

ON THE NEW HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL VERSION 4 FOR THE WATER BALANCE SIMULATION OF LANDFILL LINER SYSTEMS

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Article Info:

Received:
15 December 2021
Revised:
20 February 2022
Accepted:
21 February 2022
Available online:
31 March 2022

Keywords:

Landfill liner system
HELP model
Water balance
Simulation

ABSTRACT

23 years after the last original US HELP version 3.07, in 2020 the US Environmental Protection Agency released a new version, called HELP 4. With this Excel-based version, the original HELP model has arrived in the modern Windows world. However, the model itself remains HELP 3.07. The paper deals with experiences of the author using HELP 4 and compares simulation results of four HELP versions (HELP 4.0.1, DOS HELP 3.07, and HELP 3.07 and HELP 3.95 D included in HELP 3.95 D) for two applications. First, the RCRA example of the original HELP version 3 in (US) customary units for 30 years of synthetically generated weather data for Nashville, TN. Second, the water balance test field F1 on the landfill Georgswerder in Hamburg, Germany, for 1988 to 1995 in metric units. The user interface is easy to use; however, it is more restrictive than necessary and not usable outside the USA without having weather data files of HELP 3.07 for import. The average annual totals of all tested HELP 3.07 model versions are close together. Differences occur probably due to computer numeric and because HELP 4.0.1 neglects the last day of leap years. The computing times of HELP 4.0.1 are for a factor of about 50 larger than for HELP 3.07 included in HELP 3.95 D. Despite reasonable criticism that may be made, the HELP model is a valuable tool for those who are aware of its limitations and merits further work on both the model and the Windows/Excel interface to match the current state of the art.

1. INTRODUCTION

Water balance calculations are an important tool for designing liner and top cover systems, particularly for developing sustainable landfilling (Grossule & Stegmann, 2020). The Hydrologic Evaluation of Landfill Performance (HELP) model, originally developed for the Environmental Protection Agency of the USA, presumably is the mostly applied model in the world for this purpose. The HELP model is a quasi-two-dimensional hydrologic model of water movement across, into, through and out of landfills and may be applied to open, partially closed, and fully closed sites. It calculates the water balance based upon meteorological, vegetation, soil and design data for periods of one up to one hundred calendar years.

The history of the HELP model comprises almost 40 years (Figure 1). Version 1 was released in 1984 with an extensive documentation (Schroeder et al., 1984a, 1984b) and version 2 in 1988, however, without a detailed documentation. HELP version 3, released in 1994 with the last update in late 1997 (HELP 3.07), was a major enhancement including an extensive documentation (Schroeder

et al. 1994a, 1994b), the alternative use of internationally common metric units besides English units, and a user interface. Figure 2 depicts a schematic of a complete landfill profile illustrating typical layer sequences and features as well as the main hydrologic processes modelled by HELP 3. The versions 1 to 3 run in the operating system Microsoft DOS, which is completely out of date at least since the support end of Windows XP in April 2014.

Based upon HELP 3.07, in the late 1990's Waterloo Hydrogeologic Inc., Ontario, Canada, developed Visual HELP, a graphical user interface for Microsoft Windows 98/2000/XP including a database for the weather generator WGEN (Richardson & Wright, 1984), which is included in the HELP model. This database contains parameters for the weather generation for more than 2000 locations all over the world. Though Visual HELP is still available, the company no longer supports it.

The author performed an extensive validation study for HELP 3.07 (Berger, 1998, 2000; see also Berger, 2015) using especially measured water balance data of the test fields (large lysimeters) on the landfill Georgswerder in Hamburg, Germany (Melchior, 1993, Melchior et al. 2010). Further-



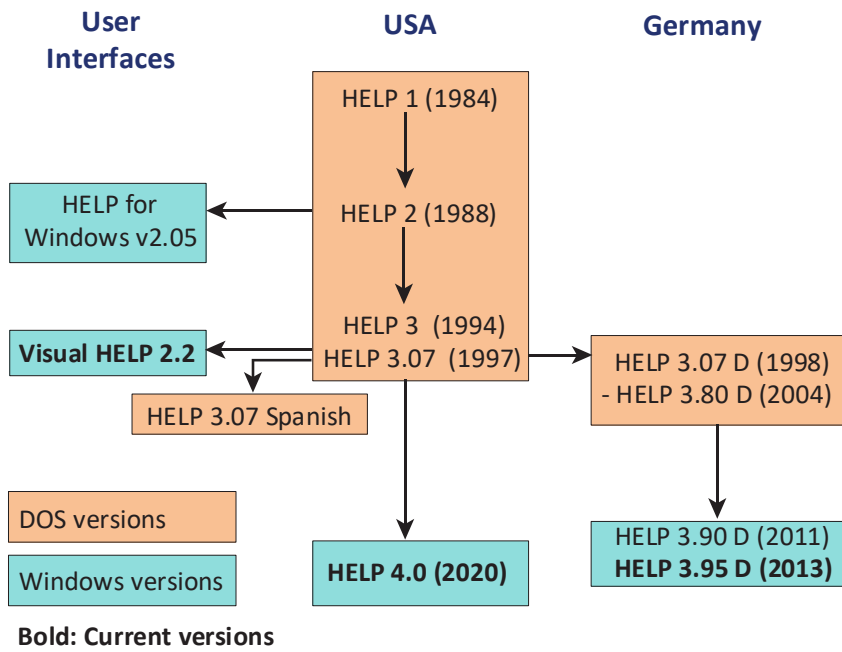


FIGURE 1: History and versions of the HELP model.

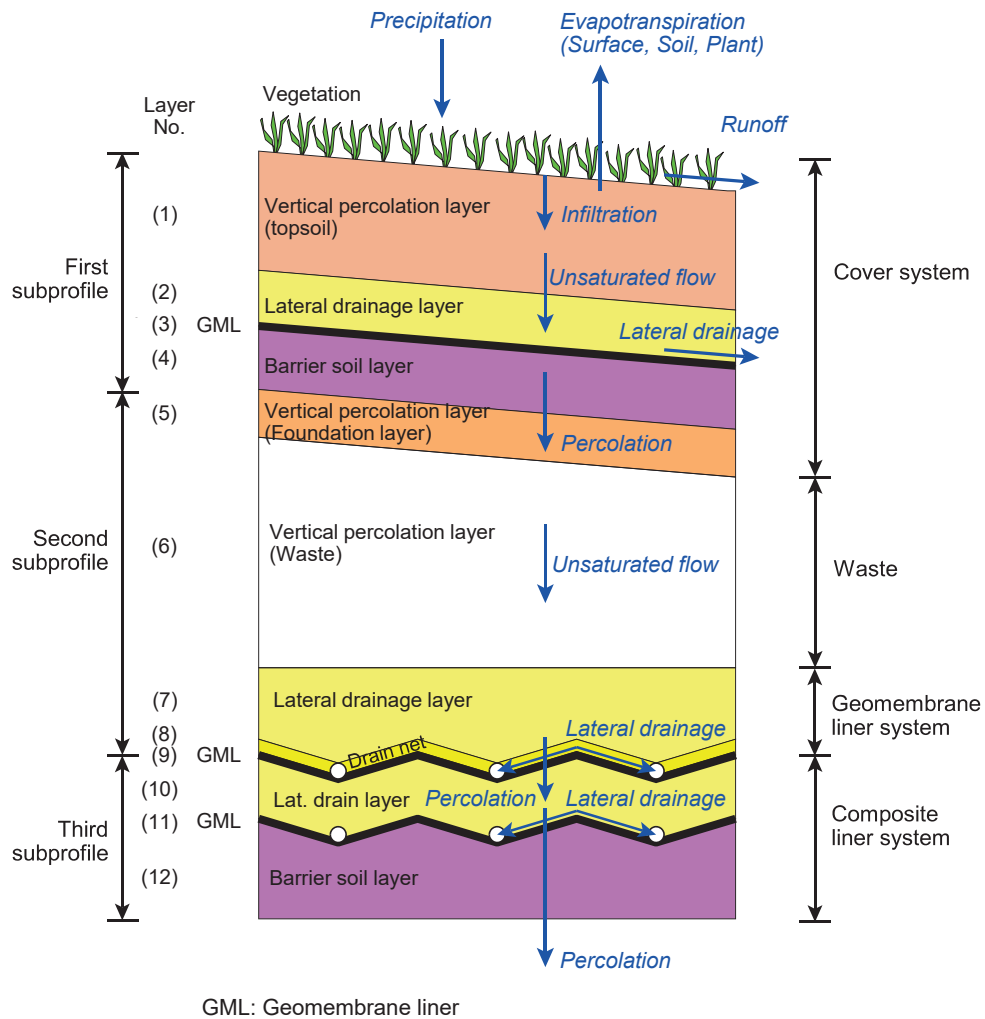


FIGURE 2: Schematic of a typical landfill profile including the main hydrologic processes modeled by the HELP model (modified and supplemented from Schroeder et al. 1994a, p. 7; RCRA example).

more, the author developed several enhancements, at the beginning for the Microsoft DOS operating system (HELP 3.07 D to 3.80 D). After Microsoft had announced the support end of 16-bit DOS programs in Windows, the author developed a user interface for modern Microsoft Windows versions. The latest is HELP 3.95 D from 2013, which runs in Windows (10/8/7) (Berger & Schroeder, 2013).

In late 2020, the US EPA released a new HELP version 4, which is Microsoft Excel-based and runs in modern Windows, too (Tolaymat & Krause, 2020).

The paper deals with the new HELP version 4 and its enhancements beyond the former original version HELP 3.07 and compares simulation results obtained with HELP 3.07, HELP 3.95 D and HELP 4.

2. MATERIAL AND METHODS

2.1 Brief characterization of HELP Version 4

HELP version 4.0 (Tolaymat & Krause 2020) was developed by the Center for Environmental Solutions and Emergency Management of the US EPA's Office of Research and Development. HELP 4.0 uses a Microsoft Excel workbook with embedded macros to support the user interface. It has been tested for use in Excel 2007 (Windows operating system) and higher and works on 64-bit processors.

Apparently, HELP version 4 includes the same model as the latest HELP version 3 (HELP 3.07, November 1997).

HELP 4 offers several options for data input (Tolaymat & Krause 2020), obviously developed for use in the United States. First, input files of HELP 3.07 can be imported. Second, data input of daily weather data has been updated. Precipitation and air temperature data from the National Oceanic and Atmospheric Administration (NOAA) and solar radiation data of the National Renewable Energy Laboratory (NREL) can be imported. Furthermore, synthetic generation of daily weather data based upon the weather generator WGEN (Richardson & Wright 1984) is included and updated. HELP 3 included a database with parameters for synthetic weather generation for more than 100 locations throughout the USA with differing numbers of locations for precipitation, air temperature and solar radiation. In contrast to HELP 3, HELP 4 includes a database with calculated weather generation parameters for more than 13,000 points located on a 0.25 x 0.25 degree grid across the continental USA (Tolaymat & Krause 2020, p. 14). Input weather data can be edited in the user's interface, which seems to be the only way for creating weather data of locations outside the USA (however, see section 3.1). Data for calculating evapotranspiration (wind speed, relative humidity, and vegetation data including evaporative zone depth), soil and design data including data for calculating the runoff curve number, and general information can also be input manually. The only parameter, which to the author's knowledge is new in HELP 4, is the longitude, which is used together with the latitude for synthetic weather generation. Consequently, longitude is obviously restricted to values for the continental USA.

2.2 Execution of simulations

The following HELP versions were applied in this study.

- (1) HELP 4.0.1: Excel version, downloaded from the EPA website on 2020-12-09 (Tolaymat & Krause, 2020)
- (2) HELP 3.07: DOS version from 1 November 1997 (Schroeder et al. 1994a, 1994b)
- (3) HELP 3.95 D (version no. 3.95.1.7): Windows version including the model versions
- (3a) HELP 3.07 (recompiled original version with a very few software-technical adjustments such as longer file names) and
- (3b) HELP 3.95 D (Berger & Schroeder, 2013).

All model applications except for the DOS HELP 3.07 were run on a PC with an Intel Core i5-6500 CPU (3.2 GHz) and a usual hard disk drive in Windows 10 (64-bit) with German and English (USA) localization. HELP 4.0.1 was run in Microsoft Excel 2016 with the same localization as Windows. DOS HELP 3.07 was run approximately 10 years ago on a PC with Windows XP, which allowed DOS-programs to be executed without additional utilities such as DOS-boxes.

2.3 Simulated systems

Two applications were run with the models:

- (1) The RCRA (Resource Conservation Recovery Act) example included in HELP 3 with 30 years of synthetically generated weather data for Nashville, TN in (US) customary units, and
- (2) A simplified operational validation run of the water balance test field F1, which was constructed within the cover system of the landfill Georgswerder in Hamburg, Germany, for the 8 years from 1988 to 1995 (Melchior 1993, Melchior et al. 2010) in metric units. The validation run was simplified by using constant layer and vegetation properties, which actually were changing especially in the first two years after construction.

The RCRA example refers to a fully closed site. The layer sequence is depicted in Figure 2, comprising a cover with a composite liner, the waste body and a bottom liner system, which is designed as double liner system. Table 1 summarizes the main design properties used in the simulations.

The second application is the water balance test field F1 on the landfill Georgswerder in Hamburg, Germany (Melchior 1993, Melchior et al. 2010; see also Berger 1998, 2015). The landfill Georgswerder was operated from 1948 to 1979 for the disposal of municipal waste including bulky waste and construction waste. However, some hazardous waste was disposed, too. After detecting dioxin in the landfill leakage in 1983 the City of Hamburg decided to construct a cover system on the landfill. Due to lacking knowledge on efficiency and long-term performance of cover systems, a research project was initiated at the Institute of Soil Science of Universität Hamburg. For this project, six test fields (large lysimeters) with different cover systems were constructed within the cover system of the landfill in 1987 with the same materials and the same technology as the cover of the landfill to obtain representative measurement results. The test fields were operated extensively in the research phase from 1988 to 1995 and

TABLE 1: Main design properties of the RCRA example.

No	Layer and Layer type ¹	Thickness (inch)	Soil texture and HELP no.	Further main properties
1	Top soil, VPL	30	Silt loam, 9	
2	Mineral lateral drainage layer, LDL	12	Coarse sand, 1	Maximum drainage length: 200 ft. Drain slope: 4%
3	Geomembrane liner, GML	0.04	Low density polyethylene, 36	Placement quality: poor 1 pinhole/acre, 10 installation defects/acre
4	Mineral barrier soil layer, BSL	36	Silty clay (moderately compacted), 28	
5	Waste, VPL	300	Municipal waste, 18	
6	Mineral lateral drainage layer, LDL	12	Loamy fine sand, 5	Maximum drainage length: 100 ft. Drain slope: 3%
7	Drain net, LDL	0.2	Drainage net, 20	
8	Geomembrane liner, GML	0.06	High density polyethylene, 35	Placement quality: good 1 pinhole/acre, 10 installation defects/acre
9	Mineral lateral drainage layer, LDL	12	Gravel, 21	Maximum drainage length: 100 ft. Drain slope: 3%
10	Geomembrane liner, GML	0.06	High density polyethylene, 35	Placement quality: good 1 pinhole/acre, 10 installation defects/acre
11	Mineral barrier soil layer, BSL	36	Barrier soil, 16	
	Further properties	Value		
	SCS Curve number ² (1)	82.2		
	Evaporative zone depth (inch)	21		
	Vegetation Maximum leaf area index (1)	fair grass 2.0		

¹ Layer types: VPL: vertical percolation layer, LDL: lateral drainage layer, GML: geomembrane liner, BSL: barrier soil layer; ² Curve number of the curve number method of the US Soil Conservation Service (SCS) for calculating the surface runoff

to a lesser extent until 1998. Since 1999, the Environmental Protection Agency of Hamburg operates those test fields with the layer design of the landfill as part of the aftercare program.

Each of the six test fields is 50 m long in slope direction and 10 m wide, three having a slope of 4% (called test fields F1 to F3) and three having a slope of 20%, respectively; all test fields are exposed to the north. Test field F1 has a compacted soil liner, but no geomembrane. The major layer, design and vegetation data used in the simulations are as follows (layers listed from the top to the bottom):

1. Restoration layer (humous top soil), HELP layer type vertical percolation layer (VPL), 25.7 cm thick, constructed of a glacial marl, German soil texture loamy sand;
2. Restoration layer (non-humous top soil), VPL, 49.5 cm thick, glacial marl, loamy sand;
3. Mineral lateral drainage layer, layer type lateral drainage layer (LDL), 21.8 cm thick, constructed of a mixture of coarse sand and fine gravel, maximum drainage length 50 m, drain slope 3.5%
4. Compacted mineral soil liner, layer type barrier soil layer (BSL), 61.5 cm, constructed of a compacted glacial marl, sandy loam;
5. Curve number 55.0
6. Evaporative zone depth 75.2 cm (entire restoration layer)
7. Maximum leaf area index 3.5 (good grass)

3. RESULTS AND DISCUSSION

3.1 Applying the user interface of HELP Vs. 4

Briefly described, the major experiences of the author applying HELP 4 were as follows:

- 1) HELP 4 must be run with an English (or compatible) localization. In a German localization, input files of HELP 3.07 cannot be imported and simulations cannot be executed due to the different decimal separator (English: dot, German: comma).
- 2) Input files of the HELP 3.07 RCRA examples were imported fast and without error message.
- 3) The import of HELP 3.07 weather data files (daily values of precipitation, air temperature and solar radiation) is more restrictive than necessary. The number (1 to 37) at the end of each input line with ten daily values is required though these entries are ignored in the source code of the model HELP 3.07, subroutine READCD, and actually are unnecessary.
- 4) A least the import of HELP 3.07 solar radiation data (files .D13) in metric units (MJ/m²) requires a blank character between two daily values and thus is more restrictive than the import routine of HELP 3.07 (subroutine READCD), which allows a numerical character instead of the blank character. (The author assumes that this also holds for precipitation and air temperature.) This is important insofar that the metric unit MJ/m² is for a factor of 23.89 larger than the US customary unit Langley (ly). Thus, the values are for this factor smaller

and instead of one decimal place, used for values in the unit ly, three instead of two decimal places are more appropriate for values in the unit MJ/m². This means that six instead of five numerical characters (including the decimal point) are required for the unit MJ/m².

- 5) Analogously to item 4) the import of HELP 3.07 evapotranspiration parameters (files .D11) is more restrictive than necessary due to required blank characters that are unnecessary according to the subroutine READIN of HELP 3.07. Furthermore, the error message of HELP 4 refers to an invalid .D10 (instead of .D11) file structure.
- 6) The import of HELP 3.07 soil and design data (files .D10) is also more restrictive than necessary. During the import of D10-files of the second application (landfill Georgswerder) layer descriptions that were accepted by the model's subroutine READIN led to an incomplete import in the HELP 4 user interface. Just two of four layers were imported; no error message was displayed, but an import confirmation. The incomplete import was caused by the second line of layer descriptions in the imported D10-files if these just contained blank characters.
- 7) When importing HELP 3.07 soil and design data files (.D10), for each vertical percolation layer the HELP 4 user interface asks for its type, i.e. soil layer or waste layer, obviously for internal purposes. The model HELP 3.07 does not require this information.
- 8) Usage of HELP 4.0.1 outside the USA without having HELP 3.07 input files for import is not reasonably possible at the present knowledge of the author based upon the HELP 4.0.1 version he was using. Though evapotranspiration parameters (.D11-files) and soil and design data (.D10-files) can easily be input manually, this is not a reasonable option for daily weather data due to curious restrictions of the editable data and the lacking recalculation of the monthly values. The first two years of precipitation and air temperature data and the first seven years of solar radiation data were locked and could not be edited. It was possible to enter or copy new data at the end of the existing data, but deleting e.g. a year of data somewhere in the middle (after the first locked years) led to the deletion of all subsequent years of data. The reasons for this behavior are unclear to the author. The author currently cannot exclude that the Windows and Excel localization and settings of his PC may play a role. However, he assumes the main reasons are in the Excel program of HELP 4.
- 9) Finally, the user interface of HELP 4 is easy to use.

3.2 Comparison of simulation results for the RCRA example

Average annual totals and computing times of the four HELP model versions for the RCRA example are summarized in Table 2. The average annual totals of the three model versions HELP 3.07 (1, 2, 3a) are not identical, but close together with deviations of usually less than one thousandth. The first assumption for explaining these small differences is computer numeric including maybe the operating system. Model versions (2) and (3a) have almost identical FORTRAN source codes, but were compiled with different compilers, which will have led to slightly dif-

ferent evaluation sequences including variable transformations from double and single precision FORTRAN variables to numerical representations of the numeric coprocessor and vice versa. Model (1) obviously uses Excel calculations and numerical representations of variables. For a second explanation, see section 3.3. Due to differences in the modeling approaches model (3b) should produce different results than models (1), (2) and (3a).

A striking result is the sum of computing and file saving time of the new HELP version 4 that is about 50 times as high as that of the two model versions 3.07 and 3.95 D of HELP 3.95 D. The Excel-based model (1) required 115 seconds for the complete execution compared to approximately 2 seconds of the compiled model (3a) (and 3b) on the same PC. Neglecting the file saving time reduces the execution (computing) time of model (1) for about a quarter. (Model (1) created a PDF and an Excel output file, whereas model (3a) just created a text output file.)

3.3 Comparison of simulation results for the test field F1 on the landfill Georgswerder

Average annual totals and computing times of three HELP model versions for the test field F1 are summarized in Table 3.

In this example the average annual totals calculated by HELP 4.0.1 and HELP 3.07 are close together, too; however, not as close as in the RCRA example in section 3.2. Curiously, the precipitation deviates for 0.15 mm per annum or in total for 1.2 mm in eight years that are missing in HELP 4.0.1. The daily results show that HELP 4.0.1 did not consider leap years, but neglected the last day (day 366) of leap years. The precipitation on 31 December 1988 was 1.2 mm and on 31 December 1992 0 mm. This is contradictory to the user manual (Tolaymat & Krause, 2020, p. 16). Thus, neglecting the last day of leap years should be the main reason for the deviations of model (1) and (3a), and not computer numeric (see section 3.2). In this case, computer numeric includes the special fact (for HELP 4 this is an assumption of the author) that both versions are calculating internally in US customary units and therefore are performing unit conversions from and to metric units in pre- and post-processing, respectively.

Similar to the RCRA example in section 3.2 the computing and total run time of HELP 4 in this example is about a factor 50 higher than for the two model versions of HELP 3.95 D.

An operational validation of the HELP model(s), i.e. the comparison of measured and simulated discharges is valuable and interesting. However, based on average annual totals it does not make sense due to the deterioration of the mineral liner of test field F1, which occurred in two stages. The deterioration of the mineral liner leads to an increasing leakage through the liner and consequently to a decreasing lateral drainage in the lateral drainage layer on the liner. The HELP model does not model the deterioration. Therefore, the simulated and measured average annual totals of the liner leakage and the lateral drainage cannot match. An operational validation of the model HELP 3.95 D based upon cumulative daily values from 1988 to 1995 is described in Berger (2015).

TABLE 2: Average annual totals and computing times of four HELP model versions for the RCRA example, simulated with 30 years of synthetically generated weather data for Nashville, TN, USA.

Model version	1) HELP 4.0.1	2) HELP 3.07	HELP 3.95 D	
			(DOS, Win XP)	3a) HELP 3.07
Quantity / Variable				
Precipitation (inch)	47.49	47.49	47.49	47.49
Runoff (inch)	1.893	1.892	1.892	1.63
Actual evapotranspiration (inch)	31.779	31.781	31.783	29.81
Lateral drainage collected from layer 2 (inch)	13.7121	13.17156	13.71004	15.90518
Percolation through layer 4 (inch)	0.227766	0.22769	0.22764	0.26516
Average head on top of layer 3 (inch)	3.5168	3.533	3.533	4.142
Lateral drainage collected from layer 7 (inch)	0.0987	0.09869	0.09866	0.11936
Percolation through layer 8 (inch)	0.126056	0.12604	0.12601	0.1422
Average head on top of layer 8 (inch)	0.0001	0.000	0.000	0.000
Lateral drainage collected from layer 9 (inch)	0.1261	0.12604	0.12601	0.14219
Percolation through layer 11 (inch)	0.000005	0.00001	0.00001	0.00001
Average head on top of layer 10 (inch)	0.0007	0.0001	0.0001	0.0001
Change in water storage (inch)	-0.1148	-0.115	-0.115	-0.113
Computing time (sec)	88	n.d.	2	2
File saving time (sec)	27	n.d.	Included	Included
Total run time (sec)	115	n.d.	2	2

File saving time of model 1 for creating a PDF and an Excel output file; n.d.: not determined; Included: file saving time is included in computing time. Times determined on a PC with Intel i5-6500 (3.2 GHz) CPU

4. CONCLUSIONS AND OUTLOOK

23 years after the last US HELP model version 3.07 was released, the EPA published the new version HELP 4 in 2020. Already at the time of its release in 1994, the DOS user interface of HELP version 3.0x was not up-to-date. With the new version 4, the user interface of the original HELP model has arrived in the modern Windows world. However, the model itself is still HELP 3.07. Thus, model concept and approaches are almost 30 years old, some approaches are even older.

Despite reasonable criticism (for an overview see Berg-

er 2015), the HELP model is a valuable tool for those users who are aware of its limitations. Therefore, in the author's opinion both the user interface and the model should be enhanced:

1. The restrictions of the user interface described in this paper should be eliminated.
2. An option for importing daily weather data from Excel files should be added to enable convenient usage of the model outside the USA and to enhance the usability within the USA.
3. The model requires and merits a substantial enhance-

TABLE 3: Average annual totals and computing times of three HELP model versions for the test field F1 on the landfill Georgswerder in Hamburg, Germany (years 1988-1995).

Model version	(1) HELP 4.0.1	HELP 3.95 D	
		(3a) HELP 3.07	(3b) HELP 3.95 D
Quantity / Variable			
Precipitation ¹ (mm)	788.66	788.81	788.81
Runoff (mm)	6.046	5.841	1.483
Actual evapotranspiration (mm)	460.12	460.195	459.691
Lateral drainage collected from layer 3 (mm)	317.6173	317.73105	321.66617
Percolation through layer 4 (mm)	6.237859	6.21916	4.7924
Average head on top of layer 4 (mm)	5.826	5.835	5.905
Change in water storage (mm)	-1.359	-1.174	1.18
Computing time (sec)	45	1	1
File saving time (sec)	9	Included	Included
Total run time (sec)	54	1	1

¹ Measured precipitation corrected for systematic measurement errors which were assumed for the standard rain gauge of the USA; File saving time of model (1) for creating a PDF and an Excel output file; Included: file saving time is included in computing time. Times determined on a PC with Intel i5-6500 (3.2 GHz) CPU.

ment and update of the modeling approaches to the current state of knowledge and capability of PCs. Important enhancements are (see also Berger 2015):

- a. The internal segmentation of layers and the evaporative zone should be made much finer. Currently layers are divided in up to three segments and the evaporative zone is divided into seven segments independently of their thickness. Thus, segments may become very thick and the vertical water movement may be modelled very coarse. A proposed maximum thickness of a segment of for example 10 cm (4 inches) would fix this problem.
- b. The unit-gradient approach for calculating unsaturated flow should be replaced by an approach that includes the matric potential.
- c. Besides grass and bare soil, different types of vegetation should be modelled, for examples shrubs and deciduous and coniferous trees. This requires revisions of the modelling approaches of vegetative growth and decay, potential and actual evapotranspiration.
- d. The very simple frozen soil sub-model should be enhanced (for example the model HELP 3.95 D includes a pragmatic enhancement).

However, the already high computing and file saving times of the Excel calculations will further increase due to the enhancements, which users may find off-putting.

ACKNOWLEDGEMENTS

The author thanks all developers of the HELP model for their extensive model development and documentation including the release of the source code of the HELP versions 1, 2 and 3. The author thanks Dr. habil. Stefan Melchior, Prof. Dr. Günter Miehlich (retired) and all co-workers of the Project Georgswerder at the Institute of Soil Science of Universität Hamburg for the careful planning and realization of the test field measurements on the landfill Hamburg-Georgswerder and Dr. Volker Sokollek (retired), formerly Environmental Protection Agency of the City of Hamburg, for his support of the project.

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