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20 YEARS OF LONG-TERM WATER BALANCE MEASUREMENTS OF A LANDFILL COVER SYSTEM WITH COMPONENTS CONSTRUCTED FROM PRE-TREATED DREDGED MATERIAL

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SUMMARY: The cover system of the mono-landfill Hamburg-Francop for disposal of dredged material comprises a mineral liner of pre-treated fine-grained dredged material ('METHA-material') and an overlying drainage layer of pre-treated sandy dredged material ('METHA-sand'). Water balance and effectiveness of the cover with respect to minimising infiltration into the waste body have been investigated in a test field of 50 m length and 10 m width (lysimeter) from 1996 to 2015. Continous measurements of water flow (average annual discharge from the mineral liner of 14.9 mm with a dreasing tendency) and hydro-chemical measurements indicate that the mineral liner is performing well since more than 20 years after construction. Reasons are the low saturated hydraulic conductivity of about $1 * 10^{-9}$ m/s and the large thickness of the liner of 1.5 m; the high load of 2.5 m thick covering layers; the 1.0 m thick lateral drainage layer constructed from relatively slowly-draining METHA-sand; the sufficient amount of plant available water in the recultivation layer; and, finally, to a certain extent the root barrier on top of the drainage layer, composed of compacted loam. The measurements are continued by Hamburg Port Authority as part of the long-term monitoring of the Francop site.

1. INTRODUCTION

Maintaining the navigable depth in the Port of Hamburg (Northern Germany) as the largest German seaport requires continuous dredging of the river Elbe and the harbour basins. Currently, about 10 million m^3 of sediment are dredged annually, of which around one fifth is taken on land, processed and then disposed of or re-used. Since 1993, Hamburg Port Authority (HPA) operates a technical plant for the mechanical separation of harbour sediments called

'METHA' (Detzner et al. 1997). In the METHA, the bulk of the dredged material is separated into a fine-grained and partially dewatered material called 'METHA-material' and a coarse-grained sandy material called 'METHA-sand'. The METHA-material is deposited at the landfill Hamburg-Francop (for a description, see Glindemann and Maass 1988), a hill-shaped landfill based on a former settling basin for dredged material. The cover system of this landfill comprises, from bottom to top, a mineral, an overlying drainage layer constructed of METHA-sand, a compacted loamy root barrier, topped by a soil cover.

Initial measurements revealed low saturated hydraulic conductivities of homogenized and compacted METHA-material of less than $2 * 10^{-9}$ m/s (Blümel and Tamminga 1987). This low value was one requirement for the use of the METHA-material as barrier material in the liner systems and the cover system of the disposal site. However, field studies on the performance of compacted cohesive soil liners showed that these liners may loose their effectiveness and may become highly permeable within a few years after construction due to desiccation, shrinkage and the formation of macro-pores (Melchior 1993, see also Berger et al. 2009). In these studies, shrinkage occurred in spite of the fact that these compacted soil liners had a low content of organic matter (TOC = 0.32 %), an only moderate clay content (17 %) and a high degree of compaction realised near the optimum water content of the Proctor curve (bulk density 1.95 g/cm^3). In contrast, the shrink potential of the METHA-material is relatively large. In May 1994, the Free and Hanseatic City of Hamburg, Amt Strom- und Hafenbau (since 2005 Hamburg Port Authority HPA) comissioned a research project to the Institute of Soil Science of the University of Hamburg to investigate the water balance and the long-term effectiveness of the Francop cover system with a mineral liner constructed from layers of dredged material. For this project, two large-scale lysimeters (test fields) were constructed and equipped in 1995 at the Francop site based on the experience of the Hamburg-Georgswerder project (Melchior 1993, Berger et al. 2009). After the end of the research project in 1999, HPA continued the measurements as part of the monitoring of the Francop site with the Institute of Soil Science as scientific partner. This paper summarizes the most important results of 20 years of measurements of the test fields. For detailed information on the research project see Tresselt (2000) and Groengroeft et al. (2001).

2. DESIGN, CONSTRUCTION AND INSTUMENTATION OF THE TEST FIELDS

In 1995, two lysimeters (test fields) were constructed, each 10 m wide and 50 m long in slope direction. The test fields are located on the northern slope of the Francop site at an inclination of 8 %. One of the test fields, called the 'standard design field' FS, has the standard cover design of the Francop site to investigate the long-term performance of the cover system. The layer sequence from the top to the bottom is as follows (see Figure 1): A vegetation of grasses and perennial weeds is growing on a 1.2 m top soil of loamy material, the uppermost 0.1 m being humic. Below follows a 0.3 m thick root barrier of compacted loamy material, a 1.0 m thick lateral drainage layer of METHA-sand and a 1.5 m thick barrier of METHA-material. To reduce the risk of desiccation and the formation of macro-pores in the barrier its thickness was increased to 1.5 m, and the overload of the layers on the barrier was increased to 2.5 m. The slowly draining METHA-sand of the lateral drainage layer has a saturated hydraulic conductivity of about an order of magnitude smaller than required according to the German regulations for landfills. For compensation the thickness of the drainage layer was increased to 1 m instead of the minimum requirement of 0.3 m in the regulations. In the second test field, called the 'alternative design' or 'desiccation field' FA, the process of desiccation was investigated under accelerated conditions. That means the thickness of the layers above the barrier was reduced (0.6 m sand as drainage layer and 0.2 m humic topsoil, see Figure 1). The barrier of this test field FA desiccated and became pervious in the year 2000. Therefore, test field FA is not considered further in this paper.

The test fields were constructed with the same machinery, the same soils and the same quality assurance as the entire cover of the Francop landfill in order to investigate cover systems with representative material properties and construction quality. Additional samples were taken to document the properties of the layers of the test fields. Special care was given to the construction of the boundaries of the lysimeters. There are no rigid walls cutting through the barriers to avoid preferential flow paths and to allow a uniform compaction of the barrier on the entire area.

Precipitation is the only water input into the lysimeters. Surface runoff, interflow/drainage on the root barrier and lateral drainage within the drainage layer above the barrier are collected separately for each test field. Underneath the barriers collection pans of geomembranes (HDPE) filled with sand are located to collect the leakage through the barriers (see Figure 1).

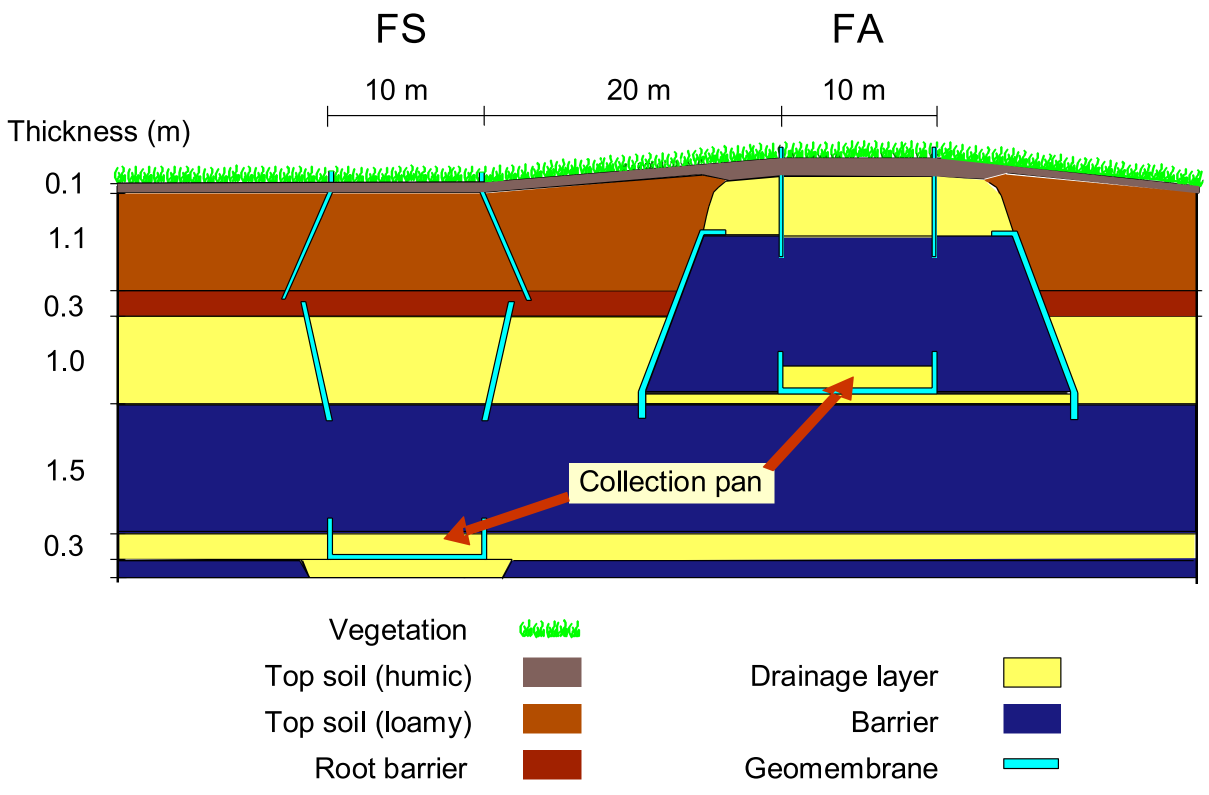

Figure 1. Layer design of the test fields (FS: standard test field, FA: alternative design test field).

The data were collected automatically in a redundant way to avoid gaps within the data sets. Manual readings were used to control the automatically collected data. The following parameters were measured during the research project from 1995 to 1999:

- Meteorological parameters (precipitation, air temperature, relative humidity, barometric pressure, wind velocity and direction, and soil temperatures in various depths);
- Discharges from all layers of the test fields (surface runoff, interflow on the root barrier, lateral drainage above the barriers, and leakage through the barriers; measured with collection bins, level meters and flow meters);

- Soil hydrological data (matric potential with tensiometers, water content with time domain reflectometry (TDR));
- Soil chemical, soil physical and soil mineralogical properties;
- Water chemical properties, measured every three months.

For details on the construction, the experimental setup and instrumentation, and the material properties of the test fields see Tresselt (2000).

Since 1999, the monitoring of the lysimeters has been reduced to the discharges and the chemical composition (anions and cations, pollutants) of the discharging waters. Additionally, a climate station is maintained at the Francop site, measuring precipitation, air temperature and other meteorological data.

3. RESULTS AND DISCUSSION

3.1 Material Properties of the Layers

Table 1 shows main soil properties determined in the laboratory after construction. The barrier is made of METHA-material which is compacted in three lifts (each being 0.5 m thick). The lateral drainage layer consists of METHA-sand (25 % fine sand (63 – 200 μm) and 65 % medium sand (200 – 630 μm). The materials used for the root barrier and the top soil originate from different ground works in the city of Hamburg and are primarily of glacial origin.

Table 1. Properties of the layers of the cover system (laboratory measurements after construction).

Layer / Material property	Barrier	Lateral drainage layer	Root barrier	Loamy top soil	Humic top soil
Grain size distribution:					
Sand (%)	26	100	65	62	78
Silt (%)	57	0	19	22	13
Clay (%)	17	0	16	16	9
Loss on ignition (%)	10	0.2	1.2	1.2	11
Dry bulk density (g/cm^3)	0.88	1.55	1.82	1.78	0.88
Total pore volume (vol. %)	65	41	32	33	65
Saturated hydraulic conductivity (m/s)	$1.2 \cdot 10^{-9}$	$7.1 \cdot 10^{-5}$	$2.5 \cdot 10^{-10}$	$5.8 \cdot 10^{-9}$	$1.0 \cdot 10^{-4}$

3.2 Water Balance and Discharge of the Standard Design Test Field FS

Figure 2 shows the annual water balance of the standard design field FS from 1996 to 2015. To calculate the water balance, precipitation data measured at the Francop site were used (no yearly sum for 1999 available). The remainder of the water balance equation (precipitation minus all discharges) comprise the actual evapotranspiration, the change in water storage between the beginning and the end of the balanced periods (years) and the sum of all measurement errors. Figure 3 shows the time series of the daily discharges from 1996 to 2015 (measurement gaps shown in Figure 3 were closed for calculations if possible).

The average annual precipitation (1996-1998 and 2000-2015) was 761 mm; the annual minimum was 499 mm (1996) and the maximum 1086 mm (2007).

The annual surface runoff usually was very small (a few mm per year), except for the first year 1996 (28 mm) when the coverage of the grassy vegetation was not yet closed and the years 2002 (11 mm) and 2007 (15 mm). In these years, large amounts of the surface runoff were caused by particular extensive rainfalls of high intensity.

The average annual interflow on the root barrier from 1996 to 2015 was 19.3 mm and had a relatively broad range of values (0.4 to 75.5 mm, 2014 and 2002, respectively). There is a trend of decreasing annual sums of interflow which may be caused by an increasing permeability of the root barrier. Like surface runoff, the discharge on the root barrier, too, is related to particular extensive rainfall events.

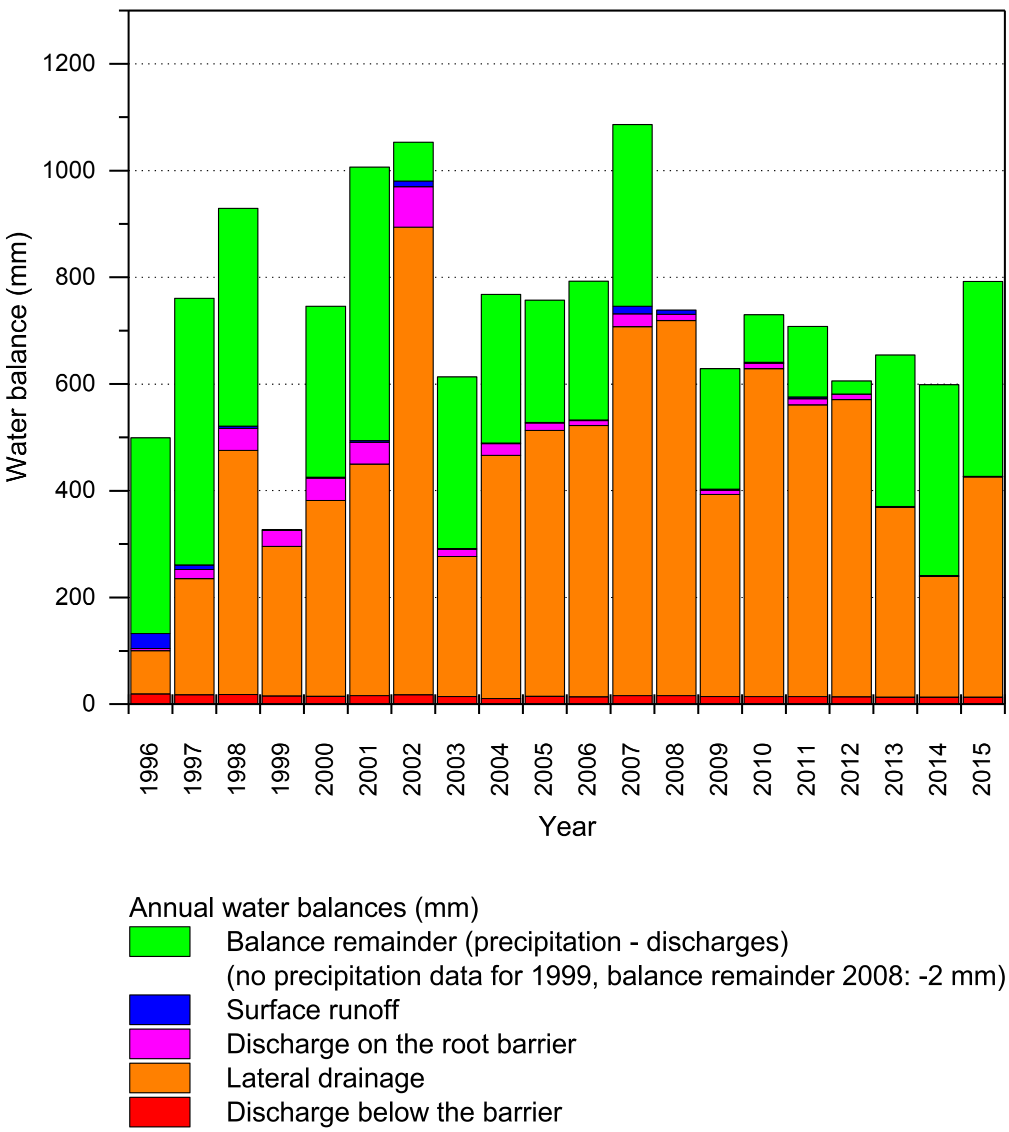

Figure 2. Annual water balance (mm) of test field FS from 1996 to 2015.

The annual discharge below the barrier on average was 14.9 mm from 1996 to 2015. It was relatively constant over the years, however, with a decreasing tendency especially in the first years after construction, presumably due to consolidation of the material and a resulting loss of pore water. Assuming flow through the barrier at a hydraulic gradient of 1 the annual average value corresponds to a hydraulic conductivity according to Darcy's law of $4.7 * 10^{-10}$ m/s.

Consequently, the barrier was working well as intended for more than 20 years since its construction. The daily discharge values below the barrier are nearly constant over the year (peaks in the daily values shown in Figure 3 are caused by the measurement technique and by disturbances). However, they show a slight seasonal pattern with maximum values in late summer and autumn and minimum values in late winter and spring. As described by Melchior (1993) and Tresselt (2000), this seasonal pattern can be explained by temperature-dependent water movement. One major aspect is the temperature gradient between the top and the bottom of the barrier, which changes its direction twice per year and has a downward impact on water movement during summer and autumn and an upward impact during winter and spring; both impacts, however, are relatively small.

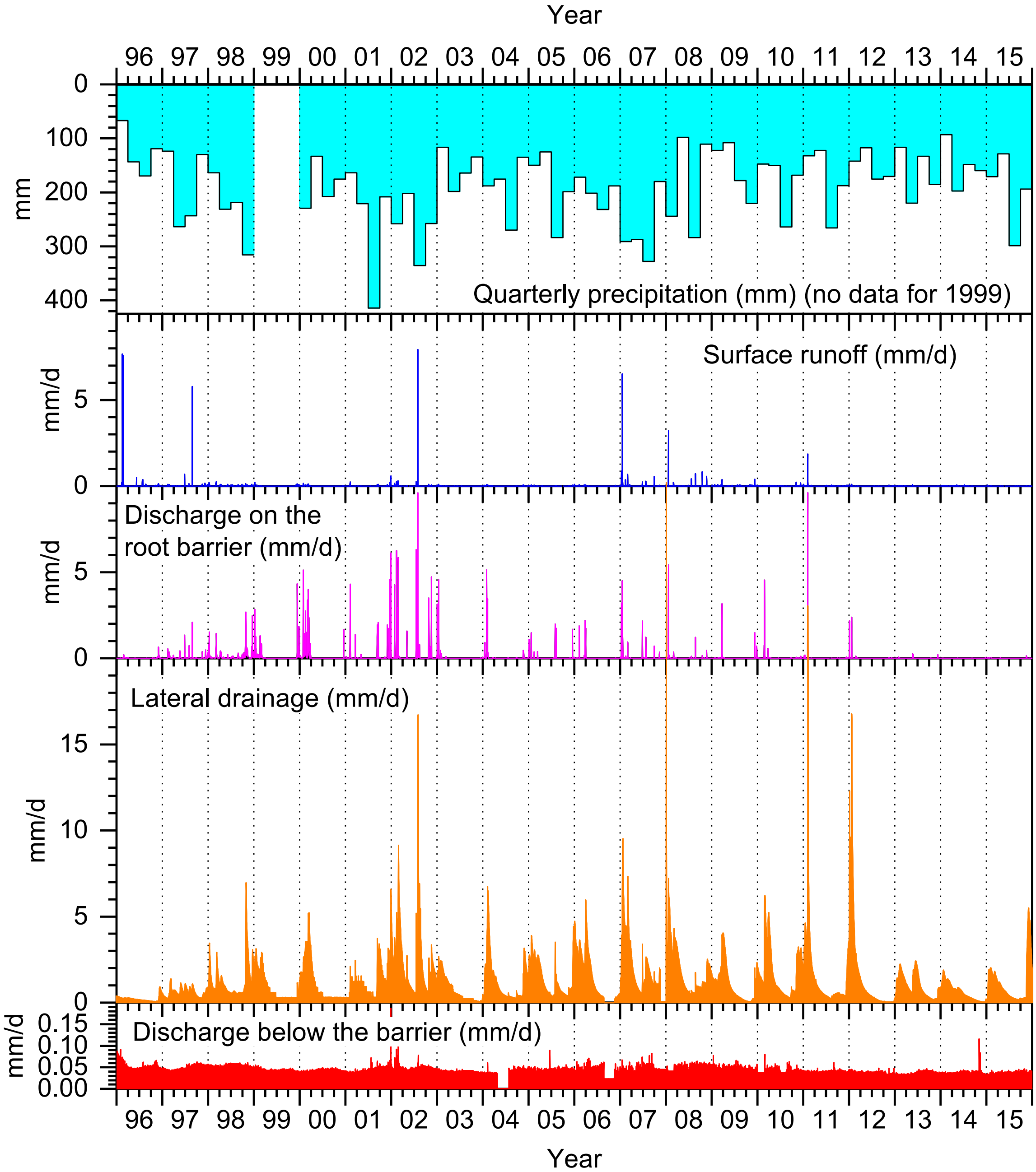

Figure 3. Time series of daily discharges (mm/d) of test field FS and quarterly precipitation (mm) of the Francop weather station from 01.01.1996 to 31.12.2015.

The largest annual discharge is lateral drainage. It largely depends on the inflow into the drainage layer, which is mainly determined by precipitation and evapotranspiration. Other values (surface runoff, interflow on the root barrier, changes in water storage of the upper layers) are only of minor importance. The annual total of lateral drainage in 2002 is extremely high. In contrast, the value of the remainder of the water balance equation, and this means in particular of actual evapotranspiration, for 2002 is extremely and unrealistically low; the values from 2003 to 2015, too, are too low. This is caused by lateral drainage values that are too high compared to the values of the years before 2002. Simulations with HELP 3.95 D (Berger and Schroeder 2013) for the period 2002 to 2015 resulted in an average annual actual evapotranspiration of 459 mm, and indicate that the measured lateral drainage on the annual average is more than double as high as it should be in the test field FS with intact boundaries and an intact measurement system. Most likely external water was flowing from outside the test field boundaries into the lateral drainage layer of FS. Therefore, a bow-shaped sheet piling was constructed above the top end of the test field in December 2014 to prevent external inflow of water into the test field.

The time series of the daily lateral drainage shows a pattern typical for drainage layers. As a reaction to large inflow / precipitation events peaks in the lateral drainage occur followed by exponential decreases of the flow rates when the inflow into the drainage layer stops.

An evaluation of the interlinking and of time lags between surface runoff, interflow on the root barrier and lateral drainage based on hourly data can be found in Berger et al. (2009).

3.3 Water Chemical Analyses

The concentration of specific ions in the leachate of the test fields results from both, the elemental input by precipitation and the chemical processes within the percolated layers. The time series of the ion concentrations allow to some extent conclusions regarding the hydraulic system behaviour since the construction of the test fields in 1995.

The concentration of the very mobile chloride ion (Cl^-) in the lateral drainage layer above the barrier decreased within a few years to a level of about 10 to 20 mg l^{-1} which is typical for natural conditions in this area (Figure 4). In contrast, the chloride concentration in the percolate below the barrier remained nearly constant on a level of about 150 mg l^{-1} which is typical for the river Elbe. This indicates that the barrier was not percolated by fresh water from the layer above, but that the water in the barrier percolated downward very slowly.

Like chloride, also the sulphate ion (SO_4^{2-}) is relatively mobile. However, the barrier material shows relatively high concentrations of sulphur, an element that is largely affected by redox processes within the barrier. During material processing and construction of the barrier, the material came into contact with oxygen. This resulted in high concentrations of sulphate in the discharge below and in the drainage above the barrier for the first years that were decreasing (Figure 5). Since 1997, the concentrations in the discharge below the barrier were low due to reducing conditions. On the barrier, due to the contact between draining water and the barrier and oxidation processes along the boundary, sulphate is transported upwards by diffusion, resulting in varying concentrations in the drainage water. At the end of the monitoring period, the sulphur measured in the lateral drainage above the barrier and in the discharge below the barrier summed up to 9.2 % of total sulphur of the barrier of which about 95 % occurred in the drainage water.

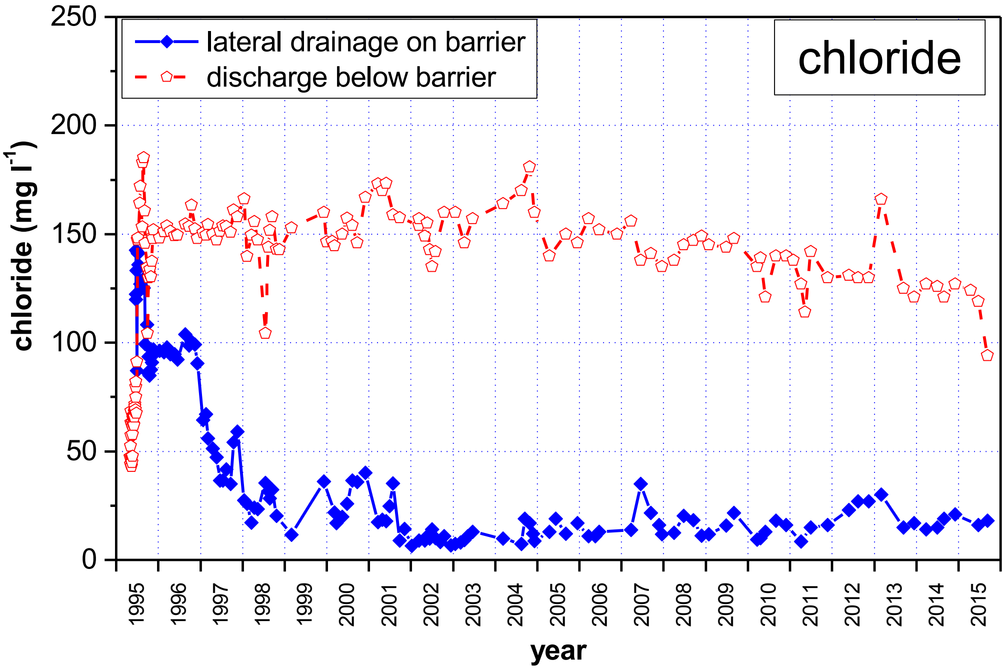

Figure 4. Time series of chloride concentration in the lateral drainage on the barrier and the discharge below the barrier of test field FS.

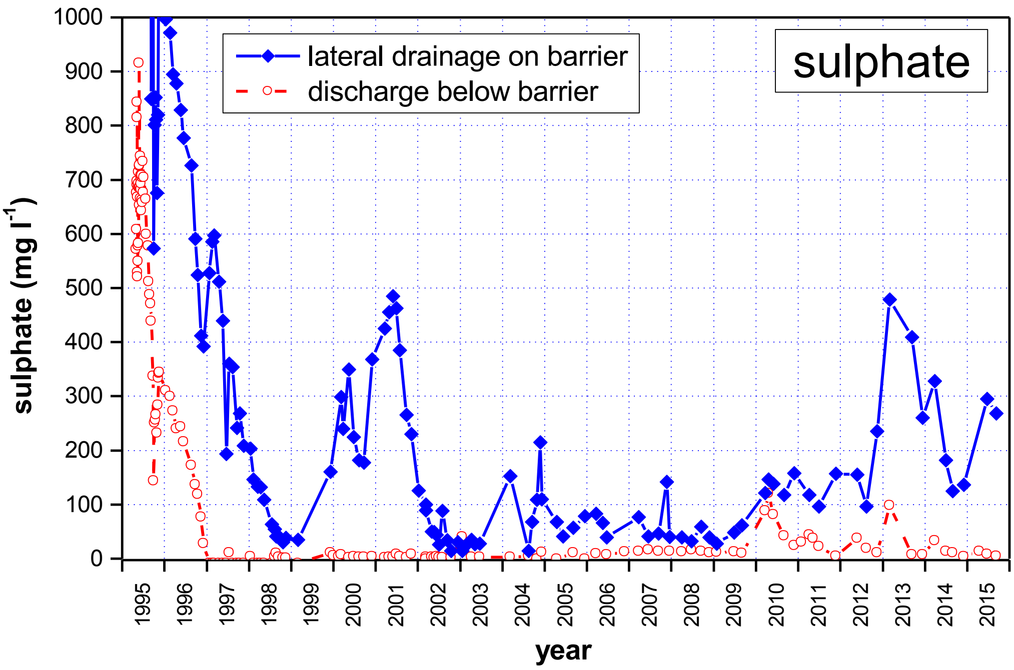

Figure 5. Time series of sulphate concentration in the lateral drainage on the barrier and the discharge below the barrier of test field FS.

4. CONCLUSION

The study of the water balance and the discharges of a field-scale lysimeter with layers of dredged materials on the landfill Hamburg-Francop from 1996 to 2015 allows the following conclusions:

- The barrier constructed of METHA-material has performed well for more than 20 years after construction. The average annual leakage is 14.9 mm corresponding (under specific assumptions) to an in-situ hydraulic conductivity of $5 * 10^{-10}$ m/s (the saturated hydraulic conductivity measured in the laboratory after construction was $1.2 * 10^{-9}$ m/s). This is far below the maximum value required in the German landfill ordinance (DepV 2009) of $5 * 10^{-9}$ m/s. As shown previously, the METHA-material has a high risk of crack formation due to dewatering. However, so far neither the discharges nor the hydro-chemical parameters indicate preferential flow through the barrier. This is likely due to the following reasons:
  (1) The large thickness of the barrier (1.5 m in contrast to the minimum requirement of the German regulations for landfills of 0.5 m);
  (2) The large overload of 2.5 m layers above the barrier that countervails cracking of the barrier;
  (3) The 'slow' lateral drainage layer on the barrier, keeping its surface wet all over the year;
  (4) To a certain extent the root barrier on the lateral drainage layer which smoothes the inflow into the drainage layer, and
  (5) The sufficient amount of plant available water in the recultivation layer of 156 mm.
- The field measurements of the discharge below the barrier confirm the appraisal of aptitude for the use of the METHA-material in the construction of landfill liners that has been published by the working group 'waste' of the German states (Länderarbeitsgemeinschaft Abfall, 'LAGA') in 2008 (LAGA Ad-hoc-AG „Deponietechnische Vollzugsfragen" 2008).
- The lateral drainage layer constructed of METHA-sand also has performed well for more than 20 years. Its low saturated hydraulic conductivity ($0.7 * 10^{-4}$ m/s, a factor of 14 smaller than the minimum requirement according to the German regulations) is compensated by a much higher thickness. Consequently, lateral drainage occurred all over the year. Therefore it is reasonable to assume that the surface of the barrier was kept wet all over the year. This contrasts to the drainage layers of the test fields on the landfill Hamburg-Georgswerder (k_f $1.3 * 10^{-3}$ m/s, overlain by only 75 cm recultivation layer) that in many years had no lateral drainage for several months during summer.
- The entire 4 m thick cover system of the Francop site has performed well.
- The design of the entire cover system as well as its components constructed from pre-treated dredged material has proved to be suitable under the climate of the site.

The measurements of the water balance and the hydro-chemical parameters are continued by Hamburg Port Authority (HPA) as a part of the long-term monitoring of the landfill.

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