ABSTRACT
This paper presents our approach of principles for quality assurance in water balance modeling: Good Modeling Practice (GMP) is a new term in modeling practice, that comprises a number of quality criteria concerning the qualified system analysis, the collecting of qualified (input) data, the qualified mathematical model, an experienced and qualified modeler and a comprehensive documentation of the model calculations. Using the water balance measurements of runoff, drain and base flow of five test fields (Bautzen/Nadelwitz, Germany) an objective valuation criterion is developed and tested. The objective valuation criterion identifies a parameter set with which simulation data best fits the measured data. For the calculation of prognostic discharge by means of numeric models this parameter set should be used in order to generate the most realistic results.

Keywords
Water Balance Simulations, Quality Criteria, Quality Assurance, Modeling, Long Term Prognosis, Good Modeling Practice (GMP).

1. INTRODUCTION
The major task of surface sealing (covering) systems for municipal waste deposits is to prevent precipitation to infiltrate into the waste body and - as a consequence - to minimize fluent and gaseous pollutants to be emitted to the environment. Principally surface covering systems for waste deposits consist of two components: the actual seal element and a recultivation layer. On a short and intermediate time scale the water regime of surface sealing systems is substantially determined by its layer structure and local factors as climate. On longer-term scales (> 50 years) the infiltration rate underneath a sealing system will more depend also on ecological factors. This is as the structural boundary conditions change due to the natural aging of the sealing system. For synthetic seal elements or “low permeable soils with natural characteristics” this change in structural condition has often a negative effect on the sealing properties of landfill cover. In such cases a by then naturally grown vegetation should be able to take over the task of the sealing system and control the water regime by minimizing the amount of water recharge. Past investigations (summarized in [1]) showed that the variability of the water balance of sealing systems is essentially determined by the local climate, the vegetation atop of the recultivation layer and the pedological, soil mechanical and soil physical characteristics.

For practical applications the effectiveness of a sealing system is of most interest, that is the resulting infiltration rate in comparison to the compactness of the sealing system, including the costs. This effectiveness is determined by the quantity of water entering the sealing system (precipitation), the evapotranspiration capacity of the vegetation, the physical properties of the structure and the layers (permeability, presence of compacted layers for the formation of lateral discharge, presence of drainage layers, presence of macrospores), and slope of the cover system.

The general water balance of landfill cover systems can be described with the following equation (Water Balance Equation).

\[ P = Q_S + Q_I + Q_P + ET + \Delta S \] (1)

\[ P \] ... total precipitation (rain, dew, hail, snow)
\[ Q_S \] ... surface runoff
\[ Q_I \] ... interflow (hypodermic runoff)
\[ Q_P \] ... percolation (ground water recharge)
\[ ET \] ... Evapotranspiration
\[ \Delta S \] ... alteration of soil water inventory

As the water balance of sealing systems cannot be generalized due to the multiplicity, complexity and entwinement of the
processes a recommended component of the planning of covering systems for waste deposits is water balance modeling. Principally all climate relevant processes such as precipitation, current evaporation, soil water storage, snow cover storage, ground water formation (recharge) and runoff can be described with physically based water balance models [2-8]. If necessary further processes can be coupled to the soil water movement such as material transfer and or chemical-physical material reactions [1, 9].

The working group "Geotechnics of Waste Deposits and Waste Sites" [10] recommends the software program HELP (Hydrologic Evaluation of Landfill performance, version 3.80 D [11]) as computation program for the dimensioning of sealing systems for waste deposits in Germany. While the HELP model was originally designed for US climate and soils, model advancements for German conditions were made available through the University of Hamburg [12, 13]. The program HELP is an application oriented, generic simulation model for the water balance of sealing systems and waste site profiles. HELP is a deterministic, time-discrete, quasi-two-dimensional, layer-oriented location model. The term “quasi two-dimensional” indicates that the vertical flow and laterally surface and drain flows are modeled. The modeling of the water movement in a HELP model is based on a simplified Darcy-Buckingham-Equation under neglect of the matrix potential.

2. GOOD MODELING PRACTICE

Quality control and criteria for quality control are elementary components of each systems analysis. Therefore, quality control must also be established at all work procedures and on all working levels of a modeling. According to international standards quality control covers:

- Abstraction and formulation of a conceptual model (system analysis)
- Data acquisition and collection
- Numerical model (selection of a suitable model)
- Verification (plausibility check of the input data), calibration (derivation of the best fits) and validation (alignment with measured data)
- Sensitivity analysis (quantification of the effect of soil parameter variations within their "natural range" on model results)
- Prognosis/heuristics
- Comprehensive documentation of the input data of each model run, of the results determined, and the uncertainties of the data and the model results.

The discussion and documentation of uncertainties is a component of the sensitivity analysis, which must show, which parameters and boundary conditions determine the system. Closely connected and predominantly a component of the systems analysis is the data acquisition. Quality criteria for this part of the modeling are the complete documentation of all measurements, samplings and accomplished analyses. For the laboratory methods the principles and quality standards of the GLP (Good Laboratory Practice) are used. In addition there has to be a statistic evaluation and interpretation of the data under indication of uncertainties. The collection of criteria of quality control mentioned above can be summarized as criteria of Good Modeling Practice (GMP).

GMP is a new term in the modeling practice, firstly discussed in connection with the modeling of final waste deposits [14]. The criteria for GMP are as follows:

- a qualified system analysis,
- the collecting of qualified (input) data,
- a qualified mathematical model (verified, calibrated and validated),
- a qualified and experienced modeler, and
- a comprehensive documentation.

When the quality criteria according to GMP are considered, water balance simulation calculations can be a meaningful tool for the prognosis of a future water balance, especially for the prognosis of the discharge of landfill covering systems. GMP was practiced exemplarily in the simulations of the Bautzen/Nadelwitz landfill cover test fields.

As part of the quality assurance within the framework of GMP an objective valuation criterion was developed and tested. As modeling means fitting of the simulated data to the measured data this objective valuation criterion allows to clearly identify the best-fit model run during a simulation; it identifies the parameter set with which the simulated data best fits the measured data [15]. For the calculation of the prognostic discharge this as “best fit” identified parameter set should be used in order to produce the most realistic numeric model results.

The objective valuation criterion \( \Delta \) is defined as the weighted sum over mean daily deviations between model results and measured data (see eq. 1). In the case of the Bautzen/Nadelwitz test sites, for each of the five test fields three data series can be simulated: runoff, drain and base flow (recharge). The sum over this three daily mean deviation is weighted, because we consider a good fit to the measured recharge through the landfill cover system into the waste body to be more important than the model fits to the runoff and the drain.

\[
\Delta = \sum_{j} a_j \frac{\text{mean daily deviation of model results from measured value (j)}}{\text{mean daily discharge of measured value (j)}}
\]

In this formula the index \( j \) stands for the water balance terms runoff \( (j = 1) \), drain \( (j = 2) \) and base flow (or recharge) \( (j = 3) \). The indexed parameter \( a_j \) is the weighing factor with the values \( a_1 = 1/6, a_2 = 1/6, \) and \( a_3 = 2/3, \) (with \( a_1 + a_2 + a_3 = 1 \)).

The formula above is to express the following: On each day of the observation period each simulated value (cumulative runoff, cumulative drain and cumulative discharge) is compared with the respective measured value (a cumulative discharge). This comparison results in daily deviations for the water balance terms runoff, drain and base flow \( (j = 1, 2, \) and 3) \([\text{mm}])\). The calculated means of these daily deviations of the entire observation period are normalized with the respective measured mean daily discharge quantity. The resulting objective valuation criterion \( \Delta \) is stated in percent (%).
3. WATER BALANCE SIMULATIONS

3.1 Description of the Test Fields

Since 1998/1999 a test field plant is operated at the deposit Bautzen/Nadelwitz in order to long-term monitor the water balance of various landfill cover sealing systems [17]. One of the sealing systems is designed according to the German standard system (TASi, [16]). It consists of a sealing layer, a foil, a drainage layer and a top soil layer that is to be planted (recultivation layer).

The overall concept of the test field plant is to allow the investigation on the effectiveness of alternative surface sealing systems in comparison to the German standard system. The municipal waste deposit Bautzen/Nadelwitz is located in eastern Germany, about 50 km to the Czech and the Polish border at about 200 m asl (above sea level). The mean annual precipitation amounts to 650 to 680 mm.

The physical structure of the test fields is schematically shown in figure 1. With test field #7 the requirements of the German standard sealing system were realized (but without foil). Field #7 will serve as the reference to the alternative sealing variants as realized in the test fields #1, 3, 4, 5 and #6. The main feature of the alternative sealing variants are different kinds of bentonite layers [17]. The common structure of all test fields are the following basic elements (from top to bottom) [17]:

- Erosion protection mat,
- Recultivation layer,
- Drainage system,
- Sealing layer,
- Water collection system.

The mean daily deviations of the model results from the measured values are as large as the measured mean daily discharge quantities themselves, then the objective valuation criterion $\Delta$ amounts to 100%.

The aim of this study was to evaluate the potential equivalence of alternative surface sealing systems to the German standard sealing system. The German standard sealing system is explained in TASi (Technische Anleitung Siedlungsabfall, [16]). Therefore, a major task of this study was not only to simulate the performance of the five Bautzen/Nadelwitz landfill cover test sites (including one test site according to TASi), but to objectively compare their performance to each other and to the TASi reference test site. This comparison became possible only with the help of the objective valuation criterion $\Delta$. Additionally, we used that objective valuation criterion $\Delta$ to compare the results of different types of water balance models; results are outlined in [15].

The measured mean daily discharge quantities themselves, then the difference of the model results from the measured values are as large as the measured amounts to 100%.

Figure 1. Overview on the test fields Bautzen/Nadelwitz [17]
3.2 Method of Modeling

In a first step of the modeling procedure each test field is simulated in the so-called 0-variant. The soil input data correspond either to the directly measured values or are "best appraisers". In the 0-variant all soil input data are constant for the duration of the "observation period". The model considers variations of the climate as well as of the vegetation according to the data of the local climatic station and the observations on the test fields.

During the observation period (1999-2004, including the installation in 1999) precipitation, temperature, and global radiation are available on a daily basis, the relative humidity is available on a quarterly basis. Wind velocity and leaf area index (LAI) are provided annually.

After this 0-variant model run is performed all input data and the model results are noted in a specially designed documentation form (see figure 8). Using the water balance measurements of runoff, drain and base flow of the test fields from the observation period the value of the valuation criterion $\Delta$ is calculated and noted in the documentation form. In the following steps of the modeling procedure (1-variants) the soil input parameter are individually varied within the range of their natural uncertainty.

The effects of the changing input parameters on the model results are objectively quantified again by comparing the valuation criterion $\Delta$. These model runs are time constant 1-variations. A next step in the model procedure is the test either time variant soil and vegetation parameters would further improve the agreement between model simulation results and the water balance measurements of runoff, drain and base flow. The simulation is considered to be finished when the valuation criterion $\Delta$ approaches a minimum value. For this model run, the input parameters are considered the "best-fit" parameters (best-fit-variant). This set of parameters is used for the calculation of prognostic discharge.

In the so-called "prognosis calculations" the soil parameter set of the "best fit"-variant are used to model the five year period (2005-2009) that follows the observation period. In case the soil characteristics of the "best fit"-variant varied temporally within the observation period, the soil parameters of the last year of the observation period (2004) are used for the prognosis calculation. For all prognosis calculations the climatic input data of the years 1999-2004, a leaf area index of 4 ("very good grass vegetation"), and maximal rooting depths are used.

For the so-called "future calculations" (2010-20100) the water balance of a 90 year period is simulated. A similar procedure is used as for the prognosis calculations, but a leaf area index of 7 (forest) is used for the 90 year period (2010-2100).

According to the criteria of GMP the quality assurance of the modeling is discussed in the following chapters.

3.3 Criterion: Qualified System Analysis

All relevant water balance terms are evaluated for the system analysis. They are summarized in a conceptual model (figure 2).

3.4 Criterion: Qualified (Input) Data

Most of the soil physical input parameters of the test fields were determined in field and lab experiments in December 2001 [18]. These are the layer characteristics, soil type, and suction-saturation-characteristics (usable field capacity, permanent withering point, saturated hydraulic conductivity). The porosity is calculated from the sum of air capacity and field capacity using a compaction factor of 3. Cumulative volume data of recharge, interflow and runoff were measured weekly in the water collecting system of the test fields [17]. The data is checked for comprehensiveness and plausibility.

For some intervals during the observation period temperature and precipitation data was missing. Here we calculated five-day sliding mean values from comparable seasons during the observation period (see figure 3).
as for persons who are not familiar with modeling in general, like decision makers or personnel involved in a licensing processes.

An example for such a comprehensive model documentation is shown in figure 8. The columns represent individual model runs (no. 23 through 34), the objective valuation criterion $\Delta$ is listed in the last row.

### 3.5 Criterion: Qualified Mathematical Model

A qualified mathematical model must be able to reproduce the terms of the conceptual model. In this water balance simulation study, we used the model HELP 3.80D (Hydrologic Evaluation of Landfill Performance) and refer to literature for further details [13].

### 3.6 Criterion: Qualified Modeler

It might be quite a task to clearly define the criterion “qualified modeler”. But in principle the modeler should be a certified modeler, an experienced modeler or should be supported and consulted by such a person and be familiar with the topic he/she is modeling.

### 3.7 Uncertainty Analysis of the Modeling

Uncertainty analysis is required for all parts of the modeling procedure: the input data, the model and the output data. Uncertainty analysis in modeling is not very common, and there are no standardized routines for the expression of uncertainty in modeling. A first step should be the analysis of the different types of uncertainties, for instance in cause-and-effect diagrams. One example for a water balance model is shown in figure 4.

![Figure 4. Example for conceptual uncertainty analysis of modeling.](image)

To ensure comparability of measurement or modeling result over space and time, careful documentation of the influence quantities and their magnitude is essential. The cause-and-effect approach is a suitable instrument to document these elements in a highly structured and concise way [19]. Actually it is difficult to include the uncertainties into a mathematical model.

### 4. RESULTS

#### 4.1 Observation Period

Figure 5 displays the measured values of the cumulative base flow for the observation period as well as the results of the different types of model runs of test field #5, Bautzen/Nadelwitz. Quite often, like in this case, the 0-variant does not at all, like in this case, or not satisfyingly reproduce the measured discharge data. Therefore, in further steps of the model procedure, in the so-called 1-variants, the soil parameters of the individual layers of the sealing systems are varied until the “best fit” variant is identified with the help of the objective valuation criterion $\Delta$.

![Figure 5. Measured values of the cumulative base flow and model results of different model variants of test field #5, Bautzen/Nadelwitz.](image)

Often the variation of the soil input parameters ranges within the their measurement uncertainty and/or estimate inaccuracy. For example, for the $k_s$-value this “natural range” can easily be one order of magnitude. From the simulation of the measured data we learned that the permeability of the sealing layer was often underestimated. Further we learned, that in addition to the time constant 0- and 1-variants it was often necessary to consider time dependent 1-variants with soil parameters changing during the observation period.

Such behaviour can be interpreted for the individual test fields as due to either effects of soil compaction shortly after the construction of the test fields, or due to material ageing/weakening/damaging in the course of the five year observation period as in the case of a sealing layer (Cu-foil, etc.). Such observations strongly support the request for long-term on-site monitoring of water balance terms as a fundamental component of a model validation without which prognostic water balance calculations are only little convincing.

We applied GMP during all test field simulations and compared the measured recharges of the German standard waste deposit sealing system (according to TASi, field #7) with the alternative sealing systems (fields #1, #3, #5 and #6) in order to fulfill the aim of this study and to test their equivalence. For every test field the cumulative results of the evapotranspiration ET, runoff, drain and base flow were calculated and documented (figure 6). We evaluated the equivalency of an alternative sealing system to the German standard sealing systems on the basis of the individually simulated discharge quantities.
Additional model runs were prepared for selected test fields using the HELP internal soil database instead of our measured data. The aim was to test the plausibility of the model results when measured soil input data are missing and “best estimates” are used instead. The results showed a good reproducibility of the cumulative drain and base flow. But, as documented in [12, 13], the reproducible modeling of the runoff is problematic with HELP, especially in case of low runoff values.

### 4.2 Prognosis

Figure 7 shows exemplarily the results of the prognosis for field #5. Prognostic calculation are of particular interest if an increasing permeability of the sealing system is observed during the observation period (e.g. field #5 and #6).

### 4.3 Future

Figure 8 shows exemplarily the comprehensive documentation sheet of field #7, the German standard sealing system. As this system serves as reference for the alternative sealing systems the measured values of this test field are simulated with particular care. Here the methodology for the modeling of prognosis and future is demonstrated and due to the good validation in the observation period, the results of the prognosis and future calculation are considered meaningful. The future calculation is meant to provide information either a naturally grown vegetation (LAI = 7, forest) is able to control the water balance of the sealing system and eventually minimizes the recharge into the waste body.

### 5. CONCLUSIONS

As quality assurance and criteria for quality control are elementary components of each system analysis it must also be established at all work procedures and working levels of a modeling. Therefore an objective valuation criterion was developed and tested that identifies a parameter set with which simulation data best fits the measured data. The measured values of the discharge could be well reproduced. The "best fit" variant can be objectively identified with the help of the valuation criterion Δ. Furthermore, the simulation results of different models become objectively comparable to each other with the help of the valuation criterion.

Often an adjustment of the soil parameter set in the course of the model procedure is necessary. In many cases the range of the variation of the soil parameters is similar to measurement uncertainty or inaccuracy of the soil input parameters (“natural range”). The effects of parameter variation on the model results should be evaluated in the sensitivity analysis. The uncertainties of input data, model and model results should be clearly stated.

A methodology is developed that allows the prognostic calculation of the water balance in landfill cover systems. For the application of the prognostic methodology the use of qualified measured input data is essential, especially test field data.

With regard to the equivalence tests of the alternative sealing systems the prognostic calculations show that all types of alternative sealing systems are altering. The progresses modeling reveals that the recharge rate, which adjusts after alteration of the sealing element, couldn’t be fully compensated with the help of increasing vegetation evaporation. This means that for the long term evaluation of alternative sealing systems, their quality is not equivalent to the standard sealing systems. This does not mean, that alternative sealing systems cannot be used as long-term solutions for municipal waste deposits. But it has to be stated that such sealing systems with artificial sealing layers (bentonite, foil etc.) instead of low permeable natural soils have to be combined with capable evapotranspiration landfill covers, that control on the medium time scale the water balance of the cover system. [21].

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*Figure 6. Cumulative results of ET, runoff, drain and base flow (example: field 6).*

*Figure 7. Results of the prognosis, exemplarily for field 5.*

If an increasing permeability is observed, a time dependent model 1-variant will be the best-fit variant. For the prognostic calculation, the soil parameter set of the last year of the simulated observation period will be used. This is – naturally – the highest permeability value. As a result, the average effectiveness of the sealing system in the prognosis is smaller than the the average effectiveness during the observation period.
Figure 8. Example of a comprehensive documentation form, containing the model results of test field #7 of various model variants of the observation period (no. 23 through 29), the prognosis (no. 30) and the future (no. 31). No. 32 through 34 are model runs (best-fit, prognosis and future) that are based exclusively on soil parameters taken from the HELP internal database. This documentation is part of the GMP.

We recommend that in future methodical developments of equivalence investigations on the equivalence of surface sealing system that are based on water balance modeling "natural ranges" of the soil physical characteristics should be complemented with statements regarding their "natural ranges" implemented in the models (this is a kind of uncertainty consideration). The range of the soil physical characteristics must be considered in the sensitivity analysis of the model calculations. If no measured soil characteristic values of the material or soil, which is planned for the construction of the alternative sealing system, are available, soil physical data from validated data bases (e.g. the HELP internal data base) should be used. But all model based equivalence investigations of surface sealing systems must be validated with measured data.

A quality assured modeling needs a sensitivity analysis. The documentation of the modeling should be accomplished very carefully and be comprehensible for third persons (see our recommendation for such a documentation in figure 8).
6. REFERENCES


