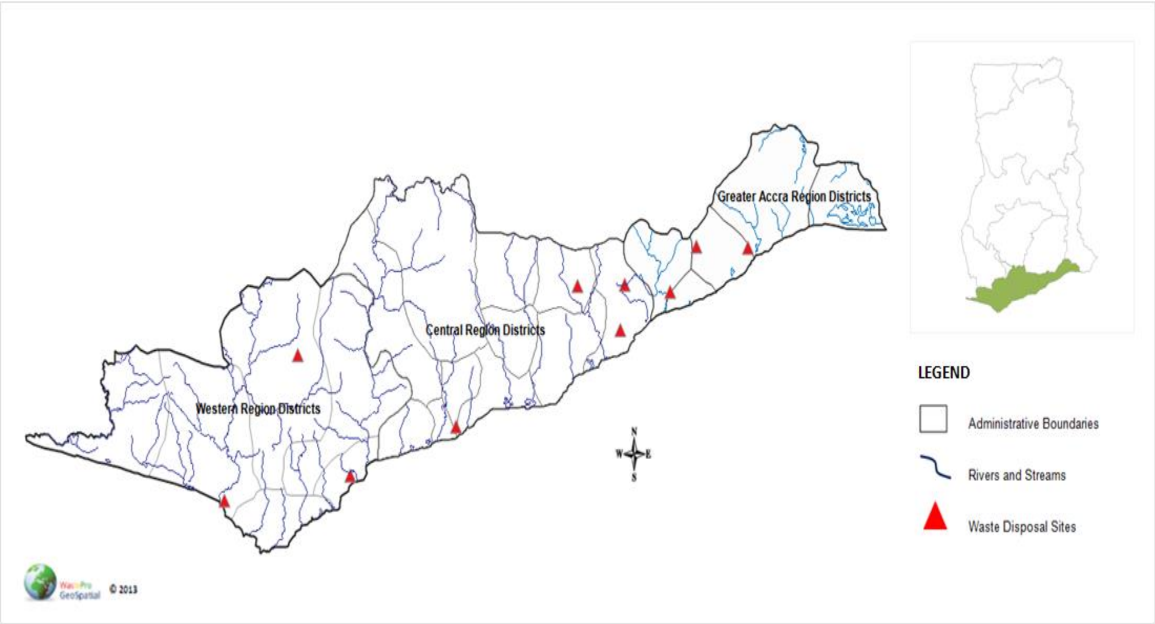

Fig. 1 Locations of major waste disposal sites in coastal districts and regions

The study sites fall within the dry and wet equatorial climatic zones which have mean annual precipitation values ranging between 700 – 1500 mm [8-10]. The dry equatorial zone occurs along the middle to eastern coast of Ghana including the Greater Accra and Central regions. The wet equatorial zone covers the Western region extending from the coast to the inland areas. These two climatic zones experience a double maxima rainfall regime. However the peak rainfall in the second season which occurs in October is not as heavy as the first which occurs in June. This geographical area is drained by the Southwestern and Coastal Rivers Systems which comprises of the Pra, Tano, Bia, Ankobra, Densu, and Ayensu rivers.

Fig. 2 Conditions at major waste disposal sites in coastal regions

The geology of the coastal areas is dominated by basement crystalline rocks and to a lesser extent by minor geological formations including cenozoic, mesozoic, and paleozoic sedimentary strata [11]. The minor geological formations are made up of two coastal formations, namely, the coastal block-fault and the coastal-plain. The coastal block-fault occurs in areas around Accra, Cape Coast and Sekondi-Takoradi where most of the major dumpsites are located. The coastal-plain formation occurs is in the south-eastern and south-western areas of the country such as Ada and Half Assini.

Three aquifer types occur in the cenozoic and mesozoic sediments formation located in the coastal regions [11]. The first aquifer is unconfined and occurs in the recent sand very close to the coast. It has a depth ranging between 2 m and 4 m and contains fresh meteoric water. The intermediate aquifer is either semi-confined or confined and occurs mainly in the red continental deposits of sandy clays and gravels. The depth of this aquifer varies from 6 to 120 m, and it contains mostly saline water. The third aquifer is the limestone aquifer, which varies in depth between 120m and 300 m and has an average yield of about 148 m^3/h. The groundwater in this aquifer is fresh and occurs under artesian condition.

2.2 The HELP Model

The HELP model is a computer model developed to assist landfill designers and regulators in evaluating cover systems, bottom liners and leachate collection systems [12-13]. Fig. 3 presents a schematic representation of the water balance components for the HELP Model. The input data types required for the HELP model include climatologic, vegetative cover, soil characteristics and landfill design site data. The output results for the HELP model includes daily volumes, monthly totals, annual averages, annual totals, amount of leachate collected and the percolation rates through the bottom of the landfill.

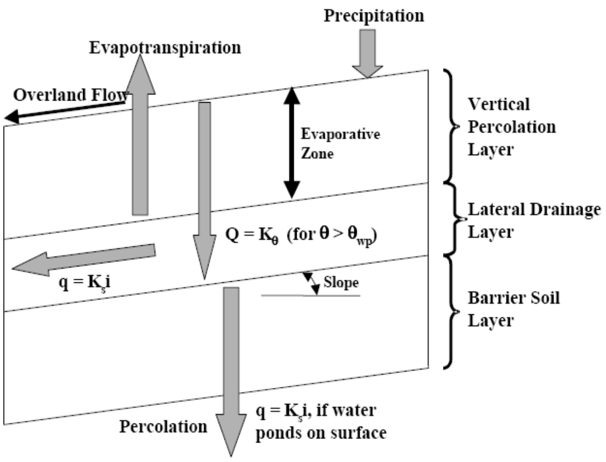

Fig. 3 HELP Model representation of water balance components

Vertical drainage is modeled by Darcy's law using the Campbell equation for unsaturated hydraulic conductivity based on the Brooks-Corey relationship. Saturated lateral drainage is modeled by an analytical approximation to the steady-state solution of the Boussinesq equation employing the Dupuit-Forchheimer assumptions [12].

2.3 HELP Modeling of Landfill Cover Design Options

Four landfill covers were evaluated with the aid of the HELP Model. These design options shown in Fig. 4 are based on the USEPA RCRA-type and the evapotranspirative or alternative landfill cover design specifications. Table 1 presents a list of the various landfill cover system design options and the respective characteristics. The RCRA-type covers are based on the barrier concept that requires them to employ resistive principles i.e. a layer having low saturated hydraulic conductivity [14]. Alternative covers generally rely on the water storage capacity of the soil layer rather than low conductivity materials to minimize percolation [15-17].

Topsoil layers were modelled as vertical percolation layers. All sand and gravel layers were modelled as lateral drainage layers. The compacted soil layers in the Subtitle D and C Covers were modelled as barrier layers. The compacted soil layers in all evapotranspirative covers were modelled as vertical percolation layers [17]. The difference in model layers for the compacted soil layers used was due to the design intent for each respective cover. The compacted soil layers in the Subtitle D and C covers were designed to serve as barriers while the compacted soil layers in the ET Cover and capillary barriers were designed to store water and allow for unsaturated water movement [17].

Table 3, Table 4, Table 5 and Table 6 present the HELP Model setup for the Subtitle C, Subtitle D, anisotropic barrier and capillary barrier covers respectively. For each design option simulation a fair stand of grass vegetation condition and a surface slope of 5% having a horizontal slope length of 50 meters was assumed. The synthetic climatic data and landfill site characteristics for the Oblogo No.1 dumpsite [18] were used to represent the conditions in the study areas under consideration. The installation defects and placement quality for the geomembrane liners were assumed to be good. A leaf area index (LAI) of 2 and an evaporative zone depth of 55 cm was used for each of the simulations. The simulation period was one calendar year. The topsoil type was initially assumed to be loam. The simulations were repeated for two other types of topsoil which can also be found in this geographical area i.e. sandy clay loam and clay loam to assess their significance. Table 7 shows the HELP Model input setup for these two soil types.

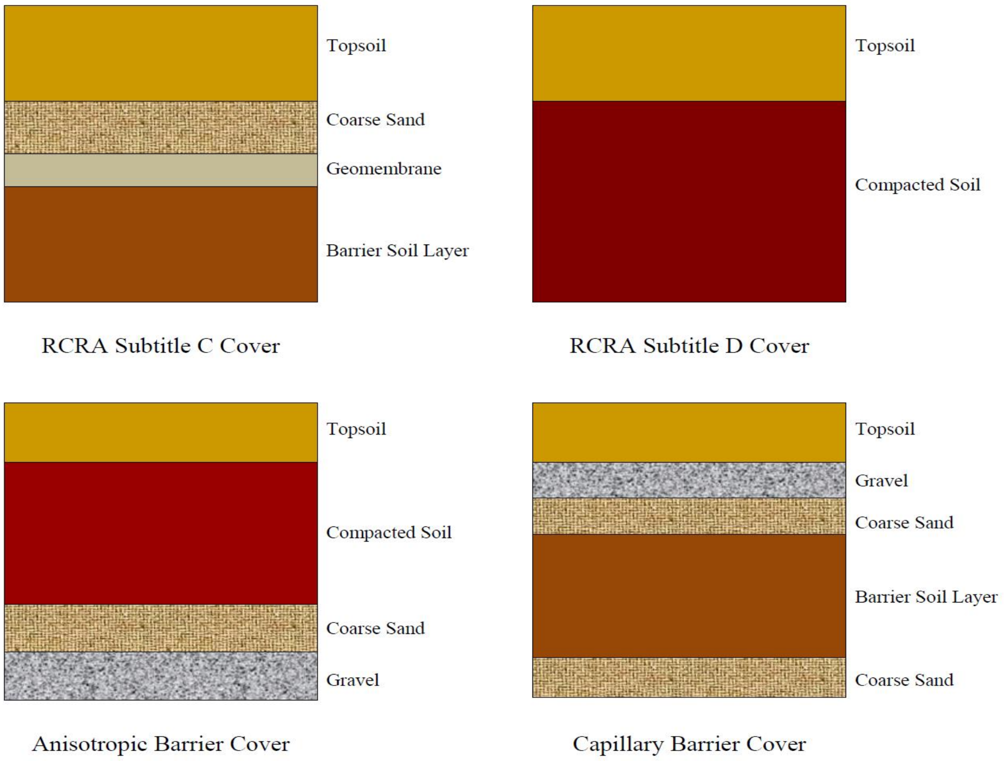

Fig. 4 Profile of various USEPA landfill cover design options

Table 1 Landfill cover system design option characteristics

Cover System Design Option	Number of layers	Total thickness (cm)
RCRA Subtitle C cover	4	120
RCRA Subtitle D cover	2	60
Capillary Barrier cover	5	142
Anisotropic Barrier cover	4	105

Table 2 HELP Model setup for Subtitle C cover soil profile

Layer Material	Type of Layer	HELP Classification	Thickness (cm)
Loam	Vertical percolation	8	60
Coarse Sand	Lateral drainage	1	30
Low density Polyethylene	Geomembrane liner	36	0.15
Barrier Soil	Barrier soil liner	16	60

Table 3 HELP Model setup for Subtitle D cover soil profile

Layer Material	Type of Layer	HELP Classification	Thickness (cm)
Loam	Vertical percolation	8	15
Compacted Loam	Barrier Soil Liner	22	45

Table 4 HELP Model setup for anisotropic cover soil profile

Layer Material	Type of Layer	HELP Classification	Thickness (cm)
Loam	Vertical percolation	8	15
Compacted Loam	Soil barrier	22	60
Coarse Sand	Lateral drainage	1	15
Gravel	Lateral drainage	21	15

Table 5 HELP Model setup for capillary barrier cover soil profile

Layer Material	Type of Layer	HELP Classification	Thickness (cm)
Loam	Vertical percolation	8	30
Coarse Sand	Lateral drainage	1	15
Gravel	Lateral drainage	21	22
Compacted Loam	Soil barrier	16	45
Coarse Sand	Lateral drainage	1	30

Table 6 HELP Model setup for other soil profile layers

Layer Material	Type of Layer	HELP Classification
Sandy Clay Loam	Vertical percolation	10
Compacted Sandy Clay Loam	Vertical percolation	24
Clay Loam	Vertical percolation	11
Compacted Clay Loam	Vertical percolation	25

3. Computer Simulation Results

3.1 Monthly and Seasonal Variation of Landfill Water Balance Components

Fig. 5, Fig. 6 and Fig. 7 shows a comparison of the monthly evapotranspiration, runoff and bottom layer percolation values respectively for the various landfill cover design options. It is observed that there are two peaks in June and October for the evapotranspiration, runoff and percolation which corresponds to the peak rainy months in the bi-modal rainfall regime that is exhibited in the coastal climatic zone. Minimum evapotranspiration, runoff and percolation values are observed in the dry months i.e. December to March.

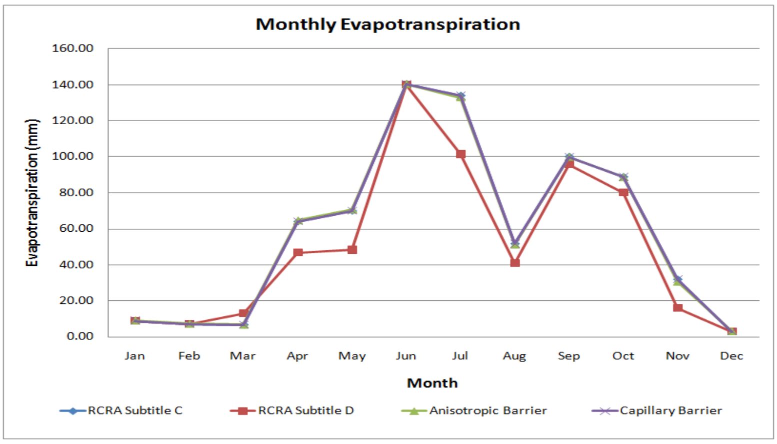

Fig. 5 Monthly evapotranspiration for various design options

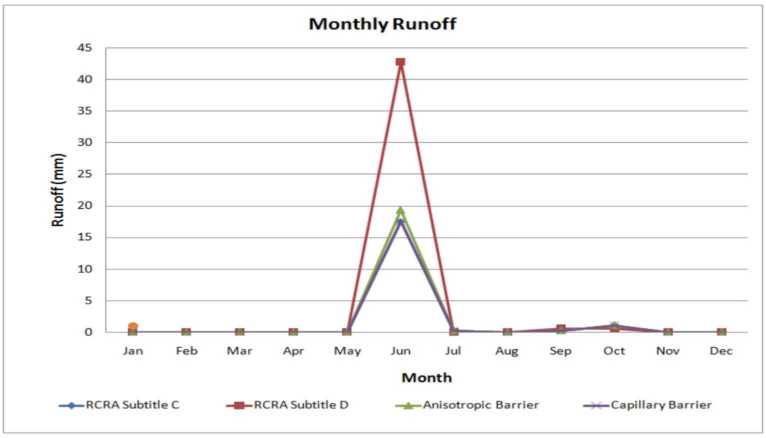

Fig. 6 Monthly runoff for various design options

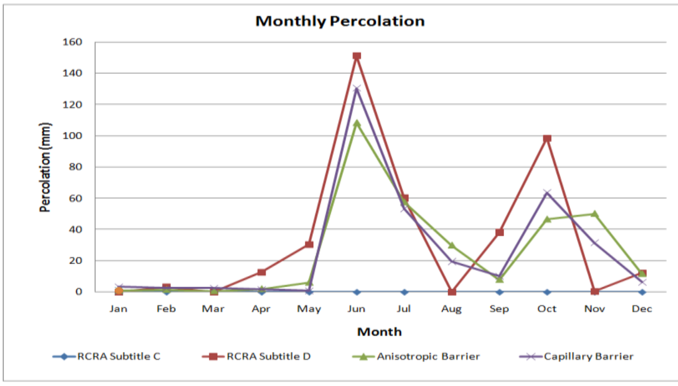

Fig. 7 Monthly percolation for various design options

3.2 Annual Evapotranspiration and Runoff

Table 7 shows the annual totals for evapotranspiration and surface runoff for the various design options. Evapotranspiration from the RCRA Subtitle D cover which has a barrier soil liner just beneath the topsoil layer was about 600 mm. However, evaporation from the RCRA Subtitle C, anisotropic barrier and capillary barrier covers which have either vertical percolation or lateral drainage layers beneath the topsoil layer were above 700 mm.

Table 7 Annual evapotranspiration and runoff for various design options

Landfill Cover Design Option	Evapotranspiration(mm)	Runoff(mm)
RCRA Subtitle C cover	705.8	19.0
RCRA Subtitle D cover	600.2	44.1
Anisotropic Barrier cover	705.0	20.9
Capillary Barrier cover	705.0	19.0

The highest runoff values were obtained for the RCRA Subtitle D, ET and anisotropic barrier cover which has a barrier layer just beneath the topsoil layer. Generally it is observed that the landfill cover design options with the lower values of runoff had comparatively higher values of evapotranspiration

3.3 Percolation from Bottom Layer

Table 8 shows the annual totals and peak daily percolation from the bottom layer for the various landfill cover design options. It observed that the annual total percolation through the bottom layer for the RCRA Subtitle C cover is less than 0.1 m^3. The largest value of 21,571 m^3 was observed for the RCRA Subtitle D cover. Generally, the landfill covers which have a geomembrane layer produced much less lower percolation values compared to the covers that consist of natural soil layers. A similar trend was observed for the peak daily leakage values.

Table 8 Annual totals and peak daily percolation for various cover system designs

Landfill Cover Design Option	Annual Percolation (m^3)	Peak Daily Percolation (m^3)
RCRA Subtitle C cover	0.025	0.00029
RCRA Subtitle D cover	21571	1138
Anisotropic Barrier cover	17246	594
Capillary Barrier cover	17302	1476

3.4 Significance of Using Different Types of Topsoil Material

The effect of using different types of topsoil on evapotranspiration, runoff and percolation is illustrated in Fig. 8, Fig. 9 and Fig. 10 respectively. Annual evapotranspiration rates for the RCRA Subtitle D cover increased by 2.6% and 4% respectively when sandy clay loam and clay respectively were used. Annual evapotranspiration rates for the RCRA Subtitle C, anisotropic barrier and capillary barrier covers decreased by 4.7%, 5.9% and 4.7% respectively when sandy clay loam was used. The annual rates for the RCRA Subtitle C, anisotropic barrier and capillary barrier covers increased by 0.1%, 1.9%

and 0.1% respectively when clay loam was used. These results seem to suggest that the type of topsoil has a marginal effect on the annual evapotranspiration rates.

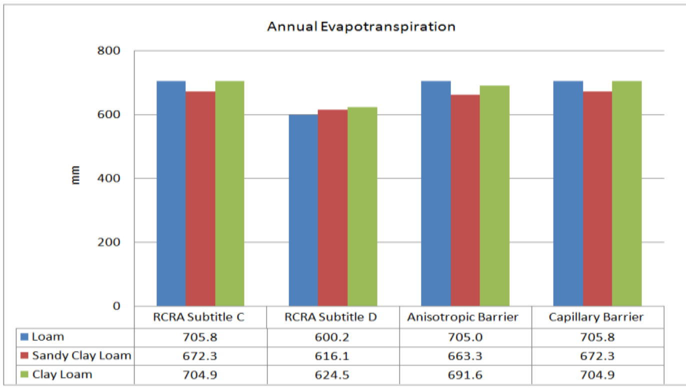

Fig. 8 Annual evapotranspiration for different topsoil types

Annual runoff rates for the RCRA Subtitle D cover increased by 285% and 235% respectively when sandy clay loam and clay respectively were used. Annual runoff rates for the RCRA Subtitle C, anisotropic barrier and capillary barrier covers increased by 33.2%, 39.7% and 33.2% respectively when sandy clay loam was used. The annual rates for the RCRA Subtitle C, anisotropic barrier and capillary barrier covers increased by 56.3%, 74.2% and 56.3% respectively when clay loam was used. These results seem to suggest that the type of topsoil has a significant effect on the annual runoff rates.

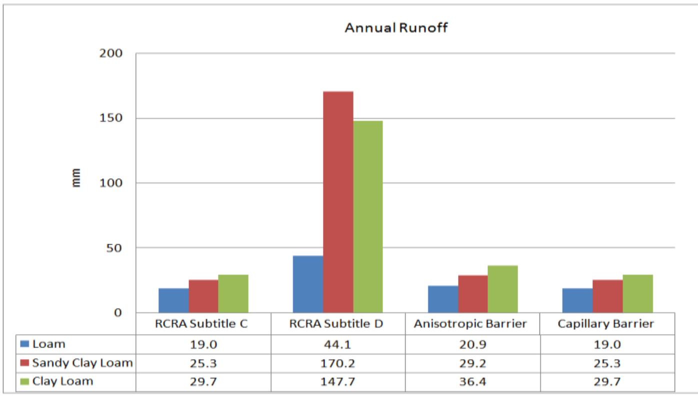

Fig. 9 Annual runoff for different topsoil types

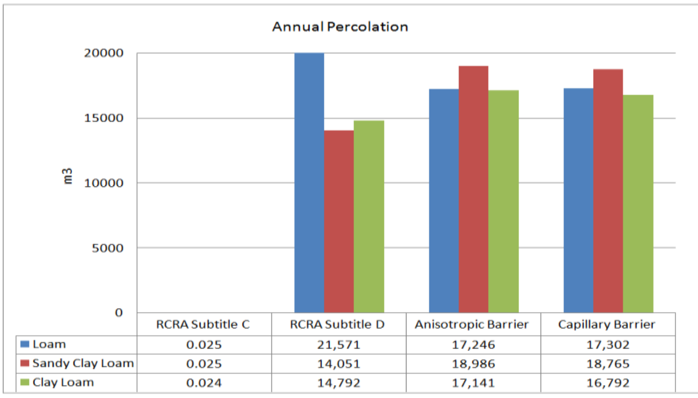

Fig. 10 Annual percolation for different topsoil types

Annual percolation rates for anisotropic and capillary barrier covers increased by 9.6% and 8.5% respectively when sandy clay loam was used whereas they decreased by 0.6% and 2.9% respectively when clay loam was used. Percolation rates for the RCRA Subtitle cover were still less than 0.1 m^3 irrespective of the topsoil type. These results seem to suggest that the type of topsoil has a marginal effect on the annual percolation rates.

4. Discussion of Results

4.1 Suitability of RCRA Cover Type Design Options

The RCRA Subtitle C design option is a prescriptive cover that is specified for hazardous waste disposal sites in the United States [14]. Construction costs for this option can be relatively expensive in comparison to the other design options [19]. The Subtitle D cover could cost as much as three times more expensive than the Subtitle C cover. The simulation results show that the annual percolation rate is less than 0.001mm/yr for the loam, sandy clay loam and clay loam topsoils. Additionally it produces comparatively higher annual evapotranspiration and lower annual runoff rates. These results seem to indicate that this option would perform very well under the site specific climatic conditions in the Western, Central and Greater Accra regions of Ghana. The HELP Model generally tends to underestimate percolation through cover profiles that contain a geomembrane within them [17]. However, a comparison of field measurements and computer simulation results by [17] seem to indicate that the HELP Model is an excellent tool for the evaluation of the RCRA Subtitle C covers. The RCRA Subtitle C cover can thus be said to be a suitable for deployment in the coastal regions of Ghana due its minimal flux rate.

The RCRA Subtitle D cover could be considered as the worst performing design option under the climatic conditions in the geographical zone under consideration. It has very high percolation rates which are in excess of 200 mm/yr for the loam, sandy clay loam and clay loam. Additionally it produces lower annual evapotranspiration and higher annual runoff rates compared to the other design options. Even though [17] found out that the HELP Model grossly overestimated percolation through covers without a geomembrane such as the Subtitle D cover, the flux rates obtained could still be considered as very high even if a safety factor of 10 is used. Consequently, using this particular landfill cover design in unlined waste disposal sites located in the Western, Central and Greater Accra regions of Ghana would most likely result in the contamination of groundwater resources especially in the areas which has shallow groundwater levels. There have been a number of documented cases of groundwater contamination in the USA from leaking landfills [20].

4.2 Suitability of Evapotranspirative Cover Type Design Options

An important advantage of evapotranspirative covers is that they are less expensive to construct and maintain than their prescriptive counterparts i.e. RCRA-type covers. The use of indigenous materials which is usually obtained from a nearby borrow site reduces construction costs. The anisotropic barrier cover limits the downward migration of water, while encouraging the lateral movement of water through drainage layers [15-17]. The capillary barrier cover utilizes the differences in pore-size distributions and the corresponding differences in capillary forces, under unsaturated conditions, to retain water in the upper soil layer [15-17]. The anisotropic barrier and capillary barrier covers performed poorly in comparison to the RCRA Subtitle C cover but marginally better than the RCRA Subtitle D cover. In principle, these two evapotranspirative covers would therefore not be suitable for use in the coastal regions.

However, the use of the HELP Model in predicting the performance of evapotranspirative cover systems have been questioned by many researchers due to the fact that the vertical drainage routine does not permit capillary rise of water from below the evaporative zone depth [16]. Model validation studies have suggested that the HELP Model overestimates percolation from alternative evapotranspirative cover in semi-arid and arid climates [21-22]. A comparison of simulation results with field observations by [23] found that errors in the mean annual estimates for evapotranspiration and percolation were 20% and 15% respectively for the HELP Model compared to for the EPIC model which was 7% and 5% respectively. It would therefore not be possible to provide definitive recommendation on the suitability of any of the evapotranspirative cover design options i.e. anisotropic barrier or capillary barrier for waste disposal sites in the Western, Central and Greater Accra regions of Ghana.

5. Conclusion and Recommendation

This paper has presented a comprehensive assessment of different USEPA landfill cover design specifications for the waste disposal sites located in the Western, Central and Greater Accra regions of Ghana. The four landfill cover design options which were modelled with the HELP computer program included two conventional RCRA-type covers and two evapotranspirative landfill covers. The RCRA Subtitle C cover which yielded flux rates of less than 0.001 mm/yr was found to be suitable for the study zones. However, the RCRA Subtitle D cover was determined to be unsuitable for use at landfill sites in the three coastal regions due to the production of very large flux rates in excess of 200 mm/yr. The results for the anisotropic barrier and capillary barrier covers were inconclusive since it was observed that the HELP model was not able to effectively simulate the capillary rise of water from below the evaporative zone which resulted in the overestimation of the percolation rates. The simulations in this study were conservative, as the period of simulation was limited to one calendar year. Additionally, no account was made for different topsoil vegetative conditions and evaporative zone depths. Recommendations for further study include a longer simulation period as well the study of the combined effects of different topsoil vegetative conditions and evaporative zone depths on the landfill water balance. The use of other water balance models such as EPIC [24], HYDRUS-2D [25] and UNSAT-H [26] for the evaluation of the evapotranspirative cover design options should also be considered.

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