

Equifill

Landfill site for
predominantly inorganic waste

Sustainable landfill Foundation

Colophon

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Equifill, landfill site for predominantly inorganic waste

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1. Introduction

1.1 Background

This is the reference document 'Equifill' for the complete sustainable landfill project. A reference document contains general and specific information on the concept concerned, and is a reference work for those with a detailed interest in the subject.

The following reports on the sustainable landfill project are available:

- Final report (scientific reference point)
- Summary + Frequently Asked Questions (FAQs)
- Reference documents: (i) Bioreactor, (ii) Equifill, (iii) Monolith and (iv) Database/Modelling

Further information on the sustainable landfill project can be obtained from the secretariat of the Stichting Duurzaam Storten (Dutch Sustainable Landfill Foundation) c/o Vereniging Afvalbedrijven (Dutch Association of Waste Companies) for the attention of Jeanne Kok (+31 (0)73-6279444).

The Dutch Sustainable Landfill Foundation¹ aims to contribute to a sustainable society with the sustainable landfill project. The starting point for sustainable landfill is that the current Dutch and EU waste management hierarchy will be implemented. This means that prevention, reuse and incineration are optimised in the first instance. Sustainable landfill will provide a necessary safety net for the remaining waste, which will minimise any effects on the environment.

1.2 Aim of the project

The Dutch Sustainable Landfill Foundation also aims to minimise emissions from landfills, in line with the Bruntland Committee's definition of sustainability. It is concerned not merely with reducing the absolute quantity of emissions but also on reducing the legacy for future generations.

The aim of the project was initially to determine the practical feasibility of a number of theoretically conceivable sustainable landfill concepts for specific situations. It was quickly apparent that it was possible to go yet a step further because analyses demonstrated that the diverse concepts provided sufficient building blocks for a generic sustainable landfill concept.

The following operational objective was formulated on this basis:

Demonstrate that a landfill concept is possible, whereby the emissions will be reduced within 30 years to a level that requires no specific reduction measures.

1.3 Approach

The idea for Sustainable landfill came from the competition 'Tidiness is good - landfill through the ages' (from the VVAV now VA). The Dutch Sustainable Landfill Foundation (members of the VA) gave a consortium of advisors and specialists the task of establishing the feasibility of

¹ Dutch Landfill Sector with the following participants: Vereniging Afvalbedrijven (Association of Waste Companies), NV Afvalzorg, Afvalverwerking Stainkoeln, Essent and A&G of the VBM)

sustainable landfill within five years. The consortium of advisors that contributed to the project included, amongst others, staff from the following companies: ECN, TNO-MEP, Grontmij, GroundwaterTechnology, GeoDelft, Royal Haskoning (of the IWACO), ERM-NL and Advibe (replaced ERM-NL).

The project had the following phases:

- **phase 1: start up (2000- 2002)**; development of theory, testing framework, start of testing on different scales. This involved carrying out laboratory tests and larger scale experiments in lysimeters and a pilot project at a landfill site. The results are stored in a database, and the first interpretations of them have taken place.
- **phase 2: development (2003)**; completion of the data, confirmation of theory, policy feasibility (approach, restrictions, possible solutions) and a view to practical implementation.
- **phase 3: Generalisation and finalising (2004-2005)**; practical implementation (design, economic), ascertain integral feasibility.

When assessing whether sustainable landfill is a feasible concept, use was made of the (inter)nationally available information from practice and research (pilot, lysimeters, laboratory, and practice), and the three pilots that were undertaken during this project. These pilots concerned:

- organically-dominated landfill (Bioreactor): a technology aimed at stabilising organic matter as quickly as possible, thereby reducing emissions of pollutants.
- non-organically dominated landfill (Equifill): a technology aimed at a landfill with stabilised organic matter, whose emissions from pollutants are low;
- cold immobilised landfill (Monolith): a technology aimed at binding specific wastes that cannot be landfilled in the Equifill. This technology changes the leaching mechanism from bulk leaching (by percolating water) to surface leaching (water mainly comes into contact with the outer material).

1.4 Most important outcomes of the project

The sustainable landfill project has three important outcomes:

- The total emissions are lower than those from conventional landfill.
- The emissions occur faster than those from conventional landfills.
- Better prediction and control of emissions is possible.

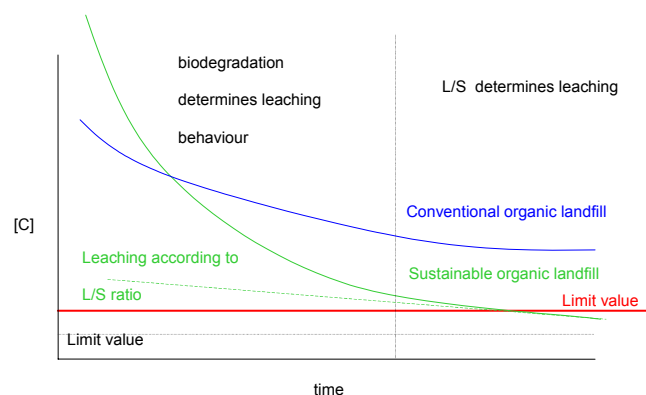


Figure 1 Concentrations in leachate as a function of time for conventional and sustainable landfills.

Firstly, the application of sustainable landfill in comparison with the conventional landfill process results in a reduction in the total emissions (through waste-waste interactions). Secondly, the period over which emissions arise is reduced (see Figure 1). This not only leads to fewer emissions in total (the area under the curve is smaller for sustainable landfill) but also to a reduced burden on future generations (the curve for sustainable landfill diminishes more steeply). This means that perpetual aftercare is no longer necessary. This is not only financially advantageous but also leads to a large reduction in the risk to future generations.

These positive effects are possible because the biochemical process is actively influenced by optimising the circumstances under which the necessary degradation of the material to be landfilled takes place. An example of this is the addition of sufficient water, which results in processes occurring earlier and more efficiently.

The third outcome of the sustainable landfill project is that the knowledge built up has led to the better simulation models, which can predict and control emissions more accurately (the Black Box has been opened). It is possible to structure sustainable landfill in such a way that emissions are below the limit values for all the important elements, and there could also be a stable pattern of emissions. Thus it is possible that the expensive landfill cap can be put in place later or even be omitted, without leading to an additional burden on the environment. This is financially advantageous to the operator and the aftercare organisation (responsible for aftercare), and therefore to the rest of society. Moreover, the omission of such a cap is in accordance with present EU legislation but not with that of the Netherlands. The sustainable landfill project thus also shows that the requirements specific to the Netherlands are not necessary. Furthermore, capping in accordance with Dutch rules actually postpones the occurrence of emissions. The problem is thus passed on to future generations. This is precisely the opposite of sustainability.

1.5 Comparison of sustainable and conventional landfills

The differences and similarities between conventional (Landfill Decree Soil Protection) and sustainable landfill are indicated in Table 1.

Table 1 Comparison between conventional and sustainable

Aspect	Conventional	Sustainable
Location choice	Not regulated	Important, surroundings should have self-cleansing capacity
Design	Conforms with Landfill Decree	No capping Additional measures (drainage, ventilation)
Exploitation	Conforms with Landfill Decree	More effort aimed at controlling process
Acceptance	Within the rules landfill bans	Within rules on landfill ban and dependent on influence on biochemical process
Emissions	Capture	Minimise
Aftercare	Eternal	Minimise
Conforms with Dutch rules	Yes	No (no capping) but can always be brought within the rules
Conforms with EU rules	Yes	No, acceptance on the basis of bulk properties instead of waste properties Yes, if acceptance is limited
Costs	Reference	Just as expensive to more expensive

1.6 Hypothesis

Equifill is a landfill concept, for which the premise is that all the pollutants within the landfill should be brought, within as short a time as possible, into equilibrium with the surroundings. This situation can be attained by instituting appropriate acceptance criteria, pre-treating wastes prior to landfilling, and taking measures during the operational phase (partial leaching and processing via the water treatment system). Balancing the available inherent buffering capacity for pH, redox and metal binding capacity in the wastes is crucial for this. The pH of equilibrium should be between 7 and 8 because this condition is stable in the long-term (surroundings also neutral) and it also represents minimal leaching for numerous pollutants.

2. Legal Framework

2.1 Introduction

The legal framework consists of legislation concerning waste as well as soil/groundwater. The legislation on waste defines the conditions for the method of disposal of waste, whilst the rules on soil and groundwater give target levels for quality. These two approaches are not entirely consistent, resulting in differences in the limit values. For example European legislation on waste accepts a certain loading of the soil if drinking water quality is guaranteed at the point of compliance. The Groundwater Directive provides that indirect discharges of dangerous substances must be prevented.

The sustainable landfill project considers and tests legislation on both waste and soil/groundwater. The legislation consists of the European regulation (section 2.2.) and the Dutch regulation (section 2.3). The legislation is presented schematically in Figure 2.

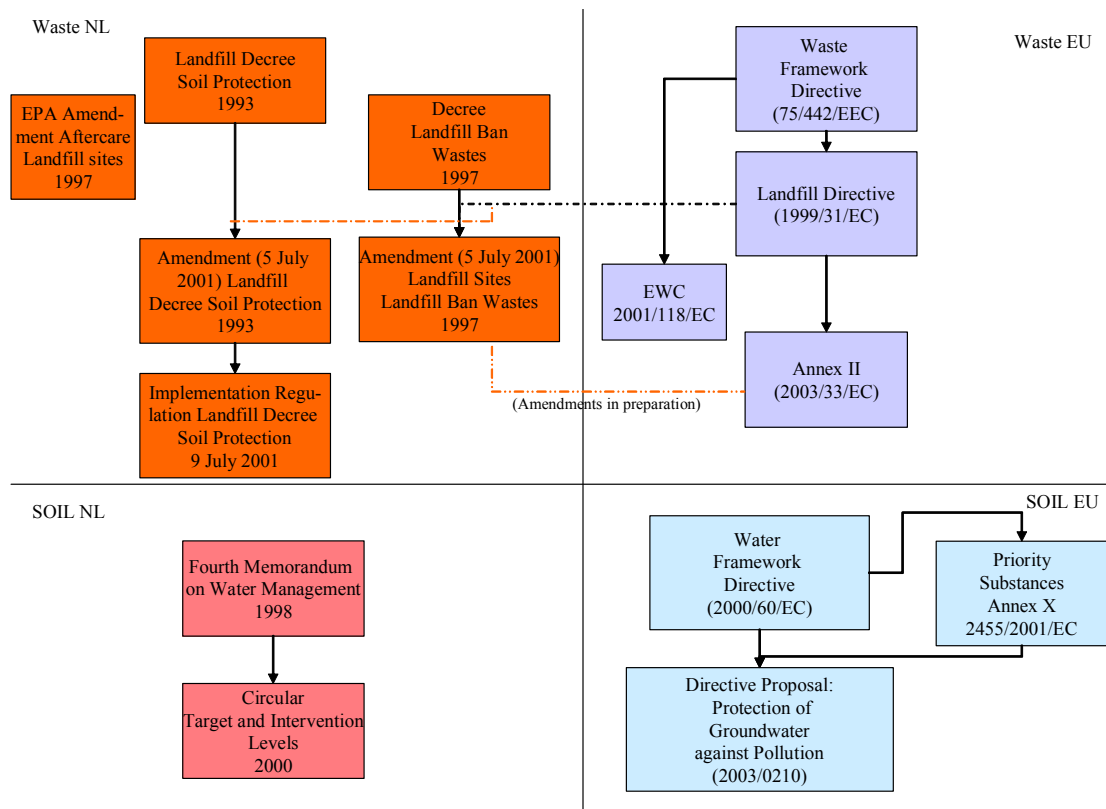


Figure 2 Schematic representation of the legal framework of Dutch and European legislation on waste and soil/groundwater protection.

2.2 EU legislation on waste

The European legislative framework contains the following landfill-related decisions that must be implemented into national legislation:

- Directive 75/442/EEC of 15 July 1975 on waste (Framework Directive);
- Directive 1999/31/EC of 26 April 1999 on landfill of waste (European Landfill Directive);

- Decision 2003/33/EC of 19 December 2003 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC (further elaboration Annex II of European Landfill Directive);
- Decision 2001/118/EC: European Waste Catalogue (EWC).

An evaluation of the properties of the sustainable landfill concept against the EU rules is given in:

- Annex A (1999/31/EC: European Landfill Directive);
- Annex B (2003/33/EC: Annex II).

Several relevant aspects are examined below.

2.2.1 Waste Framework Directive 75/442/EEC

The sustainable landfill project is entirely consistent with the fundamental principles of waste disposal as described in this Directive. This means that one of the functions of landfill is to act as a safety net for waste that cannot be treated in any other way (landfill has the lowest priority).

Definition of waste:

Any substance or objectwhich the holder discards or intends or is required to discard.

2.2.2 European Landfill Directive 1999/31/EC

Directive 1999/31/EC of the Council of 26 April 1999 on the landfill of waste.

The framework within which the sustainable landfill technologies are developed is in accordance with the European Landfill Directive. This Directive was officially published on the 16 July 1999. However, the Member States could not reach an agreement on common standards, such as limit values for the acceptance of certain wastes at a landfill, during the preparation of this Directive. The TAC (Technical Adaptation Committee) continued its work after the publication of the Directive in order to fill this gap, see details below on Annex II (section 2.2.3).

The European Landfill Directive distinguishes between three classes of landfill sites:

- landfills for inert waste:
 - * only for inert wastes that conforms to Annex II;
- landfills for non-hazardous waste:
 - * for municipal waste;
 - * non-hazardous wastes that conforms to Annex II;
 - * stable, non-reactive hazardous wastes with a leaching behaviour equivalent to non-hazardous wastes that conform to Annex II and the additional acceptance criteria of Annex II;
- landfills for hazardous waste:
 - * for hazardous wastes that conform to Annex II;

It is not forbidden to identify sub-classes. The original version of Annex II provides that the criteria for acceptance of wastes within a particular class must have regard to:

- protection of the surroundings, in particular groundwater and surface water;
- protection of the environmental protection systems;

- safeguarding the desired waste-stabilisation process;
- protection against risks to human health.

2.2.3 Annex II of the European Landfill Directive 2003/33/EC

Decision establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC (2003/33/EC).

As previously mentioned the TAC (Technical Adaptation Committee) continued its work after the publication of the Directive. The starting points for the TAC were widely supported:

- acceptance criteria and limit values based on the assessment of the actual risks to the environment caused by landfilling. This means that the following factors influence the assessment:
 - * properties of the surroundings;
 - * acceptance criteria and limit values dependent on the surroundings;
 - * acceptable risks translated into acceptance of wastes and protection measures.
- acceptance criteria and limit values for groundwater and surface water, based on scenario calculations with the use of scientific models.

A number of institutes subsequently undertook a number of scenario calculations in order to relate the results of the leaching tests to the objective (POC: point of compliance - a location point at which the set conditions are always met). Annex II of the European Landfill Directive is based on this model approach (see 2.1.2) which extrapolates a Point of Compliance concentration (in this case drinking water quality) to a 'source term' (the landfill). This approach is further explained in section 2.7.2. This means that wastes that may be accepted if according to the relevant dispersion model it will not influence the groundwater quality at POC to such an extent that the drinking water standards are breached. Thus neither the eventual positive nor negative effect of landfilling different waste types together is taken into account.

The research led to acceptance criteria and procedures being set, which were inserted into Council Decision of the 19 December 2002 in accordance with Article 16 of and Annex II to the European Landfill Directive (1999/31/EC).

The acceptance criteria, derived from the aforementioned calculations, for the acceptance of wastes at a particular class of landfill site are set in the decision. Thus the decision gives further elaboration to the 1999 Directive. Leaching from the waste must be lower than the set value. The leaching requirements are defined at $L/S=2$ and $L/S=10$. It is for the Member States to choose between the two. A composition requirement applies for a limited number of substances.

2.2.4 European Waste Catalogue (EWC) 2001/118/EC

Decision of 16 January 2001 amending Decision 2000/532/EC as regards the list of wastes.

The EWC provides a unique code for all wastes and indicates whether the waste is considered to be hazardous or non-hazardous. The EWC can only be used if the substance is definitely a waste.

The EWC is one of the means of assessing acceptance at a landfill site. The distinction between hazardous and non-hazardous makes the catalogue particularly relevant. Hazardous wastes are marked with a * in the catalogue.

2.3 European legislation on water quality

In addition to the European legislation on landfill sites, a number of directives concerning groundwater (policy) are also of importance:

- Directive 2000/60/EC of 23 October 2000 establishing a framework for water policy;
- Decision no. 2455/2001/EC (Annex X² of 2000/60/EC) establishing the list of priority substances in the field of water policy;
- Proposal for a Directive on the protection of groundwater against pollution (2003/0120 (COD)).

2.3.1 Water Framework Directive

Directive 2000/60/EC of 23 October 2000 establishing a framework for Community action in the field of water policy.

This Directive provides a framework for water policy. Water is a heritage that must be protected. Pollution by priority hazardous substances should cease or gradually be brought to an end.

The list of priority substances is presented in Annex X (2455/2001/EC). See below for proposal for Directive (2003/0120 COD).

2.3.2 Decision on priority substances in the field of water policy

Decision no 2455/2001/EC (Annex X, 20 Nov 2001) establishing the list of priority substances in the field of water policy and amending Directive 2000/60/EC.

The named substances (26) are persistent substances, chlorinated hydrocarbons, metals (lead and mercury) and others. See below for proposal for directive (2003/0120 COD).

2.3.3 Proposed Directive on the protection of groundwater

Proposal for a Directive on the protection of groundwater against pollution (2003/0120 (COD)).

A proposal for a Directive on the protection of groundwater was adopted in 2003. A recent version was published at the beginning of 2006 (Council Common Position). Prevention is the most important premise for this directive proposal (comparable to the Dutch SP). The draft Directive sets a requirement that indirect discharges of polluting substances into the groundwater must be prevented and limited. Indirect discharges are understood to mean: "discharges of pollutants into groundwater after percolation through the soil or subsoil." This is taken to include emissions from landfill sites.

In the short-term (22 June 2006) Member States must set threshold values for a number of substances. Concentrations above the threshold value indicate that the groundwater body concerned is in poor chemical condition; this must be prevented.

² Annex X is 2455/2001/EC and is an annex of Decision 2000/60/EC

Uniform threshold values have been set for two substances:

- nitrates: < 50 mg/l;
- active ingredients in pesticides, including their relevant metabolites, degradation and reaction products: < 0.1 µg/l.

For the following substances, threshold values must be established³:

- inorganic: Ammonium, Arsenic, Cadmium, Chloride, Lead, Mercury and Sulphate;
- organic: Tri- en Tetra-chloroethylene.

The indirect discharge of the following substances must be prevented:

- organohalogen compounds and substances which may form such compounds in the aquatic environment;
- organophosphorus compounds;
- organotin compounds;
- substances or preparation, which have been proved to possess carcinogenic or mutagenic properties;
- persistent hydrocarbons and persistent bioaccumulable organic toxic substances;
- cyanides.

For the following substances, indirect discharge is only permitted on the condition that it will not affect the attainment of good chemical water quality:

metals and their compounds;

- arsenic and its compounds;
- biocides and plant protection products;
- materials in suspension;
- substances which contribute to eutrophication (in particular, nitrates and phosphates);
- substances which have an unfavourable influence on the oxygen balance (and can be measured using parameters such as BOD, COD, etc.).

2.4 Dutch regulations on landfills

2.4.1 Landfill Decree Soil Protection (LS) + Implementing Regulation

The Landfill Decree Soil Protection (20 January 1993) asserts that both a bottom liner and a cap should to be put in place. The cap is a requirement of the Dutch government that goes further than the European Landfill Directive. The latter gives only recommendations, and no prescription for the cap.

In the Netherlands the capping must be installed as quickly as possible, and definitely within thirty years of laying the bottom lining. The bottom lining can, if it is not to be installed, be replaced by a geohydrological construction that affords at least the same level of environmental protection.

A system of investigation and intervention has been implemented following the implementation of the European Landfill Directive. The influence on the quality of the groundwater is set on the

(1) ³ per Member State specific

basis of the trigger level. If the trigger level is exceeded further investigation must be undertaken to establish if the exceedance was caused by the landfill site, also see Table 2.

Table 2 Assessment of groundwater quality

Trigger level =	Signal level + 0.3 * target level
Signal level =	Background level (reference point) *1.3
	V
Trigger level =	Background level *1.3 + 0.3 *target level

In words, this means that the groundwater concentrations may increase by 30% + 30% of the target level before an additional investigation must be undertaken.

If it appears that the landfill site was indeed the cause of the intervention point having been reached, an emergency plan must be drawn up in consultation with the competent authority. The so-called restoration obligation is thus applicable (where this is technically possible).

2.4.2 Decree on Landfill Sites and Landfill Ban (DLLB)

The Landfill Ban prohibits the landfilling of 35 categories of waste. The most substantial are: household waste, commercial waste, industrial waste with comparable composition to commercial waste, green waste and construction and demolition waste.

Definition of treatment: physical, thermal, chemical or biological processes that change the properties of the waste in such a way that the volume or hazardous properties are reduced, the treatment is facilitated or the recovery is enhanced.

It has been forbidden to landfill untreated waste since the implementation of the European Landfill Directive. This landfill ban does not apply to inert waste, or where treatment does not contribute to the reduction of negative consequences for human health or the environment due to the landfill.

Definition of waste:

- C₃-wastes: hazardous inorganic waste whose leaching value is less than or equal to the values indicated in the table attached (see annex 2.3);
- C₂-wastes: hazardous inorganic waste whose leaching value is greater than the value indicated (see annex 2.3), with the exception of mercury-containing waste, unprocessed arsenic sulphide sludge and tempering salts.

This distinction is not made in the European Directive.

2.4.3 Environmental Management Act Amendment (6 November 1997)

A separate regulation was made under the Environmental Management Act (Wet Milieubeheer) which required aftercare for an unlimited period for landfills which were still operational. The aftercare provisions are actually set out in an aftercare plan (EMA) drawn up by the operator. The Provincial Board must agree with the plan. The Provincial Boards are in charge of the measures as described in the aftercare plan.

If a 'closed landfill' declaration is issued, the operator is not held responsible for any damage which becomes apparent after the declaration is conferred. Subsequent damage can be paid for from the amassed aftercare fund.

2.4.4 Implementation of the European Landfill Directive in the Netherlands

A number of decrees, including the Landfill Decree Soil Protection and the Landfill Ban⁴, were amended to transpose the European Landfill Directive into Dutch legislation. The Implementing Regulation for Landfill Decree Soil Protection was also amended⁵.

From the above and the transposition table (Article e.g. decree vs implementation Dutch legislation) it appears that the Dutch legislation is stricter than the EU rules on a number of points, see Table 3.

Table 3 *Transposition capping and leachate collection*

EU	NL
Annex I point 2: Water and leachate management control water from precipitations entering into the landfill body	Art 3,4,5,8 LD
collect leachate unless it can be shown that there is no potential hazard	Art 4. point 4: a cap must be put in place which prevents water infiltrating the landfilled waste leachate must always be collected

⁴Decree of 5 July 2001 amending the Ivb and several other decrees in order to implement Directive 1999/31/EC (European Landfill Directive).

⁵ Decision DLLB published in State Journal 493 d.d. 23 October 2001

Implementation timetable for the European Landfill Directive and Annex II

The following data are relevant for a timely implementation of the Directive (Article VI State Journal 336):

- | | |
|--|----------------|
| • Publication Directive | 16 July 1999 |
| • submission conditioning plan | 16 July 2002 |
| • number of direct landfill bans come into force | 16 July 2002 |
| • classification of landfill sites for hazardous waste | 16 July 2002 |
| this also applies for a number of other requirements for landfill sites for hazardous waste. | |
| • amendment of permit | 1 January 2004 |
| This is to determine that certain requirements are applicable from 16 July 2009. | |
| The intention is that the requirements apply as soon as possible. | |
| • direct landfill ban for untreated waste at a landfill for hazardous waste | 16 July 2004 |
| • conditioning plan completely implemented | 16 July 2009 |

In addition Article 15 of the Directive states:

August/
September 2004⁶

At intervals of three years Member States shall send to the Commission a report on the implementation of this Directive, paying particular attention to the national strategies to be set up in pursuance of Article 5. The report shall be drawn up on the basis of a questionnaire or outline drafted by the Commission in accordance with the procedure laid down in Article 6 of Directive 91/692/EEC. The questionnaire or outline shall be sent to Member States six months before the start of the period covered by the report. The report shall be sent to the Commission within nine months of the end of the three-year period covered by it.

The Commission shall publish a Community report on the implementation of this Directive within nine months of receiving the reports from the Member States.

The drawing up and submission of the conditioning plan is a task for the operator (landfill). According to information from VROM⁷, most permits have been amended.

2.5 NL regulations on soil

2.5.1 Circular on Soil Protection

Groundwater quality standards, amongst others, are given in the Circular Target Levels and Intervention Levels Soil Remediation. A distinction is made between those for shallow and those for deep groundwater. The target levels describe the situation that may be presumed not to have been influenced; concentrations below the target levels can therefore be considered uncontaminated. The intervention levels indicate when the functional properties of the soil for human health, animals and plants are seriously diminished or are at risk of diminishing. In other words, there is no threat of serious (soil) pollution. Values are given for the following:

⁶ Verbal information via VROM

⁷ Mid-May 2004

- metals;
- inorganic components;
- aromatic compounds;
- polycyclic aromatic hydrocarbons;
- chlorinated hydrocarbons;
- pesticides/herbicides;
- other components (including mineral oil and phthalates).

The values are given in Annex 2.4. As can be seen from the tables there are no target or intervention levels for NO_3 . For nutrients, including phosphate and nitrogen compounds, it is assumed that there is a small residence time in the soil and a continual supply via the soil to the groundwater. Consequently, the means of eliminating such compounds should focus on supply; especially in the framework of deregulation. The preference is that it should be approached via other legislative frameworks, including legislation on fertilisers.

Conclusion: the Circular Target and Intervention Levels Soil Remediation does not provide the grounds for testing the problems presented by NO_3 ; however soil protection is effected via other legislative frameworks.

2.5.2 Fourth Memorandum on Water Management (1998)

The Fourth Memorandum on Water Management gives the national targets values (and also Negligible Risk (NR)) and the Maximum Permissible Risk values. The target level is a policy consideration of numerical values for the protection of ecosystems and human health in both the short and long-term. The values are presented in Annex 2.5. The following values were set for the nutrients and eutrophying substances, see Table 4.

Table 4 Limit values (groundwater) for several nutrients and eutrophying substances

Parameter	Target level	MPR ⁸
Nitrate (mgN/l)	5,6 = 24.8 mg NO_3 /l)	11.3 = 50.0 mg NO_3 /l)
Ammonium compounds (mg N/l)	2,0-10	
Chloride (mg Cl/l)	100	
Sulphate (mg SO_4 /l)	150	
Tot Sulphide (ug S/l)	10	

Thus as indicated, the policy objective is to reach an NO_3 concentration in groundwater of approximately 25 mg/l, with 50 mg/l as the upper limit. This roughly equates to the EU's groundwater quality proposal (2003/0210).

2.6 Assessment and evaluation

2.6.1 Assessment against EU rules

For an assessment of the EU rules and the properties of the sustainable landfill concepts see:

- annex A (1999/31/EC: European Landfill Directive);
- annex B (2003/33/EC: Annex II);
- annex C (2000/60/EC: Water Framework Directive);

⁸ maximum permissible risk

- annex D (2003/0210/EC: Groundwater Directive proposal).

This assessment indicates whether the article or recital concerned is:

- in accordance with the sustainable landfill concept (allows/opening for SL);
- in accordance with SL, depending of the interpretation (depending on implementation is SL may or may not be inconsistent with EU rules);
- not in accordance with the sustainable landfill concept (substantial or potential hindrance for SL).

There are no identified items, which would form a barrier to sustainable landfilling, but there are articles which, dependent on the interpretation, could (potentially) form a barrier for the implementation of sustainable landfill (see further evaluation in 2.6.2).

2.6.2 Evaluation sustainable landfill and legislation

The waste-related EU legislation provides a framework within which the properties and requirements of sustainable landfill fit.

EU legislation on groundwater quality is still in development. This makes it difficult to assess whether sustainable landfill would be compatible with it. The objectives of both sustainable landfill and soil policy are identical, namely that there is no negative impact on the quality of the surroundings. The European Landfill Directive does not require a bottom liner or cap for landfills for inert waste.

The emission of nitrogen from a landfill is at a level higher than 50 mg/l NO_3 and is fairly constant during subsequent delivery. The means of establishing the threshold value (for example depth of the measuring point) in the groundwater has not been set by all Member States. This could be a potential problem for sustainable landfilling.

The Dutch requirement for a cap is not in accordance with sustainable landfill. Infiltration is necessary in the management phase in order that final storage quality is reached; thereafter equilibrium is reached and isolation measures are superfluous.

Objective of sustainable landfill defined on the basis of the EU legal framework:

Annex II of the European Landfill Directive sets acceptance criteria for three classes of landfill sites. These criteria were determined on the basis of a permissible effect on a presumed nearby drinking water source. The European Landfill Directive does not require a bottom liner or cap for landfills for inert wastes. Therefore, it follows that the emission from a landfill for inert wastes can be considered acceptable. The following objective has been devised from the European legal framework:

A sustainable landfill complies as soon as possible, but in any case within approximately 30 years after the end of the operational period, sustainably with the emission limits (POC) for a landfill for inert waste. In addition, the threshold values (groundwater quality: in parts still to be determined) with respect to the groundwater quality will also not be exceeded. An example of a threshold value: ammonium: 2-10 mgN/l, nitrate: 50 mg/l.

2.7 Consistency of sustainable landfill acceptance criteria for with the European Landfill Directive

2.7.1 Introduction

An important element in the development of sustainable landfill technologies is the setting of the acceptance criteria. It is known that the control of the mix of wastes (cocktail) determines for the biochemical process in the landfill and thus emissions over time. At the same time, the limit values set for acceptance also determine economic feasibility. A very stringent acceptance policy (only inert wastes) yields a sustainable landfill but has no additional value. The challenge for sustainable landfill (for acceptance) is to establish as broad as possible a scale of wastes that may be accepted, and at the same time safeguarding the objective.

The maximum leaching values from wastes are determined by extrapolation from the threshold values (groundwater quality objectives) via a standardised model calculation to a source term (emission from the landfill).

Thus, ultimately the source term determines whether a waste can be accepted (EU approach). The source term can also be defined differently: the leaching from the total waste body landfilled. This definition recognises the fact that wastes (as commonly accepted) react with one another, and the interactions between the wastes determine the emissions, not the sum of the separate emissions per waste. Sustainable landfiling takes the source term as its starting point for acceptance, and examines both the narrow and broad definitions.

2.7.2 Development of EU acceptance criteria

The framework within which the sustainable landfill technologies are being developed is in accordance with the European Landfill Directive. As indicated previously, a number of institutes have under taken scenario calculations in order to relate the results of the leaching tests on wastes to the objective (POC: point of compliance; a location point at which the set conditions are always met), in this case drinking water quality. The approach is shown schematically in Figure 3.

The formulation of acceptance criteria is led by the quality objective for the surrounding area, the path and the source. Five steps were identified in order to clarify this approach (see Figure 3):

- step 1: Establish objective, at which value (in concentration, time and place) is the objective achieved (POC);
- step 2: What does the landfill look like (design, height, surface, etc);
- step 3: Establish infiltration into landfill, leakage through cover, concentration leachate and dispersion to surroundings;
- step 4: Extrapolate maximum concentration back to emission requirements at source (leaching requirements);
- step 5: Establish acceptance criteria coupled to a test (substances and combinations of substances).

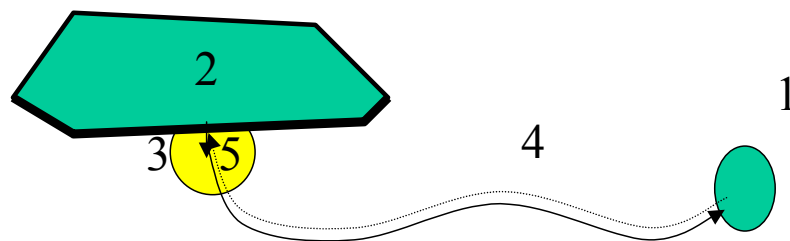


Figure 3 Schematic representation of the realisation of acceptance criteria for the acceptance of waste at landfills. The steps 1 to 5 are explained in the text above.

The TAC has formulated the standard conditions for all the steps. For these standard conditions the source term to be accepted (this applies for each waste) is determined by extrapolation from POC2. The sustainable landfill concepts follow the conditions for steps 1, 2, 3 but deviate from the standard conditions at steps 4 and 5. This means that the source term is defined more precisely. This does not have any influence on the model calculations as long as it is ensured that the source term remains within the requirements set (the quintessence of sustainable landfilling). A number of cases are implemented differently for the conditions within steps 1, 2 and 3 within the framework of the sustainable concepts (for example an infiltration regime can also be artificially imposed instead of the result of natural precipitation).

2.7.3 Acceptance criteria for sustainable landfill

The additional value of sustainable landfill is in step 5. Here it can be seen that the combination of substances is more than the sum of the substances.

The leaching properties are determined by extrapolation from threshold values (groundwater quality objectives) via a standardised model calculation to a source term (emission from the landfill).

Thus, ultimately it is the source term that determines whether a waste can be accepted. The EWC is used to define a source. The source term can also be defined differently: the leaching from the total waste body landfilled. This definition recognises the fact that wastes (as understood) react with each other, and the interactions between the wastes determine the emissions and not the sum of the separate emissions per waste. Sustainable landfilling takes the source term as its starting point for determining acceptance.

The source term is a dynamic entity during the landfill process. The properties change (over time) with the supply of waste because the mix of wastes changes over time. The control of the mix using leaching requirements is a set condition for sustainable landfill.

3. Methods

3.1 Description of experimental framework

The samples used for laboratory, lysimeter and pilot testing were composed of different waste streams, such as those delivered to Nauernasche Polder landfill at the start of this project. The landfill contains a cell installed for the pilot project (see section 3.4). The waste streams were initially subjected to a rapid leaching test (see section 3.2.2). On the basis of these results, it was determined whether the waste stream was 'suitable' to landfill in the sustainable landfill cell. A sub-sample of all the wastes landfilled in the pilot project was taken. These sub-samples were used by ECN for laboratory research (see section 3.2.1) and the lysimeter experiments (see section 3.3).

The eluates from the laboratory tests, lysimeter experiments and the pilot project were filtered (0.45 µm) and analysed for dissolved organic carbon (DOC) (Shimadzu 5000a TOC analyser), anions (ion chromatography), and major and trace elements by inductively coupled plasma-atomic emission spectrometry (ICP-AES). In addition to the usual series of heavy metals, a number of other elements commonly determined by ICP-AES are also measured using this technique. The macro chemical composition (elements such as Ca, Al, Fe, Si, Na, K) is especially important for subsequent geochemical modelling of solubility-controlled processes.

The results from laboratory tests, lysimeters and the pilot project will be compared in order to establish the relationship between the laboratory and practice. The assessment of materials is often done using laboratory tests. It is therefore important to establish whether the emissions in practice are consistent with behaviour on the laboratory scale.

3.2 Laboratory tests

3.2.1 Characterisation tests

Different laboratory tests were undertaken in phase 1 on a waste mixture that is composed of different streams as landfilled in the pilot project at Nauerna (see Table 5) and used in the lysimeter tests by ECN (see section 3.3). pH-static leaching tests were undertaken (PrEN 14429) on this mixture as well as on a waste mixture to which additional organic material was added (5% shredder waste and 5% sewage sludge) during the laboratory testing stage. The addition of extra organic matter increases the mobility of pollutants. Furthermore, column tests were carried out in accordance with NEN 7343, in order to measure the emissions over the long-term. The results from these experiments in this phase will be used as a comparison with the results from lysimeter testing and the pilot project. pH-static leaching and column tests were also done at a later stage to characterise the leaching from organic micro-pollutants. This entailed analyses being undertaken on PAH (polyaromatic hydrocarbons), VOX (volatile organic halides), BTEX (benzene, toluene, ethylbenzene and xylene) and mineral oil.

3.2.2 On-site verification measurements

All the wastes used in the pilot project were tested with a shortened leaching test to determine their suitability for sustainable landfill. This involved 50 g samples equilibrating on a mechanical stirrer for 1 hour in 100 ml of demineralised water (L/S=2). The pH and electrical conductivity (EC) are measured after the leaching test. A sensory check is also undertaken to

determine if the suspension contained mineral oil. The suspension is then filtered (0.2 μm) and the DOC and Cl^- determined in the leachate solution. The upper limit for admission into the sustainable landfill cell was 4000 mg/kg Cl^- (target level was 1000 mg/kg) and 1500 mg/kg DOC (target level was 500 mg/kg). Photometric methods and instruments from Hach-Lange (formerly Dr. Lange) are used to analyse Cl^- and DOC.

3.3 Lysimeter experiments

In October 2001 three lysimeter experiments were set up at ECN. The composition of the waste is the same as that used in the laboratory experiments and the pilot project (see Table 5). Three scenarios were chosen for these experiments:

lysimeter 1: Landfill methods as operated at Nauerna. The waste is divided and compacted by shovels at the landfill. The cell is thus built up in layers.

lysimeter 2: Embedding of more polluted streams in relatively clean/impermeable materials. This option is in the sustainable landfill concept to ensure that the emission from certain strongly leaching materials is limited by reducing their contact with water so that the contribution of these materials to the total is reduced.

lysimeter 3 (lysimeter-ORG): Reference scenario: In this scenario the waste is again divided as is customary at the landfill. However, a couple of other wastes, which it was known beforehand are not suitable for the sustainable landfill concept, are added to this lysimeter. These were a 5 w/w% addition of car shredder material and a 5 w/w% addition of dried sewage sludge. Both materials have a relatively high proportion of organic matter and heavy metals. These waste streams are landfilled in standard landfill practice.



Figure 4 Above view of lysimeter. The inner container is shown which ensures leachate and runoff are kept separate.

The lysimeters separately collect the leachate and runoff. This is done by using an inner container at the bottom of the lysimeters (see Figure 4). The water collected in the inner container is the leachate, the water that is collected outwith this container is the runoff. During

the course of the project it became apparent that the runoff in the lysimeters was of approximately the same quality as the leachate. It is probable that preferential channels affected the runoff.

3.4 Pilot project

The filling of the test cell was started on 28 April 2000 in cell 13AA at the Nauernasche Polder landfill. The volume of the test cell is 12000 m³. The test cell is completely isolated from the rest of the landfill by a geosynthetic membrane. The leachate is collected and drained by means of drains at the bottom of the cell and a gravel chamber in the lowest corner of the cell. An overall view of the construction of the pilot project is shown in Figure 5. In the level part of the cell there is a gravel column (see cylinder middle left in Figure 5), which is filled with 'rough granular' material to drain rainwater quickly (the vertical drain however remained closed during the whole project due to a changed view on the flushing of components). The cell is separated from the rest of the landfill by a plastic lining. However, in November 2000 a period of heavy rainfall may have resulted in leachate from an adjacent cell spilling over into the test cell. No correction was made for this, as it is not known how much water was involved. This overspill will also be a relatively small contribution to the total water quantity over the whole five year term. Representative samples were taken from all the loads, which were tested against the quality control parameters (pH, EC, chloride, DOC and mineral oil).



Figure 5 Overall view of the building of the pilot project at Nauernasche Polder. A bottom liner can be seen at the side of the cell. The waste was placed in layers with an excavator. Steel planks were used to safeguard the mobility of the crane.

The results of the chemical analyses (major and trace elements, Hg, anions, DOC, PAH, EOX (extractable organic halides) and VOX (volatile organic halides) are converted into a cumulative emission from the test cell. The L/S ratio attained (L/kg) is calculated using the fraction of the quantity of leachate collected in a given period divided by the total weight of the waste in the cell.

Table 5 *Overview of waste streams and quantities landfilled in the Equifill pilot project. The samples for laboratory research and the lysimeter tests were mixed using the same proportions.*

EWC code	Description	Quantity (wet tonnes)	Percentage weight (%)
01 05 08	chloride containing drilling muds and waste other than 01 05 05 and 01 05 06	467.62	2.75
07 05 12	sludge from on-site effluent treatment other than 07 05 11	15.38	0.09
08 04 12	sludges from adhesives and sealants other than 08 04 11	3.42	0.02
10 09 08	casting cores and moulds other than 10 09 07	90.54	0.53
12 01 16*	waste blasting material containing dangerous substances	288.82	1.70
12 01 14*	machining sludges containing dangerous substances	1728.22	10.15
12 01 17	waste blasting material other than 12 01 16	7.06	0.04
15 01 04	metallic packaging	11.82	0.07
16 03 06	organic waste other than 16 03 05	26.16	0.15
17 01 07	mixtures of concrete, bricks, tiles and ceramics other than 17 01 06	53.12	0.31
17 03 02	bitmious mixtures other than 17 03 01	4.42	0.03
17 05 03*	soil and stones containing dangerous substances	950.30	5.58
17 05 04	soil and stones other than 17 05 03	267.76	1.57
17 09 04	mixed construction and demolition waste other than 17 09 01, 17 09 02 and 17 09 03	55.02	0.32
19 05 01	non-composted fraction of household and comparable waste	9.44	0.06
19 10 04	fluff light fraction and dust other than 19 10 03	20.60	0.12
19 10 05*	other fractions containing dangerous substances	35.96	0.21
19 12 09	other mineral substances (e.g. sand and stone)	9429.49	55.37
19 12 12	other waste from mechanical waste treatment other than 19 12 11 (including mixtures of materials)	1401.22	8.23
19 13 02	solid waste from soil remediation other than 19 13 01	144.71	0.85
19 13 03*	sludge from soil remediation containing dangerous substances	1944.51	11.42
20 03 03	street cleaning residues	75.12	0.44
Total		17030.71	

* waste which are hazardous according to the EWC.

3.5 Determining methane emissions from pilot project

Methane emissions are measured by the so-called box-method. This method collects methane in a box (0.7*0.8*0.5 m) placed over parts of the landfill. The methane content is determined with a laser diode; this in turn enables the methane flux to be determined.

4. Results and discussion

4.1 Precipitation and leachate production lysimeters

When monitoring the lysimeters, precipitation on the ground is also recorded. The cumulative precipitation and the cumulative leachate production (total of leachate and runoff volume) per lysimeter as a function of time are shown in Figure 6. It is clear from Figure 6 that the leachate production in lysimeter 3 lags behind that in lysimeters 1 and 2. The difference is approximately 45% and can probably be explained by the addition of the dried sewage sludge (d.m. 94%) and shredder waste (d.m. 93%). These materials take in water until they are saturated, and only then does leachate production begin. The other materials in the lysimeters have an average dry matter content of 65%. The precipitation and leachate production in lysimeters 1 and 2 are synchronous over the winter months. Generally, the leachate production in lysimeter 3 remains constantly behind the precipitation; this indicates that each year this lysimeter must again become saturated before leachate is produced.

Over time (the start point in time was October 2001), it can be seen that during the autumn/winter (October-March) the volume of percolate produced approximates to half the volume of precipitation. During the spring/summer (April/September) the precipitation curve continues to rise whilst the leachate production all but stagnates as a consequence of the much greater evaporation during this period. The average precipitation and evaporation in the Netherlands per month is given in Figure 7. It shows that the evaporation is higher than the precipitation in the period April to August in the Netherlands.

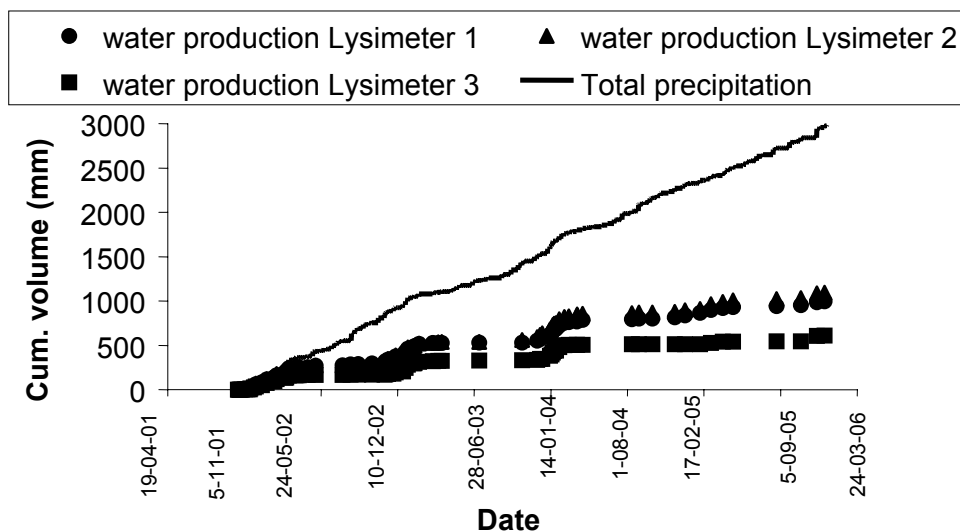


Figure 6 Cumulative precipitation and the cumulative leachate production per lysimeter as a function of time. Lysimeter 1 is filled in the same way as the pilot project at Nauerna, lysimeter 2 is filled with more polluted streams packed into the basic material (sludge), lysimeter 3 is filled in the same way as the pilot project at Nauerna with an extra addition of 5% sewage sludge and 5% shredder waste.

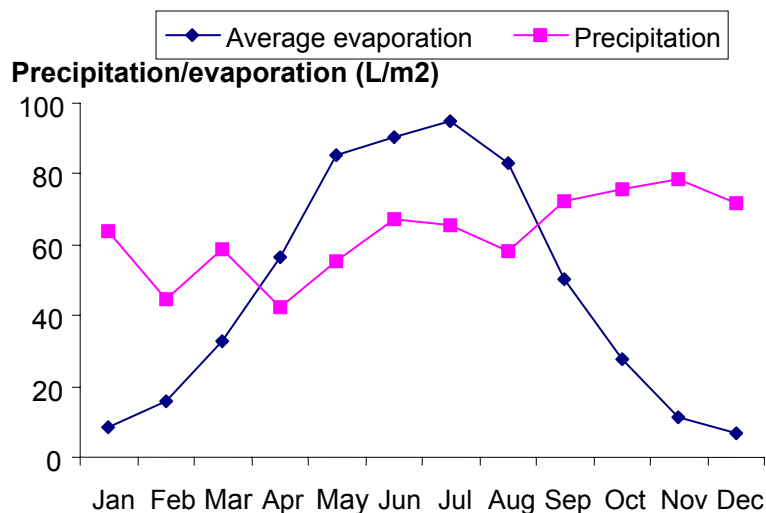


Figure 7 30 year average precipitation and evaporation in the Netherlands (Source: KNMI)

It is evident from water balance calculations that lysimeters 1 and 2 have approximately the same proportion of leachate production, evaporation and uptake (Figure 8). Lysimeter 3 however shows a different picture; 80% of the precipitation evaporates or is taken up by the material. It is probable that the field capacity of this mixture is greater than for the 'sustainable landfill mixture'. Especially in the first couple of months of the pilot the leachate production remained behind compared to lysimeter 2. For this reason 25 litres of water was added to lysimeter 3 after two months; thereafter the leachate production in lysimeter 3 was more in line with lysimeters 1 and 2 (Figure 6) but remained behind during the whole project.

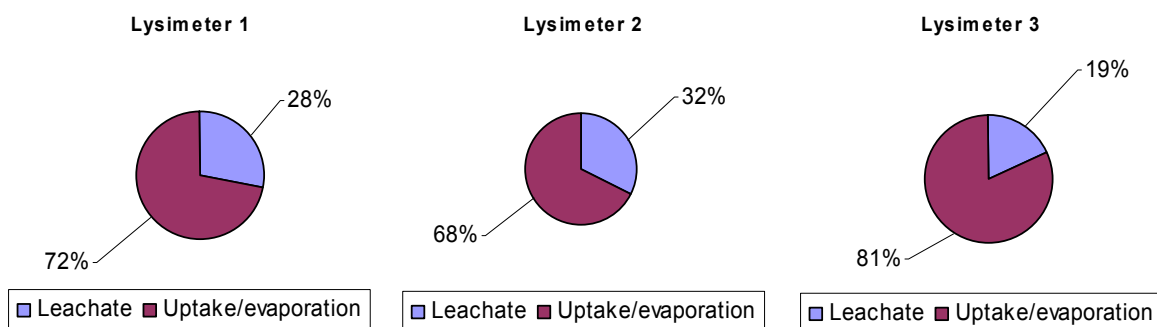


Figure 8 Relationship between leachate production and uptake/evaporation in the lysimeters

4.2 pH, conductivity, redox potential and temperature measurements on lysimeter experiments

In addition to the leachate volume, the pH, electrical conductivity, redox potential and temperature of each sample are measured. The results of these measurements are given in Figure 9. The results from the leachate (P) and runoff samples (R) are presented separately for each lysimeter. The pH seems to follow a trend; in the summer period (with little leachate production) the pH increases by 1 to 2 units,

especially in the first year. Thereafter the pH stabilises again. It was previously thought that the increase in pH could possibly be explained by the leaching of alkaline drilling muds (pH 10.6) in the lysimeters. Laboratory research by Chabbi & Rumpel (1) shows that the pH increases significantly (2 units) due to plant growth. Each summer plants also grew in the lysimeters and during this period a pH increase of approximately 1-2 units was seen. The results discussed above are thus in accordance with this study. When pH is plotted as a function of L/S (

Figure 10), it is clear that the L/S attained at the pH peaks in the samples is different for the lysimeters. This is an additional indication that the pH increase is indeed seasonal.

Figure 9 also shows that the redox at the beginning of the test is distinctly lower than the current measured values. The change took place after approximately one year after the start of the test. This is most probably due to the oxidation of the waste body, and to the limited scale of the lysimeters (1.5 m^3) in comparison with the pilot project at Nauerna ($12,000 \text{ m}^3$).

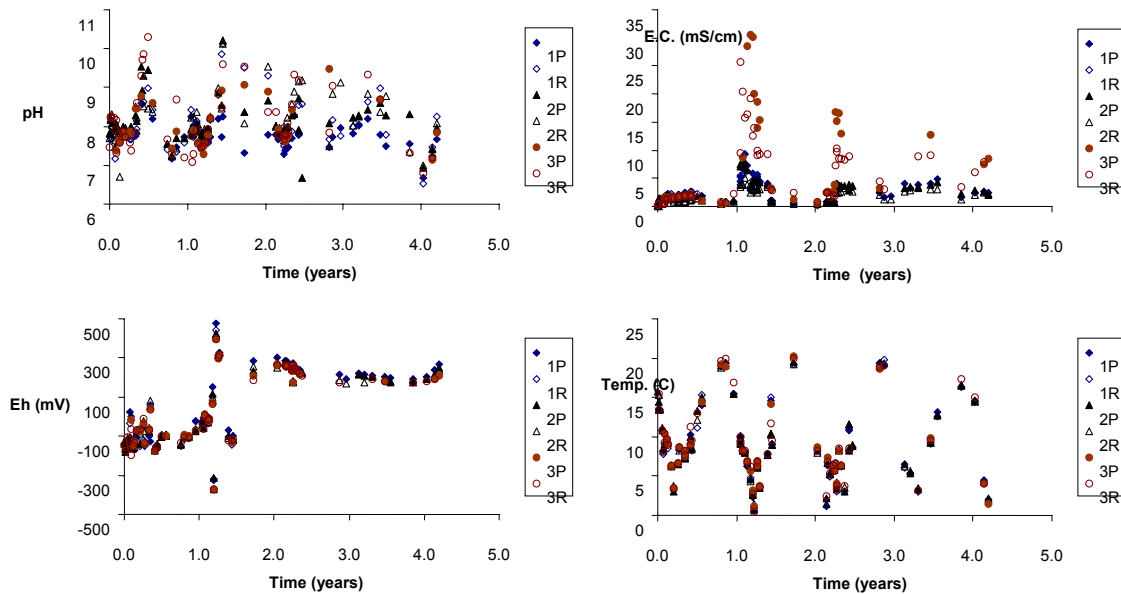


Figure 9 pH, E.C., redox and temperature as a function of time (the starting point in time is October 2001). P indicates the collected leachate and R indicates the runoff.

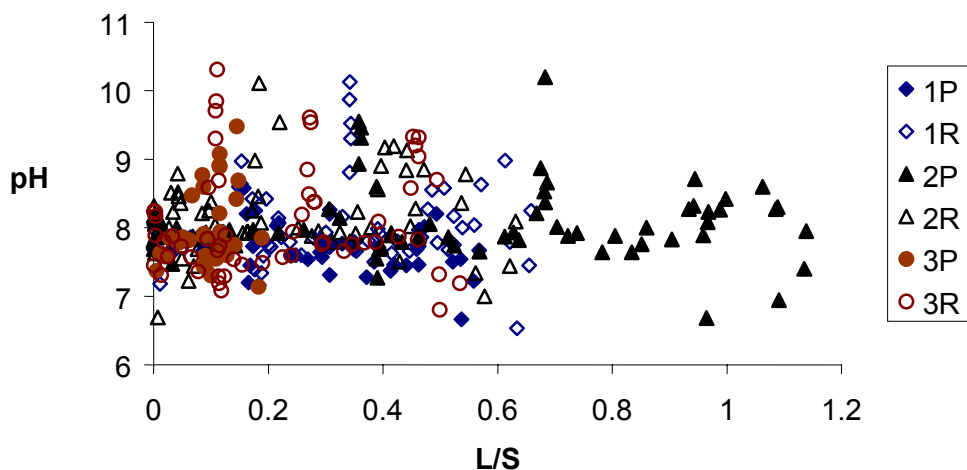


Figure 10 pH as a function of the L/S. P indicates the collected leachate and R indicates the runoff.

The electrical conductivity (E.C.) increases from the beginning to a constant value (0.7-2.5 mS/cm) and decreases again slightly after approximately 300 days (0.4-1 mS/cm). It abruptly increases sharply after around 350 days to values of 8-10 mS/cm in lysimeters 1 and 2 right up to 30 mS/cm for lysimeter 3. A peak in the electrical conductivity is continually observed in the following years. The absolute height of the peak becomes continually lower over time. The increase in the electrical conductivity cannot be explained on the basis of the input of individual waste streams in the lysimeter and the pilot project at Nauerna, see Figure 11. The results of the electrical conductivity measurements in the short on-site tests, which were undertaken during the construction of the pilot project at Nauerna, are given in this figure. The highest measured electrical conductivity in a fraction is approximately 8 mS/cm. The average

of the electrical conductivity measurements is 3 mS/cm. It seems that the increase is not caused by the individual wastes.

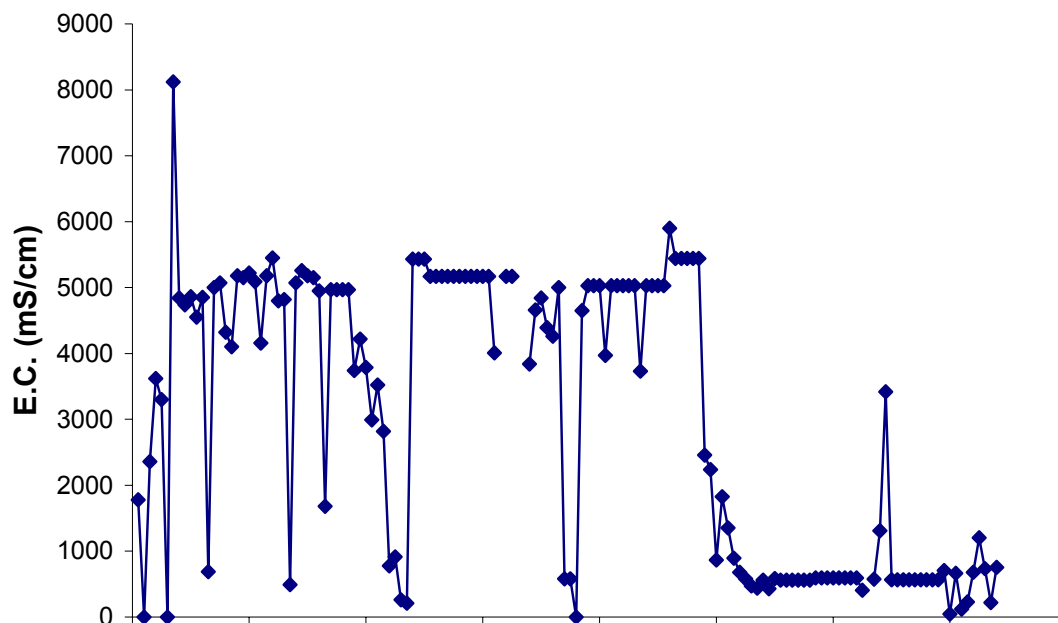


Figure 11 Results from electrical conductivity measurements on individual waste streams during the short on-site tests undertaken during construction of pilot project at Nauerna.

There are three possible explanations for the peaks in the E.C. results. The increase in the electrical conductivity could be linked to sea salt being blown about. At the end of October 2002 there was a very heavy south-westerly storm. In this period there were also regular hard south-westerly winds. The lysimeters are less than one kilometre from the sea. At that time it was established that sea salt was falling as far as the area around the lysimeters (salty deposit on the windows of the buildings). This salt load can perhaps not completely explain the effect seen; the electrical conductivity of sea water is approximately 55 mS/cm. Half of the leachate would have to have come from sea water for that to be the case.

Another reason for the peaks in electrical conductivity is that leachate production is very low over the summer (see section 4.1). The small quantity of water infiltrating the waste is present for a long time, and so has the chance to dissolve the salts present in poorly accessible parts. This water is subsequently flushed out during the wet period and therefore initially has a higher salt load.

Likewise, the effect of preferential channels can contribute to a temporary increase in the electrical conductivity. When the waste dries out, shrinking and/or fissure formation can occur. This can give rise to new channels and those previously dry areas within the waste body can suddenly come into contact with water. This results in a higher electrical conductivity in comparison with the previous situation.

In reality, all three effects can be involved. However, the absolute importance of these mechanisms cannot be ascertained on the basis of the measurements undertaken.

4.3 Leaching as a function of pH and L/S ratio

The dominant leaching mechanism for the emission of an element can be deduced from the results of the emissions as a function of the L/S ratio (on the laboratory, lysimeter and pilot scales). The results of the laboratory tests, lysimeters and the pilot project are compared in order to establish the relationship between those produced in the laboratory and in practice. The assessment of a material's effect on the environment is commonly done using laboratory tests. It is therefore important to establish if emissions in practice correspond to behaviour in the laboratory.

Three leaching mechanisms can be roughly distinguished: solubility-controlled, availability-controlled, and solubility-controlled followed by depletion. These mechanisms are important for the long-term behaviour of an element.

When the leaching of an element is solubility-controlled, one (or more) mineral phase(s) is present in the system that to a large extent determines the solubility of that element. There is equilibrium between the solid and liquid phases as long as these mineral phase(s) are present. Thus the concentration in the liquid phase will be equal to the equilibrium concentration (solubility) of the material concerned. This mechanism is characterised by consistent concentrations in the leachate solution as a function of the L/S ratio. When the cumulative emission is calculated as a function of the L/S ratio and plotted logarithmically, the curve has a gradient of 1.

The leaching of pollutants is controlled by availability when there is very limited or no interaction with the solid matrix. This mainly concerns soluble salts and elements, which are very soluble in the pH range concerned. The concentrations are high at low L/S values and decrease rapidly after one of the waste's pore volumes is flushed. This trend can be obscured in the lysimeters and the pilot project, where preferential channels can lead to subsequent discharge of these elements from relatively inaccessible areas within the waste body. The cumulative emissions of availability-controlled elements quickly level off.

It is also possible that solubility control by a mineral results in the depletion of the element at higher L/S values. The concentrations at lower L/S values will then remain the same due to solubility control. At a certain point, the element is depleted and the concentrations will decrease. The cumulative leaching has a gradient of 1 at first; the curve will then level off once the element is depleted.

Finally, there are also elements for which more complex processes play a role, such as redox conditions. These elements are discussed in section 4.3.4. This report provides an overview of all the elements that were analysed in this project. The results are either discussed per element or in groups in which the elements display the same behaviour. Four groups of mechanisms have been distinguished, namely: solubility-controlled emissions, availability-controlled emissions, solubility-controlled emissions followed by depletion, and a number of elements for which atypical observations were noted.

Towards the end of the project it was established that the calculated cumulative L/S ratio in the pilot project was not correct. It seems that the flow meters used in the pilot project at

Nauerna did not give the correct volume, due to the presence of air in the pipes (the pipe was completely filled with water). This problem is currently being resolved so that the measured volumes can be corrected at a later date. However, at the time of writing it is not possible to correct the volumes. The L/S ratios given in this report are thus certainly too high. In order to reproduce the effect of the L/S on the calculated emissions, the results of a column test in Figure 12 have been corrected using an L/S ratio a factor of 10 lower. It can be seen that the data principally shifts towards the original leaching curve. The emission at a certain L/S ratio is approximately a factor of 2 lower under the assumption that the L/S ratio will in actual fact be a factor of 10 lower. This assumption is very probably an overestimation of the actual correction that will be made in due course. This means that the interpretation of the emissions from the pilot project will not change when the measured L/S values are corrected. The comparison of the emissions with the acceptance criteria of the European Landfill Directive will take place using the results of the column test. This also means that no change in the interpretation will take place.

The results of the laboratory and lysimeter testing and the pilot project are compared as a function of the L/S value. Any deviation in the emissions from the pilot project, analogous to the outline in Figure 12, should be taken into account when considering this comparison (the absolute extent of the effect cannot yet be determined).

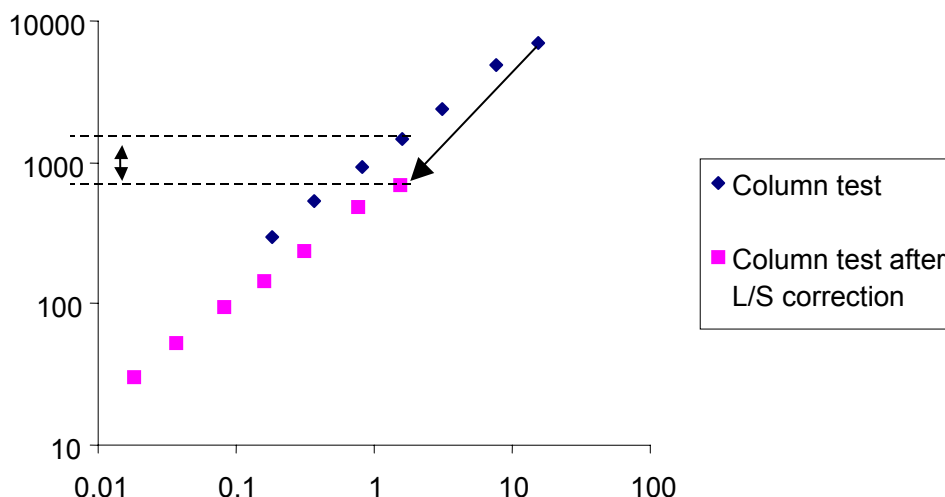


Figure 12 Influence of the L/S correction on the cumulative emission. The result of a column test (♦) is used in this example, in which it is assumed that the L/S is a factor of 10 lower (■).

4.3.1 Solubility-controlled emissions of pollutants

The emissions of the solubility-controlled elements are given in Figure 13 to Figure 15. In general, the emissions from all the tests are within a very narrow bandwidth; this also applies to the measured concentrations in solution. This means that the tests done on the three scales give a consistent view, and that in these cases the emissions measured in the column test are a good indication of emissions over the long-term. This evaluation will compare the emission from the column test, the lysimeter experiment containing waste such as that landfilled at Nauerna (Lysimeter 1) and the pilot project (Pilot). These three tests are the most similar.

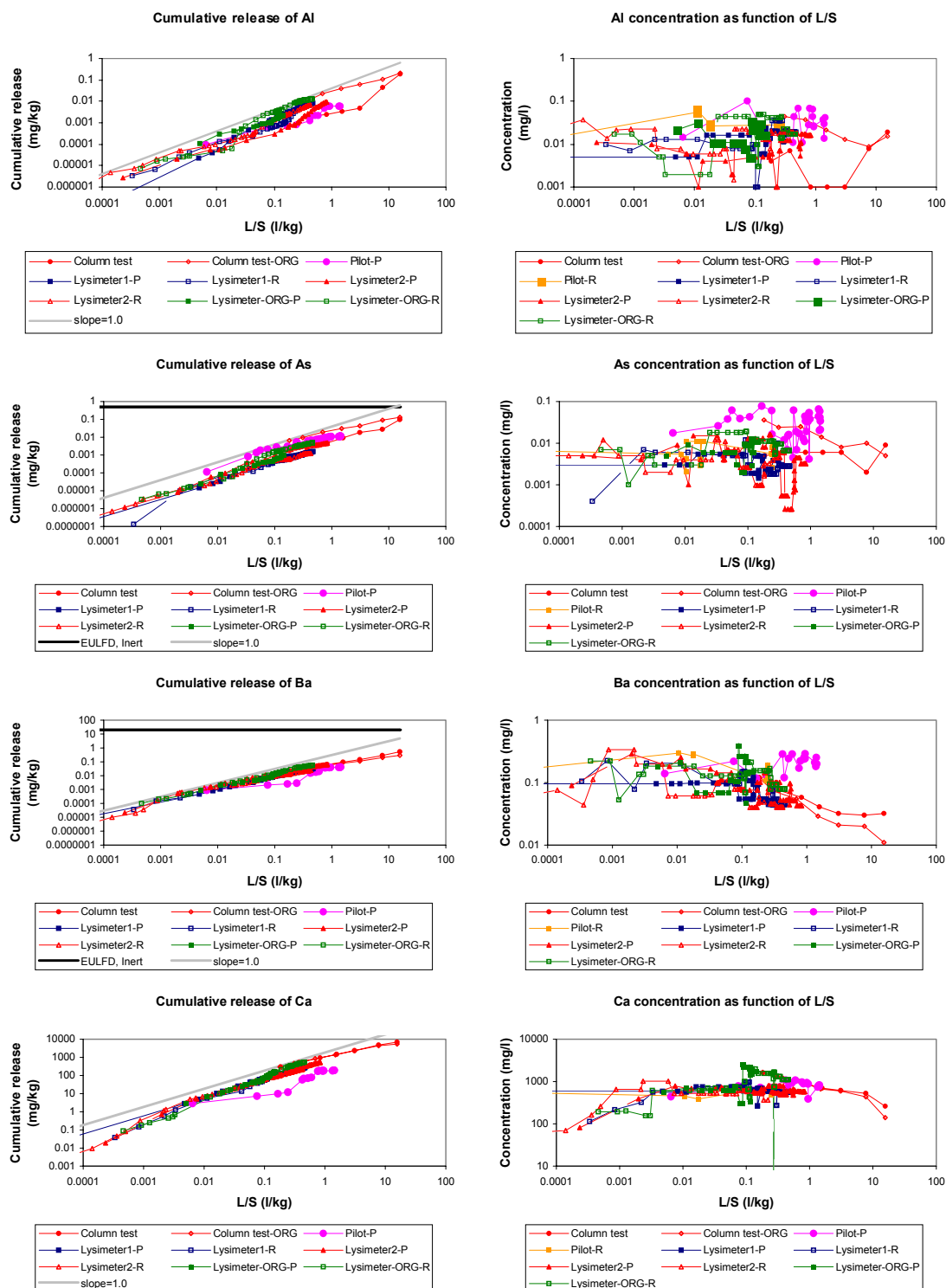


Figure 13 Emissions of Al, As, Ba and Ca as a function of the L/S ratio in laboratory measurements (column test), lysimeter experiments and pilot project. P indicates the leachate, and R indicates runoff

In addition, the release of pollutants from the lysimeter-2 mixture (more polluted streams packed into poorly permeable materials) gives comparable results in many cases. When extra organic matter is added, the results can deviate due to the different composition and can

therefore not be directly compared with the other experiments. These results can however be compared to the emissions from the column test on this mixture (Column test-ORG).

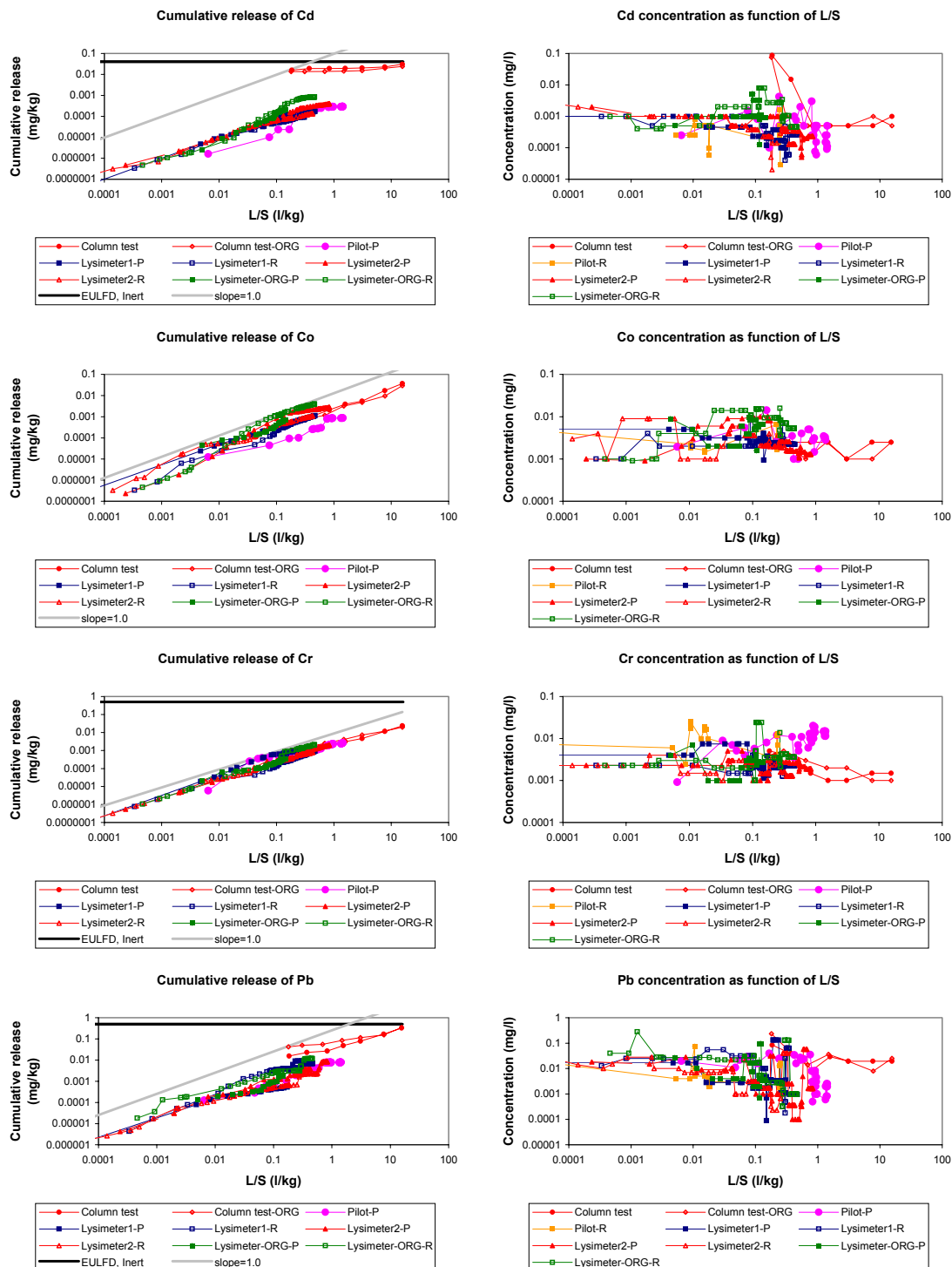


Figure 14 Emissions of Cd, Co, Cr and Pb as a function of the L/S ratio in laboratory measurements (column test), lysimeter experiments and pilot project. P indicates leachate, and R indicates runoff.

The maximum measured differences in **AI** emission are approximately a factor of 7. These differences can be attributed to the sensitivity of the pH for **AI** leaching. The lysimeters show a

somewhat larger distribution in pH values (Figure 9) and in **Al** concentrations than the pilot project data.

The pilot project data for **As** lies on the higher side of the concentration range. The reducing conditions in the pilot project can reduce **As(V)** to **As(III)**. This is a more mobile component than **As(V)**. It should be noted that many measurements from the column test and lysimeters are approximately around the limit of detection for **As**. The emissions are consistent for the experiments on all the different scales. It is expected that the **As** emissions will not exceed the standard (LFD, inert) in the long-term.

The **Ba** emissions show a very limited distribution in all the experiments undertaken, and are not critical with respect to the standard. The concentrations in the lysimeters now seem to be decreasing, as was the case with the column test. However, the concentrations in the leachate now remain higher (at $L/S > 0.5$) than in the other experiments. This could be due to the low redox potential in the pilot project, which results in the reduction of sulphate. The leaching can no longer be controlled by $BaSO_4$ minerals, which increase the solubility of **Ba**.

The leaching of **Ca** also systematically shows a small distribution for all results (also for the experiments for which extra organic matter was added). The emission from the pilot project is consistently lower than the other experiments. It is possible that the high carbonate concentrations in the pilot project cause the formation of calcite (precipitation); this lowers the concentration of dissolved **Ca**. However, the **Ca** concentrations measured in the pilot project do not differ so markedly with respect to the other experiments. Therefore, it is not entirely obvious why the **Ca** emission from the pilot project is lower than the emissions from the other experiments.

The emissions of Cd, Co, Cr and Pb are given as a function of L/S in Figure 14. The **Cd** concentrations in the first and second fractions from the column tests are markedly high. Thus the cumulative emission from the column test deviates greatly compared to the other experiments. The other concentrations are very low and often smaller than the limit of detection. This deviation could possibly be associated with $CdCl_2$ complexes. These complexes can increase the solubility of **Cd**. In Figure 16 it can be seen that the **Cl** concentrations in the first and second fractions of the column test are also relatively high in comparison with the other measurements. The pores are easily accessible and the concentration can become high because the column test can be effectively leached during the experiment (with respect to the preferential flow in the pilot project and lysimeters). When the first fraction of the column test is not taken into account, then the **Cd** emission is not critical. The results of the pilot project and the lysimeters also indicate that **Cd** is not critical with respect to the applicable legislation. Therefore, it can be concluded that **Cd** is not critical.

The **Co** emissions are not regulated under the European Landfill Directive. They are distributed over approximately one order of magnitude, when all the results are taken into consideration. The emissions from the pilot project are slightly lower than the other experiments.

Cr emissions are not critical with respect to the LFD. The emissions also give a very consistent picture. The measured concentrations range from around the limit of detection to a maximum of a factor of 10 above.

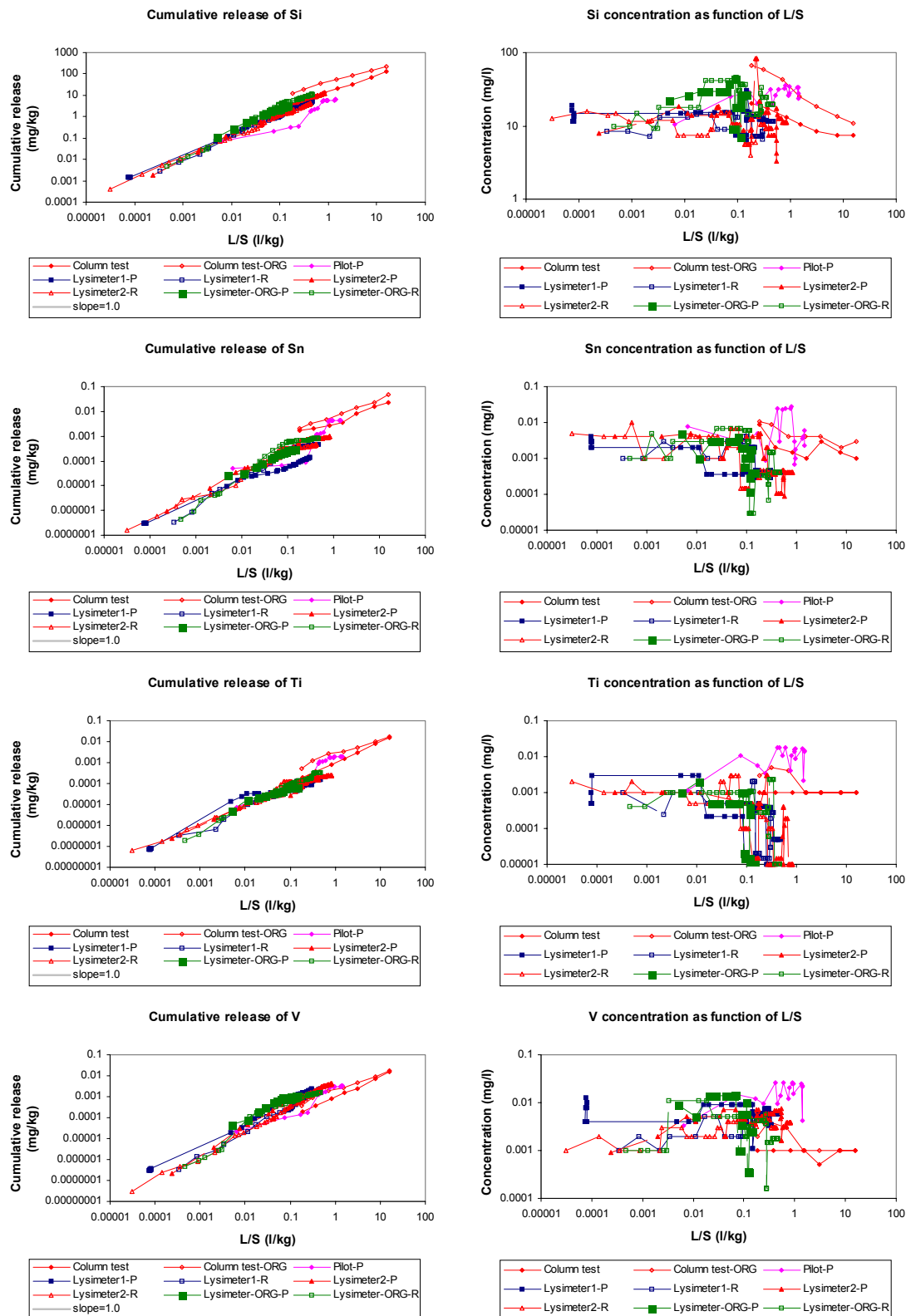


Figure 15 Emissions of Si, Sn, Ti and V as a function of the L/S ratio in laboratory measurements (column test), lysimeter experiments and pilot project. P indicates leachate, and R indicates runoff.

The **Pb** concentrations are somewhat higher in the first fraction of the column tests than the other measurements. This also causes the emission curve to shift higher. The emissions are

solubility-controlled in all the experiments. The pilot project also shows that depletion may now be taking place, as shown by a flattening of the emission curve. When the results of the column experiments are compared with the standards sets by the LFD, it is apparent that the emissions are approximately a factor of 2 under the standard. It is expected that the **Pb** emissions will also not be critical in the long-term, on the basis of the results from the lysimeter experiments and the pilot project.

The results for Si, Sn, Ti and V are given in Figure 15. The emissions of **Si** occur very consistently. The concentrations measured in all the experiments also show a relatively narrow bandwidth.

The same is true for the emissions of **Sn**. The cumulative emissions have a relatively limited range. The concentrations in the lysimeters seem to decrease between $L/S=0.1$ and 1. The reason behind this is unknown. The cumulative emissions will no longer correlate with the column test results, if this trend continues. The column test results show that **Sn** is solubility-controlled to $L/S=10$. It is possible that reducing conditions also play a role in the emission of **Sn**.

In general, the **Ti** concentrations are very low, at around the limit of detection (0.001 mg/L). The concentrations in the leachate from the pilot project seem to be continually higher than the other measurements, except those from the column test with the organic mixture.

The **V** concentrations are also relatively low, and a maximum of one order of magnitude above the limit of detection of 0.001 mg/L. It is also the case that the concentrations in the leachate from the pilot project seem to be continually higher than the other measurements, except those from the column test with the organic mixture.

4.3.2 Availability-controlled emissions of pollutants

Elements which display little or no interaction with the solid matrix show a so-called availability-controlled leaching behaviour. The concentrations in the eluate will be relatively high to begin with (low L/S values). The concentrations begin to decrease after flushing with a quantity of water of approximately one pore volume. The decrease in the concentrations measured can be seen in the cumulative leaching curve as it begins to level off (deviation from the gradient 'slope=1').

Availability-controlled leaching can also provide insight into the extent of preferential flow through a system. The elements discussed below show no apparent interaction with the solid material and can thus be used as a measure of the contact with the solid matrix.

On the basis of the leaching behaviour of the mobile elements, an estimate can be made of the contribution of the mobile phase of a landfill site. A column test in the laboratory has an effective flushing of approximately 85% based on a comparison of the total content with the amount leached. A comparison of leaching from the column test with the leaching from the lysimeter and pilot project can reveal the importance of preferential flow. This is described in detail in section 4.6.

B seems to show limited interaction with the solid matter. The concentrations do not decrease immediately, and the cumulative leaching continues to increase with a gradient of 1 until $L/S=1$. Thereafter the cumulative leaching (and the concentration in solution) begins to

decrease. The pilot project shows somewhat higher concentrations in the leachate at $L/S > 1$. The reason for this is

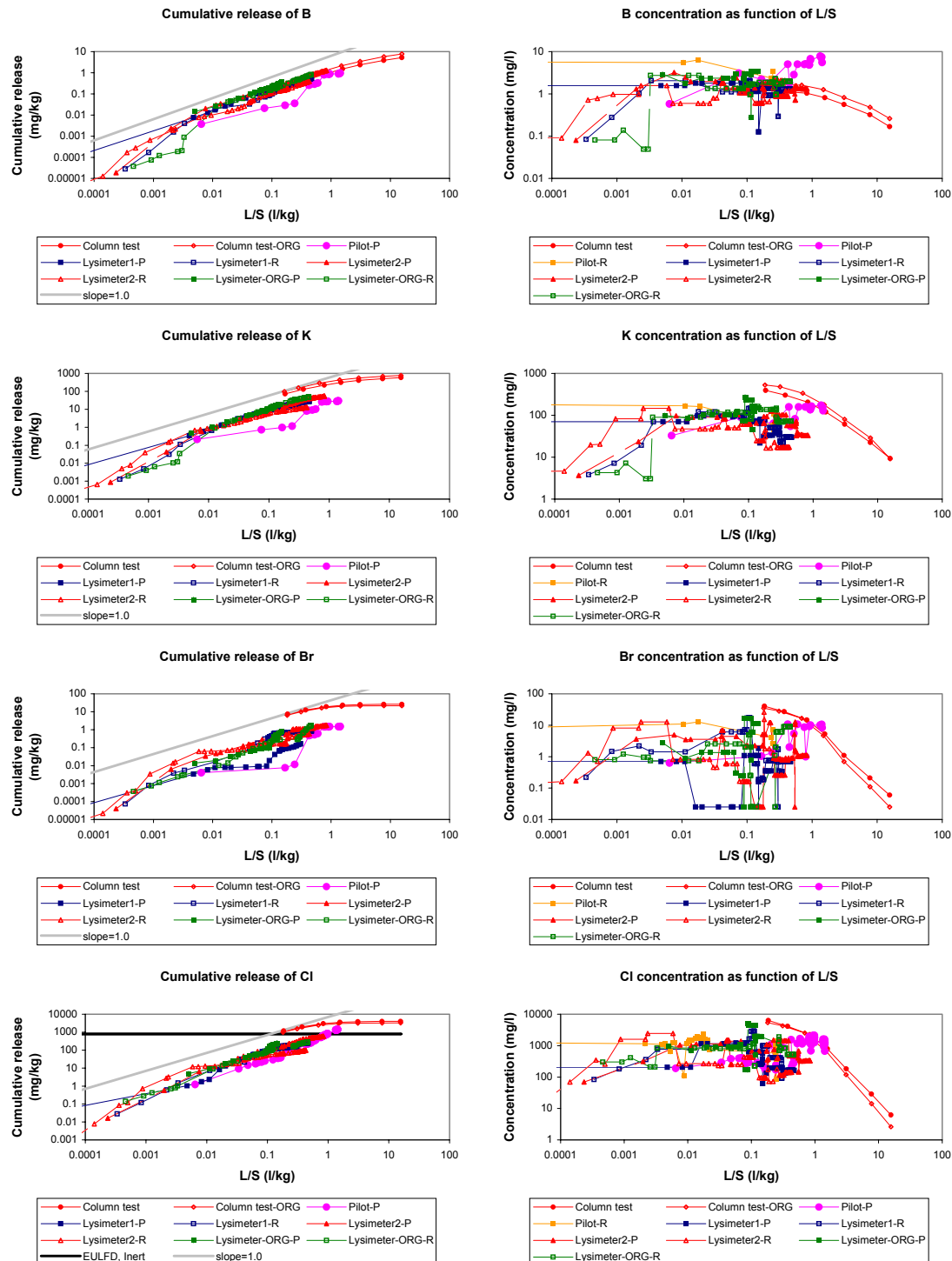


Figure 16 Emissions of B, Br, Cl and K as a function of the L/S ratio in laboratory measurements (column test), lysimeter experiments and pilot project. P indicates leachate, and R indicates runoff.

unknown. The concentrations should be lower because the pilot project has more preferential flow than the column test. However, the concentrations measured will not present a problem to the feasibility of sustainable landfill.

Br, **Cl** and **K** show the same behaviour, whereby the cumulative leaching has already levelled off at L/S values of less than 1. The concentrations measured and the cumulative leaching from the lysimeter and the pilot project are consistent. A higher concentration at comparable L/S values can be seen for these elements in the column test. The **Cl** emissions are clearly critical with respect to the European Landfill Directive for inert waste. A possible way of reducing **Cl** concentrations would be for example to pre-treat the salt-containing waste using a heap leaching process (temporary storage outside which, through percolation by rainwater, results in leaching). Waste streams that cannot be pre-treated would possibly be suitable for immobilisation by cement-stabilisation. It is possible that the high **Cl** emission does not present a problem at Nauerna, as the landfill may be in an area with high salt concentrations in the groundwater. This situation would have to be discussed with the

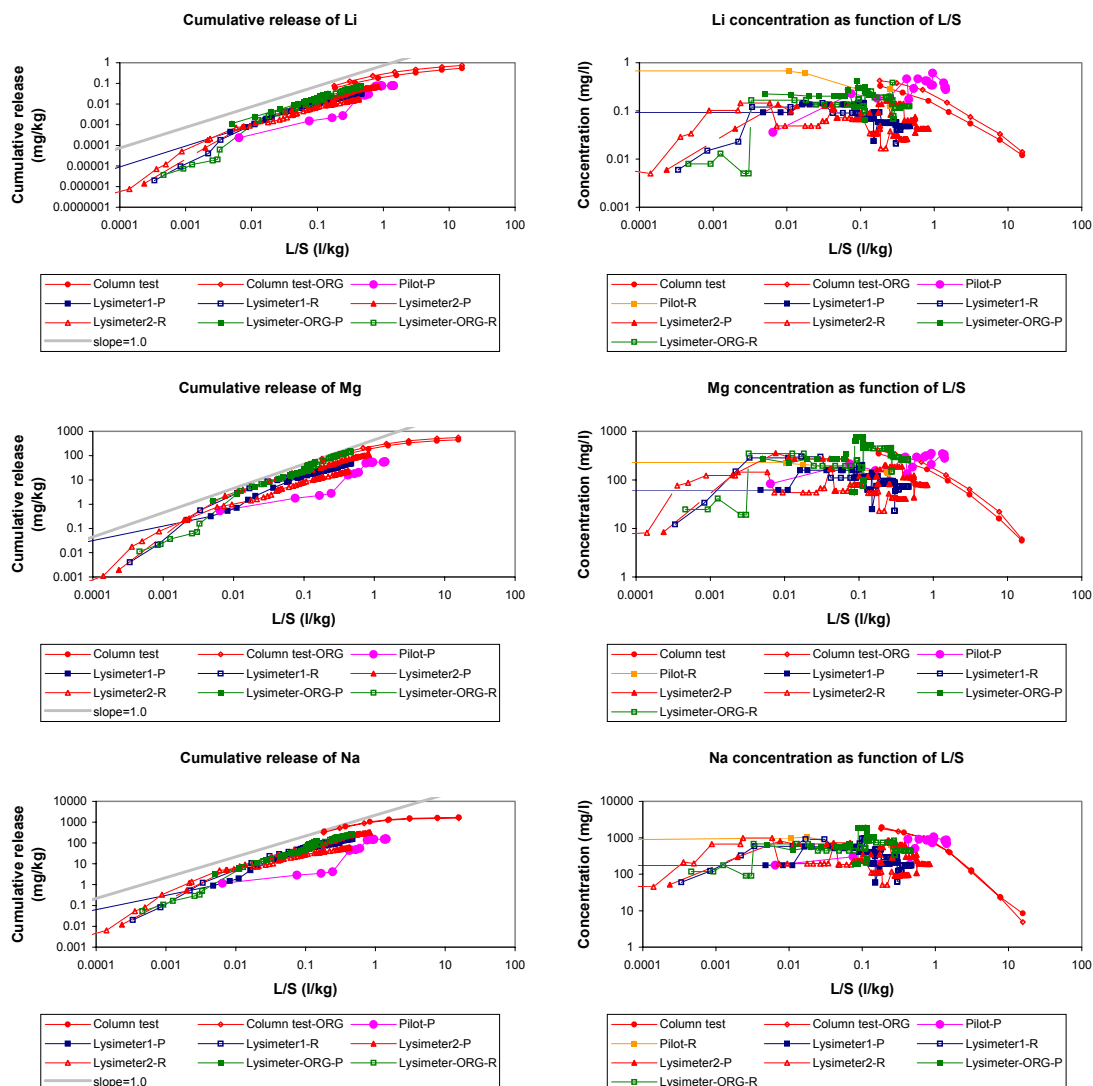


Figure 17 Emissions of Li, Mg and Na as a function of the L/S ratio in laboratory measurements (column test), lysimeter experiments and pilot project. P indicates leachate, and R indicates runoff.

competent authority in order to obtain clarification. Annex II of the European Landfill Directive does allow scope for a site-specific risk assessment.

On the basis of these results it can be expected that the concentrations of **Br**, **Cl** and **K** will remain constant for longer than would be expected on the basis of the measurements from the column test. Due to the preferential flow it does take longer for the salts to be flushed from the poorly accessible parts. Furthermore, it is apparent that the **Br** concentrations are sometimes very low (limit of detection). This is due to the interfering components in the leachate, as a result of which **Br** cannot be well determined.

The leaching of **Li**, **Mg** and **Na** (Figure 17) are also consistent and are comparable to the leaching of **Br**, **Cl** and **K** as well (Figure 16). The concentrations in the column tests decrease rapidly. This effect has not yet been observed as strongly in the lysimeter and the pilot project. The European Landfill Directive does not set standards for these elements.

4.3.3 Solubility-controlled emissions of pollutants followed by depletion

A third leaching mechanism is the solubility-controlled emission of pollutants followed by depletion. Initially this has a cumulative leaching curve with a gradient of 1. The leaching is then controlled by a particular mineral, as a result of which the concentrations in solution remain the same. An element is depleted above a certain L/S, and the concentration in solution will decrease. The results for **Ni**, **P**, **Sr** and **Zn** are given in Figure 18.

Initially the **Ni** decreases slowly in the column test, and later more rapidly. It seems that the cumulative leaching could become critical when the waste mix contains too much organic matter; **Ni** complexes strongly with DOC. The leaching of **Ni** is not critical in the normal mix. The concentrations in the pilot project and the lysimeters also seem to decrease slightly at higher L/S values. Further measurements would be able to show whether this trend continues.

The **P** concentrations show a somewhat greater distribution than many other elements. The reason for this is not known. It is possible that this is due to the differences in (micro)biological activity occurring on the different scales. The behaviour of **P** initially seems to be solubility-controlled. Depletion then follows at higher L/S values: the concentrations in the column test then decrease as a function of L/S. It also seems that a relatively constant leaching is seen in the pilot project above L/S=1, possibly as a consequence of preferential flow.

The leaching of **Sr** is fairly consistent in the different experiments. The cumulative emissions from the pilot project are however generally lower than the other measurements. The decrease in the **Sr** emission from the column test begins at L/S values greater than 1.

The leaching of **Zn** shows relatively large differences between the different experiments. The pilot project shows the lowest emission; the column tests have the highest emissions. The leaching of **Zn** is not critical with respect to the European Landfill Directive for inert waste. The differences in leaching are too large to be explained by preferential flow in the pilot project and the lysimeters. **Zn** can form complexes with dissolved organic matter. It is possible that organically complexed **Zn** plays a greater role in the column test than in the other experiments. However, it is not yet clear how important this mechanism is in the experiments.

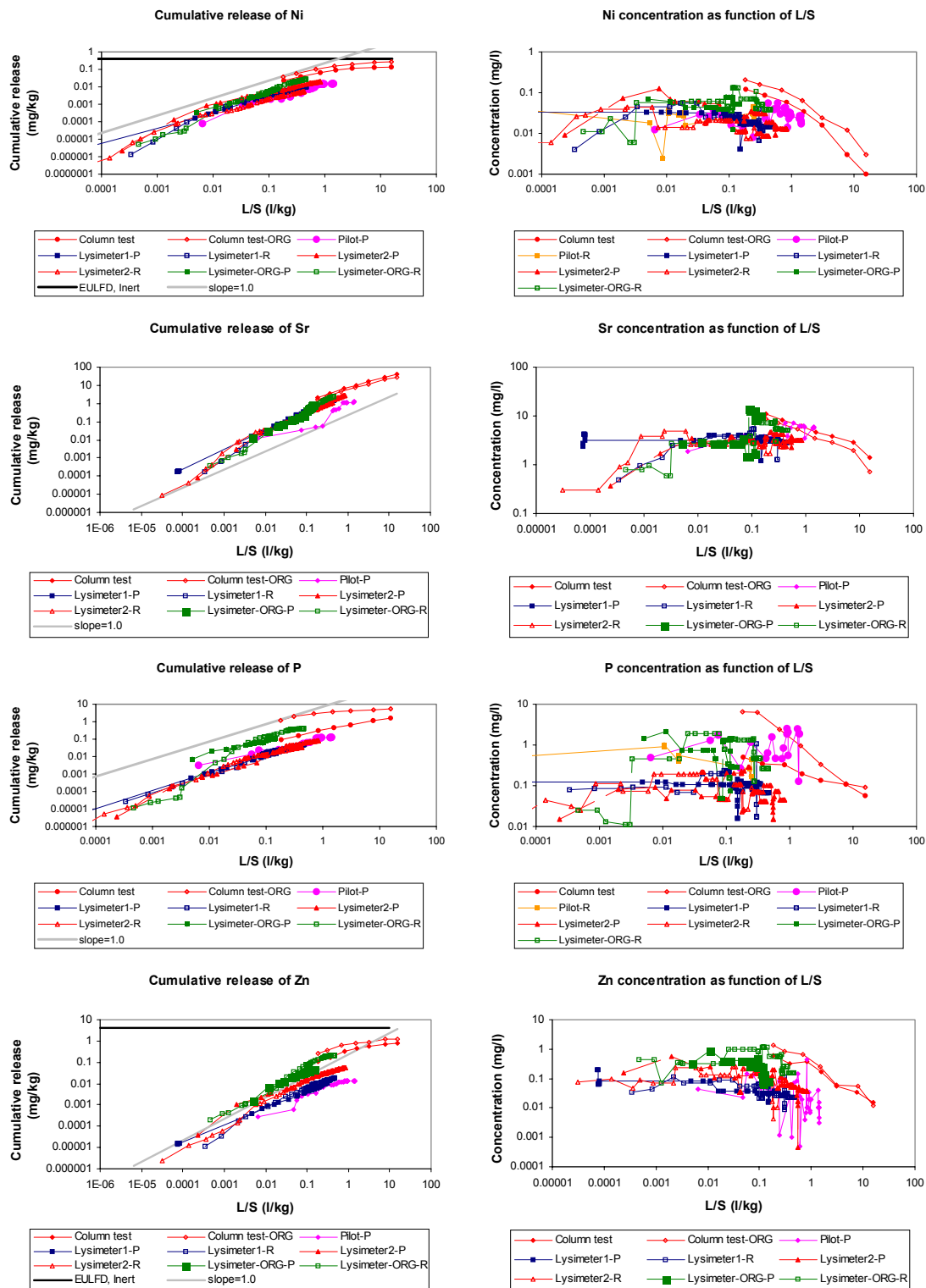


Figure 18 Emissions of Ni, P, Sr and Zn as a function of the L/S ratio in laboratory measurements (column test), lysimeter experiment and pilot project. P indicates leachate, and R indicates runoff.

4.3.4 Particular observations for the leaching of pollutants

In addition to the elements for which leaching is solubility or availability-controlled (or a combination of these), there are different elements for which a number

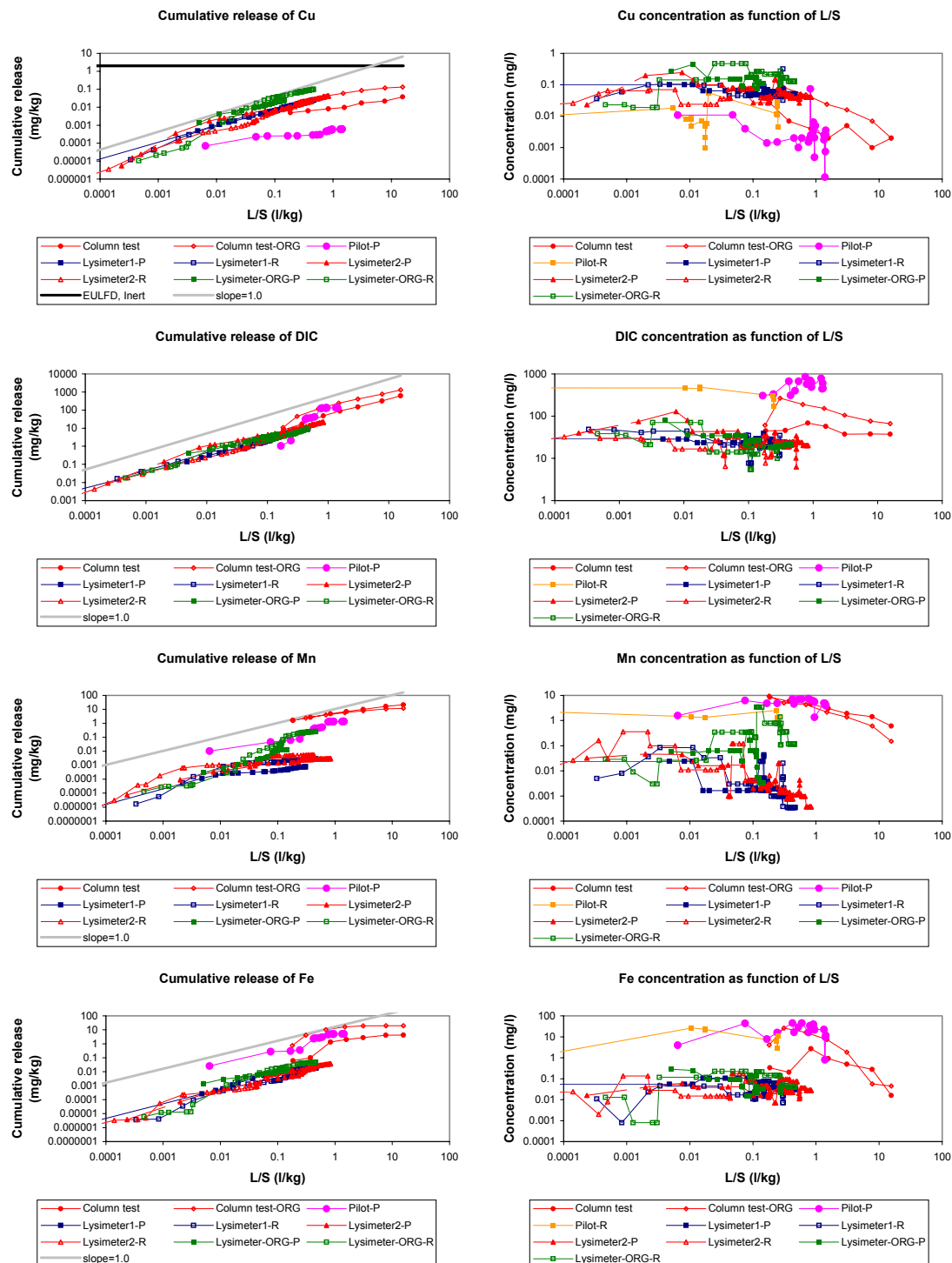


Figure 19 Emissions of Cu, DIC, Fe and Mn as a function of the L/S ratio in laboratory measurements (column test), lysimeter experiments and pilot project. P indicates leachate, and R indicates runoff.

of interesting observations were noted. These elements are considered in more detail in this section, and explanations for the differences are given as far as possible.

Figure 19 shows the leaching curves for **Cu**, **DIC**, **Fe** and **Mn**. The leaching of **Cu** in the column test is higher in the organically rich waste mixture than the normal waste mix, which is

as expected due to the higher DOC level in the organically rich sample. This is likewise confirmed by the leachate from the lysimeter in which 10% organically rich waste is mixed (5% shredder waste and 5% sewage sludge) that has a higher **Cu** concentration than the leachate from lysimeters 1 and 2. The data from the pilot project are approximately one order of magnitude lower than those from the lysimeters. This can probably be attributed to the more oxidising conditions in the lysimeters (higher redox potential), under which the Cu(II) complexes strongly with DOC. More reducing conditions prevail in the pilot project, under which the less soluble Cu(I) species is more dominant and/or poorly soluble (Cu(I) or Cu(II)) sulphides are formed. It is also possible that the affinity of Cu(I) for complexation with DOC is smaller than that of Cu(II). The leaching of **Cu** is not critical with respect to the European Landfill Directive for inert waste in any of the experiments undertaken. It was notable that the role of organic matter in the leaching of Cu under reducing conditions is limited with respect to the leaching under more oxidising conditions.

The leaching of carbonate (**DIC**) proceeds reasonably systematically in all the experiments but is higher in the pilot project and the organic column test. The high **DIC** concentrations in the pilot project are probably the result of the degradation of organic matter in the cell, whereby CO₂ is formed which is soluble in water as CO₃²⁻. It is also probable that more organic matter degrades in the organic column test, leading to higher concentrations than in the column test with the normal waste mix. The high **DIC** concentrations have a strong buffering effect on the pH of the leachate.

The concentrations of **Fe** and **Mn** both show relatively large differences between the different experiments. The leaching of **Fe** is substantially higher in the pilot project and the column tests. **Fe** is sensitive to reducing conditions. The usually poorly soluble Fe(III) can be reduced to the far more soluble Fe(II) under anaerobic conditions. Thus, this results in higher **Fe** concentrations in the pilot project and in the column test than the more oxidised lysimeter experiments.

Mn is a typical redox indicator. **Mn** increases sharply at low redox; this is the case in the pilot project. The difference in the emission between the lysimeters and the pilot project are probably caused by differences in redox potential. The redox potential in the pilot project is also consistently somewhat lower than in the lysimeters. The leachate from the pilot project had a slightly lower redox potential of approximately -150 to -200 mV in the first year. The leachate from the lysimeters had a redox potential of approximately -100 to -150 mV. It seems that **Mn** is very sensitive to this and as soon as differences in redox potential occur this can be seen in the level of **Mn** (and Fe).

The data for **F**, **Mo**, **Sb** and **Se** are set out in Figure 20. There is a relatively limited set of data available for **F**. This element was not originally analysed in the column test. The emission of **F** gives a strange curve but the levels are in line with the other experiments. In order to assess whether **F** could become a critical component with regard to the acceptance criteria of the LFD, the maximum emission was calculated for the highest measured concentration that would be maintained to L/S=10. It appears from this calculation that the emission of **F** could then be 7.87 mg/kg. For the time being it can thus be concluded that **F** is not a critical parameter.

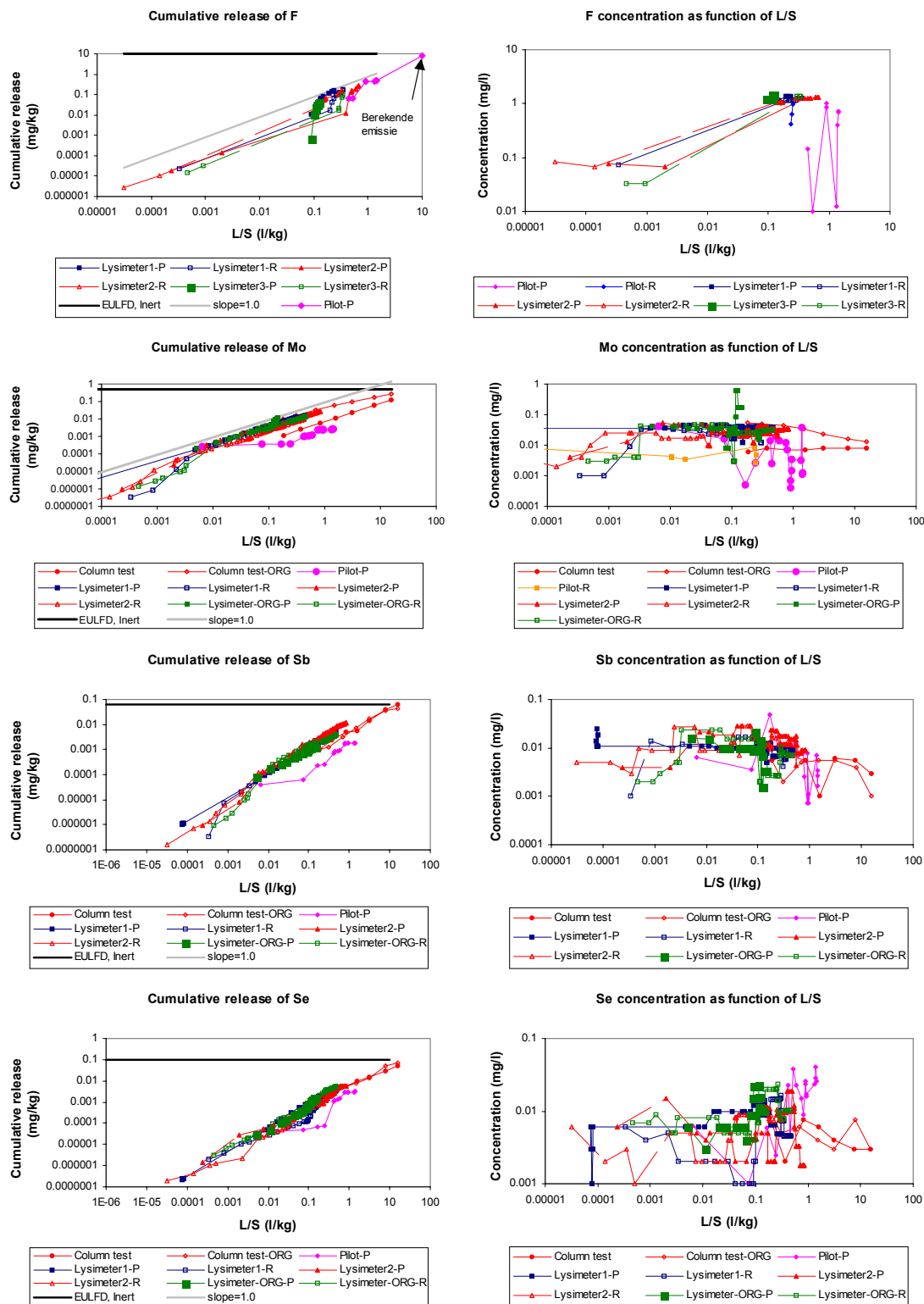


Figure 20 Emissions of F, Mo, Sb and Se as a function of the L/S ratio in laboratory measurements (column test), lysimeter experiments and pilot project. P indicates leachate, and R indicates runoff.

The emissions of **Mo** from the pilot project are consistently around one order of magnitude lower than the other results. **Mo** is a relatively mobile element. Thus it could be that preferential flow in the pilot is also important for Mo. There is a difference with the salts (**Na** for

example); the **Mo** emissions from the lysimeter experiments are in line with the column test. For the salts it was established that preferential flow plays a role in the lysimeters as well as in the pilot project. Thus, the difference cannot be completely explained by preferential flow; it is possible that the redox situation plays a role in the leaching of **Mo**. However, no further research was undertaken on this. The **Mo** emissions from the column experiments are a factor of 2 lower than the requirements of the LFD for the acceptance of inert waste.

The **Sb** emissions from the column experiments and the lysimeters give a consistent picture, whereby the cumulative L/S=10 emission from the column test reaches critical values with respect to the LFD. However, the emissions in the pilot project are continually lower than the other experiments, and the emission now seems to be levelling off. Subsequent measurements will indicate if this behaviour changes or if there is a temporary levelly off of the **Sb** emission. The Sb concentrations measured are in general lower or around the limit of detection (approximately 5 ppb with ICP-AES). This means that a more sensitive technique will be needed for the additional measurements (hydride generation and analysis with atomic fluorescence spectrometry) in order to establish if Sb actually is a critical element. On the basis of these results it cannot be unequivocally concluded that Sb is a critical element with respect to the acceptance criteria for inert waste. However, the Sb emissions reported can be seen as the upper limit for the Sb emission.

Se emissions from the column experiments and the lysimeters also show a consistent emission. The **Se** emissions from the column experiments at L/S = 2 reach values a factor of 2 below the LFD requirements for inert waste. The **Se** emissions from the pilot project deviate between L/S=0.1 and 1 from the other data but now seem to be again in line with the other data. It is not yet completely clear how the emissions will progress in the future.

Figure 21 shows the emissions of different nitrogen compounds. The **NH₄⁺** emissions show large differences; the column experiments and the pilot project have relatively high emissions/concentrations. The lysimeter experiments show relatively low emissions. These differences led to more experiments being undertaken and are described in section 4.8. It appeared that the oxidising conditions in the lysimeters provide favourable conditions for aerobic bacteria which can nitrify **NH₄⁺** to nitrate. In the pilot project and the column test there is apparently insufficient oxygen present to effect these conversions.

The **NO₂⁻** and **NO₃⁻** emissions also show apparent differences between the different experiments. These emissions are probably largely related to the conversion of **NH₄⁺**. The **NH₄⁺** concentrations from the pilot project are relatively high, whilst the **NO₂⁻** and **NO₃⁻** concentrations are relatively low. The **NH₄⁺** is not/scarcely converted under the anaerobic conditions in the landfill so that little **NO₂⁻** and **NO₃⁻** are formed. The lysimeter, to which extra organic matter was added, has relatively high **NH₄⁺** as well as **NO₂⁻** and **NO₃⁻** concentrations between L/S 0.01 and 0.1. The extra organic matter partly emanates from dried sewage sludge; this material contains much nitrogen.

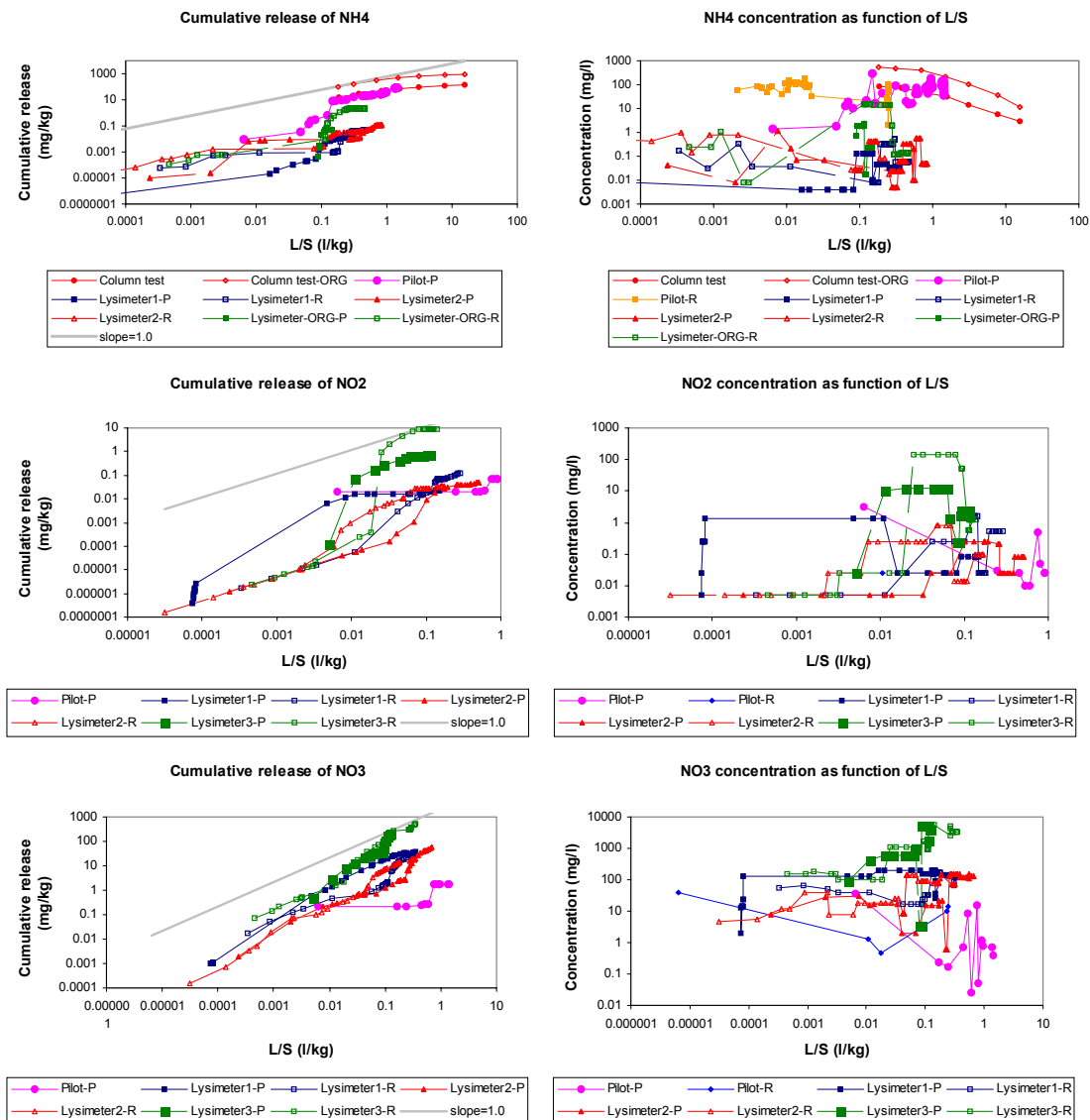


Figure 21 Emissions of NH_4^+ , NO_2^- and NO_3^- as a function of the L/S ratio in laboratory measurements (column test), lysimeter experiments and pilot project. P indicates leachate, and R indicates runoff.

The emissions of **S** and **SO₄** are given in a graph in Figure 22. The cumulative emission of **S** and **SO₄** follows the line of solubility control. It is evident that the leaching behaviour of total **S** (determined using ICP-AES after acidification of the eluate) is a factor of 7 lower in the pilot project than the leaching of **SO₄** (determined in unpreserved eluate using ion chromatography). In oxidising systems all **S** must be present in the form of **SO₄**. When this is assumed, there must be approximately a factor of 3 between the emissions of total **S** and **SO₄** (due to difference between **S** and **SO₄²⁻**). It is probable that acidification of the samples for ICP-AES (with HNO_3 to $\text{pH} < 2$) causes the production of H_2S gas. This results in the total **S** concentrations being too low, and gives rise to a discrepancy between total **S** and **SO₄** that cannot be explained by the presence of other sulphur species such as S^{2-} or thiosulphates. **SO₄** is indeed higher than the total sulphur determined. Therefore, it is important to note that the **SO₄** concentrations in reduced samples cannot be assessed on the basis of the total sulphur determined with ICP-AES.

The cumulative emission of SO_4 is critical with respect to the LFD for inert waste. In Figure 22 it can be seen that in general the SO_4 concentrations show very little variation; the cumulative leaching also follows a line with slope=1. This indicates solubility control of SO_4 by a mineral phase. This means that reduction of SO_4 leaching by pre-treating waste (washing or heap leaching) will have little effect on the quality of the wastes with regard to the leaching of SO_4 . Indeed, the solubility-controlling mineral even seems to control the leaching of SO_4 to nearly $\text{L/S}=10$ (depletion does not yet occur). The last fractions of the column tests show that depletion is to be expected around L/S values of approximately 10 but these L/S values are far too high for pre-treatment procedures. An alternative for a number of sulphate-containing residues could be immobilisation by cement-stabilisation. This would require research into the suitability of the waste concerned for this technique. Materials such as residues from construction and demolition segregation can be very heterogeneous and coarse, and thus for example unsuitable for immobilisation.

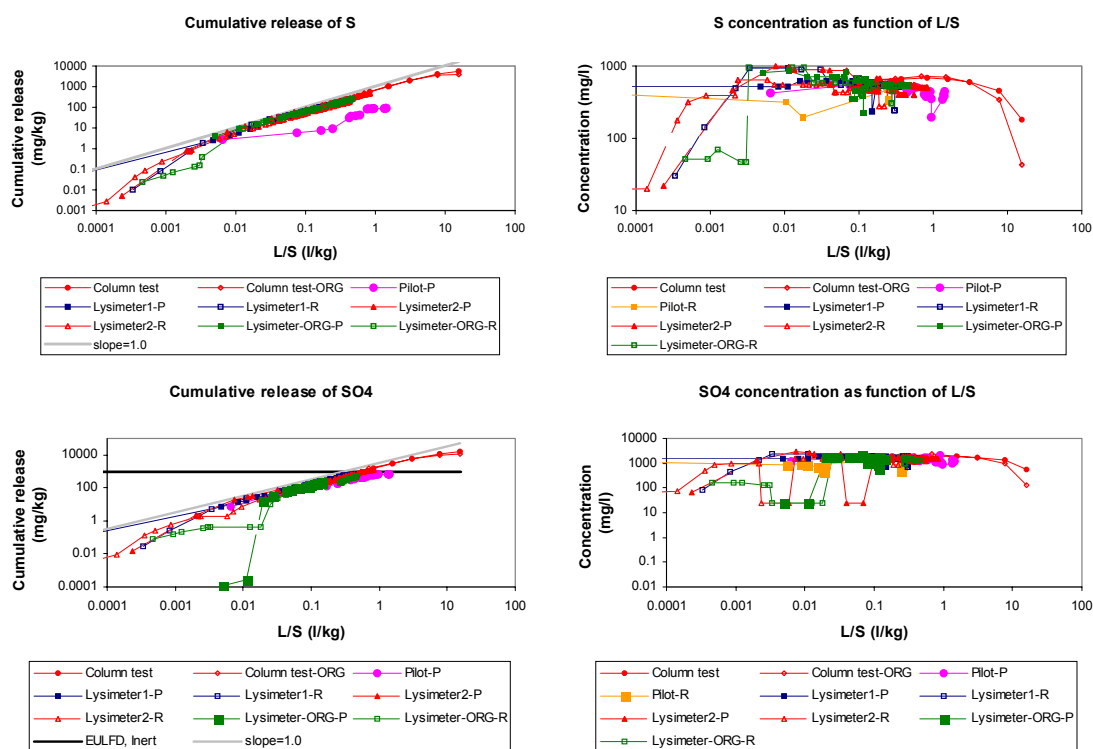


Figure 22 Emissions of S and SO_4^{2-} as a function of the L/S ratio in laboratory measurements (column test), lysimeter experiments and pilot project. P indicates leachate, and R indicates runoff.

Finally, a number of **Hg** analyses were also undertaken on the eluate from the pilot project; the results of these are given in Figure 23. Although the data are limited, it appears from these results that **Hg** is not critical with regard to the LFD for inert waste. The emissions already seem to have levelled off; should the concentrations later increase to a gradient of 1, the standard would still not be exceeded at $\text{L/S}=10$. On the basis of these results, it is expected that **Hg** will not give rise to difficulties in meeting the legislative standards.

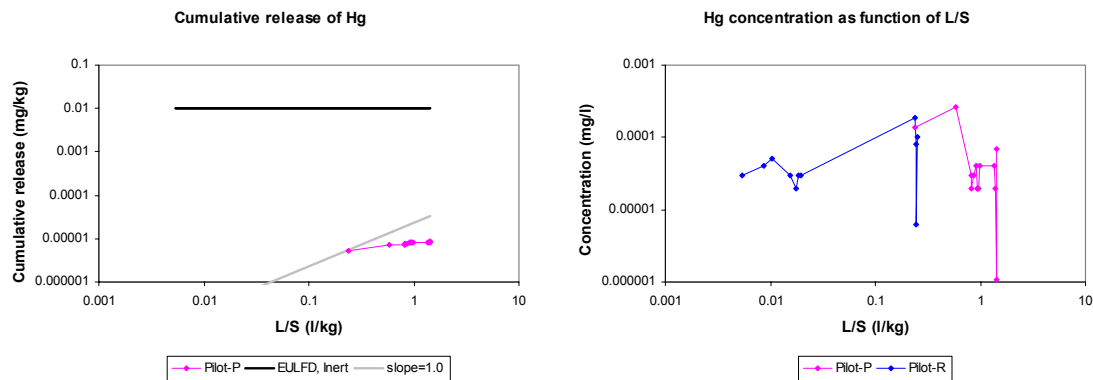


Figure 23 Emissions of Hg as a function of the L/S ratio in the pilot project. P indicates leachate, and R runoff.

4.4 Geochemical modelling of inorganic processes on laboratory, lysimeter and field scales

In order to illustrate that mixed waste behaves far more systematically than would be expected from a similar mixture, the leaching of Pb and Mo were compared with the solubility of PbMoO_4 on the basis of saturation indices obtained by modelling. The results of geochemical speciation calculations for Pb and Mo are given in Figure 24 and Figure 25. It can be seen from these figures that the mineral $\text{PbMoO}_4(\text{s})$ is important for the solubility control of Pb and Mo in the relevant pH range for the pilot at Nauerna. The mineral $\text{Pb}(\text{OH})_2(\text{s})$ appears to be important for Pb above pH 10; $\text{PbMoO}_4(\text{s})$ no longer provides a good explanation in this range. The bend at the transition from PbMoO_4 to $\text{Pb}(\text{OH})_2$ at pH10 can be well explained by the observed course of solubility control. The same effect is seen for Mo; however, no other possible solubility-controlling mineral was found for Mo.

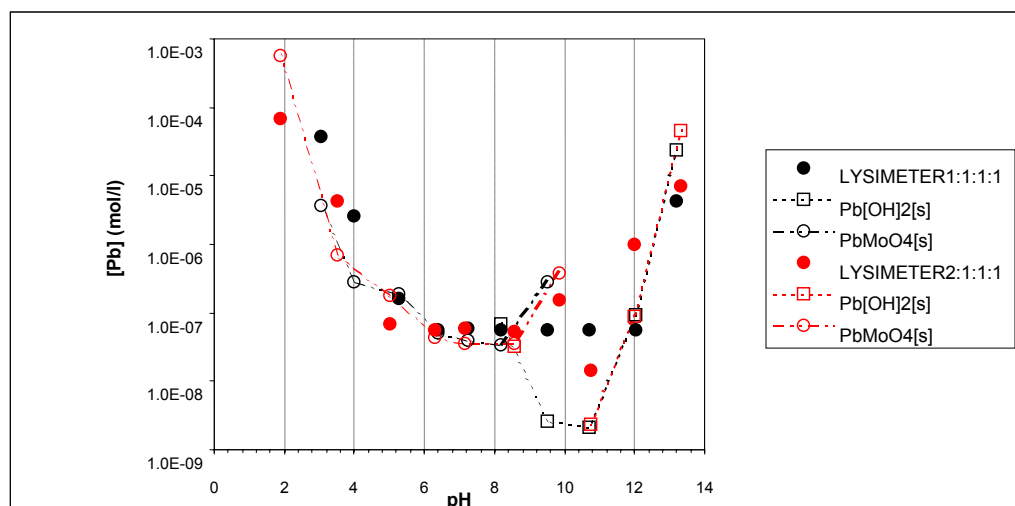


Figure 24 Results of Pb leaching as a function of pH in lysimeter mixtures and the predicted leaching (using Orchestra) on the basis of possible solubility-controlling minerals.

The lead emission was calculated from the leachate data from Nauerna using the Orchestra programme, which is linked to the database, for part of the time series since construction (Figure 26). The samples used were taken in the period between 25-5-2000 to 15-8-2001. It is

noticeable that the chemical phase (PbMoO_4) that seems to be the most important solubility-controlling phase in the column, lysimeter and pH static experiments (Figure 24 and Figure 25), also seems to turn up in the field leachate (Figure 26) and even seems to follow the fluctuation over time. This makes the conclusion that PbMoO_4 is a relevant solubility-controlling phase in the Nauerna pilot even more convincing. Moreover, this indicates that the mixed landfill behaves systematically in its totality, despite having great heterogeneity at the local level. This observation has considerable significance for the 'black box thinking' that has held sway for a long time in landfilling, in that it could now be replaced by a mechanistic process approach.

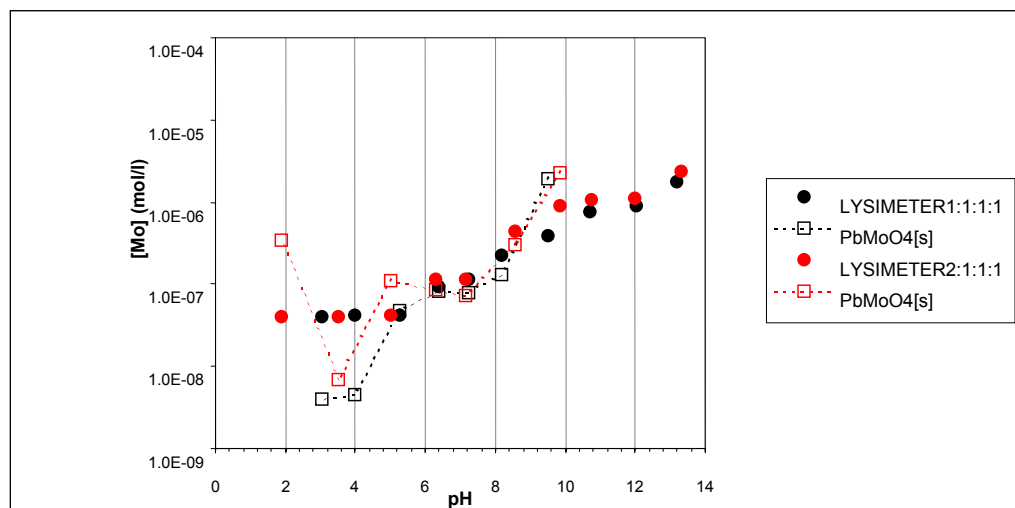


Figure 25 Results of Mo leaching as a function of pH in lysimeter mixtures and the predicted leaching with (using Orchestra) on the basis of possible solubility-controlling minerals.

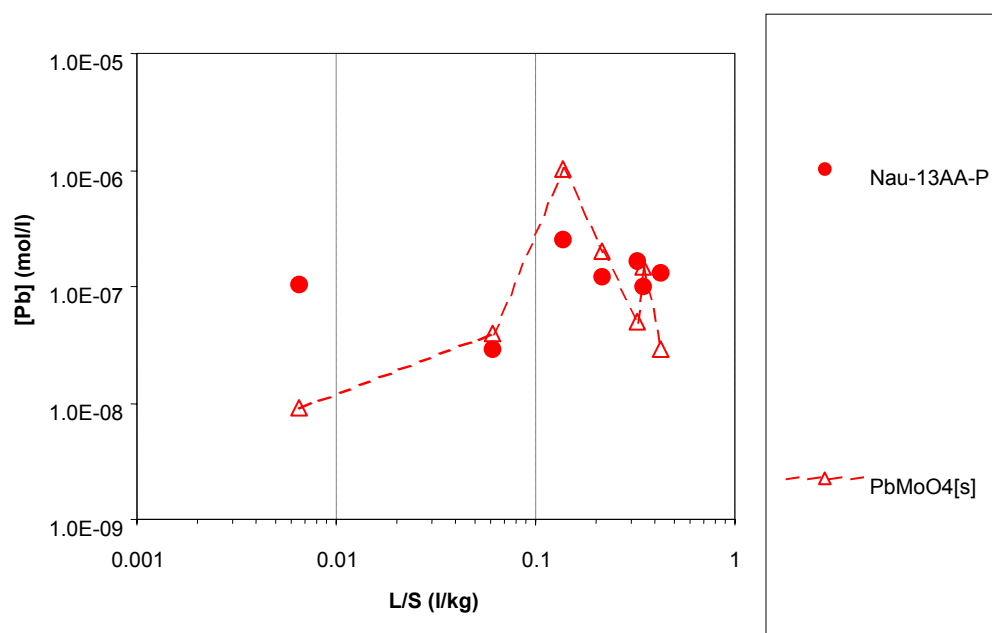


Figure 26 Comparison of Pb concentrations measured in leachate (pilot project, circle symbols) and the predicted Pb concentrations (triangles with line) with

geochemical modelling. The predicted Pb concentrations in leachate are calculated on the basis of solubility control by the mineral PbMoO_4 .

The conclusions from these observations for lead are:

- a mixed landfill behaves in its totality very systematically and far more predictably than would be assumed on the basis of the discernible heterogeneity;
- on the basis of these observations, the prediction of leaching behaviour of mixed waste becomes feasible (see reference document on geochemical modelling);
- the identification of those fractions which contribute disproportionately to the concentrations in the leachate can be established with more success beforehand. Further research into the possibilities of this (by undertaking independent modelling and verification measurements) can definitively show what is currently feasible.

4.5 Emissions of organic pollutants

The emissions of a number of organic micro-pollutants were measured on a number of occasions. The results are given in Figure 27. In general it can be seen that the distribution of the concentrations measured is greater than for the inorganic pollutants. This is connected to the low concentrations of these pollutants and the fact that these hydrophobic and/or volatile compounds are more difficult to measure quantitatively than the inorganic pollutants. A frequently occurring problem when analysing organic micro-pollutants is sorption of these compounds on the glassware during sampling and processing in the laboratory.

Although the concentrations of the organic micro-pollutants can show a rather wide distribution, it is apparent that the leached concentrations are relatively low. The leaching of **PAHs** is higher than the target level for groundwater but in all cases lower than the intervention level. The individual components of the sumparameter **BTEX** can also be higher in certain cases than the target level for groundwater but are never higher than the intervention level. This also applies to **mineral oil**. On the basis of these data it is not expected that the organic micro-pollutants will present an obstacle to the applicability of the sustainable landfill concept.

4.6 Preferential flow due to behaviour of mobile substances

The leaching of mobile inorganic components on different scales (laboratory, lysimeter and pilot project) can provide an insight into the fraction available for leaching in practice. The system is saturated in a controlled manner in the column test in the laboratory, and thus there is little or no material that does not take part in the leaching process. It can be the case that particular parts of the landfill body are not available for leaching as a result of preferential flow on larger scales, and especially when leaching occurs under unsaturated conditions (lysimeter and pilot project).

In Figure 28 to Figure 30 the cumulative emission of Na, K and Cl are given as a function of L/S. It is apparent that the emissions of Na, K and Cl in the lysimeter experiments and the pilot project at Nauerna are lower than those measured in the laboratory. The difference can be explained by preferential flow in the waste because these salts show very little or no interaction with the matrix.

Table 6 shows the cumulative emission (for lysimeter and pilot project) as a percentage of the emission from the column test. The figures illustrate that the emissions in the pilot project and

the lysimeters rise less steeply than the emission from the column test. The difference in emission becomes greater as the L/S increases. This could indicate a depletion of the mobile phase and that the concentrations will be determined more and more by diffusion-controlled supply from the stagnant phase. No further research was carried out in this project in order to quantify these so-called dual porosity processes.

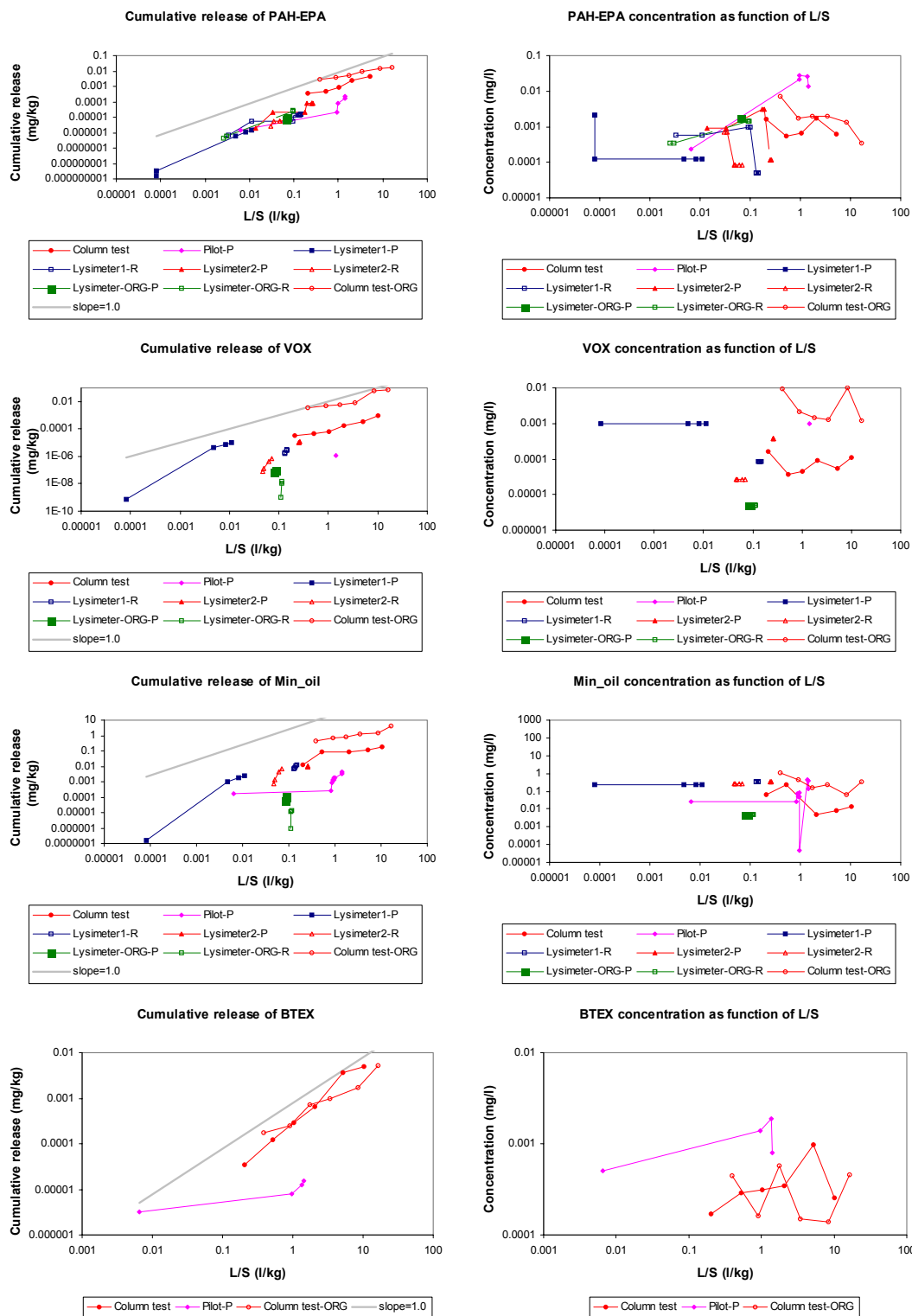


Figure 27 Emissions of sum of 16 PAHs (PAH-EPA), volatile organic halogens (VOX), sum of benzene, toluene, ethylbenzene and xylene (BTEX) and mineral oil (Min-oil) as

a function of the L/S ratio in laboratory measurements (column test), lysimeter experiments and pilot project. P indicates leachate, and R runoff.

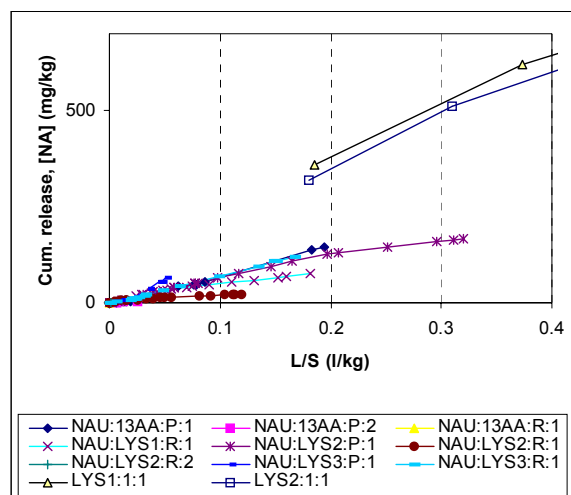


Figure 28 Differences in emission of Na measured between lysimeter and pilot project and laboratory measurements (column test)

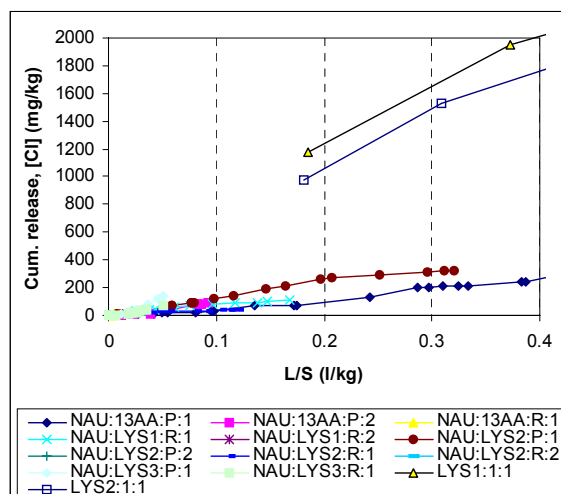


Figure 30 Differences in emission of Cl measured between lysimeter and pilot project and laboratory measurements (column test)

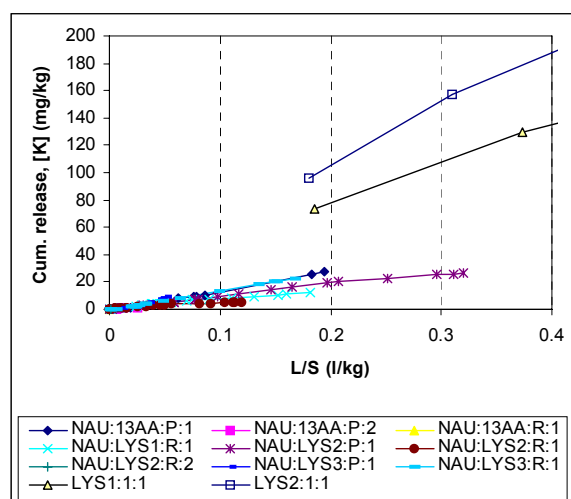


Figure 29 Differences in emission of K measured between lysimeter and pilot project and laboratory measurements (column test)

Table 6 *Calculated leaching percentages for Na, K and Cl compared to the column test. The calculations were undertaken on emissions measured between L/S 0.05 and 0.7.*

Experiment	% Na	% K	% Cl
Nauerna 13AA	46	36	28
LYS 1	23	16	22
LYS 2	33	23	21
LYS 3	38	33	36

Figure 28 to Figure 30 and

Table 6 indicate that ca. 20-30% of the total volume is effectively flushed. It is assumed that the column test can be seen as being representative of the total leachable content. If it is assumed that in a column on the laboratory scale circa 15% is not flushed (previously established for comparable material) then this leads to an average flushing of 25% of the body on the operational scale (range 15 – 35%). It should be noted that the differences between the pilot project (Nauerna 13AA) and the different lysimeters (LYS1 to 3) are not considered significant (

Table 6). The method used for calculating the leaching percentages is not accurate enough for this. In general it can be established that the flushing of the waste body will be somewhere between 15 and 35% in practice.

4.7 Methane emissions from pilot project

The methane emissions are determined using the so-called box method. The methane flux measured was $8 \text{ mL CH}_4 \cdot \text{m}^{-2} \cdot \text{hr}^{-1}$. This emission is low when compared to a household waste landfill for example, where fluxes of $0.15\text{-}3.5 \text{ L CH}_4 \cdot \text{m}^{-2} \cdot \text{hr}^{-1}$ are measured (2,3). In Finland and France it has been determined that no oxidising top layer or other actions are necessary when the methane flux amounts to less than $1 \text{ L CH}_4 \cdot \text{m}^{-2} \cdot \text{hr}^{-1}$. The low methane emissions in this sustainable landfill concept are in accordance with the inorganic nature of the waste in the landfill.

4.8 Additional experiments: ammonium leaching in lysimeter tests

The leaching of ammonium from the pilot project at Nauerna and the lysimeters at ECN show large differences. Different experiments were carried out to explain these differences. The hypothesis was that the ammonium concentrations in the leachate from the lysimeters was low because the water collected is in contact with the air for a period before the collection containers are emptied/sampled. During this period (often several weeks) the leached ammonium will breakdown; this gives rise to the observed difference.

The first set of experiments arose from the irrigation of lysimeters 1 and 2 and the collection of the leachate. The leachate from lysimeter 1 is put under N_2 directly after collection. The water from lysimeter 2 is collected in the normal manner. It can be seen from Table 7 that the ammonium concentrations directly after irrigation are approximately at the level of the limit of detection. These results indicate that the mechanism of ammonium degradation during the storage period of the collection containers is illogical.

Table 7 *Ammonium concentrations in leachate lysimeters directly, and 24 hours after, irrigation. Lysimeter 1 is constantly kept under N_2 , lysimeter 2 was left open to the air.*

	Time (hours)	NH4 (mg/L)	NO2 (mg/L)	NO3 (mg/L)
Limit of detection		0.015	0.05	0.05
Lysimeter 1	0	0.014	0.02	56.6
Lysimeter 1	24	0.033		
Lysimeter 2	0	0.011	0.01	13.4

Lysimeter 2	24	0.037
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It was decided that further investigation into the cause of the possible difference in concentrations between the pilot project and the lysimeter experiments would be undertaken as a consequence of the results in Table 7. Therefore, four cores from lysimeter 3 (extra organic matter and as expected higher in ammonium) were removed at a depth of 30-50 cm. It was expected that this material would still contain ammonium; thus, a leaching test and analysis for ammonium were undertaken. However, it appeared that this sample also contained almost no ammonium (0.026 mg/L). The refrigerated waste mixture from lysimeter 3 was subsequently also leached at L/S=10. It appeared to contain ammonium. Thereafter the ammonium concentrations in the eluate were monitored over time (samples at the laboratory maintained at room temperature, no micro-organisms were added). The results are given in

Figure 31 Ammonium, nitrite and nitrate concentrations in a leachate solution from lysimeter mixture as function of time.

Table 8 and are presented in a graph in Figure 31.

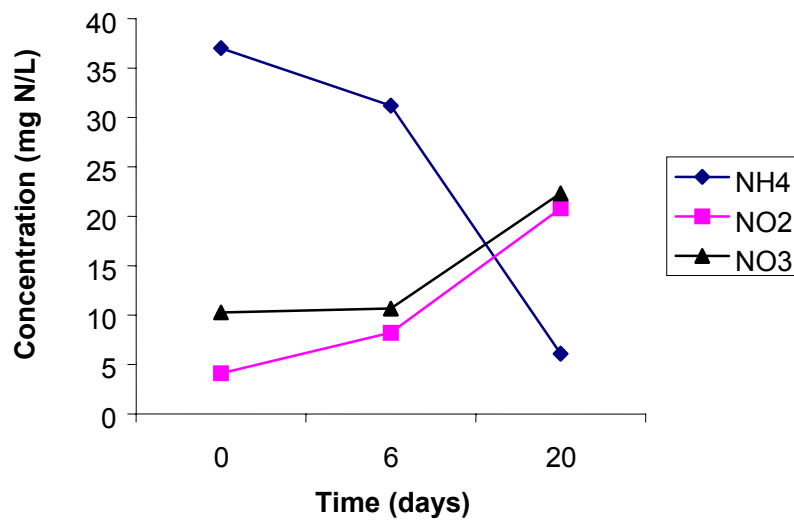


Figure 31 Ammonium, nitrite and nitrate concentrations in a leachate solution from lysimeter mixture as function of time.

Table 8 *Ammonium concentrations in the waste mixture from lysimeter 3 after 24 hours leaching at L/S=10 at different time intervals.*

Time (days)	NH ₄ (mg N/L)	NO ₂ (mg N/L)	NO ₃ (mg N/L)
Limit of detection	0.015	0.05	0.05
0	37.00	4.11	10.26
6	31.19	8.22	10.66
20	6.08	20.79	22.31

It can be seen from

Figure 31 Ammonium, nitrite and nitrate concentrations in a leachate solution from lysimeter mixture as function of time.

Table 8 that the ammonium concentration at L/S=10 is 37 mg N/L; this is in accordance with an emission of 370 mg N/kg. The ammonium emission was approximately 800 mg N/kg in the original pH-static and column experiments on this sample. This means that as much as half of it remains.

Figure 31 Ammonium, nitrite and nitrate concentrations in a leachate solution from lysimeter mixture as function of time.

Table 8 also shows that the ammonium concentrations have dropped to 6.1 mg N/L after 20 days, and the concentrations of nitrite and nitrate rise in this period. The nitrogen balance agrees well. These experiments indicate that ammonium in the leachate can be converted under the influence of oxygen, and that the conversion products are mainly nitrite and nitrate

The results of the different ammonium tests indicate that the waste mixture in the lysimeters no longer contains much ammonium. It can be concluded that the ammonium in the lysimeters has disappeared due in particular to (microbiological) conversions because the ammonium concentrations in the leachate from the lysimeters have always been low (except for a number of measurements on the runoff from lysimeter 3). When flushing was the dominant mechanism, much higher concentrations were measured initially. It is probable that the ammonium in the lysimeters can be relatively easily converted by the more aerobic conditions in the waste body in comparison with the pilot project. This explains why there are lower emissions in the lysimeters with respect to the pilot project.

These findings can be used to explore the possibilities for the (accelerated) break down of ammonium at landfill sites in general and within the sustainable landfill project in particular (bioreactor concept). From discussions with Afvalzorg, it appears that the degradation of ammonium through the water treatment system is currently progressing well. Thus, there is no reason to carry out further experiments at Nauerna. It is important to investigate how quickly NH_4 in leachate degrades/is converted under aerobic conditions and what consequences that has for the installation of the water management system during the aftercare phase because the Nauerna pilot also shows levels of NH_4 that would probably exceed future rules.

4.9 Emissions sustainable landfill vs conventional landfill

An inventory was made for Nauerna in order to gain an initial impression of the leachate concentrations as a function of time and a comparison with other cells. Many data for the metal concentrations as a function of time are available for this landfill. The results of the comparison on the basis of the concentrations measured are given in Figure 32. A distinction has been made between the influent water from the water treatment system (WTS), the separate cells at Nauerna (Other cells), the leachate and runoff from the pilot project for sustainable landfill (13AA, P and 13aa, R) and the lysimeter experiments (Lysimeters). The DOC and chloride concentrations are at comparable levels in the other cells and the sustainable landfill project (13AA).

The concentrations of As, Cr and Pb for the sustainable landfill cell (13AA) and the lysimeters lie roughly at the bottom of the concentration range in comparison with the other cells. It is difficult to establish unequivocally how far these results are due to processes being influenced by the sustainable landfill concept. The results do seem to indicate that there are more favourable conditions in the landfill body, which result in lower emissions of pollutants. Substantiation for the understanding of the chemical processes, which provides the possibility of controlling these processes, is further elaborated in the (English) reference document on the modelling of chemical processes in landfill sites.

The Cu concentrations in cell 13AA are also at the bottom of the range in comparison with the other cells. Only the results from the lysimeters are clearly higher than the concentrations which were measured in cell 13AA. This can probably be attributed to the more oxidising conditions in the lysimeters, under which the Cu(II) strongly complexes with DOC. More reducing conditions prevail in the pilot project under which the Cu(I) species is more dominant. It is possible that this species has a lower affinity for DOC or inorganic complexes, (resulting in sulphide formation) become more important.

The leaching of ammonium seems to be comparable with the other cells, except for the lysimeters. The explanation for this is given in the description of the experiments in section 4.8.

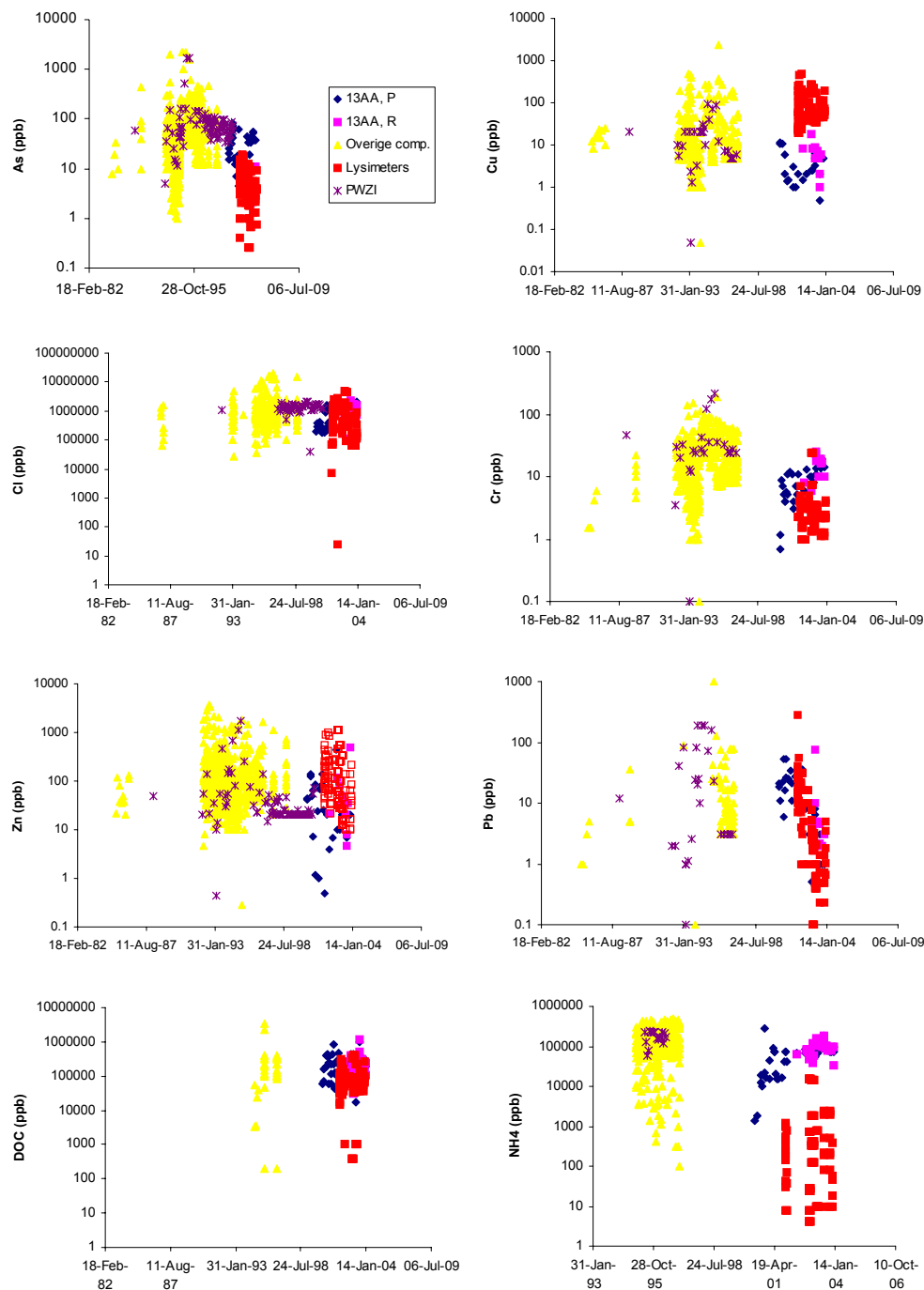


Figure 32 Concentrations in leachate as a function of time. The data from Nauerna are compared with the pilot project sustainable landfill and the lysimeter experiments in the graph.

4.10 Comparison with the European Landfill Directive

A comparison was made with the criteria set by Annex II of the European Landfill Directive for the acceptance of waste at landfills for inert waste on the basis of the results from the

laboratory column tests on the integral waste mixture in the Nauerna pilot and supported by the closely related lysimeter and field measurements. The results are given in Table 9. It appears that a large number of parameters now already comply with the criteria for inert waste. Cl and sulphate do not comply, and Sb is at the limit.

The Sb concentrations measured are in general lower or around the level of the limit of detection (approximately 5 ppb with ICP-AES). This means that additional measurements with a more sensitive technique (for example hydride generation and analysis with atomic fluorescence spectrometry) are needed to establish if Sb is actually a critical element. It cannot be unequivocally concluded that Sb is a critical element with respect to the acceptance criteria for inert waste on the basis of these results. However, the reported Sb emissions can be seen as the upper limit for the Sb emission.

Table 9 *Comparison of cumulative emission at L/S=10 from the column test on the integral waste mixture for the Nauerna pilot with the European Landfill Directive Annex II criteria for acceptance of wastes at landfill sites for inert waste. By way of comparison the emission from the more organically-rich mixture is also recorded.*

Element	Integral	Integral+ORG		EU-LFD	EU LFD	Ratio	Ratio	Integral+ORG	Integral+ORG
	L/S=10	L/S=10	EU-LFD						
	mg/kg	mg/kg	mg/kg	mg/kg*					
As	0.099	0.129	0.5		0.2			0.26	
Ba	0.534	0.289	10		0.05			0.03	
Cd	0.031	0.024	0.04		0.76			0.60	
Cl	4029	3316	800		5.04	1.7 ***		4.15	1.4***
Cr	0.023	0.02	0.5		0.05			0.04	
Cu	0.038	0.133	2		0.02			0.07	
DOC	353	1733	500		0.71			3.47	
Mo	0.123	0.274	0.5		0.25			0.55	
Ni	0.136	0.271	0.4		0.34			0.68	
Pb	0.323	0.349	0.5		0.65			0.70	
SO ₄ as S	5486	3929	333	2000	16.5	2.7*		11.80	2*
Sb	0.064	0.043	0.06		1.07			0.72	
Se	0.053	0.072	0.1		0.53			0.72	
Zn	0.833	1.265	4		0.21			0.32	
Hg	No data		0.01						
F**	7.87****		10		0.78				
<p>* Special criterion for SO₄</p> <p>** Based on a limited set of leachate data</p> <p>*** After correction for preferential flow (2/3 of the waste body is flushed only very slowly, or not at all)</p> <p>**** After correction for solubility-controlled flushing on the basis of the highest measured concentration (must still be proved)</p>									

An additional criterion is applicable to sulphate but despite this greater tolerance, sulphate still exceeds the acceptance value. Preferential flow is not taken into account for Cl, and since it has been established from the mobile parameters that Cl is flushed from only 30% of the waste body, it can be assumed that the peak concentration in groundwater at a position of 20

m from the landfill is reduced by a factor of circa 3 due to the far slower flushing of the remaining Cl fraction. This reduces the exceedance factor to approximately 1.7. Given the local situation in the case of Nauerna with high salt concentrations in the groundwater and the adjacent North Sea Canal, which is influenced by the sea locks/channels, such an exceedance would allow a decision to be made on the emission levels that are acceptable in the long term, based on a comparison of the expected impact and actual concentrations found.

It should be noted that the emission of F in the column test (leaching test for the assessment against Annex II criteria) is not measured. Therefore, the emission measured in the pilot project is converted to an emission at L/S=10. Hereby, it is assumed that the highest F concentration measured will be maintained from now until an L/S ratio of 10 is reached in the pilot project (in practice this is certainly hundreds of years). On the basis of this conversion it can be assumed that F will not be critical. This could be verified by additional measurements.

4.11 Analysis

4.11.1 Source term

The combination of laboratory, lysimeter and field data form a dataset for the different inorganic and organic parameters which can be used to give source term descriptions, these can then be used for impact modelling. This would necessitate the adaptation of the spreadsheet, [which was used for the EU modelling and led to the current Annex II criteria](#), to take [account of the negotiations occurring within the EU Member States](#). In such a calculation consideration can now also be given to an assessment of preferential flow, which is not distinguished in the Annex II evaluation.

In Table 10 the relevant quantities for the source term description are reproduced for a number of components.

Table 10 *Source term description*

Element	Kappa	C ₀ (mg/l)
Cl	0.9	4000 (column); 500 (lys, pilot)
SO ₄ as S	0.1	750
PO ₄ as P	0.15	0.3
Co	0.05	0.002
DOC	0.2	100

4.11.2 Translation of source term to acceptance

The spreadsheet that was developed for the calculation of the Annex II criteria is applied after correction of the parameters so that the Annex II values are obtained under the standard conditions. The source term data are inputted in order to ascertain what the current data mean for the acceptance criteria. It appears that on the basis of a comparison of the leaching values with the Annex II criteria, all the parameters of the European Landfill Directive comply with the criteria for the inert landfill, with the exception of Cl and SO₄ and sometimes Sb (on the limit). In order to verify whether Sb is really a critical parameter, further research must be undertaken, whereby the leachate is analysed for Sb using a more sensitive technique. There are more sensitive techniques than ICP-AES available. These techniques were not however applied in this research.

Other solutions are possible for Cl and sulphate, which on the one hand relate to local circumstances and on the other to possible pre-treatment. Wastes which cannot be treated with the Equifill concept can possibly be treated using cement-stabilisation in the Monolith landfill. This outcome is of great importance because it means that for the waste mixture, such as that used in the pilot, no far-reaching aftercare measures will be necessary. That means that a once applied measure does not have to be kept in place in the aftercare phase. No values are given in the EU LFD for NH_4 but it is expected that these will be set in due course. This means that a solution must be sought for NH_4 . NH_4 does decrease sharply at higher L/S values, just as is the case with Cl. This means that the emission level that is predicted on the basis of leaching will not be reached. The initial level in the pilot project is around 80-90 mg/l and will decrease over time. A strict acceptance policy with respect to degradable organic matter is important to ensure that NH_4 in particular does not increase further (see experiments with increased organic matter) because a 10% addition of material rich in organic matter gives rise to a 6 fold increase in NH_4 .

4.11.3 Acceptance criteria

Equilibrium conditions in the landfill are sought on the basis of the concept. These conditions already appear to be present to a large extent. Mixed wastes have a certain buffering capacity that keeps metal binding, pH, redox and DOC under control. The controlling parameters, which are relevant parameters influencing the whole landfill, are the acid/base neutralising capacity (ANC/BNC), redox capacity, degradable organic waste (determined via DOC) and the proportion of components which do not react with the matrix (for example Cl, VOX). An assessment concept was developed for these mobile components that assumes a moving average of the cumulative leaching from the landfill. The concept does not yet take preferential flow into account, which is important for the assessment of these parameters. An acceptance standard is assumed against which the individual waste streams will be tested. All the individual streams to be landfilled in a cell contribute to the behaviour of the landfill site in practice. A form of quota system per cell can be formulated for mobile components such as Cl and DOC, which may (or may not) take preferential flow into account. This approach is presented graphically in Figure 33 for Cl Figure 34 for DOC in the Nauerna pilot project. It can be seen from the figures that the individual waste streams have very variable leaching behaviours and that almost all the measurements are under the limit for incidental waste streams (the standard that could be applied to waste streams with high chloride leaching, provided that the total quantity of this waste remains limited). The blue line shows the moving average of all individual waste streams. The leaching of Cl and DOC in the pilot project (black line) increases cumulatively and seems still to be increasing very gradually to the final storage quality limit. The cumulative leaching is also clearly levelling off.

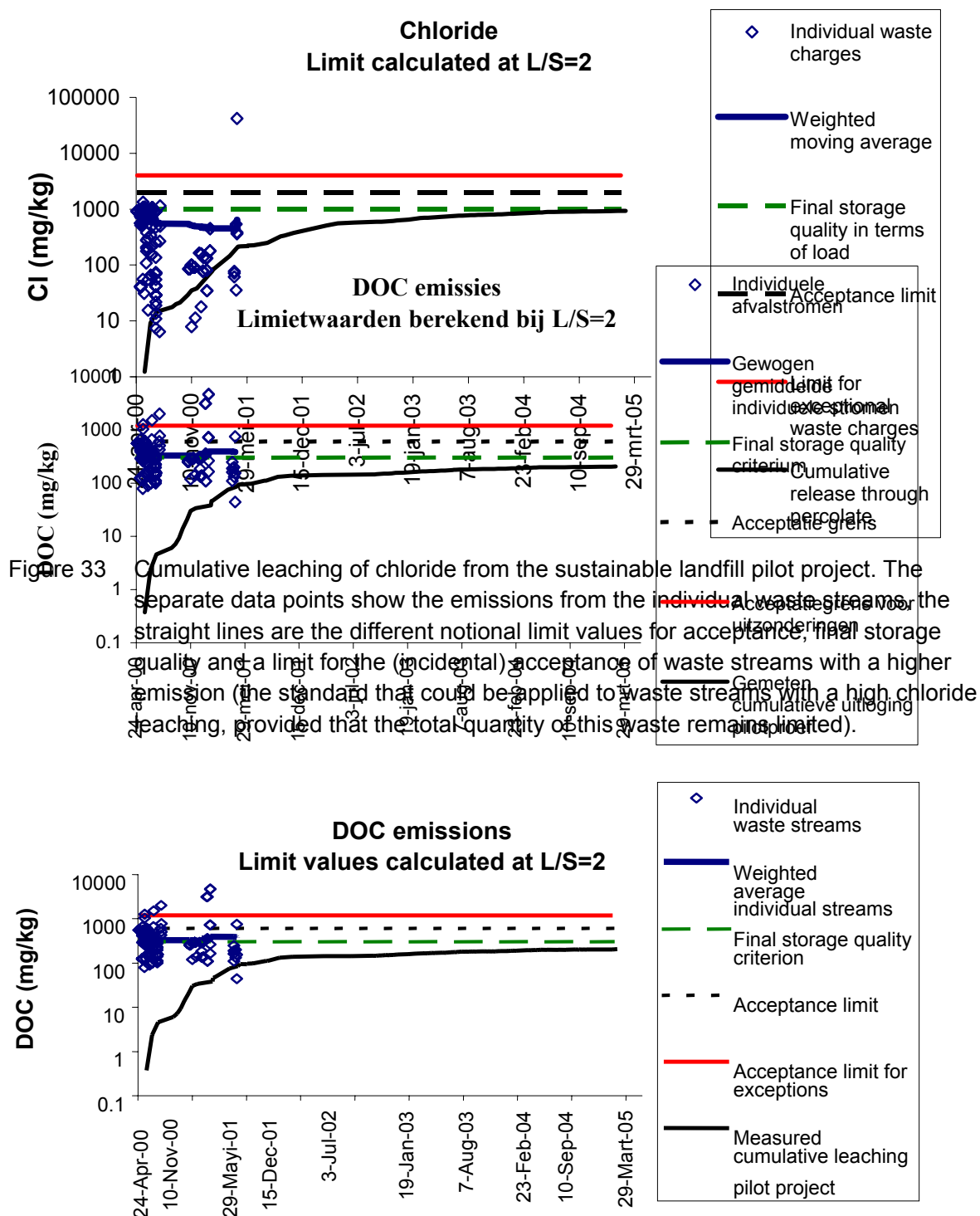


Figure 34 Cumulative leaching of DOC from the sustainable landfill pilot project. The separate data points show the emissions from the individual waste streams, the straight lines are the different notional limit values for acceptance, final storage quality and a limit for the (incidental) acceptance of waste streams with a higher emission (the standard that could be applied to waste streams with a high chloride leaching, provided that the total quantity of this waste remains limited).

In principle no restriction is applicable on the basis of the wastes that were used in the Nauerna pilot; these can be landfilled (see Table 5). It should be noted that the final mixture in the landfill will have to continue to show analogous emissions to those described in this report. This means that for example a waste as alkaline as drilling muds should not dominate the behaviour of the landfill site. The effects of high pH and/or salt load could then become evident. Therefore, it is recommended that the behaviour of a mixture of wastes be considered during the construction of a sustainable landfill according to the Equifill concept.

When testing against the acceptance criteria for these waste streams it should be noted that streams such as residues from construction and demolition segregation are very heterogeneous and coarse. This waste stream is difficult to sample in practice. However, this material is very coarse-grained and thus has a small surface, and so provides a relatively low contribution to the total emission from the landfill body. The leaching of sulphate can however still cause a problem when large quantities of gypsum waste are landfilled. Requirements could possibly be set for the gypsum fraction; visual inspection of this sort of waste can regulate the sulphate load.

Waste streams with a high probability of containing leachable Sb must be avoided because Sb is on the limit of acceptance for inert landfill.

If too a high level of Cl and other easily flushed components would lead to such an increase in the concentrations in leachate such that the discharge conditions cannot be met, then a prior washing step in the form of 'heap leaching' can possibly be introduced to reduce the level to such an extent that the rest of the stream can be accepted without problems arising. The processing of such a concentrated leachate is simpler than having to treat a strongly diluted leachate that does not meet the relevant requirements. Discharge to sea can be an option for a solution with only high concentrations of salts. Further consideration of such an option is necessary. Wastes that cannot be treated using the Equifill concept can possibly be treated via cement-stabilisation in the Monolith landfill. Further research is desirable for sulphate because it is present in numerous wastes, and due to the relatively high solubility of gypsum, can lead to problems in many cases.

4.11.4 Draft design

The draft design for the predominantly inorganic waste is given in Figure 35. The different phases are presented schematically in this figure. In this situation it is assumed that the waste is analysed before delivery to the landfill site. The landfill site manager can assess if and in which cell the waste concerned should be landfilled, on the basis of the so-called quota system, in order to influence the quality of the whole landfill site as favourably as possible.

The behaviour of the heavy metals can be determined on the basis of characterisation and modelling of the mixture of wastes. This is described in detail in the English language reference document on geochemical modelling of the behaviour of wastes.

The conditions in the landfill remain favourable due to the controlled construction of the landfill body, ensuring that the European legislation and the criterion that the landfill site is stable within 30 years can be complied with.

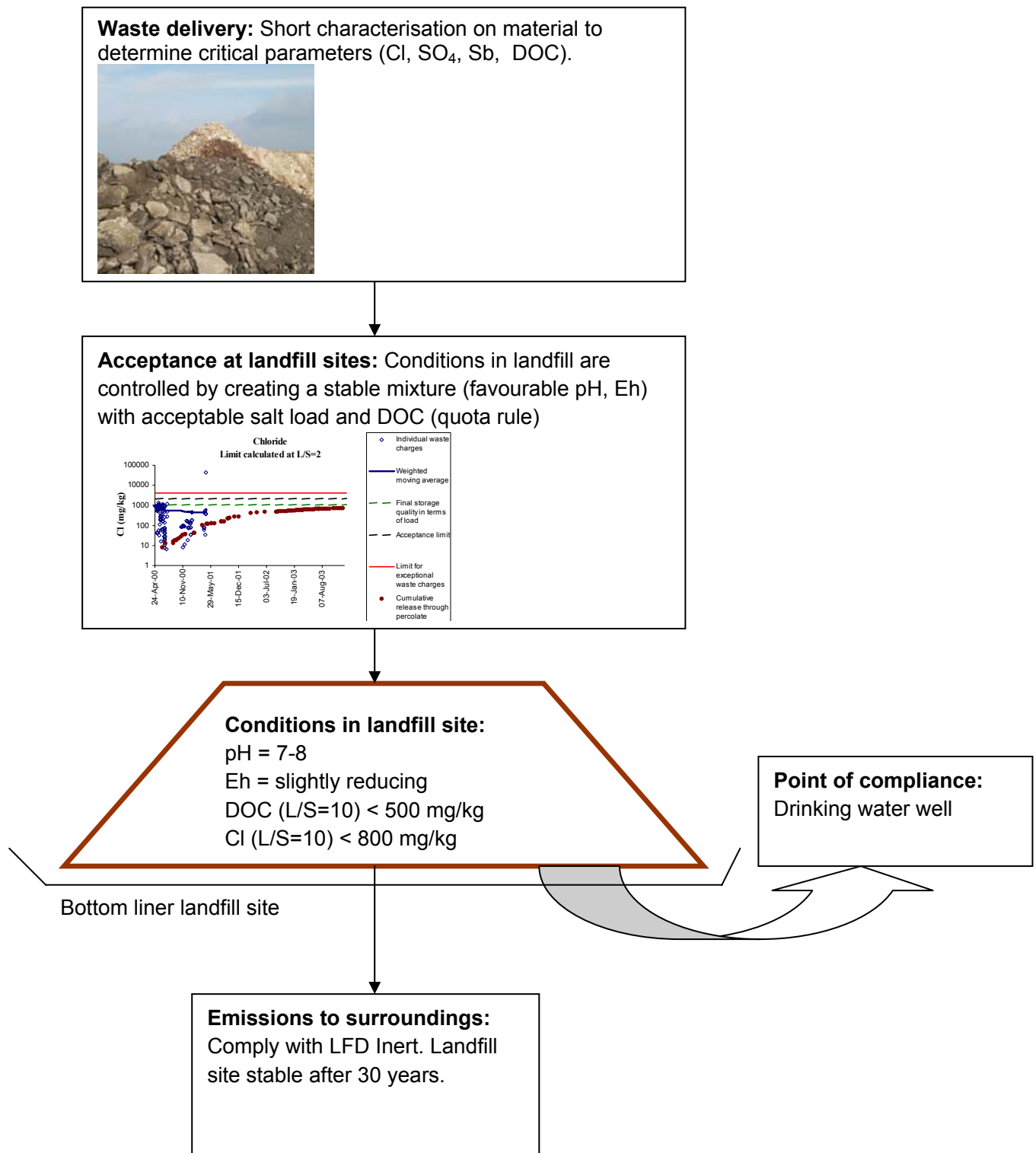


Figure 35 Draft design sustainable landfill, predominantly inorganic waste.

4.11.5 Management

The management of the concept is feasible for a group of mobile parameters. Description of a moving average of the landfill emission on the basis of waste fractions could be considered. This could be used to make certain that a certain quota (e.g. Annex II or Building Materials Decree criteria) is not exceeded.

Another alternative method of management could be to make an estimate of the waste streams to be received before delivery (this can change over time) and ascertain to what extent the predicted emissions data can be quantified through modelling (see recommendation on modelling waste mixtures).

A third alternative is through sampling, by preserving sample fractions per relevant stream volume, compiling a composite sample and establishing the extent of the exceedance of the criteria (basic approach for the implementation of the Nauerna pilot) by sampling. Thus it can be established during and at the end of the operational phase how the waste mixture will behave over the long-term. This could serve as a basis for demonstrating the condition of the landfill. By combining this information with the leachate measurements an eventual decision on the transfer of the landfill site to the aftercare phase can be substantiated.

4.12 Feasibility

4.12.1 Technical

It seems that the concept is technically feasible. The filling of a landfill cell will not be fundamentally different than is now the case. No problems were identified with respect to the stability of the landfill due to the choice of the material streams. The contaminated land decontamination residues were interspersed with more mechanically stable residues from construction and demolition segregation during the construction of the landfill body. Consideration can perhaps be given to a more conservative engineering of the bottom, the side and the upper side of the landfill body during the construction of a cell, by landfilling only relatively clean materials in these areas. The bottom liner, which must be laid for a non-hazardous waste landfill, remains necessary in order to collect and treat the leachate during the operational phase. An expensive top liner can be omitted during the aftercare phase once inert behaviour has been established.

The technical feasibility is determined to a large extent by having a good overview of the behaviour of the materials to be landfilled and the translation of this into the acceptance policy. This necessitates having a logical system with which the landfill site manager is able keep an account of any quota (for example for chloride and DOC) for each cell. The manager will also be able to account for the total composition of the waste in order to ensure that the mixture remains stable.

4.12.2 Environmental protection

A starting point for assessing acceptable release is the criterion as defined by the EU in Annex II. This means that the groundwater next to the landfill may not exceed the standards for drinking water because of the presence of the landfill. This requirement cannot ignore the local circumstances, which in the case of Nauerna are determined by salt water intrusions. Another possible starting point is the reference to natural land conditions. If the emission values are approaching those for surface level, then an assessment against natural land conditions becomes clear.

4.12.3 Legal

There are a number of aspects, which are connected in terms of authorisation and response to exceedance for components such as Cl and sulphate, over which permission from the authorities would have to be obtained. In particular this concerns getting a slightly higher

emission of both components accepted where natural background levels are already elevated (for example due to high salt concentrations in the groundwater).

4.12.4 Economic

Economic evaluation of this concept is not simple, because there are a number of factors which are difficult to assess. However, if the waste body complies with the inert waste criteria and a solution can be found for the components which do not directly comply with the criteria, the aftercare provisions and the need to install a cap with high quality standards are redundant; this results in a very large cost saving of 40 €/m². The anticipated costs of aftercare - for monitoring and maintenance - will be lower if the competent authority accepts that the landfill is inert after completion than would be the case of a landfill being designated as non-hazardous. Essent and Afvalzorg have roughly compared the costs of sustainable landfill with conventional landfill. The results of the costs estimates are given in **Fout! Verwijzingsbron niet gevonden.** and Table 12. The assumptions for investments and operational costs are given; the costs for conventional and sustainable landfill are calculated per m² and per m³. **Fout! Verwijzingsbron niet gevonden.** shows the calculation per m² and per m³ at a maximum landfill height of 15 m. From the table it appears that the costs of sustainable landfill are comparable with conventional landfilling costs; the difference per m³ is less than 2%.

Table 11 *Cost calculation Equifill versus conventional landfill at a maximum landfill height of 15 m (average landfill height 11 m).*

Higher and lower costs sustainable landfill						
Investment costs:						
a) Combination top liner		40	€/m ²			
b) Infiltration system		15	€/m ²			
c) Cover sustainable landfill		12	€/m ²			
d) HDPE membrane and drainage for sustainable landfill		25	€/m ²			
e) Combination bottom liner		60	€/m ²			
Operational costs:						
a) Administration and overhead		3.00	€/m ³ landfill			
b) Conventional operation		0.85	€/m ³ landfill			
c) Leachate treatment conventional landfill		5.00	€/m ³ water			
d) Leachate treatment sustainable landfill		2.00	€/m ³ water (diluted and pre-treated)			
e) Extra operational costs sustainable landfill		2.00	€/m ³ landfill (supervision, electricity)			
f) Aftercare provision conventional landfill		5.10	€/m ³ landfill			
g) Aftercare provision sustainable landfill		2.30	€/m ³ landfill (less monitoring, no top liner)			
h) Landfill gas proceeds		0.00	€/m ³ landfill			
Item	Costs	Sustainable		Conventional		Diff.
		€/m ²	€/m ³	€/m ²	€/m ³	€/m ²
Investment top liner		12.00	1.09	40.00	3.64	-28.00
Investment pipe work		15.00	1.36	0.00	0.00	15.00
Bottom liner, infrastructure and financial provision		60.00	5.45	60.00	5.45	0.00
Administration and overhead		33.00	3.00	33.00	3.00	0.00
Operational costs		130.85	11.85	108.35	9.85	22.00
Leachate treatment		46.80	4.25	30.00	2.73	16.80
Aftercare provision		25.30	2.30	56.10	5.10	-30.80
Landfill gas proceeds		0.00	0.00	0.00	0.00	0.00
Total		322.45	29.31	327.45	29.77	-5.00

The height of a landfill site can also have an influence on the costs. Table 12 shows the costs of sustainable landfill and conventional landfill at a maximum landfill height of 30 m. It appears that the sustainable landfill per m³ is approximately 5% more expensive in this case than conventional landfill. The cost estimates, made on the basis of the assumptions given, indicate that the costs for sustainable landfill are roughly equivalent to those for conventional landfill.

Table 12 *Cost calculation Equifill versus conventional landfill at a maximum landfill height of 30 m (average landfill height 21 m).*

Higher and lower costs sustainable landfill						
Investment costs:						
a) Combination top liner		40	€/m ²			
b) Infiltration system		15	€/m ²			
c) Cover sustainable landfill		12	€/m ²			
d) HDPE membrane and drainage for sustainable landfill		25	€/m ²			
e) Combination bottom liner		60	€/m ²			
Operational costs:						
a) Administration and overhead		3.00	€/m ³ landfill			
b) Conventional operation		0.85	€/m ³ landfill			
c) Leachate treatment conventional landfill		5.00	€/m ³ water			
d) Leachate treatment sustainable landfill		2.00	€/m ³ water (diluted and pre-treated)			
e) Extra operational costs sustainable landfill		2.00	€/m ³ landfill (supervision, electricity)			
f) Aftercare provision conventional landfill		5.10	€/m ³ landfill			
g) Aftercare provision sustainable landfill		2.30	€/m ³ landfill (less monitoring, no top liner)			
h) Landfill gas proceeds		0.00	€/m ³ landfill			
Item	Costs	Sustainable €/m ²	€/m ³	Conventional €/m ²	€/m ³	Diff. €/m ²
Investment top liner		12.00	0.57	40.00	1.90	-28.00
Investment pipe work		30.00	1.43	0.00	0.00	30.00
Bottom liner, infrastructure and financial provision		60.00	2.86	60.00	2.86	0.00
Administration and overhead		63.00	3.00	63.00	3.00	0.00
Operational costs		248.85	11.85	206.85	9.85	42.00
Leachate treatment		46.80	2.23	30.00	1.43	16.80
Aftercare provision		48.30	2.30	107.10	5.10	-58.80
Landfill gas proceeds		0.00	0.00	0.00	0.00	0.00
Total		508.95	25.43	506.95	24.14	2.00

5. Conclusions

5.1 General conclusions for Equifill

During the five year long project on sustainable landfill much knowledge was built up on the processes occurring within landfill sites. Until now a landfill site was often seen as a black box (all sorts of wastes were placed in it and only time would tell what would come out of it). The results of this project show that an end of this 'black box thinking' can now be envisaged and that it can be replaced by a process-based approach. The results of geochemical model calculations show that many of the chemical processes in the landfill site are understood. This makes it possible to make assertions on the long-term behaviour of landfill sites.

The aim of the project was: *'Demonstrate that a landfill concept is possible, whereby the emissions will be reduced within 30 years to a level that requires no specific reduction measures.'* On the basis of the results of this project it can be postulated that it is indeed feasible to reduce the emissions to an acceptable level within 30 years. It is assumed that the period of 30 years starts after the operational phase. An active water treatment plant is still present in the operational phase to reduce the emissions from the landfill site. It should be noted that for this landfill concept, on the basis of the wastes used, there are two critical components, namely chloride and sulphate (and possibly antimony). More comprehensive conclusions on the critical elements are given in the specific conclusions for Equifill. Extra attention will be necessary to ensure that the emissions of these components remain acceptable during the implementation of sustainable landfilling at a new landfill site.

The outcome of the project is of great importance, as it means that for waste mixtures, such as that used in the pilot, no extensive aftercare measures will be necessary. That means that a once applied measures do not have to be maintained in the aftercare phase. No values are given for NH_4 in the European LFD but it is expected that these will be established in due course. This means that a possible solution must be sought for NH_4 . The starting level in the pilot project is around 80-90 mg/l, which will sharply decrease after an L/S of 0.5, at which point it is assumed that no new formation takes place. In particular to prevent NH_4 increasing further it is important not to accept easily degradable organic matter (see experiments with increased organic matter) because an addition of 10% organically rich material results in a 6 fold increase in NH_4 .

The sustainable landfill concept assumes a stable situation for the landfill site after 30 years. The European Landfill Directive sets standards for emissions of individual wastes from the start of operations. This difference could lead to an incorrect assessment of the concept. An assessment of the projected emissions on delivery (after ca. 30 years) should be the case, instead of an assessment beforehand. The (European) legislation will have to be adapted to make an assessment of the total landfill site possible (thereby taking account of waste-waste interactions); this approach could be introduced when revising the European Landfill Directive.

The flushing of mobile components in the active phase of the landfill site is important in reducing the concentrations. Therefore, it is important to aim towards maximum flushing of the landfill body in the active phase by not covering the landfill site during this period. A more

accurate estimate must be obtained of the mobile phase in the Nauerna pilot project; this is currently taken to be 30%.

Acceptance criteria

Equilibrium conditions in the landfill are sought on the basis of the concept. These conditions already appear to be present to a large extent. Mixed wastes have a certain buffering capacity that keeps metal binding, pH, redox and DOC under control. The controlling parameters, which are relevant parameters influencing the whole landfill, are the acid/base neutralising capacity (ANC/BNC), redox capacity, degradable organic waste (determined via DOC) and the proportion of components which do not react with the matrix (for example Cl, VOX). An assessment concept was developed for these mobile components that assumes a moving average of the cumulative leaching from the landfill. The concept does not yet take preferential flow into account, which is important for the assessment of these parameters. An acceptance standard is assumed against which the individual waste streams will be tested. All the individual streams to be landfilled in a cell contribute to the behaviour of the landfill site in practice. A form of quota system per cell can be formulated for mobile components such as Cl and DOC, which may (or may not) take preferential flow into account.

Management

The management of the concept is feasible for a group of mobile parameters. Description of a moving average of the landfill emission on the basis of waste fractions could be considered. This could be used to make certain that a certain quota (e.g. Annex II or Building Materials Decree criteria) is not exceeded.

Another alternative method of management could be to make an estimate of the waste streams to be received before delivery (this can change over time) and ascertain to what extent the predicted emissions data can be quantified through modelling (see recommendation on modelling waste mixtures).

A third alternative is through sampling, by preserving sample fractions per relevant stream volume, compiling a composite sample and establishing the extent of the exceedance of the criteria (basic approach for the implementation of the Nauerna pilot) by sampling. Thus it can be established during and at the end of the operational phase how the waste mixture will behave over the long-term. This could serve as a basis for demonstrating the condition of the landfill. By combining this information with the leachate measurements an eventual decision on the transfer of the landfill site to the aftercare phase can be substantiated.

Technical feasibility

It seems that the concept is technically feasible. The filling of a landfill cell will not be fundamentally different than is now the case. No problems were identified with respect to the stability of the landfill due to the choice of the material streams. The contaminated land decontamination residues were interspersed with more mechanically stable residues from construction and demolition segregation during the construction of the landfill body. Consideration can perhaps be given to a more conservative engineering of the bottom, the side and the upper side of the landfill body during the construction of a cell, by landfilling only relatively clean materials in these areas. The bottom liner, which must be laid for a non-hazardous waste landfill, remains necessary in order to collect and treat the leachate during the operational phase. An expensive top liner can be omitted during the aftercare phase once inert behaviour has been established.

The technical feasibility is determined to a large extent by having a good overview of the behaviour of the materials to be landfilled and the translation of this into the acceptance policy. This necessitates having a logical system with which the landfill site manager is able keep an account of any quota (for example for chloride and DOC) for each cell. The manager will also be able to account for the total composition of the waste in order to ensure that the mixture remains stable.

Environmental protection feasibility

A starting point for assessing acceptable release is the criterion as defined by the EU in Annex II. This means that the groundwater next to the landfill may not exceed the standards for drinking water because of the presence of the landfill. This requirement cannot ignore the local circumstances, which in the case of Nauerna are determined by salt water intrusions. Another possible starting point is the reference to natural land conditions. If the emission values are approaching those for surface level, then an assessment against natural land conditions becomes clear.

Legal feasibility

There are a number of aspects, which are connected in terms of authorisation and response to exceedance for components such as Cl and sulphate, over which permission from the authorities would have to be obtained. In particular this concerns getting a slightly higher emission of both components accepted where natural background levels are already elevated (for example due to high salt concentrations in the groundwater).

Financial feasibility

Economic evaluation of this concept is not simple, because there are a number of factors which are difficult to assess. However, if the waste body complies with the inert waste criteria and a solution can be found for the components which do not directly comply with the criteria, the aftercare provisions and the need to install a cap with high quality standards are redundant; this results in a very large cost saving of 40 €/m². The anticipated costs of aftercare - for monitoring and maintenance - will be lower if the competent authority accepts that the landfill is inert after completion than would be the case of a landfill being designated as non-hazardous. The total costs of conventional and sustainable landfill are judged to be comparable on the basis of the cost assessment (costs per m³ waste).

5.2 Specific conclusions Equifill

From the results of the monitoring it appears that the emissions from the laboratory, lysimeter and pilot scales are consistent for the majority of elements. Differences can be explained for mobile components by preferential flow in the lysimeters and pilot project.

Predictive modelling of emissions from waste mixtures on the basis of available characterisation information seems feasible (see English language reference document on database and modelling). This means that in principle it is possible to indicate the final situation that can be reached in a landfill cell in advance, on the basis of the expected waste supply. Furthermore, the results indicate that the mixed landfill, despite great heterogeneity at the local level, behaves extremely systematically in its totality.

The chloride emissions exceed the standards for the acceptance of waste at an inert landfill site. A solution can only be found for this by reducing the total available chloride content, given that chloride is a mobile component that is barely/is not bound by the solid matrix. A quota

system for this component can provide a solution so that the emissions comply with the current legislation for the acceptance of inert waste. The treatment of salt-containing wastes by cement-stabilisation and subsequent landfilling at a Monolith landfill site can also be considered. Another option is pre-treating chloride-containing waste streams with a sort of heap leaching process as an initial connected step for the removal of undesirable levels of mobile components. This could lead to considerably better control of the leachate quality for less manageable elements such as this.

Sulphate appears to encounter problems in all landfill concepts. The solubility of gypsum gives rise to the problem; the solubility control ensures constant (too high) concentrations. This means that reducing the sulphate leaching by pre-treatment of wastes (washing or heap leaching) will have little effect on the quality of the wastes with respect to the leaching of sulphate. Besides, the solubility-controlling mineral even seems to control the leaching of sulphate to almost $L/S=10$ (depletion has not yet occurred). The final fractions from the column tests do show that depletion can be expected around L/S values of 10 but these L/S values are much too high for pre-treatment procedures. An alternative for a number of sulphate-containing residues could be immobilisation using cement-stabilisation. However, the suitability of the waste stream concerned for this technique should be examined. Materials such as residues from construction and demolition waste segregation can be extremely heterogeneous and coarse, and thus for example unsuitable for immobilisation. The question is if this has consequences for the criteria, for the acceptance or that other solutions need to be found.

At the Nauerna location it is possible that the high chloride and sulphate emissions do not present a problem in practice because the landfill site is located in an area with high salt concentrations in the groundwater. A decision on the acceptable long-term emission levels may be actuated by the exceedances based on a comparison of the predicted impact and actual concentrations in the groundwater. This situation must be discussed with the competent authority so that further clarification is obtained. Annex II of the European Landfill Directive does allow scope for a location-specific risk assessment.

It is notable that the leaching behaviour of total sulphur (determined using ICP-AES after acidification of eluate) in the pilot project is a factor of 7 lower than the leaching of sulphate (determined in unconserved eluate with ion chromatography). Sulphur must be present in the form of sulphate in oxidising systems. Given this, there must be approximately a factor of 3 between the emissions of total sulphur and sulphate (due to the difference between S and SO_4^{2-}). It is likely that H_2S gas escapes on acidification of the samples for ICP-AES (using HNO_3 to $pH < 2$). This results in the concentrations of total sulphur being too low, and the discrepancy between total sulphur and sulphate, which cannot be explained by the presence of other sulphur species such as S^{2-} or thiosulphates; sulphate is indeed higher than the total determined sulphur. It is therefore important to note that the sulphate concentrations in reduced samples cannot be assessed on the basis of the total sulphur determination using ICP-AES.

The emissions of antimony are critical with respect to the acceptance of waste at an inert landfill site. The emissions in the pilot project are however continually slightly lower than the other experiments and the emission now seems to be levelling off. Subsequent measurements will indicate if this behaviour changes or if there is a temporary levelling off of the antimony emission. The antimony concentrations measured are generally lower than or around the level of the limit of detection (approximately 5 ppb with ICP-AES). More sensitive techniques than

ICP-AES are available. These techniques were however not used in this research. Additional measurements are needed with a more sensitive technique (hydride generation and analysis with atomic fluorescence spectrometry) to establish if antimony is actually a critical element. On the basis of these results it cannot be unequivocally concluded that antimony is a critical element with respect to the acceptance criteria for inert waste. However, the reported antimony emissions can be seen as the upper limit for the antimony emission.

It is important for antimony to investigate if its solubility (which has limited mobility in many 'natural' matrices) can be controlled, using better stability data for the modelling. Streams with an increased risk of antimony leaching should be identified (especially residues from thermal processes).

On the basis of the fluoride analyses it can be concluded that the emissions are very unlikely to be critical. It should be noted that the fluoride emission in the column test (leaching test for the assessment of Annex II criteria) is not measured. Therefore, the emission measured in the pilot project is converted to an emission at L/S=10. On the basis of this conversion it can be stated that fluoride is very unlikely to be critical. This could still be verified with additional measurements.

The copper emissions measured in the pilot project are approximately an order of magnitude lower than the lysimeters. This can probably be attributed to the more oxidising conditions in the lysimeters (higher redox potential), under which the Cu(II) strongly complexes with DOC. In the pilot project more reducing conditions prevail under which the less soluble Cu(I) species is more dominant and/or poorly soluble (Cu(I) or Cu(II)) sulphides are formed. It is also possible that the affinity of Cu(I) for complexation with DOC is smaller than the affinity of Cu(II). The leaching of copper is not critical in any of the experiments carried out with respect to the European Landfill Directive for inert waste. It is certainly noticeable that the role of organic matter in the leaching of Cu under reducing conditions is limited in comparison with the leaching under more oxidising conditions.

The concentrations of Fe and Mn both show relatively large differences between the different experiments. The leaching of Fe is substantially higher in the pilot project and the column tests. Fe is sensitive to reducing conditions; the generally poorly soluble Fe(III) can be reduced under anaerobic conditions to the far more soluble Fe(II). This then results in higher Fe concentrations in the pilot project and the column tests with respect to the more oxidising lysimeter tests.

Mn is a typical redox indicator. Mn increases sharply at low redox; this is the case in the pilot project. The difference in emissions between the lysimeters and the pilot project are probably caused by differences in redox potential. The redox potential in the pilot project is also consistently somewhat lower than in the lysimeters. It seems that that Mn is extremely sensitive to this and this will be evident in the Mn (and Fe) levels as soon as differences in redox potential occur.

When the concentrations measured in the pilot project are compared with the measurements from conventional cells at the Nauerna landfill site, it is apparent that the concentrations of As, Cr, Cu en Pb in the sustainable landfill cell are roughly at the bottom of the concentration range. On the basis of such a comparison it is difficult to establish unequivocally the extent to which these results are due to processes being influenced by the sustainable landfill concept. The results do however seem to show favourable conditions in the landfill body, which result in

lower emissions of pollutants. The ammonium concentrations seem comparable to the other cells.

6. Recommendations

It is recommended that the chloride and sulphate emissions at Nauerna are discussed with the competent authority. Strictly speaking the emissions are higher than the standards for inert waste but this is probably not a problem at the Nauerna location (area with high salt concentrations in the groundwater). Annex II of the European Landfill Directive does allow scope for a location-specific risk assessment.

Continuation of the monitoring on pilot and lysimeter scales. During further analysis additional antimony measurements could also be undertaken with a more sensitive analytical technique (hydride generation with AFS). It is also recommended that a definitive view of the exact L/S values in the pilot project be obtained, and that the data are corrected accordingly.

Flushing mobile components in the active phase of the landfill site is important for reducing their concentrations. Therefore, it is important to aim towards maximum flushing of the landfill body in the active phase by not covering the landfill site during this period. An alternative option is to lower the salt load of waste beforehand. It is suggested that preferential flow is modelled using Orchestra.

It should be noted that the F emission in the column test (leaching test for the assessment of Annex II criteria) is not measured. Therefore, the emission measured in the pilot project is converted to an emission at L/S=10. On the basis of this conversion it can be stated that F will not be critical. This could still be verified with an additional column test.

A possible method of pre-treatment for reducing mobile components is a sort of heap-leaching process. On a scale of a few m³ a definitive view must be obtainable over a relatively short timescale on whether the level of flushable components can be reduced sufficiently quickly using a form of heap-leaching.

7. References

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- (3) Bour, O.; Couturier, C.; Berger, S.; Riquier, L. "Evaluation des risques liés aux émissions gazeuses des décharges: propositions de seuils de captages"; INERIS-DRC-05-46533/DESP-R01; 2005.

Appendix A

Analysis and legislation, European Landfill Directive (EN TEXT, paraphrased)

Green: in accordance with SL (allows/opening for SL)

Orange: in accordance with SL depending on interpretation

Red: not in accordance with SL and poses substantial/potential hindrance

Article/ Recital	Quotation	Analysis	Assessment
Directive 1999/31/EC of 26 April 1999 on the landfill of waste (European Landfill Directive)			
Recital			
2	only safe and controlled landfill activities	Conforms with SL	
6	landfill should be adequately monitored and managed to prevent or reduce potential adverse effects on the environment	Conforms with SL	
8	the hazardous nature of waste intended for landfill should be reduced where appropriate; the handling should be facilitated	Pre-treatment (for example stabilisation or organic matter) can contribute to control, the question is whether pre-treatment in the landfill is acceptable	(PRE)TREATMENT
9	Member States...establishment of an adequate network of disposal plants based on a high level of environmental protection		n/a
12	regulation of landfills regarding protective measures against any threat to the environment in the short as well as long-term perspective and more especially against the pollution by leachate infiltration into the soil	The protective measures (provisions) are not necessary in the long-term if it can be guaranteed that there no pollution will occur by leachate of the soil. Ergo: the quality of the leachate should be such that no pollution occurs	ESTABLISH DEFINITION OF POLLUTION
13	The classes of landfill and types of waste to be accepted in the various classes must be clearly defined		
16	measures should be taken to reduce the production of methane gas from landfills, through the reduction of the landfill of biodegradable waste and the requirements to introduce landfill gas control	Reducing biodegradable waste is a task for Government. SL aims to achieve stabilised organic matter as soon as possible. Gas control fits well in the concepts	

20	procedure for waste acceptable in the different categories of landfill, including standardised limit values	Conforms with SL	
20	the criteria must be particularly specific with regard to inert waste	Conforms with SL, all criteria must be particularly specific	
22	certain hazardous wastes to be accepted in landfills for non-hazardous waste acceptance criteria should be developed by the technical committee	Conforms with SL, sustainable concepts selected on process properties together and individually	
28	the operator should make adequate provision by way of financial security to ensure that all the obligations flowing from the permit are fulfilled, including the closure procedure and aftercare	Conforms with SL: the adequate provision for the aftercare takes a different form since the obligations involve less cost	
30	when a competent authority considers that a landfill is unlikely to cause a hazard to the environment for longer than a certain period, the estimated costs to be included in the price to be charged by an operator may be limited to that period	Conforms with SL: this is the "golden section". SL is aimed at achieving a limited period of hazard to the environment (less than 30yr).	OPENING FOR SUSTAINABLE LANDFILL
31	training and knowledge acquired by landfill operators and staff afford them the necessary skills	SL will require more knowledge and training for the operator	BASIC REQUIREMENT FOR SUSTAINABLE LANDFILL
Articles			
Art 1, 2, 3		Conform with SL	
Art 4	Landfill site classes <ul style="list-style-type: none"> - for hazardous wastes - for non-hazardous waste - for inert wastes 	SL does not contain hazardous waste landfill	
Art 5.2.abc	This strategy should guarantee that the proportion of biodegradable municipal waste is reduced to 35% wrt 1995	SL needs a limited amount of stabilised organic waste (Equifill). Sustainable landfill does not limit the 'safety net' function of landfill sites	
Art 5.4	The dilution or mixture of waste solely in order to meet waste acceptance criteria is prohibited	SL does not mix waste but selects wastes, bringing them separately to the landfill. Research should show that the behaviour of the wastes is not determined by an eventual dilution effect	RESEARCH

Art 6.c.i to iii	landfill for non-hazardous waste may be used for: (i) municipal waste, (ii) non-hazardous waste, (iii) stable, non-reactive hazardous wastes with a leaching behaviour equivalent to non-hazardous wastes	Conforms with SL	
Art 6.c.iii	(iii) stable, non-reactive hazardous waste with a leaching behaviour equivalent to non-hazardous wastes. These wastes shall not be deposited in cells destined for biodegradable non-hazardous wastes	This means that hazardous waste can only be landfilled with stabilised organic matter	
Art 6.d	landfills for inert waste shall only be used for inert waste		
Art 7, 8, 9	"....."	Conforms with SL	
Art 10	financial security for the costs of closure and aftercare of landfill sites for a period of at least 30 years	Conforms with SL	
Art 11	Procedures for acceptance of wastes	SL will set additional conditions on the acceptance of wastes	
Art 12	"....."	Conforms with SL	
Art 13.c	the operator shall be responsible for maintenance, monitoring and control in the aftercare phase for as long as may be required by the competent authority, taking into account the time during which the landfill could present hazards	Conforms with SL	
Art 13. Closure and aftercare	the operator shall be responsible for monitoring and analysing landfill gas, leachate and the groundwater regime in the vicinity of the site for as long as the competent authority considers that a landfill site is likely to cause a hazard to the environment	Conforms with SL	
Art 14 Existing landfill sites	within a year <....> the operator presents to CA a conditioning plan for approval, including any corrective measures	In Wm permit as of 1/1/04	
Art 15	"....."	N/A to operator	

Art 16 Committee	Any amendments for adapting the Annexes to this Directive shall be adopted by the Commission assisted by the committee established by Article 18 of Directive 75/774/EC in accordance with the procedure set out in Article 17	See Annex II and Decision 2002/33/EC	
Annex I	General Requirements		
1.1 Location	hydrogeological conditions of the area	Conforms with SL	
2. Water and leachate management	control water from precipitations entering into the landfill body	SL explanation: control means preventing risks or hazard arising.	
	prevent surface water and/or groundwater from entering into the landfilled wastes	Surface water and groundwater must be prevented, precipitation dependent!!	
	collect contaminated water and leachate. If shown that the landfill poses no potential hazard to the environment, the competent authority may decide that this provision does not apply (prevent water entering the landfill body)	If SL creates this situation (possible over the course of time) it is thus possible to get an exemption from the requirement to collect contaminated water and leachate	OPENING SUSTAINABLE LANDFILL
	these provisions may not apply to landfills for inert waste	In principle water and leachate control are not necessary for inert landfill sites. If SL produces an inert landfill (within 30 years), water and leachate control is not necessary	
3. 1 Protection of soil and water	a landfill site must be situated and designed to meet the necessary conditions for preventing pollution of the soil, groundwater or surface water	Conforms with SL	
	protection of soil, groundwater and surface water is to be achieved by the combination of a geological barrier and a bottom liner during the operation/active phase	A geological barrier is scarcely available in NL and thus no additional item for SL; A bottom liner in the operational/active phase is in conformity with the concepts of SL	
	by the combination of a geological barrier and a top liner during the passive phase/post closure	Isolating top liner: this is not a seal!!	
3.2	geological barrier (geological and hydrogeological conditions below and in the vicinity of a landfill site) providing sufficient attenuation capacity to prevent potential risk to soil and groundwater	Attenuation capacity Not a special item for SL because also applies to non-SL landfill sites	

	landfill bases and sides shall consist of a mineral layer which satisfies permeability and thickness requirements:		
	Hazardous waste landfill: $K \leq 10^{-9} \text{ m/s}$ Thickness $\geq 5 \text{ m}$		
	Non-hazardous landfill: $K \geq 10^{-9} \text{ m/s}$ Thickness $\geq 1 \text{ m}$		
	Inert landfill $K \geq 10^{-7} \text{ m/s}$ Thickness $\geq 1 \text{ m}$		
	where the geological barrier does not naturally meet the above conditions it can be completed artificially and reinforced by other means giving equivalent protections. An artificially established barrier should be no less than 0.5 metres thick		
3.3 Leachate collection and bottom sealing	Leachate collection (drainage layer 0.5m) and sealing system required for hazardous and non-hazardous landfill	Conforms with SL	
	Member States may set general or specific requirements for inert waste landfills	Building Materials Decree (NL)	
	If the CA after a consideration of the potential hazards to the environment finds that the prevention of leachate formation is necessary, a surface sealing may be prescribed.	This is a recommendation. Thus it is not a necessary requirement to install a top cap. The CA should assess if there are potential hazards to the environment.	ESTABLISH ASSESSMENT FRAMEWORK
	Recommendations for the surface sealing for hazardous: - Gas drainage layer -> not required Required: - Artificial sealing liner - Impermeable mineral layer - Drainage layer - Top soil cover	No direct relation to SL	

	<p>For non-hazardous:</p> <ul style="list-style-type: none"> - Artificial liner: not required <p>Required:</p> <ul style="list-style-type: none"> - Gas drainage layer - Impermeable mineral layer - Drainage layer - Top soil cover 	There will be a conflict with SL if the national legislation adopts the recommendation that a impermeable mineral layer must be used	ESTABLISH ASSESSMENT FRAMEWORK
3.4	If, on the basis of an assessment of environmental risks (Directive 80/68/EEC or 91/692/EEC) the CA has decided that collection and treatment of leachate is not necessary, or that there is no potential hazard to the environment, the requirements of paragraphs 3.2 and 3.3 may be reduced accordingly.	If SL shows with respect to Directive 91/692/EEC that there is no longer an environmental risk to soil, groundwater and surface water, the requirements for leachate collection and lining can be adapted. This is in accordance with the SL concepts if this can be shown after 30 years (or earlier). The water directive is currently being revised.	DEMONSTRATE BY RESEARCH
	For landfills for inert waste these requirements may be adapted by national legislation		
3.5			
4. Gas control	Collection etc	No specific point of attention for SL	
5. Nuisances and hazards	Limit etc	No specific point of attention for SL	
6. Stability	Ensure stability	No specific point of attention for SL	
7. Barriers	Prevent free access	No specific point of attention for SL	
Annex II see Decision 2003/33/EC)			
Annex III monitoring procedures in operation and aftercare phases			
1,2,3		No specific point of attention for SL	
4. Protection of groundwater	A. Sampling: 1 measuring point in the groundwater inflow region and 2 in the outflow region.	Possible that it is desirable for SL to have a more extensive measuring net in the active phase	
	B. Monitoring: the parameters to be analysed in the samples taken must be derived from the expected composition of the leachate and the groundwater quality in the area	See above	

	C. Trigger levels: Significant adverse environmental effects should be considered to have occurred in the case of groundwater, when an analysis of a groundwater sample shows a significant change in water quality. A trigger level must be determined taking into account the specific hydrogeological formations in the location of the landfill and groundwater quality		
	The trigger level must be laid down in the permit whenever possible		
5. Topography of the site		No specific point of attention for SL	

Appendix B

Analysis and legislation, Annex II European Landfill Directive

Green: in accordance with SL (allows/opening for SL)

Orange: in accordance with SL depending on interpretation

Red: not in accordance with SL and poses substantial/potential hindrance

Article/ Recital	Quotation	Analysis	Assessment
Decision 2002/33/EC Annex II			
Recitals			
1 to 6		No points of attention for SL	
7	The measures provided for in this Decision are not in accordance with the opinion of the Committee established by Article 18 of Directive 75/442/EEC on waste. They therefore have to be adopted by the Council in accordance with Article 18 (4) of that Directive		
Art 1, 2		No points of attention for SL	
Art 3.	Member States shall ensure that waste is accepted at a landfill only if it fulfils the acceptance criteria of the relevant landfill class as set out in section 2 of the Annex to this Decision	Criteria for the acceptance of wastes. Inasmuch as the criteria are established per waste, the application of SL is limited, since the emission is determined by the cocktail of wastes. By research it should be shown that this limitation for SL should be removed and adjusted by revision of legislation. EWC (2000/532/EC) with wastes is guiding.	LIMITING FOR THE APPLICATION OF SUSTAINABLE LANDFILL
Art 4 to 8		No point of attention for SL	
Annex			
Introduction	In accordance with ... Member States are not prevented from maintaining or introducing more stringent protective measures than those established in this Annex, provided that such measures are compatible with the Treaty...	The NL interpretation and the requirements 'body' can be/become a limitation for SL concepts.	DEPENDENT ON DUTCH ADDITIONAL RULES, SEE ANALYSIS OF NL LEGISLATION
1.1	... a full characterisation of the waste	Conforms with SL	

1.1.1	Basic characterisation: - Composition - Leachability - -	Composition requirement can be an attention point. There is a development to convert this composition requirement for mineral oil for example, into leaching requirements.	COMPOSITION REQUIREMENT CAN BE LIMITING FOR ACCEPTANCE OF WASTES WITHIN SL
1.1.1.c	Assessing wastes against limit values		
1.1.1	If the basic characterisation shows that the waste fulfils the criteria (part 2 of the annex), the waste is deemed to be acceptable at this landfill class.	Basic rule of acceptability As such conforms	
1.1.1	If a waste does not fulfil the criteria, the waste is not acceptable at this landfill class	This rules out the acceptability of a combination of wastes on the basis of their combined behaviour	LIMITATION
1.1.1	The producer of the waste, or the person responsible for its management, is responsible for ensuring that the characterisation information is correct		
1.1.2.d	.. composition and leaching behaviour	See 1.1.1	
1.1.2.f	European waste list	This list determines the basis of the waste and thereby the unit that should be characterised. The landfilling of combinations of wastes can be facilitated if combinations/mixtures of wastes have a code	DISCUSSION INSIGHT IN WASTE LIST
1.1.3	Testing	No specific point of attention for SL	
2.	Waste Acceptance Criteria: In certain circumstances, up to 3* higher limit values..... are acceptable: - If the CA gives a permit for specific wastes	Incidental exemption through CA	DEPENDENT ON TRANSPOSITION IN NL LEGISLATION THIS CAN PROVIDE FOR A WIDENING IN ACCEPTANCE
	- If emissions from the landfill, taking into account the limits for those specific parameters, will present no additional risk to the environment according to a risk assessment	By demonstrating that risk remains the same, a tripling of the acceptance standards (limit values) is possible. Does not seem to be aiming for SL but it does offer a possible option in exceptional cases.	
2.1	Acceptance see table attached		
2.1.2.1 2.2.2 2.3.1	Member States shall determine which of the test methods and corresponding limit values in the table should be used	Has this already been established for NL??	DEPENDENT ON THE NL INTERPRETATION

2.1.2.2. 2.3.2 2.4.2	In addition to the leaching limit values ... wastes must meet the following composition requirements	Limited set of composition requirements	DEVELOPMENT TOWARDS ABANDONING COMPOSITION REQUIREMENTS
Other		No specific point of attention	

Appendix C

Analysis and legislation, Water Framework Directive

(EN TEXT, only relevant sections (paraphrased))

Green: in accordance with SL (allows/opening for SL)

Orange: in accordance with SL depending on interpretation

Red: not in accordance with SL and poses substantial/potential hindrance

Article/ Recital	Quotation	Analysis	Assessment
Directive 2000/60/EC OF THE EUROPEAN PARLIAMENT AND THE COUNCIL OF 23 OCT 2000 ESTABLISHING A FRAMEWORK FOR COMMUNITY ACTION IN THE FIELD OF WATER POLICY			
Recital			
1	Water... is a heritage which must be protected, defended and treated as such.		
5.	Framework Directive for sustainable water policy	Sustainable landfill should be in accordance with this	
43	Pollution through discharge, emission or loss of priority hazardous substances must cease or be phased out	Priority hazardous substances are presented in Annex X but this is not filled in (see 2455/2001/EC 20 Nov2001)	Does a landfill site emit priority hazardous substances?
Article			
1. Purpose	a. prevents further deterioration and protects and enhances the status of aquatic ecosystems		Prevents further deterioration but no improvement through SL
	c. cessation or phasing-out of discharges, emissions and losses of the priority hazardous substances		What are priority hazardous substances
2. 30	Priority substances identified in accordance with Art 16.... listed in Annex X.	Annex X is empty	
2.33	Pollution:..... which may be harmful to the quality of aquatic ecosystems.....		

2.40	Emission limit value: the mass, expressed in terms of certain specific parameters, concentration and/or level of an emission, which may not be exceeded... Substances (including groups of substances) as identified under Art 16.	See Art 16	
4. Environmental objectives	1.b.ii. Member States shall protect, enhance and restore all bodies of groundwater with the aim of achieving good groundwater status at the latest 15 years after the date of entry into force if this Directive		
	1.b.iii Member States shall implement the necessary measures to reverse any significant and sustained upward trend in the concentration of any pollutant resulting from the impact of human activity in order to progressively reduce pollution of groundwater.		
	5 Member States may aim to achieve less stringent environmental objectives than those required under para 1 for specific bodies of water when they are so affected by human activity that the achievement of these objectives would be infeasible or disproportionately expensive		
16	The Commission shall submit a proposal setting out a list of priority substances....		
Annex			Check list
Annex V	Groundwater chemical status: - Concentrations of pollutants - Conductivity		

Annex VIII	<p>Indicative list of the main pollutants:</p> <ul style="list-style-type: none"> - Organohalogen compounds - Organophosphorus compounds - Organotin compounds - Carcinogenic/mutagenic - Persistent hydrocarbons (+ bioaccumulable organic toxic substances) - Cyanides - Metals and their compounds - Arsenic and its compounds - Biocides and plant protection products - Substances in suspension - Eutrophying substances (nitrate) - Substances having unfavourable influence on oxygen balance COD, BOD 		<p>Which polluting substances does a landfill site emit</p>
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Appendix D

Analysis and legislation, Groundwater Directive

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(EN TEXT – paraphrased)

Article/ Recital	Quotation	Analysis	Assessment
Proposal for a Directive on the protection of groundwater against pollution (19.09.03; 2003/0210 (COD))			
Recitals			
1	Groundwater.....which should be protected from pollution		
2	... the objective to achieve levels of water quality that do not give rise to unacceptable impacts on, and risks to, human health and the environment		
3	.. to protect... concentrations of harmful pollutants in groundwater should be avoided, prevented or reduced..		
4 to 9	EU Procedural	Of no direct importance	
Article			
1 Subject matter	Establish criteria.... The Directive also establishes a requirement to prevent or limit indirect discharges of pollutants into groundwater.	Landfill site leachate that infiltrates the soil is viewed as an indirect discharge	
2 Definitions	Threshold value: a concentration limit for a pollutant in groundwater, exceedance of which would cause a body of groundwater or groundwater bodies to be characterised as having poor chemical status.		

	Significant and sustained upward trend: any statistically significant increase of concentration of a pollutant as compared to concentrations measured at the start of the monitoring programme referred to in Article 8 of Directive 2000/60/EC, taking into consideration quality standards and threshold values		
	Indirect discharges to groundwater: discharge of pollutants into groundwater after percolation through the ground or subsoil	Also includes emission from landfills	
3. Quality criteria	... good groundwater chemical status....: - A. with regard to any of the substances referred to in column 1 of Annex I to this Directive, the measured or predicted concentration does not exceed the quality standards laid down in column 2	See Annex I	
	- B. with regard to any of the other polluting substances, it can be demonstrated, in accordance with the indications given in Annex II to this Directive, that the concentration of the substance complies with indent 3 of the definition set out in section 2.3.2 of Annex V to Directive 2000/60/EC	See Framework Directive 2000/60/EC: - Conductivity - Concentrations of pollutants (so that the environmental objectives are not put at risk), not given quantitatively	
4	Threshold values		
4.1	On the basis Member States shall by 22 December 2005, establish threshold values for each of the pollutants, which within their territory have been identified as contributing to the characterisation of bodies or group of bodies of groundwater as being at risk	Threshold value (groundwater quality) is dependent upon the territory. This means that a particular threshold value may or may not be characterised as polluted. The article aims to cover the differences between the Member States (?), dependent on the interpretation, regional (within a Member State) differences are also acceptable	OPENING

	Member States shall as a minimum establish threshold values for the pollutants referred to in parts A1 and A2 of Annex III to this Directive. See Annex III	Make NL interpretation available, additions on list	
	These threshold values shall <i>inter alia</i> be used for the purposes of carrying out the review of groundwater status as provided for in Article 5.2 of Directive 2000/60/EC		
4.2	At the latest by 22 June 2006, Member States shall provide the Commission with a list of all pollutants for which they have established threshold values.	NL list?	
4.3	EU procedural		
5.Criteria for trends	Member States shall identify any significant and sustained upward trend of concentrations of pollutants in groundwater and define the starting point for reversing that trend, in accordance with Annex IV to this Directive	Is absence of sustained upward trends a contribution to sustainable landfill	
	For those bodies of groundwater where significant and sustained upward trends in pollutant concentrations are identified, Member States shall reverse the trend through the programme of measures referred to in Article 11 of Directive 2000/60/EC, in order progressively to reduce pollution of groundwater	Look up Art 11 Directive 2000/60/EC	No particular importance for SL
6. Measures to prevent or limit indirect discharges into groundwater	In addition to the basic measures set out in Article 11(3) of Directive 2000/60/EC, Member States shall ensure that the programme of measures for each river basin district includes the prevention of indirect discharges to groundwater of any of the pollutants referred to in points 1 to 6 of Annex VIII to that Directive.	2000/60/EC!!!!!!!!!!!!!!	

	Points 7 to 12 of Annex VIII to Directive 2000/60/EC ... include the provision that any indirect discharges shall only be permitted on condition that the discharges does not put at risk the achievement of good groundwater chemical status	Apparently the influence on the 'good chemical status' of the groundwater is determining for the acceptance of indirect discharges	Possibly an extra for SL
7 & 8	Not relevant procedural		
9. Implementation	Member States shall bring into force the necessary ... provisions into force to comply with this Directive at the latest [18 months after the date of entry into force of this Directive].	2005?	
10. Entry into force	This Directive shall enter into force on the twentieth day of its publication in the Official Journal of the European Union		
Annex			
Annex I	Nitrates: 50mg/l Pesticides: 0.1 µg/l (including degradation products)		
Annex II	<p>Assessment of groundwater chemical status for which Community quality standards do not exist:</p> <ul style="list-style-type: none"> - Information as laid down in Annex II (2000/60/EC) - Environmental quality objectives - (eco)toxicological characteristics etc - Amounts and concentrations of pollutants transferred from the body of groundwater to the associated ecosystems - estimated effect of the pollutants - assessment of whether objectives specified in Art 4 cannot be met. 	<p>Thus the substances that are not given in Annex I.</p> <p>Annex II (2000/60/EC)</p> <ul style="list-style-type: none"> - Location and boundaries groundwater body - Pressures to which groundwater liable (e.g. landfill sites) - Geological characteristics - Hydrogeological characteristics - Chemical composition - <p>Thus: Groundwater must comply with Annex I substances and the objectives may not be put at risk (... prevent deterioration in condition of all groundwater bodies, Art 4 (2000/60/EC). In other words, the quality of the groundwater may not deteriorate.</p>	
Annex III	Threshold values for groundwater pollutants:		

A1	<p>Minimum list ions:</p> <ul style="list-style-type: none"> - Ammonium - Arsenic - Cadmium - Chloride - Lead - Mercury - Sulphate <p>NL-additional</p> <p>-</p>		
A2	<p>Minimum list of synthetic substances:</p> <ul style="list-style-type: none"> - Trichloroethylene - Tetrachloroethylene <p>NL-additional</p> <p>-</p>		
Annex IV	<p>Methodology for establishing trends</p>		