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SOFTWARE TOOL FOR ASSESSING THE AFTERCARE COSTS OF LANDFILLS

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ABSTRACT: The aftercare period of a landfill lasts typically much longer than the deposition phase. In Austria, operators are responsible for funding and carrying out aftercare activities. The aftercare management and the related financial security have to be maintained by the operators until the authorities agree to aftercare completion. There is a severe risk of funding shortage, because financial securities are to be accrued for a legally required period of 30 years of aftercare and because actual aftercare management might last much longer. Recent observations in Austria have also shown that some landfills operators have failed to fulfil their aftercare obligations due to missing financial resources.

In the present paper, a simulation model (software tool) is presented which allows assessing the time and costs of landfill aftercare taking the type of waste, the technical landfill equipment (e.g. top cover, base liner) and the local conditions (e.g. vulnerability of groundwater, surface waters) into account. The model represents an extension of existing models developed during the last decade at TU Wien. The existing model framework enables the user to assess the necessary time of landfill aftercare depending on the aftercare strategy. Thereby the pollutant release from the landfill and its potential transport through the subsurface to different points of compliance in the environment (e.g. groundwater) are calculated. The new model additionally allows assessing the related costs of different aftercare measures and thereby enables the user to compare different post-closure strategies with respect to their overall costs for the time of necessary aftercare. Hence, operators or authorities get valuable information of how to minimize aftercare costs and make best use of the available financial resources built up during the operation of the landfill.

Case studies at Austrian landfills are used to test the model and to estimate aftercare costs in relation to site-specific conditions. Apart from the methodological basis of the model, its user interface is presented and it is applied to a case study.

Keywords: Landfill aftercare, landfill emissions, landfill aftercare costs, landfill aftercare management

1. INTRODUCTION

In a modern waste management system landfills are essential as anthropogenic sinks for substances which cannot be reused or recovered. Due to their long-term emission potential, it is necessary to avoid negative impacts on humans and the environment by managing and controlling the after closure period of landfills. The management activities comprise mainly the installation of a top cover, the monitoring of leachate (and gas) and its treatment, the maintenance and control of landfill facilities as well as site surveillance (Laner et. al 2011).According to the Austrian Waste Management Act (AWG 2002), landfill operators are responsible to assure appropriate and safe management until the authorities agree to aftercare completion. For municipal solid waste landfills, the aftercare period typically lasts much longer than the legally required 30 years, which leads to a severe risk of funding shortage. The duration of aftercare and the corresponding financial effort depends on the type of waste deposited, the conditions on site and the technical design of the landfill (Laner et al. 2011). Therefore, it is difficult to derive general aftercare costs per m³ amount of waste deposited, allowing sustainable financial planning of the landfill operators.

The aim of this study is to develop a simulation model (software tool) that allows the user to estimate the aftercare period and the corresponding costs of any landfill, by entering the type of waste deposited, the performance of the technical barrier system, the observed emissions, as well as the geological and climate conditions at the site.

2. MATERIAL AND METHODS

2.1 Existing Model – SEDENA-Tool

In the SEDENA-Tool (Laner et al. 2012), the user can assess the necessary time of landfill aftercare depending on the aftercare strategy (e.g. type and time of top sealing), available as an Excel application.

The methodology to derive completion criteria and to estimate the time of landfill aftercare consists of several elements. It is based on models on emission characteristics of the landfilled waste, models on the performance of the containment system, substance migration models in the surrounding environment and at respective points where certain criteria have to be met (points of compliance). Based on the model by Belevi und Baccini (1989), the concentrations of relevant leachate constituents are estimated. The orginal equation of Belevi and Baccini has been extended in order to consider water flow heterogeneity and the continuous release of substances due to ongoing organic degradation (1) (Laner et al. 2011a).

$$C(t) = \underbrace{C_0 * e^{\left(-\frac{C_0}{M_0}*h*\frac{W}{S}(t)\right)}}_{\text{Concentration after t years due to leaching}} + \underbrace{\frac{k_{org_f}*m_{org_f}}{\left(h*\Delta\frac{W}{S}\right)} * e^{(-k_{org_f}*(\frac{W}{S}(t)/\Delta\frac{W}{S})}}_{\text{Concentration after t years due to degradation of organic materials}} + \underbrace{\frac{k_{org_m}*m_{org_m}}{\left(h*\Delta\frac{W}{S}\right)} * e^{(-k_{org_m}*(\frac{W}{S}(t)/\Delta\frac{W}{S})}}_{\text{Concentration after t years due to degradation of organic materials}} \quad (1)$$

$C(t)$ ... Mean annual concentration after t years $[\frac{mg}{l}]$

C_0 ... Mean annual concentration at the end of the intensive reactor phase $[\frac{mg}{l}]$

M_0 ... Concentration of substances, that can be mobilised by leaching $[\frac{mg}{l}]$

h ... heterogeneity of water flow $[-]$

$\frac{W}{S}(t)$ ... water to solid ratio at the year t [l/kg DM]

$\Delta\frac{W}{S}$ ... Mean changes in the water to solid ratio per year [l/kgDM. a]

k_{org_f} ... Degradation rate of readily degradable organic matter $[\frac{1}{a}]$

m_{org_f} ... Emission potential of the of readily degradable organic matter [mg/kg DM]

k_{org_m} ... Degradation rate of medium to slowly degradable organic matter $[\frac{1}{a}]$

m_{org_m} ... Emission potential of the medium to slowly degradable organic matter [mg/kg DM]

t ... Time after completion of waste deposition [a]

In a first step, equation (1) is used to fit observed leachate data of the landfill. Thereby, the different parameter (such as $C_0, M_0, \ldots$) are estimated within pre-defined plausible ranges in order to obtain the best fit between model and measured data. In a second step the calibrated model for the leachate emissions is used to predict the future trend of emissions as a function of water throughput. Since the parameters ammonia-nitrogen (NH4-N), chloride (Cl) and chemical oxygen demand (COD) mostly determine the aftercare period of landfills, as their concentrations typically exceed current regulatory standards for the discharge of leachate into surface water bodies by at least one order of magnitude and are expected to be significant for long-term leachate pollution at most MSW landfills (Kjeldsen et al., 2002), the leachate emission model (see Equation 1) is used to predict their future emissions.

The effect of different containment system performance levels on landfill emissions is modelled considering several scenarios. Scenario A assumes the consistent function of the top barrier and the decrease of performance level of the base liner, Scenario B considers the gradual decrease of the barrier function and Scenario C the effect of a total failure. Scenario B* the decrease of the of the top barrier function and the total failure of the base liner. By varying the rate of water infiltration (e.g. based on different types of top cover), several aftercare strategies can be simulated.A weighting matrix, derived from expert interviews assessing the importance of different factors for the long-term performance of the top and base barriers is applied for the case of an expected gradual performance decrease over time (Laner et al. 2011b or Laner 2011).

The potential transport of pollutants through the subsurface to different points of compliance in the environment (e.g. groundwater) is calculated by the SEDENA Tool using the Hydrus-1D Software. The type and thickness of the different soil layers, the level of the groundwater body, the vertical mixing depth and the groundwater recharge are considered. Figure 1 shows a scheme of the subsurface migration pathway with scenario- and substance attenuation factors (AF) between the different points of compliance (PoC). The AF is defined as the ratio of the maximum concentration at the first point (e.g. leachate concentration) to the maximum concentration at the second point (e.g. PoC 1) (AF = Cfirst/Csecond) (Laner et al. 2011).

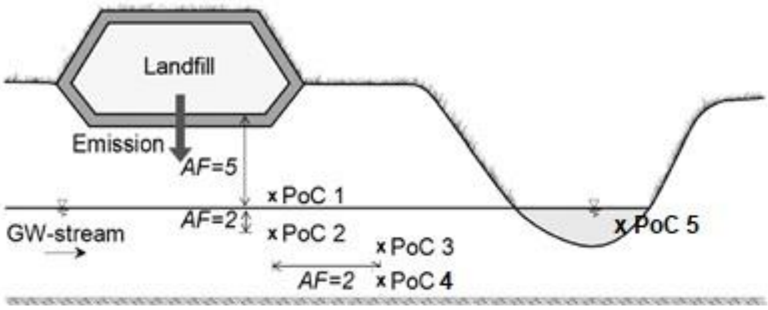

Figure 1: Scheme of the subsurface migration pathway with scenario- and substance-specific attenuation factors (AF) between the different points of compliance (PoC) (adapted from Laner et al. 2011)

The AFs combined with specific quality criteria at a certain point of compliance (e.g. groundwater) can be used to estimate tolerable landfill emission levels (i.e. emissions that meet a defined limit at the point of compliance) for each scenario.

Landfill gas emissions can be assessed based on acceptable area-specific methane flow rates. Tolerable, maximum area-specific inflow of methane to the top cover are suggested at 4.2 m³CH4/m².a or a tolerable maximum methane flux to the atmosphere of 0.42 m³CH4/m².a (ÖWAV, 2008). The gas generation is calculated using a specific mathematical model, which is based on the work of Tabasaran and Rettenberger (1987). Apart from waste quantities, it requires the type of waste deposited (degradable organic carbon content) and default values for the corresponding degradation rates. The model period until specific criteria (specific methane flow rates) are met, determines the end of intolerable landfill gas emissions.

2.2 Structure and Implementation of the Newly Developed Software Tool (NaDemo – Tool)

The adapted software tool aims to provide a user-friendly interface and the additional function of evaluating the associated costs of different aftercare measures. Thereby enabling the user to compare different post-closure strategies with respect to their overall costs for the time of necessary aftercare. The prediction of the future leachate emissions, the gas generation and the barrier performance levels can be modelled in analogy to the SEDENA-Tool methods. In order to assess the potential transport of pollutants through the subsurface of the landfill without using a finite element based transport model (Hydrus-1D software), many scenarios of pollutant transport in the subsurface assuming different soil layers have been simulated. Thereby, a clear correlation between the pollutant attenuation factor (reduction of pollutant concentration in the subsurface) and the mean residence time (exchange time of water in the subsurface) of the pollutants in the subsurface and the half-life time of pollutant release from the landfill (leachate concentration) was found. This correlation is used to assess the attenuation factors of pollutant concentrations in the subsurface.

The prediction of aftercare costs is based on cost rates for the respective measures, which are associated to the calculated aftercare period and presented as real costs according to the net present value method.

2.2.1 User Interface and application

In order to implement the NaDemO tool as a stand-alone software, the application is written in Python (www.python.org, Version: 3.9.0). Python is available entirely free of charge. The user interface (GUI) is generated using the default package TKinter. For data display and manipulation, the packages xlrd, pandas, numpy, matplotlib and lmfit are used.

The main panel consists of seven tabs ("general landfill data + emissions", " barrier and subsurface", "acceptable impact levels", "aftercare strategies", ”financial securities”, "calculation", "results"). The current version of the software is only available in German, but it is planned to translate it to English to increase the number of potential users.

2.2.2 General landfill data and model adjustment

An Excel template is provided to import the monitoring data of the landfill (such as annual leachate quantities or leachate concentration). This allows an easy input of the period of waste deposition, the amount of waste deposited, the landfill area, the annual precipitation and the leachate quantity and concentrations as time series. A multi-line drop-down menu enables the user to specify the composition of waste for the years of deposition. Based on the waste composition and on the time of top sealing and the annual leachate generation, the dry mass of the waste, the water-to-solid ratio (amount of water in liters that passed through 1 kg of waste dry matter), and the residual gas generation potential are estimated. To calibrate the leachate emission model, a least squares method is used. The calibration of the leachate emission model requires at least 4 measurements of the respective leachate parameters (e.g. COD, Cl, NH4) after closure. The user can display the model results and the observed leachate parameters as graphs as well as adjust the calibrated parameters manually. The quality of the measurement data is decisive for the accuracy of the model predictions. For example, at the time of the measurements the climatic conditions should be similar in order to obtain representative measurements.

2.2.3 Barrier and subsurface

The tab “barrier + subsurface” provides an evaluation profile to define the performance level of the top cover and the landfill base liner. Different radio buttons can be set, to select the properties for status, design and function. By clicking a button a weighting matrix, derived from expert interviews, is generated to assess different calculation factors for the long-term performance of the barrier system. This matrix can also be adapted manually. Based on these factors, the functionality of the top cover and the leachate release into the subsurface (functionality of the base liner) are determined for a period of up to 300 years.

To define the different soil layers of the subsurface a drop-down menu is available. The soil layers according to the "Bodenkundliche Kartieranleitung" can be selected whereas default values for the hydraulic conductivity and the flow rate of the respective layer are set in the background. The thickness of the soil layers can be defined via an input field in the unit meter.

To determine the properties of the groundwater, input fields for the mixing depth, the height of the groundwater body, the filter velocity, the groundwater recharge and the oxygen content are available.

2.2.4 Acceptable impact levels at the point of compliance

To calculate tolerable emission levels in the subsurface, the AFs are associated to specific quality criteria at certain points of compliance (e.g. groundwater), which are shown in Figure 1. The software tool allows the user to enter concentrations according to the applicable regulations in Austria or manually in the unit mg/l. The tolerable emission levels for landfill gas are defined as maximum area-specific inflow of methane to the top cover and as maximum methane flux to the atmosphere, entered in the unit $m^3CH4/m^2.a$. Based on the predictions of the gas generation model, the methane flux into the top cover is estimated assuming homogeneous inflow.

The point in time, when no further potential risk for the environment is estimated, is defined by the duration until the tolerable emission levels are met at the respective PoC.

2.2.5 Aftercare strategies

To simulate different aftercare strategies, the user can enter three different types of surface covers by defining the leachate generation in percentage of the precipitation at the site. The Austrian Landfill Ordinance (DVO 2008) specifies that the final top cover has to be designed in such a way that leachate is limited to 5 % of precipitation after closure. Alternative designs are also permitted, e.g. longer temporary sealing or minimum precipitation input. By entering the leachate percentage of precipitation, the user can define these as post-closure strategies.

2.2.6 Financial securities

The Federal Ministry for Environment in Austria (BMK) provides an Excel-template to assess the costs for closure and aftercare of landfills for non-hazardous waste in Austria assuming an aftercare duration of 30 or 40 years. This template is used to calculate and approve the financial securities. The developed software tool enables the user to import this Excel sheet and change as well as recalculate the individual positions if needed. These cost rates can be applied for the further calculation.

2.2.7 Calculation

If all necessary entries are completed, the user can proceed to the tab “Calculation. Figure 2 shows the upper part of the tab, where scenario, point of compliance and aftercare strategy have been selected for the calculation. Point of compliance 3 is recommended for calculating the costs, because it is assumed that measurements for monitoring the groundwater are available at this point.

In this example, data from a municipal solid waste landfill was imported, where 1.3 Mio. tons of waste have been deposited from 1991 to 2007. The landfill area is 50 000 m², and the precipitation is 1 200 mm/a. Scenario B* is selected for this example, assuming that the performance level of the top cover decreases and the performance level of the landfill base liner is ineffective. Point of compliance 3 and the aftercare strategy with 5 % leachate of precipitation are selected.

Figure 2: Screenshot of the tab "Calculation", upper part, where scenario, PoC and aftercare strategy are selected for the calculation

The calculation starts after clicking the button "start emission modelling" and the graphs of the emission model of leachate, of landfill gas and of the estimated leachate concentrations, as well as the duration until the acceptable impact levels are met, are shown below (Figure 3).

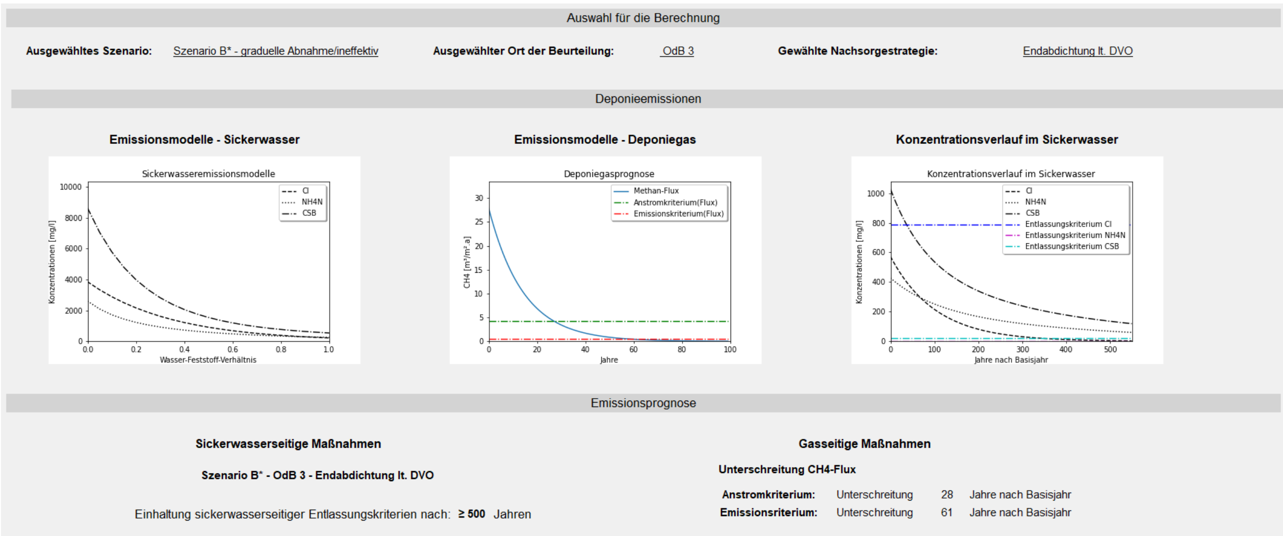

Figure 3: Screenshot of the tab "Calculation", upper part, where the results of the emission model are shown

The first graph on the left in Figure 3 shows the calibrated leachate model as a function of liquid-to-solid ratio. The second graph shows the estimated landfill gas generation, including the user defined tolerable impact levels over time. The starting point for the simulations is defined as the point in time when no further technical changes will be performed at the site, in this example the year 2008.The leachate concentrations of Cl, NH4-N and COD in mg/l over time starting from the starting point, are shown in the third graph. The horizontal lines define the estimated tolerable leachate concentration levels. In this example these levels are met ≥500 years after starting point of simulation, and the compliance of tolerable gas emission levels is estimated after 28 respective 61 years.

After calculating the emission model, the costs for various management activities can be retrieved from the tab "financial securities" by clicking the respective button. All parameters can also be set manually (Figure 4): The area for the top cover and its specific costs in €/m², the costs for collecting and disposal of landfill gas in €/a, the specific costs for leachate disposal in €/m³, the costs of maintenance and monitoring (e.g. maintenance of leachate basin) in €/a are set. Limit values for concentrations of

NH4-N, Cl and COD in the leachate for discharge into the sewer system and for discharge into surface water can be set in mg/l was well as emission loads in kg/a (this function is not available yet). To consider the technical development in leachate disposal, the investment costs and the reduction (in percent) of leachate disposal costs from a certain year can be indicated. Earnings from subsequent use of the landfill area can be considered either once or annually. In order to discount the future costs, the net present value method with a user defined discount rate is applied. If no discounting is required, the discount rate has to be set to zero.

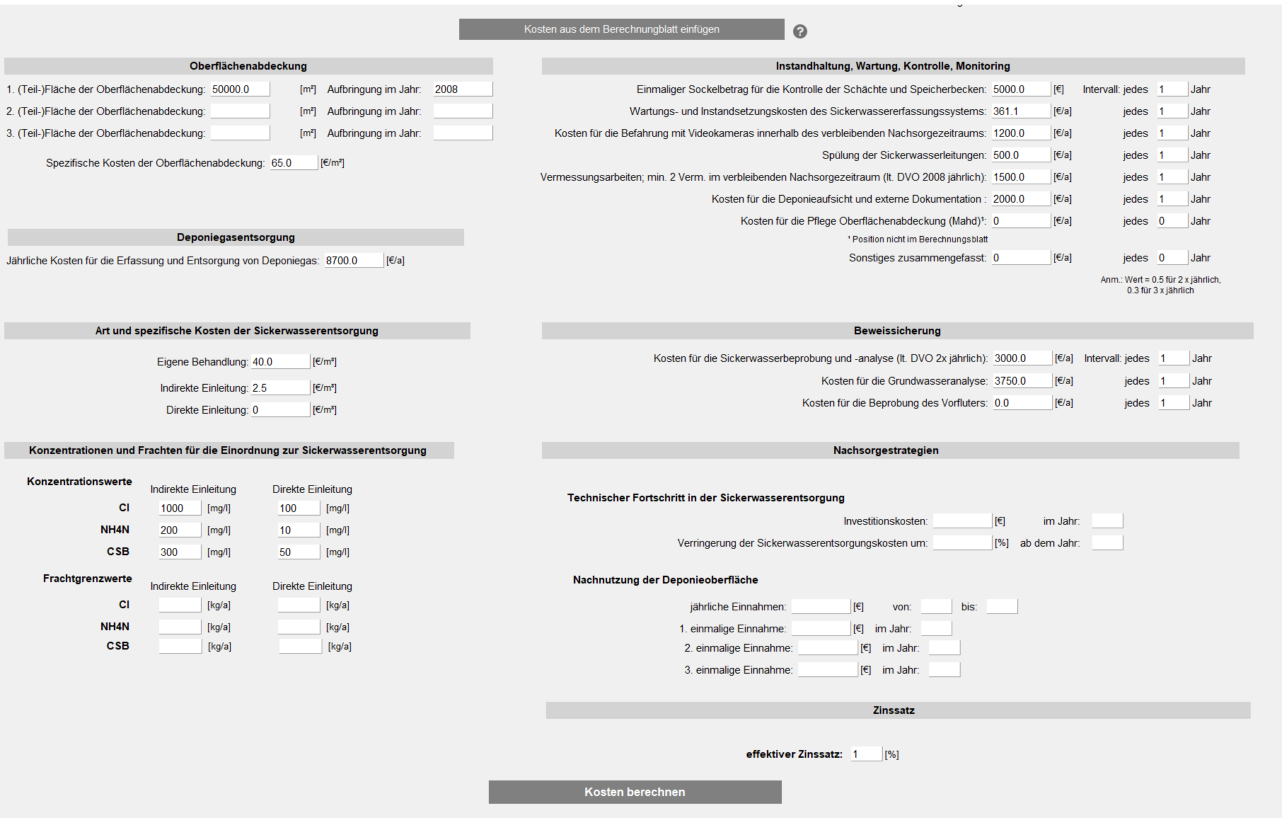

Figure 4: Screenshot of the tab "Calculation", lower part, where the specific costs for the estimation of the aftercare costs are defined

If all necessary entries have been made, the button "calculate costs" can be pressed. In the background, the time series of the predicted leachate concentration, of the estimated leachate volume and the landfill gas generation are associated to the costs and discounted for the calculated time of aftercare. These net present values are grouped into different categories and displayed as summed values. The groups are top cover, disposal of leachate, landfill gas disposal, servicing and maintenance, monitoring, earnings and total sum. The totals of the respective categories are shown as a bar chart (Figure 5). Depending on the estimated time of aftercare, different graphs are displayed, e.g. if the estimated aftercare period is higher than 200 years, the sums of the present values over a period of 100 years, 300 years and the calculated duration are displayed. The sums of the present values of the respective categories are related to the total amount of waste deposited, and are also displayed as a bar chart (Figure 5). This comparison shows that the discounting of costs hardly makes any difference whether 300 or 600 years are calculated. The same applies to the specific aftercare costs.

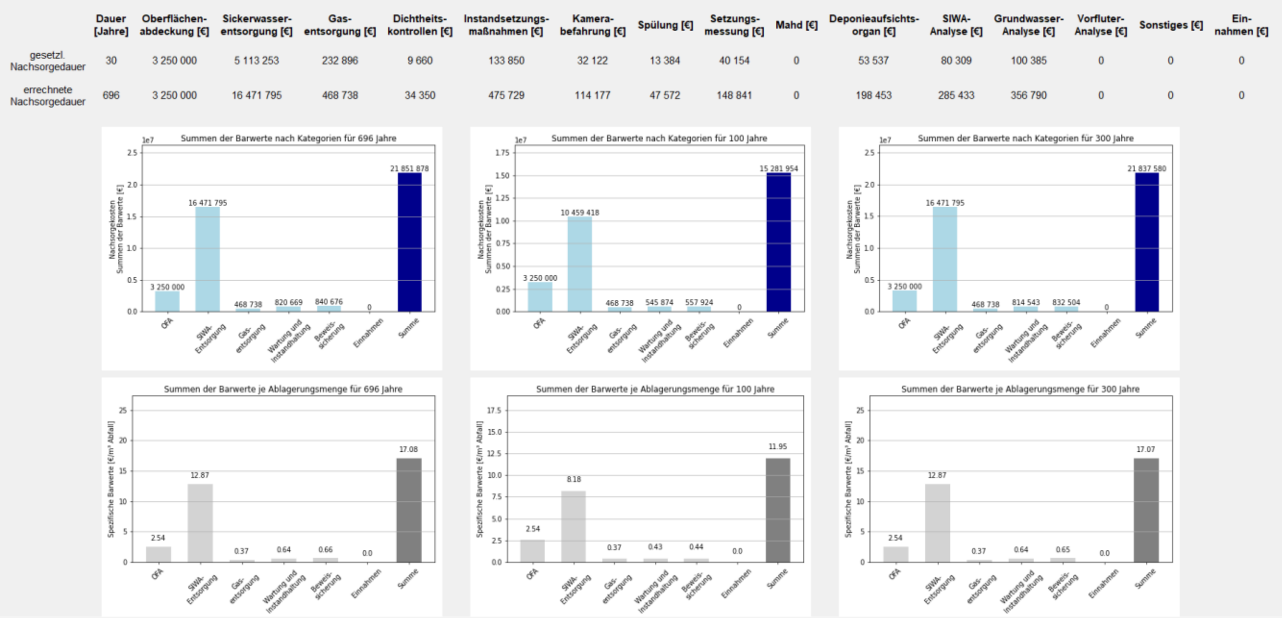

Figure 5: Sums of the present values according to catergories (top), sums of the specific present values according to catergories of the (bottom)

The current results can be stored and are shown in the tab "Results".

2.2.8 Results

On top of the tab "Results" an overview of all entered and determined landfill data is displayed (Figure 6).

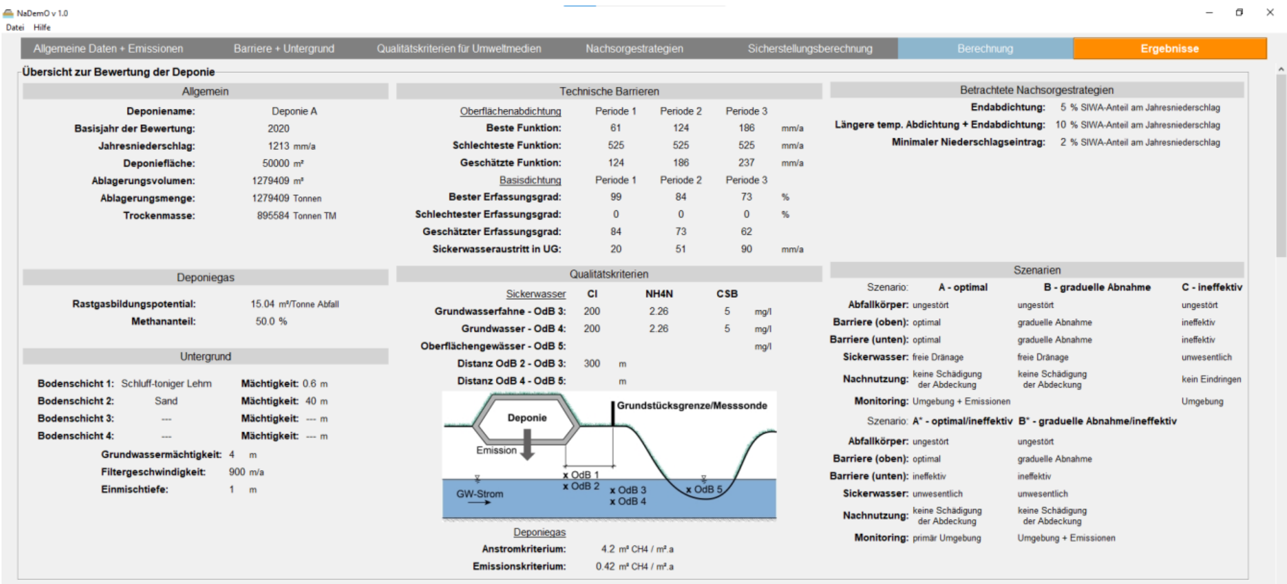

Figure 6: Summary of the entered and determined landfill data

In total, three modelling results can be stored. The overview of the model shows the selected scenario, the point of compliance and the aftercare strategy as well as the site-specific costs and limit values for the disposal of leachate (Figure 7 and 8).

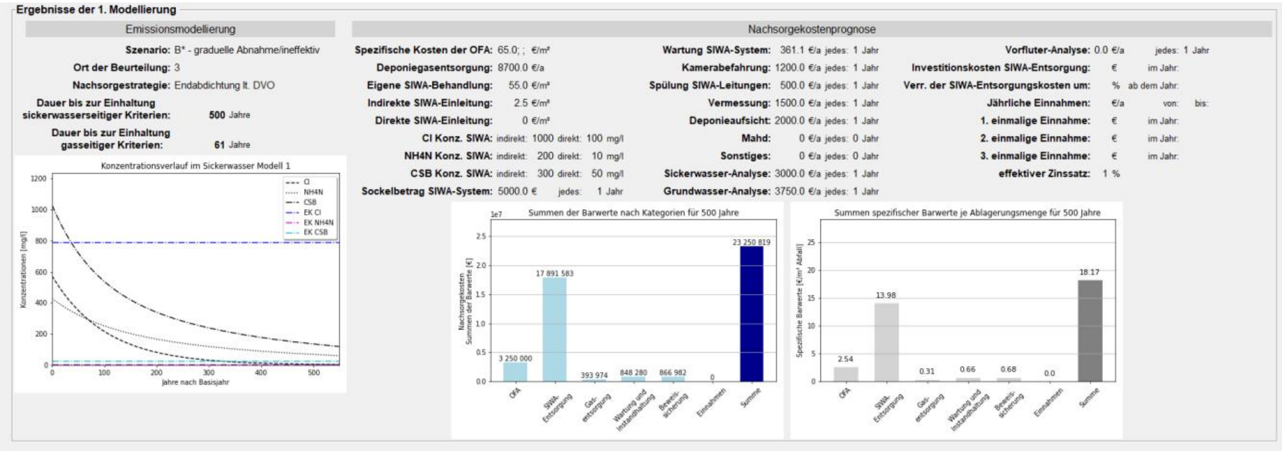

Figure 7: Summary of the parameters and results obtained by the software for a top cover allowing 5% of precipitation to infiltrate

For the first example, Scenario B*, point of compliance 3 and 5 % leachate of precipitation was chosen. A period of more than 500 years was estimated until compliance with the tolerable emission levels is reached. Based on the different cost rates, this leads to a required sum of around 24 million € or specific aftercare costs of 18.7 €/m³ of waste.

For the second example, a longer temporary top cover with 15 % leachate generation rate with respect to precipitation was chosen, this leads to an estimated aftercare period of 288 years (Figure 8). Due to the higher leachate generation, the sum of the present value for the aftercare is calculated at € 24.6 million and the specific costs at € 19.2/m³.

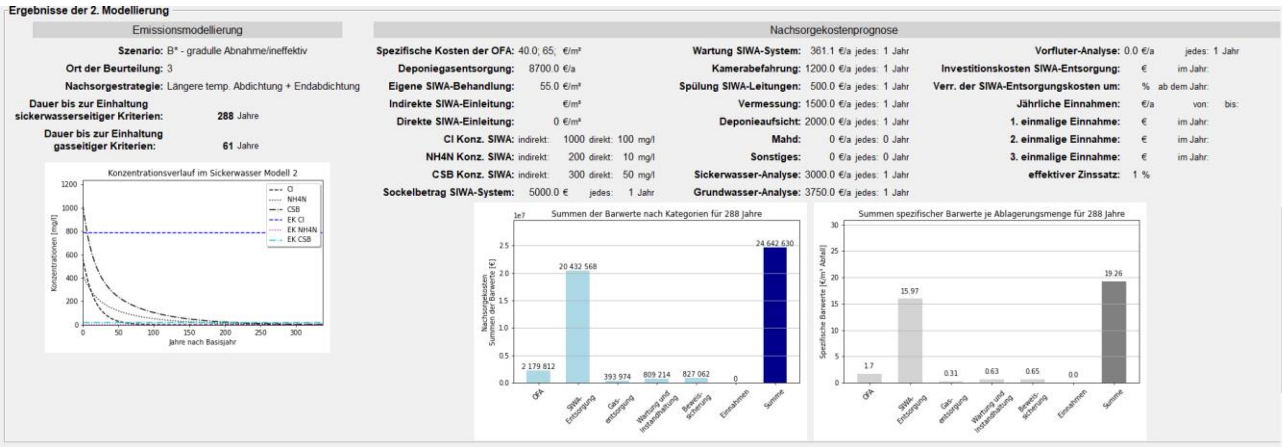

Figure 8: Summary of the parameters and results obtained by the software for a top cover allowing 10% of precipitation to infiltrate

The comparison of these two models shows that the tolerable emission levels can be achieved significantly earlier due to a higher water input into the landfill, if a top cover is used which allows more precipitation to infiltrate into the landfill. However, this corresponds to even slightly higher costs due to more leachate generation and thus higher costs for leachate treatment.

All results stored as well as an overview of the landfill input data can be exported as a PDF report.

3. CONCLUSION

The NaDemO tool allows the user to estimate the site-specific aftercare period and the corresponding costs. The selection of different scenarios (for the long-term performance of the barriers) and aftercare strategies (e.g. temporary top cover) allows for comparing the impact of different factors on the duration and costs of the aftercare. The developed tool is of interest to both, landfill operators and authorities. It provides a transparent basis for assessing the “true” costs of landfilling.

The user interface is clearly designed and divided into different categories by using different tabs.

The import of landfill data enables an easy input of basic data, and the calculations in the background simplify the determination of certain initial parameters. Further, a user manual explains the individual steps and clickable question marks in the programme provide information about inputs and calculation. The tool provides saving options, so that the user is able to save and load the entire input data.

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