AN INTEGRATED APPROACH TO THE LOCATION-BASED DESIGN OF LINING SYSTEMS USING THE FULL RANGE OF GEOSYNTHETICS

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ABSTRACT: The BLACE software has been developed at the University of the Federal Armed Forces in Munich as an efficient tool for location-based comparisons of costs and effectiveness including the optimization of lining systems for landfills. BLACE supports the user in drafting and designing long-term effective, economical surface lining systems. Its tools allow location-based water balance calculations and profitability comparisons. BLACE takes into account the positive effect of water balance layers, differences in building and subsequent costs, ageing behaviour and after-care periods, and contains a comprehensive database with data of numerous geosynthetics. Well-known manufacturers of geosynthetics have contributed to the creation of the material database by providing product data and picture material. So the BLACE user involved in drafts and designs may comfortably benefit from the complete spectrum of geosynthetics and compose stable, highly effective and long-lasting lining systems out of geosynthetic clay liners and flexible membrane liners, geosynthetic drain elements, geotextile layers used as filter or for protection, parting or reinforcement in conjunction with earth building materials. In addition, BLACE contains a database storing the monitoring results gained from many test sites throughout the German-speaking areas referring to landfill lining systems in which also geosynthetics have been in use over several years already. This database provides valuable evidence on the long-term durability and usability of geosynthetics.

1 INTRODUCTION OF THE SOFTWARE BLACE

Secure the long-term effectiveness of lining measures, decisively cut down the costs - these aims may easily be reached if in addition to the standard systems [TA SI, 1993; AbfAblV, 2001; DepV, 2002] alternative lining systems are examined with a consistent method during the authorizing and planning phases, compared with these regular systems and, if required, further optimized to meet the requirements of the respective location.

From 1998 to 2003, a research project called "Comparing the cost effectiveness of different surface linings" was conducted at the University of the Federal Armed Forces in Munich on behalf of the "Bavarian State Ministry for Rural Development and Environmental Affairs" and under the auspices of the state authorities for environmental protection and water economy. Several Bavarian communities and refuse disposal associations – among them the State capital of Munich, the Abfallwirtschaftsverband Isar-Inn, the Abfallwirtschaftsgesellschaft Donauwald, the rural district of Rosenheim and the Erbenschwanger Verwertungs- und Abfallentsorgungsgesellschaft Ingenried – contributed to the success of this project by way of a co-operation. A multi-path procedure on the basis of the data available to the co-operating partners was developed which assists landfill operators, designers and authorizing authorities in developing, proving and authorizing efficient and economical surface lining systems at the relevant landfill location with its relevant basic conditions.

These efforts led to the development of the **BLACE** software. "**B**avarian tool for **L**andfill Lining systems – **A**nalysis of **C**ost and **E**fficiency" has been developed on behalf of the Bavarian State Ministry for Land Development and Environmental Issues. The software is meanwhile being used also in other German federal states. It allowed to convert the method into an efficient and easily usable tool. Its core consists of a location-based model of a landfill which allows to "filter out" and still further optimize the most efficient among all technically feasible solutions (Fig. 1).

Databases and calculation models assist in estimating the water balance coefficients, cost-effectiveness analyses (CEfA) and dynamic transfer to reserve calculations and cost-efficiency analyses (CEA) support the evaluation of the economic efficiency, and stability assessments, emission analyses (EA) and technical data sheets are employed to design the system and its components.

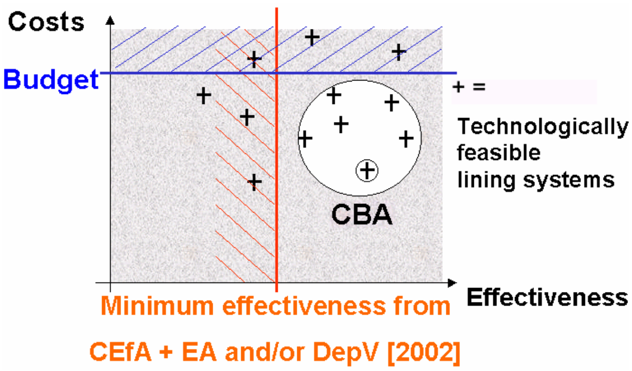

Figure 1 BLACE assists the user in selecting a technically and economically optimized surface lining system for the respective location

The design layout, the proof of the required effectiveness (=design) and stability as well as the evaluation of the economic efficiency must consider the prevailing local conditions. These include e.g. topology of the landfill's surface, climate, pollutant potential, a possibly already existing base lining system, geology (incl. the geological barrier), hydrology, biosphere and, last but not least, the local availability of building materials.

It is just the latter issue – the local availability of building materials – which frequently provides the decisive cost argument in favor of geosynthetics. The BLACE draft module should therefore also account for the use of the following products (Fig. 2): Geosynthetic clay liners, flexible membrane liners, geosynthetic drain elements, geotextile layers used as filter or for protection, parting or reinforcement. In addition, the factor "time" should be included in the calculations, e.g. because successive building phases are completed at different times and either temporary or permanent linings are used, lining constructions and geosynthetics have a varying quality and a limited useful life, and because debit and credit interest accrue on investments and profits etc. So the developers of the software focused on a location-based and time-related model of a landfill to which they attached modules for effectiveness and economy assessments.

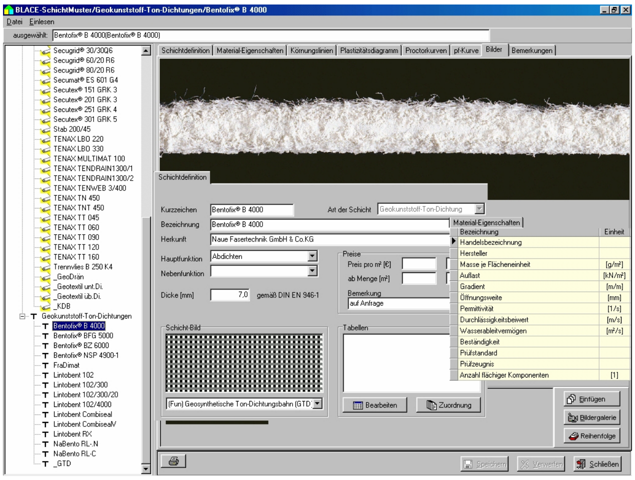

Figure 2 Database catalog supporting the selection of geosynthetics for the BLACE-based design of surface linings.

The layer set-up of variants to be examined can be designed directly in BLACE while several material samples (e.g. from material qualification tests or external monitoring activities of previous building phases) may be allocated which include the relevant characteristics (permeability to, and storage capacity for, plant available water etc.). These are considered in the moisture household and building costs calculations.

The essential advantage of this method is the use of a single consistent database for all calculations and perspectives.y

2 TEST SITES OF THE UNIVERSITY OF THE FEDERAL ARMED FORCES MUNICH FOR THE EFFECTIVENESS ASSESSMENT AND OPTIMIZATION OF LINING SYSTEMS INCLUDING WATER BALANCE LAYERS

2.1 *Overview of the University's test sites*

The Institute for Soil Mechanics and foundation engineering at the University of the Federal Armed Forces Munich (UniBwM) is currently operating the test sites shown in Table 1 at four locations with a total of 23 separate sections in order to measure the water balance coefficients and the aging of implemented system components including geotextiles. The researchers are concentrating their efforts on the technical drain and lining elements, among them the geosynthetics clay liners of different manufacturers and manufacturing methods (pinned together/sewn up with varying surface weights) and the interactions with recultivation layers. The observations of the systems' effectiveness and the conclusions as to their useful life are included in the BLACE database of the economic efficiency comparisons.

Now a short description of some test sites is given.

2.2 *Landfill North-West, Munich*

The City of Munich is one of the communal co-operation partners in the research project F166 „Economy Comparison of Surface Linings“. On the Nord-West (NW) landfill near Munich, two sections of a test site were built with recultivation layers of 1m and 2m thickness (column 1 in Table 1). Here the examinations concentrate on the technical-economic optimization potential of the recultivation layer as that element which reduces the climatic impact on the primary lining element. In addition, this test site provides data about the long-term effectiveness of self-healing mineral surface linings which have been developed at the University of the Federal Armed Forces [HORN & WUNSCH, 1997] and which consist of mineral lining material with light to medium plasticity. The self-healing capability is based on the same principle which is used for linings in water engineering: Eroded lining material particles are

Table 1 Overview of the test sites operated by the University of the Federal Armed Forces Munich

	1) Landfill North-West, Munich	***2) Landfill Asbach***	***3) Test site „Alter Schießstand“, University of the Federal Armed Forces Munich***	***4) Landfill Flintsbach***
Number of fields	2	16	4	1
Thickness of recultivation layer [m]	1.0 and 2.0	0.8÷1.5	1.5	0.6÷1
Characterization of the recultivation layers below the topsoil	Alternate surfacing from Rotlage soils	Pebbly-loamy Rotlage soils	Alternate surfacing of compost, coarse-clay-rich gravel-washing-sludges, Rotlage of different density	Loamy Rotlage soils
Drain function fulfilled by	Mineral	Mineral + geodrain	Geodrain	w/o drain element!
Lining function fulfilled by	Mineral lining (self-healing), d=0.6m and filter formed filter fabric below mineral lining	Geosynthetic clay liner (sewn up) + mineral lining, d=0.5m	Different types of geosynthetic clay liners	MD, d=0.6m
Year of building of the lining system	1998÷2000	1996	2002	1990
Applicable law when approved/built	TA Si (1993)	TA Si (1993)	<Research purposes exclusively>	LAGA data sheet
Examination aims pursued with the measuring equipment	a) Approval requirement for alternative lining system b) Under observation: Influence of recultivation layers of different thickness on the effectiveness of a self-healing mineral lining	b) Approval requirement for alternative lining system b) Under research: Large-scale determination of the system effectiveness of constructed areas of 4 950 acres; Long-term aspects: Geosynthetic clay liner with long dwell time (relative to usual monitoring period) of 6 years	Influence of different soils and stratification densities and different storage capacities of the recultivation layer on the water balance of geosynthetic clay lining liners of different manufacturers	Water balance of mineral liner w/o capillary-breaking drain layer between mineral liner and recultivation layer; Long-term aspects: Mineral liner with long dwell time (relative to usual monitoring period) of 12 years

retained by a geotextile at the escape side of a crack in the liner. The liner on the NW landfill has been laid out in the form of three 0.2-m-layers covered – without parting geotextile – by the drain layer with the thickness of d= 0.15m.

Firstly, the two test site sections established by the Bundeswehr University of Munich are part of the quality assurance catalog for the alternative surface lining system which is rated equivalent to the standard system in accordance with DKII (TA Si, 1993). Secondly, however, these test sites also reflect the influence exercised by differently thick recultivation layers on the water balance and the long-term effectiveness of mineral liners and GCL's: One field is covered with a 2-m-thick recultivation layer (=standard cross-section of the NW landfill), the other with a 1-m-thick layer (= minimum thickness according to TA Si, 1993).

In addition to meteorological data also soil moistures, soil moisture tensions and soil temperatures are recorded in several depths of the test sites as well as the amounts of water escaping at the lower side of the recultivation and lining layers. Moreover, several excavations have been made in the recultivation layer in order to document the soil mechanics of the used materials and the building condition (among others, water contents, dry densities, graining and retention lines).

The following findings were gained from the test site: there was no indication in the first three water balance years that a self-healing mineral lining system with a1-m-thick recultivation layer – consisting of gravel from the brash plain, i.e. with low storage capacity for plant water – would be insufficiently dimensioned regarding the climatic conditions of the Munich brash plain. Also in the area of the 1-m-thick recultivation layer no drying-out tendencies can so far be recognized in the lining layer. With 0.1 to 0.2 per cent of the precipitation the seepage water renewal rate is marginally low in the two test sites. Also the high packing density of the recultivation material which the designer had selected, among others, for, reason of stability, thereby contradicting the present philosophy of a plant-fostering loose set-up, has so far not shown any negative impact such as e.g. increased seepage water amounts in the two test sites. The different thickness of the recultivation layers of one and two meters respectively do not seem to impair the system performance: No significant increase of seepage water through the lining layer has so far occurred. The self healing system with its filter geotextile under the sealing layer works fine. However, the measuring period of 3 years is still too short as to allow a final assessment.

2.3 *Test sites on the premises of the Bundeswehr university and at the landfill Asbach*

In 1995, the Lower Bavarian landfill Asbach (column 2 in Table 1) was equipped on an area of approx. 22.000 m² in the building sector RA I with a controllable surface liner. In this surface lining, a some 50cm thick mineral liner was combined with a GCL on top. A control geodrain was inserted between these two lining layers.

In order to monitor the effectiveness of these geosynthetic clay liner which represent the upper lining element containers were integrated into the recultivation layer during that building phase to which the water collected in the control drain is channelled. These receiving containers allow to contain the water outflow below the Betonit mats and to monitor its quantity [SCHMITZ, 2003].

The lining elements are covered by a 0.3-m-thick mineral drain layer and an at least 1.0-m-thick grassy recultivation layer.

The test site in Neubiberg, UniBwM (column 3 in Table 3) discovers the performance of GCL's of different manufacturers in combination with different types of recultivation layers. These layers in each section of the test sites differ in its net field capacity within the effective root space. That is the storage capacity for water which is available for plants and thus also for evapotranspiration. The latter reduces the amount of seepage pouring onto the upper side of the GCL's.

The contribution of S. M. Schmitz in the proceedings on hand of "Euro Geo 03" deals with the test sites in Asbach (column 2 in Table 1) and in Neubiberg, UniBwM (column 3 in Table 1) in detail [SCHMITZ, 2003].

3 EVALUATION AND COMPILATION OF ALL TEST SITE DATA IN FIELDBASE

Both the data from the own test sites and those collected from technical literature descriptions of other test sites including their location, design and the measured precipitation amounts and water balance values are included in the BLACE-internal test site database "FieldBase". This facilitates evaluations and comparisons of effectiveness and ageing behaviour prior to drafting, designing and planning of lining systems including their recultivation layer or water balance layer respectively.

Especially to the benefit of the long-term effectiveness of geosynthetics the recultivation layer and the „water balance layer" fulfils the important function of buffering the climatic and biological impacts, in detail:

- protection from direct insolation (e.g. of the UV spectrum)
- protection from frost
- protection from burrowing animals
- amplitude reduction of the temperature hydrograph curves in the depth of the geosynthetics
- protection from desiccation for geosynthetic clay liners

For example, Fig. 3 shows on the basis of BLACE-FieldBase how the storage capacity of the recultivation layer for plant available water impacts the drain outflow, i.e. that amount of water per water balance year that reaches the drain layer above the top-most lining element.

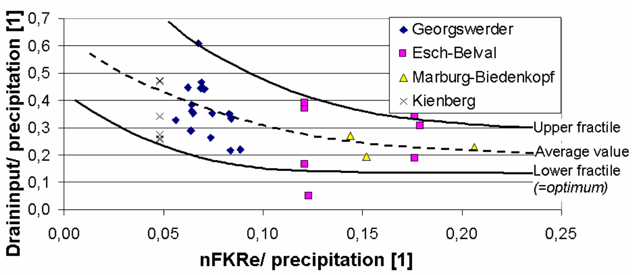

Figure 3 Effectiveness of recultivation layers at several test sites in Germany expressed as drain outflow A_{Dr} in reference to the quotient of precipitation N und net field capacity of the effective root space nFKRe [Evaluation based on the BLACE-internal test site database "FieldBase", SCHMID & SCHMITZ, 2003]

Principally, the net field capacity of the effective root space (nFKRe) provides an expressive dimension quantity to estimate the storage capacity of the recultivation layer for plant available water.

Fig. 3 shows however, that forecasts about the drain outflow and the seepage renewal rate on the basis of an estimate of the net field capacity of the effective root space and the knowledge about the yearly precipitation are still very inaccurate because also a series of additional quantities are involved (e.g. distribution of the precipitation referring to time and intensity, slope retreat distance to the nearest drain, actual root depth, exposition, insolation...) and the net field capacity of the effective root space can be determined in many cases only roughly.

The BLACE-implemented Monte-Carlo-water balance simulation promises to pride a better approach to the problem by simulating several water balance years and accounting for the scatter ranges of all relevant input parameters (Section 4). A first estimate of the recultivation layer's performance is possible with Fig. 3.

4 WATER BALANCE AND ECONOMY CALCULATIONS USING BLACE FOR DESIGN AND ESTIMATE OF AFTER-CARE COSTS

4.1 *Importance of the seepage renewal rate*

The forecast of the seepage renewal rate in the landfill body is useful in several respects:

- to estimate the (initial) effectiveness of the surface lining
- to forecast the ageing behaviour of the surface liner
- to forecast the gas amounts (with economic implications)
- to estimate the sewage treatment plant costs in the operating period and in the after-care period (relevant for transfers to reserve)
- to prepare emission forecasts for the design of the lining systems at basis and surface

To estimate the seepage renewal rate either the results obtained from test sites with comparable basic conditions e.g. from the BLACE-internal database „FieldBase" or water balance models can be used.

4.2 *Water balance calculations with BLACE*

For detailed water balance forecasts the BOWAHALD [Dunger, 2002] model has been integrated into BLACE. This offers two advantages:

a) The DOS-based model BOWAHALD can be operated via the user-friendly visual surface of BLACE.

b) In addition, it has now become possible to input value ranges of independently scattering variables such as climate, vegetation-related and soil-mechanical figures, to enable the design of the lining systems despite scattering input parameters and non-linear processes. Concurrently, sensitivity analyses can now be conducted easier and the uncomplicated calculation of variations has become possible.

These two advantages enhance the user-friendliness for water balance calculations including associated sensitivity analyses [SCHICK & SCHMID, 2003].

4.3 *Stochastic approach using the Monte-Carlo-Method*

Most of the initial quantities relevant for the estimate of effectiveness and costs are scattering so that deterministic considerations with discrete values are not sufficient to engineer lining systems because of the non-linearity of the processes involved, e.g. the water balance variations in the surface lining system. BLACE therefore uses scattering quantities – wherever it is meaningful and feasible with reasonable effort. The results again are scattering variables which can be characterized e.g. by the 5%, 50%, and 95% fractile of the respective quantity, e.g. the seepage renewal rate (Fig. 4). In order to limit the number of individual simulations to be computed, the Monte-Carlo-Method [SOBOL, 1991] is used for the water balance calculations, i.e. each combination of the single parameters to be computed is compiled via a single simulation from the possible value ranges by means of a random generator and is included in the total result depending on the probability of its occurrence. So only a representative off-hand sample of the combinatorially possible computing variations need be considered.

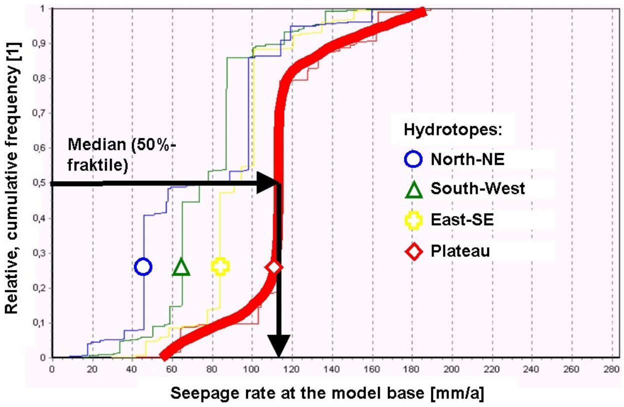

Figure 4 Operation with frequency-distributed quantities in BLACE; shown here: Relative cumulative frequency of the seepage renewal rate in different hydrotopes of Landfill „UU" [SCHULZ|FINSTERWALDER|SCHMID, 2003]

4.4 *The emission progression: Important criterium for the proof of equivalent characteristics and the end of the after-care*

As regards the technical design of surface liners, emission analyses were taken into account as additional component of the evaluation method. The emission analysis extends the view towards the long-term perspective of surface lining systems, i.e. periods exceeding the lifetime of several generations, e.g. 500 and more years. The pollutant emissions and contents of lead parameters for the respective location are tracked via the numerical solution of the differential equations of the pollutant transport. This calculation is, of course, admissible over such long periods because the mass laws of convection, diffusion, sorption and desorption are considered correctly and the initial characteristic quantities are tracked in their total probable occurrence spectrum. So it is possible to assess the stability of preferred solutions for a landfill which does hardly require any after-care and burdens the following generations with as low emissions and costs as possible. The allocation to the debit side of the economy comparisons is done by estimating the required after-care duration.

In this context, BLACE can be used to document and evaluate also the properties of the basis lining system and the Geological Barrier in their scatter range in order to process the data for an emission analysis and to transfer them together with the seepage renewal rate data to the program to solve the differential equations of the pollutant transport through basis liner and geological barrier down to the groundwater stream. The solution of these differential equations of the pollutant transport e.g. according to Mann [1993] can be found with the program DESi [Finsterwalder, 2003].

The two programs – BLACE and DESi – harmonize ideally to carry out jointly the data processing and pollutant transport calculations by considering the scatter ranges of the input parameters. On behalf of the Bavarian State Ministry for Land Development and Environmental Issues and under the technical auspices of the Bavarian State Offices for Environmental Protection and Management of Water Resources landfill projects including water balance forecasts and emission analyses have already been carried out successfully with these two programs. By comparing the calculation results with the measured pollutant concentrations in the down-stream of two closed-down landfills the method has once again been verified positively – in addition to already furnished previous proofs [Mann, 1993].

Fig. 5 shows the result of an emission analysis and forecast respectively compared to the pollutant concentration measured in the groundwater under the Northern Bavarian closed-down landfill „UU" by taking phenol as an example. Here the difference between inflow and outflow concentration and dilution in dependence on the water gauge position was considered. The pollutant mix taken into account at this location consisted in total of 19 pollutant types and groups.

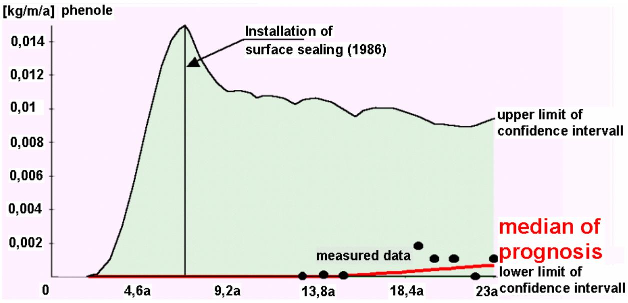

Figure 5 Forecast of the groundwater phenol content: Water gauge BKR1 closed-down landfill „UU" with entered measurement values •

4.5 *Calculation of profitability*

Like the effectiveness also the costs of the individual lining variants are time-dependent. To develop some systematics for location-related comparisons of profitability, three procedures had initially been envisaged. Among these, the utility analysis (UA) had been dropped right in the beginning because it completely neglects the debit side. Both cost/effectiveness analysis (CEfA) and cost/profit analysis (CBA) were considered to be suitable and are separately used considering their specific advantages and disadvantages.

The cost/profit analysis is especially suitable for profit comparisons from the view of the operating and/or paying authority (community / special purpose association / private landfill operator) for the calculation of transfers to reserve where the sum curves of costs are determined in which the interest and compound interest for the calculation of the required transfers to reserve are included. The method allows the dynamic, monetary assessment of the advantages and disadvantages of the lining systems in various respects, e.g. also by including stability considerations for different slope angles [SCHMID, 2002].

The cost/effectiveness analysis, on the other hand, is suitable to a special extent for authorizing and environmental bodies and for considerations of mainly technical character because it also allows to include aims in the comparison which can hardly or not at all be measured in terms of money. But also the cost/effectiveness analysis takes into account the technical performance (expressed in the form of a characteristic number indicating the effectiveness) of the systems relevant to the decision-making process and compares it with the costs.

The cost/effectiveness analysis (KWA) was integrated into the BLACE software and intensively tested. In order to verify and test the method by means of an example, seven surface lining systems were initially evaluated at the research institute on the basis of the effectiveness criteria catalog developed by GDSA [DIBT, 1995]; this assessment was of qualitative nature based on literature evaluations, research findings within the BayFORREST-Clusters „Surface Liners and Water balance " as well as on own tests and experience. The costs were estimated from statements in the literature and compared with the data of the cooperation partners. In addition, replies to a questionnaire were invited which was published per e-mail, on a web-site and in the technical journals „Bautechnik", „Geotechnik" and in „Deponie-Online" in order to sound the range of the assessments enabled by this method. The number of replies to this questionnaire was quite positive – considering the small community of experts familiar with this subject.

Both procedures for profitability comparisons - cost/effectiveness analysis and cost/profit analysis have been integrated into BLACE and are ready for operation.

Fig. 6 shows an example of such a comparison of costs using simple lining alternatives for dangerous waste from the past; for reason of illustration, however, only the estimated building costs of several alternative systems (SCHNATMEYER, 1999) and the costs arising from the waste water treatment (SCHMID, 2001) have been considered. Other costs as well as an estimate of the actual useful life including the time-dependent variations in system properties with subsequent re-investments have been left out. Purification costs of seepage water to the amount of 15€/m³ and a discount rate of 1.039 have been assumed. The latter value is equivalent to long-term interest on the money market of 6 per cent/year versus a rate of price increases of 2 per cent/year (or 5 per cent/year versus 1 per cent/year).

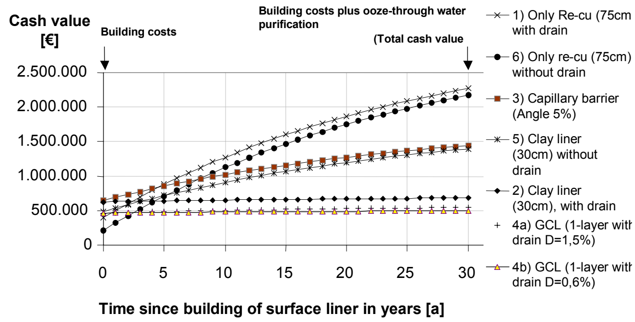

Figure 6 Building costs of capping systems and discounted follow-up costs from waste water treatment [Schmid, 2001] for the systems after Schnatmeyer [1999]

This simple cost comparison makes clear which profitability potential may be inherent in the use of geosynthetics if their long-term effectiveness is ensured by a location-related draft and design: Among the systems with sufficient effectiveness, the lining system with GCL has shown the highest effectiveness over the monitoring period and come off best both regarding the building costs and the follow-on costs arising from the treatment of the occurring seepage water. The „zero-variants" – recultivation layer with/without drain layer – had slightly lower building costs but their follow-on costs falls already after three years far below those of the technical lining systems so that here the investment in environmental protection pays off not only for the general public but – considering the total costs – also for the paying authority of the closed-down location.

5 SUMMARY OF THE BENEFITS OF BLACE TO LANDFILL OPERATORS, AUTHORIZING AUTHORITIES AND ECONOMY

Without transparency no competition – this is true also for the market of landfill surface lining systems. The heavily increased cost pressure owing to the profit reduction for landfill operators, to the excessive capacities and to limited transfers to reserve at many locations [Baum et al., 1999] gave rise to the development of BLACE, a software for location-based cost and effectiveness comparisons of lining systems. This method allows to prepare on a uniform data basis draft, design, profitability calculation and the optimization of operating and after-care phase as well as the technical acceptance test. The software offers high saving potentials – in the long run also in the after-care period – and documents uniformly, transparently and comprehensively the assessments of costs and effectiveness for all involved in the approval, design and building process. Here the whole spectrum of building materials (geosynthetics, earth building materials, asphalt) is available in order to filter out the most effective and economical variants in the competition of alternatives.

From the point of BLACE, the introduction of the new EU-conform regulations (DepV, 2002; AbfAblV, 2001) must be regarded as positive because firstly they extend to the whole system the possibility of establishing proofs of equivalency, an approach which BLACE has consistently pursued right from the beginning, and secondly, they have created an increased awareness of the involved costs with the obligation to make up calculations of transfers to reserve. So the user of the BLACE software is offered a big application potential in the working fields of drafting, technical optimization, proof of equivalency, building cost reduction taking into account also the savings using geotextiles, transfer calculations and minimization of after-care duration and costs.

Several Bavarian communities or waste disposal associations respectively and institutions – among them the Bavarian capital (LH) Munich, AWV Isar-Inn, LR Rosenheim, EVA Ingenried, AWG Donauwald and LGA Nürnberg – have contributed in the scope of a cooperation to the success of this project. Here is the place to express many thanks to all of them.

However, the BLACE tool may not only be used for landfills; it may basically also employed for abandonned locations, abandonned polluted areas and – with slight software modifications – for the groundwater protection along lines of communication as well as for water balance monitoring at dykes and banks with geosynthetic clay liners and other geosynthetic components.

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