Water Balance Models and Programmes
- Comparisons and Calculation Results -

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ABSTRACT: Numerical simulations of the water balance are important tools to design or to examine cover lining systems of landfills and mine dumps. Therefore, a vast number of models were developed world-wide. The paper represents an overview of common models and a detailed comparison of two typical practical-oriented water balance models (HELP 3.50D, BOWAHALD-2D). Furthermore, it discusses the technical comparison of the two models (programmes) and their results of numerical simulations at two locations in Germany of different climatic conditions.

1 INTRODUCTION

With every landfill, the engineers have to decide for the most qualified, ideal cover lining system. Hereby, the main targets are to reduce the leakage through the capping into the waste body (and indirectly the pollutant emission of the total landfill) and to design an appropriate system with respect to the location specific conditions. The leakage is part of the complex water processes which occur in the cover lining system. The processes depend especially on the climate (precipitation, temperature) and on the cover lining system itself (e.g. vegetation, soils used). A good aid to examine these processes and to compare different cover lining systems is the use of water balance models (programmes). In addition, these programmes support the optimization, the comparison of the hydrological efficiency of different cover lining components (e.g. restoration and drainage layer) and the specific risk estimation.

The authors show some aspects of water balance models and programmes, extend the explanations by means of two models (HELP 3.50D, Schroeder et al., 2001, BOWAHALD-2D, Dunger, 1997) and represent simulation results of the programmes at two different locations (dry, wet) in Thuringia, Germany. Their climatic values reflect the range of typical conditions in Central-Europe.

2 WATER BALANCE MODELS

2.1 Model Overview

Simulation models and programmes are tools and a calculation assistance to process complex and complicated systems and procedures. The models (programmes) can normally be distinguished by two categories, theoretical-oriented and practical-oriented models (Zeh, 2001).

The theoretical-oriented models are used to verify procedures, hypotheses and forecasts. The modeling is based on complex (exact) physical equations and dependencies. The conversion is normally carried out by numerical approaches of the finite element or finite difference method (FEM, FDM). Consequently, the handling of the programmes is complicated, i.e. one needs high computing power, and the simulation's duration is relatively long.

Practical-oriented models are used to simulate technical sceneries and various concepts. They contain relatively simple arithmetic approaches. Therefore, they are user-friendly and fast.

The water balance depends on such complex procedures. Therefore, a vast number of water balance models and programmes was widely developed. Table 1 represents a short overview of common programmes. The FDM or FEM based programmes can be completed by SWIM, SWATRE, SWMS-2D etc (c.f. Berger, 1998). A further overview is presented by two Web pages: http://www.mines.edu/igwmc/, http://dino.wiz.uni-kassel.de/model_db/models.html. A comparison of the models HELP and UNSATH-H is published by Khire et al. (1997)

However, engineers working in environmental geotechnics need simple and fast programmes for daily use. Thus, the authors discuss particularly the features of the practical-oriented water balance models HELP and BOWAHALD.

Table 1. Model overview.

Model	HELP 3.50D	BOWAHALD-2D	UNSATH-H	HYDRUS-2d
Scope of application	cover lining systems of landfills	cover lining systems of landfills and dumps	capping of slightly radioactive waste	unsaturated soil zone
Dimensions	quasi-2	quasi-2	1	2
Compartiments / Max. number	layers 20 (67 intra)	layers 10 (per 20)	continuous / 5 (250 nodes)	continuous / 5 (per 300 nodes)
Simulation period / Steps	1 - 100 years / day	1 - x years / day	1 - 366 days / days (h)	unlimited /variable
Basic approach (time / space)	-	-	FDM / FDM	FEM / FDM
Specific processes	-	-	thermal flow	convection
Computing time	low	low	medium	medium - high
Handling	simple	simple	circumstantial	circumstantial

2.2 HELP 3.50D and BOWAHALD-2D

The very common model HELP was developed originally in the USA (Schroeder et al., 1994). During the last years, it was refined into different versions which differ in language (English, German, Spanish) and in the state of development (Berger, 1998, 2000a, 2000b, Schroeder et al., 2001). It deals with the water balance of landfills, especially on cover lining systems. Figure 1 shows a scheme of the water balance computation by HELP (Khire et al., 1997). Details are represented by the comparison of both programmes (the German version: HELP 3.50D) in Table 2.

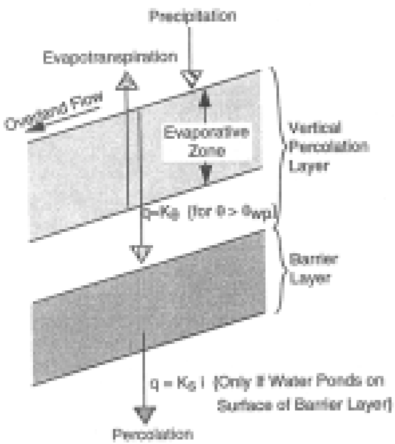

Figure 1. Schematic representation of water balance computing by HELP (Khire et al., 1997)

Like HELP the model BOWAHALD-2D was also developed to simulate the water balance at cover lining systems and covers of mine dumps. The programme and user instruction is written in German. The relevant parameters and arithmetic approaches of the climate (e.g. evapotranspiration, interception) in the model are attuned to the moderate-warm rain-climate of Central-Europe.

Table 2 (c.f. Zeh, 2001, Berger, 2000b) represents the comparison of both programmes. Differences and similarities are listed detailed. However, both are alike as regards the general structure.

The handling of the programmes has pros and cons: HELP offers a flexible input mask, but needs a considerable number of single input data files (climate). The output is clear, but the daily results are interrupted by annual average results. Thus, the formatting is time-consuming. BOWAHALD has a relatively inflexible input mask. The user has to follow the single masks (soils, structures, etc.) up to the end. The input file of climate data contain all details. The output data file is very clear without any interruption (easy formatting). Moreover, the user can select the type of output data file (e.g. lateral / vertical flows of each layer, water content in each layer).

All in all, BOWAHALD offers more variable input options. E.g. the vegetation can be varied from grass, bushes to trees. The simulations are not only carried out with daily values but also with monthly and annual values. Furthermore, the daily meteoro-

Table 2a. Comparison of the models BOWAHALD-2D and HELP 3.50D - *Structure*.

Details	HELP	BOWAHALD
Developer	Schroeder et al. Berger	Dunger
Availability	free	free
Costs	~ 110 €	~ 130 €
Operating system	DOS	DOS
Model specification	determinist, time descrete, 2D layer-oriented	determinist, time descrete, 2D layer-oriented

Table 2b. Comparison of the models BOWAHALD-2D and HELP 3.50D - A*rithmetic approaches.*

Details	HELP	BOWAHALD
Precipitation	data, generator	data, generator
Melting of snow	daily grade process	daily grade process
Interception	storage model (bio mass)	storage model (grade, vegetation species)
Surface runoff	SCS curve-number method	SCS curve-number method
Evaporation	simplified Penman/ Richie	Penman, Haude, Turc-Ivanov
Soil water movements	depends on layer type: vertical unsaturated flow, lateral / vertical saturated flow	one layer type: moisture front (plug form), capillary rise, lateral internal flow

Table 2c. Comparison of the models BOWAHALD-2D and HELP 3.50D - *Input*.

Details	HELP	BOWAHALD
Input mask	7 modules	2 modules
Location	level, latitude start/end vegetation leaf area index evaporative depth	level, latitude, exposition, vegetation coverage/ species, evaporative depth, root depth/density
Landfill profiles	4 types, restictive sequence	1 type free sequence
Soil data	hydr. conductivity pore volume, field capacity, welting point	hydr. conductivity pore volume, field capacity, welting point, capillary height
Meteorological data	precipitation, temperature, global radiation (daily), humidity (quarterly), wind velocity (year)	precipitation, temperature, global radiation (or sunshine duration) humidity, wind velocity (all daily, optional month, year)

Table 2d. Comparison of the models BOWAHALD-2D and HELP 3.50D - *Output*.

Details	HELP	BOWAHALD
Result data set	precipitation, evapotranspiration (real) surface flow, lateral flow (drainage layer), leakage, change in water storage – both models	
	water content (evapotrans. zone), head on sealing top	evapotrans. (pot.), interception, water content (layer), lateral/vertical flow (each layer)
	dissolution: daily, month, year, total	dissolution: daily, month, year, total

logical input data can be partially reduced.

In contrast, HELP has a complex option to simulate flexible membrane liners as a sealing component. Moreover, HELP is often validated (e.g. Berger, 1998, 2000b, Khire, 1997) and has an international dissemination.

At this place, the authors want to point out that the availability and the precision of the input parameters (soil, climatic) is often an underestimated problem. Furthermore in practice, soils used in-situ do not often correspond exactly with the soils used in the simulations. Thus, every simulation is only as good as the soundness of the input parameters.

3 NUMERICAL CALCULATIONS

The numerical calculations ought to yield statements about the two programmes and the behaviour of different cover lining systems at different locations.

3.1 Boundary Conditions

The territory of Germany belongs to the moderate-warm rain-climate of the average latitudes (Müller-Westermeier et al., 1999). Humid air-bulks from the

Table 3. Range of climatic specific values, annual average (Zeh et al., 2001).

Location	Temperature [°C]	Precipitation [mm]
Germany total	8,8	797
Thuringia min.	4,0 - 4,5	450
Thuringia max.	9,5 - 10,0	1400 - 1450

Table 4. Climatic parameters, annual average.

Parameter	year	Erfurt	Sonneberg
Precipitation	1951 – 1980	528,0	917,0
[mm]	1986 – 2000	530,5	1029,0
Temperature	1951 – 1980	7,9	6,2
[°C]	1986 – 2000	8,6	6,9

Atlantic are conveyed by preponderant western winds which cause rainfall throughout year. Usually, the influence of the ocean ensures relative mild winters and summers that are not exceedingly hot.

The climate of Germany is strongly determined by the topographic configurations of the highlands andpaled platter landscapes. That means, the lowlands usually have a warm, dry and sunny climate and the higher sites a chilly, rich in precipitation and have a cloudy climate during the year. The eastern parts of Germany including Thuringia are relatively dry (Thuringian average annual precipitation: 693 mm/a) and slightly cooler because of the greater distance from the Atlantic.

Table 3 shows the climatic specific values in Germany and the minimum and maximum range of climatic values in Thuringia.. The Thurinigan climate is especially influenced by the Thüringer Wald (‘Thuringian Forest’, Sonneberg) and the Thüringer Becken (‘Basin of Thuringia’, Erfurt). The latter is relatively dry and warm, whereas the first one is wet and cooler. An overview is shown by Figure 2a,b.

The simulations were carried out with climatic parameters during a period of 15 years (1986 - 2000) at Erfurt and Sonneberg. Table 4 represents the annual average of the precipitation and the temperature. The rise of the temperature at both locations and of the precipitation at Sonneberg compared with the average of 1951 to 1980 is very interesting. Hence, the authors recommend the use of latest or better prognosticated climatic parameters for future simulations.

3.2 Different Cover Lining Systems

The examined systems are generally based on the German standards of cover lining systems (c.f. Zeh et al., 2001). The authors used various covers and cover lining systems. The covers consisted of qualified restoration layers (RL) with different thickness. The cover lining systems consist of the covers combined with a mineral drainage layer (DL) and a mineral sealing (MS). Table 5 represents the examined

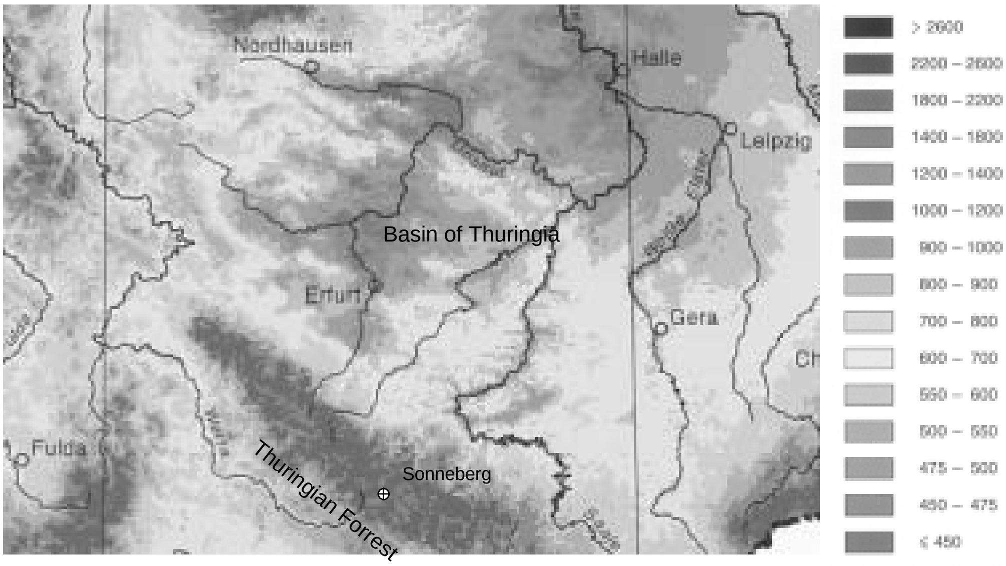

Figure 2a. Precipitation [mm], range of the annual average in Thuringia (Zeh et al., 2001).

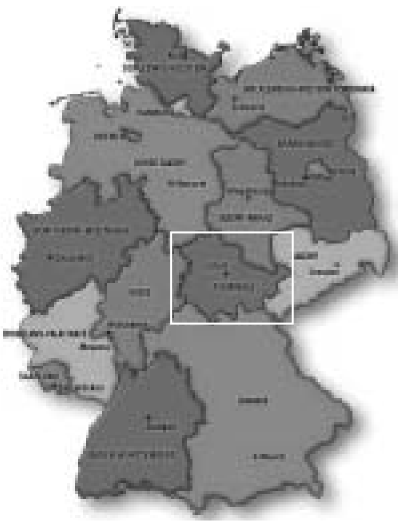

Figure 2b. Map of Germany

Table 5. The examined cover lining systems, thickness in [m].

Denomination	NA	MA	NAD/MAD
Thickness RL	0,3/0,7	0,3/0,9/0,3	see left
Soil	A/B	A/B/C	see left
Thickness DL	-	-	0,3
Thickness MS	-	-	0,5
evaporative depth	1,0	1,5	see left
max. root density at depth (BOWA.)	0,35	0,4	see left

Table 6. Soil parameters of the cover lining systems.

Soils	Pore vol. [%]	wilting point [%]	field capacity [%]	hydraulic conductivity [m/s]
A	48	13,5	39	4,05 E-6
B	39,5	11,0	32	1,62 E-6
C	34	11,0	30	5,79 E-6
DL	41,7	1,8	11,5	1,00 E-4
MS	42,7	36,7	42	1,00 E-9

Table 7. Simulation results (1986 - 2000), Erfurt [mm].

Results	HELP				BOWAHALD			
Parameters*	ET	RO	D	L	ET	RO	D	L
NA	416	2,2	-	115	481	0,7	-	48,8
MA	428	1,8	-	104	499	0,8	-	30,2
NAD	416	2,2	94	20,9	481	0,7	47,7	1,1
MAD	428	1,8	83	20,7	499	0,8	30,2	0,7

* Evpotranspiration EP, runoff RO, drainage D, leakage L

Table 8. Simulation results (1986 - 2000), Sonneberg [mm].

Results	HELP				BOWAHALD			
Parameters*	ET	RO	D	L	ET	RO	D	L
NA	397	37,7	-	601	488	2,8	-	539
MA	395	33,2	-	610	507	2,8	-	520
NAD	397	37,7	569	36,1	488	2,8	533	5,8
MAD	395	33,2	574	36,9	507	2,8	514	5,5

* Evpotranspiration EP, runoff RO, drainage D, leakage L

systems, Table 6 the corresponding soil parameters (field capacity: nFC = 1,8 - 4,2).

The main interest is to examine whether simple covers are qualified enough to reduce the leakage at the dry location (Erfurt). Therefore, a qualified restoration layer can possibly meet this goal.

The further parameters ought to be similar. Hereby, the slope and the slope length is 5 % (south direction) and 50 m to all simulations. The vegetation consists of normal grass.

3.3 Simulation Results

The results of the calculations are represented by the Tables 7 and 8. The first table contains the results of the different cover lining systems at Erfurt, the second one at Sonneberg. The systems used and the climatic parameters were shown in chapter 3.1 / 3.2. The results of a programme comparison show that they are relatively similar. The evapotranspiration's simulation at BOWAHALD is greater than at HELP. Vice cersa, BOWAHALD yields smaller values in relation to leakage, runoff and drainage.

Regarding the higher evapotranspiration at BOWAHALD, the main reason may be the more adapted climate (to European circumstances) and vegetation model. Therefore, less leachate permeates the restoration layers. The difference in the runoff has to be explained by the different frost and snow / soil melting module.

The higher leakage at HELP can be additionally explained by a relatively constant and stable head at the top of the sealing (c.f. Figure 4 below).

For a better representation, the figures are reduced to two years each of the simulation period.

Figure 3 shows a comparison of the leakage, system NA, Sonneberg. BOWAHALD yields more peaks immediately depending on the intense

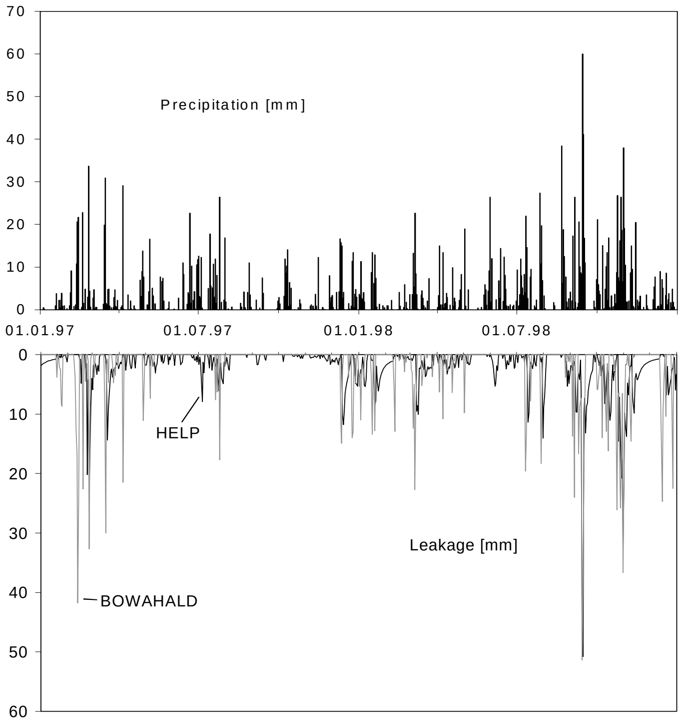

Figure 3. Precipitation [mm] and leakage [mm] of HELP and BOWAHALD, NA, Sonneberg, 1997 / 1998.

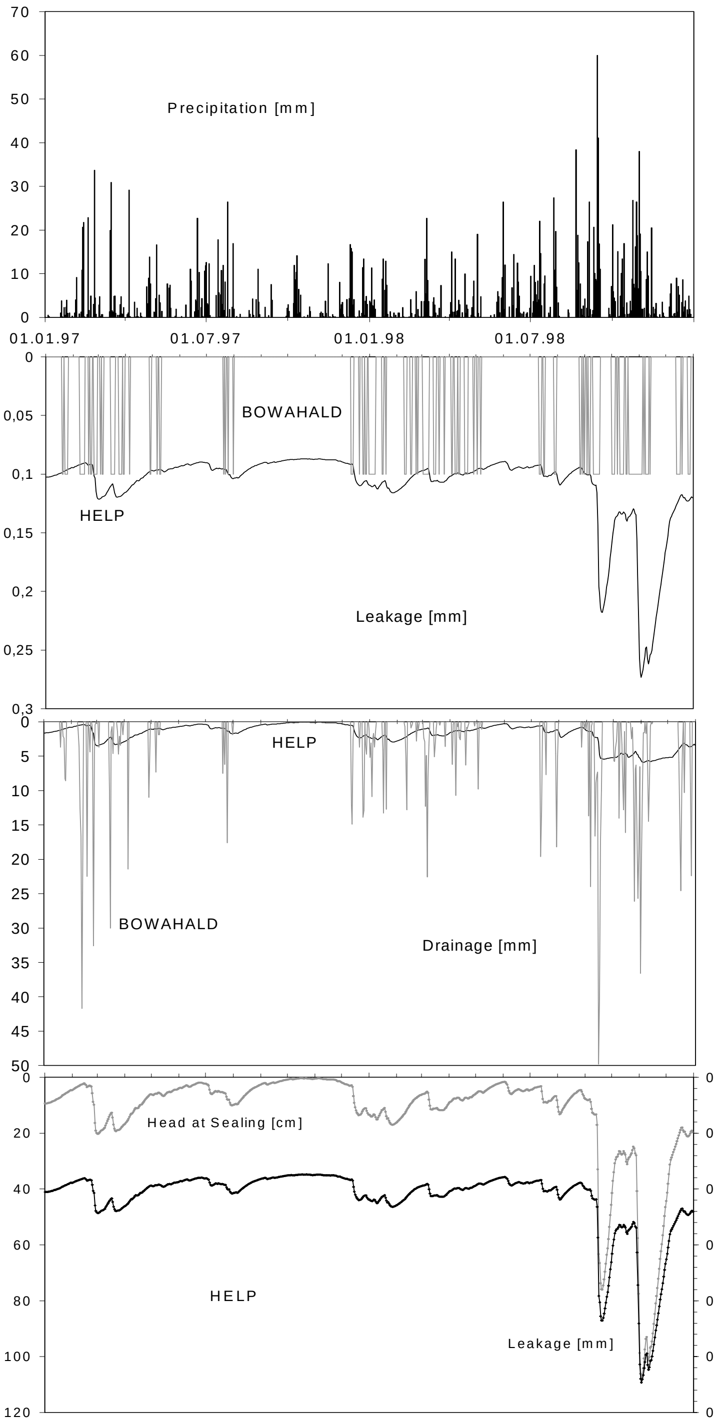

Figure 4. Precipitation [mm], leakage [mm], drainage [mm] and the combination of head [cm] and leakage [m] of HELP and BOWAHALD, NAD, Sonneberg, 1997 / 1998.

precipitation each. HELP has a more constant leakage.

Figure 4 shows different graphics of further results; but with system NAD, Sonneberg. HELP yields a stable leakage during the presented period, independent of the different precipitation (intensity). This is coherent to the relatively stable drainage flow and the stable head at the top of the sealing. The drainage layer seems to be undersized. However, BOWAHALD represents a drainage flow and leakage which are directly interlinked by the precipitation. The small constant leakage rate can be explained by the so-called piston flow at saturated soils.

Considered on the whole, BOWAHALD shows most consistent results in the simulations. In particular, the graphical progressions agree with the results of different test fields, e.g. drainage flow depending on the precipitation (c.f. Figure 4). Yet, the leakage seems to be too small. Therefore, HELP yields more conclusive results.

The simulations reveal that a drainage and a sealing above all is necessary at a wet location like Sonneberg. Furthermore, one can abstain potentially (less pollutant emission, no gas migration) from a sealing at a relatively dry location like Erfurt. Therefore, the restoration layer and the vegetation has to be well graded. This result is certified by further examinations (Zeh & Witt, 2001) which are not represented detailed here for lack of space.

A further important examination point of water balance's simulation is not shown here. A big problem by using mineral sealing components (mineral sealing, geosynthetic clay liners) is the desiccation (temperature gradient, plant roots) and as a consequence thereof the lost of the sealing effect (Zeh et al., 2001). Desiccation occurs when the welting point of cohesive soils falls below. Cracks develop and they increase intense the hydraulic permeability. Relative dry locations like Erfurt are typically endangered by desiccation.

Both programmes can type out the daily changes of water content; BOAWAHALD in each layer, HELP only in the evapotranspiration zone. Thus, the restoration layers and especially the mineral sealings can be controlled by comparing the daily water content with the specific welting point in each layer.

The simulations results for Erfurt yield no direct hazard for the mineral sealing by using grass as vegetation.

4 CONCLUSION

After a short overview of common water balance models, a detailed technical comparison shows the models (programmes) features of HELP and BOWAHALD. Combined with the simulation results of the test calculations, they prove to be useful tools to work on different questions about cover lining systems of landfills and mine dumps.

All in all, BOWAHALD is exposed at its features as an adequate alternative to HELP at least. Especially the great variation options of BOWAHALD's input and output parameters and the very consistent calculation results have to be emphasised. The missing validation of BOWAHALD is an disadvantage yet. In addition, one has to be noticed that the programmes simplify or neglect important physical equations. Effects like desiccation, vegetation development / growth, alteration (material) or water transport of unsaturated soils are not integrated in both programmes today. Therefore, simulations results always have to be regarded critically. A decision for a special cover lining system should not be made only by using calculation programmes.

As consequence, further developments and examinations are desirable. The programmes' applicability in humid and arid climate zones has to be examined. Besides, the generation and use of forecast climatic values has to take into consideration. Therewith, the conditions of the cover lining system in 100 or 200 years will be better able to assess. Further steps are the integration of the above mentioned effects in both programmes and further validation studies.

At last, one has to query if it has sense to view only the upper part of a landfill; the cover lining system. For a complete understanding of the processes, the target is to develop a model which can simulate the water movements in the total landfill.

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