Opening the Black Box

SUMMARY
of the Sustainable Landfill project

Dutch Sustainable Landfill Foundation

Colophon

Title	:	Opening the Black Box Summary of the Sustainable Landfill project
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1. Introduction

1.1 Background

This report is a summary of the Sustainable Landfill project,[1] a contribution by the Dutch Sustainable Landfill Foundation[2] to a more sustainable society. Sustainable landfill takes as its starting point the implementation of the waste hierarchy adopted by the Netherlands and the EU. Optimal use must first be made of the prevention, reuse/recycling and incineration options. For the waste that remains, the Dutch Sustainable Landfill Foundation aims to provide the necessary reserve waste disposal capacity in a way that reduces environmental impacts.

This chapter sets out the aims of the project, the approach taken and the main results.

1.2 Aims of the project

In line with the definition of sustainability by the Brundtland Commission, the goal of the Sustainable Landfill Foundation is to leave no ‘landfill legacy’ for future generations. In concrete terms this means reducing landfill emissions, not only an absolute reduction in total emissions, but also a reduction in the burden on future generations.

The initial objective of the project was to establish the practical feasibility of three sustainable landfill concepts for specific situations. It soon became apparent that it was possible to go a step further because the analyses showed that the concepts provided enough building blocks to construct a generic sustainable landfill concept.

This led to the following operational objective:

> *Demonstrate the feasibility of a landfill concept that reduces emissions to an acceptable level within 30 years, without the need for any subsequent pollution control measures.*

1.3 Approach

The idea of sustainable landfill developed from ideas generated in the competition ‘Good riddance (to bad rubbish): landfill for the next century’ (*Opgeruimd staat netjes, storten over de eeuwgrens*), organised by the predecessor of the Dutch Waste Management Association. In 2000 the Sustainable Landfill Foundation (members of the Dutch Waste Management Association) appointed a consortium of consultants and specialists to determine the feasibility of sustainable landfill within a five-year study period. The companies contributing to the work of the consortium during the course of the project include: the Energy research centre of the Netherlands (ECN), TNO Environment, Energy and Process Innovation (TNO-MEP), Grontmij, GroundwaterTechnology, GeoDelft, Royal Haskoning (formerly IWACO) and Advibe (replaced ERM-NL).

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1 This summary provides a global description of the approach taken and the results obtained from the whole project (1999–2005) and is written for a non-technical audience. Detailed information can be found in the other project documents.

2 Initiated by the Dutch landfill sector and led by the Dutch Waste Management Association, NVAfvalzorg, Afvalverwerking Stainkoeln, Essent and A&G (formerly VBM).

The project progressed in three stages:

- ***Stage 1: start-up (2000–2002)*** – theoretical development, evaluation framework, start of research, databank, initial interpretation
- ***Stage 2: development (2003)*** – data completion, confirmation of the theory, policy feasibility and initial exploration of practical implications
- ***Stage 3: generalisation and conclusions (2004–2005)*** – practical implications (design, economic), establish overall feasibility

The final evaluation of the feasibility of sustainable landfill as a concept was based on nationally and internationally available information derived from field trials and research (pilot projects,[1] lysimeters,[2] laboratory experiments) as well as the three extensive pilot studies carried out as part of the project itself. These pilot studies investigated three landfill concepts:

- A predominantly organic waste landfill (***Bioreactor***): a technology for stabilising the organic matter as quickly as possible and thus reducing emissions of pollutants
- A primarily inorganic waste landfill (***Equifill***): a technology for a landfill with stabilised organic matter and low emission of pollutants
- An immobilised waste landfill (***Monolith***): a technology for solidifying/encapsulating wastes that cannot be treated in Equifill

1.4 Main outcomes of the project

The project resulted in three main conclusions about a sustainable landfill:

1. Total residual emissions are lower than from ordinary landfills.
2. Emission release occurs over a shorter period than from ordinary landfills.
3. Emissions are more predictable and controllable.

Compared with standard landfill practices, sustainable landfilling reduces total emissions and shortens the period of time within which emissions occur (see Figure 1). This results not only in fewer emissions but a much reduced burden on future generations. Perpetual aftercare is no longer necessary. Not only does this have potential financial benefits, but the risks to future generations are also limited.

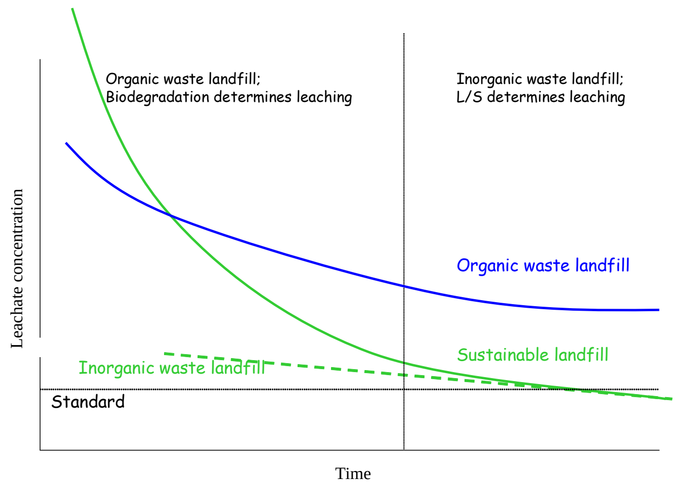

Figure 1 Leachate concentrations over time

1 Field-scale experiments

2 Semi-field-scale experiments

These benefits can be obtained by actively influencing the chemical processes inside the landfill body. An example is adding sufficient water to initiate chemical processes earlier and make them more efficient.

The third achievement of the Sustainable Landfill project is turning the knowledge that has been gained into better simulation models that predict emissions more accurately and enable better control of emissions (opening the Black Box). It is possible to design sustainable landfills so that emissions of all important contaminants are below the limit values, while maintaining a stable pattern of emissions. This means that the expensive top liner only has to be applied later or can be left off altogether, without any extra environmental impact. Financial benefits may accrue to the landfill operator and the organisation responsible for aftercare, and thus to society as a whole. Top liners are not mandatory under EU legislation, but are required by Dutch regulations. The Sustainable Landfill project has shown that these specific Dutch requirements are not necessary. In fact, the top liners required by Dutch regulations delay emissions, in effect passing the problem on to future generations. This is exactly the opposite of sustainability.

1.5 Sustainable and ordinary landfills compared

The similarities and differences between ordinary landfills (as regulated by the Dutch Soil Protection (Landfill) Decree) and sustainable landfills are listed in Table 1.

Table 1 *Comparison between ordinary and sustainable landfills*

Aspect	Ordinary	Sustainable
Site location	No explicit requirements, but addressed in environmental impact assessment	Related to the natural attenuation (cleansing) capacity of the surrounding environment
Design	According to the Soil Protection (Landfill) Decree	No top liner Additional measures (drainage, aeration)
Operation	According to the Soil Protection (Landfill) Decree	More measures to control processes in the landfill
Acceptance	Within the rules on prohibited wastes	Within the rules on prohibited wastes and dependent on the influence of biochemical processes
Emissions	'End of pipe'	Integrated process
Aftercare	Perpetual	Minimise and limit aftercare period
Meets NL regulations	Yes	No (no top liner) but can always be made compliant
Meets EU regulations	Yes	No, acceptance based on bulk properties instead of individual waste properties Yes, if acceptance is restricted
Costs	Reference	Same costs or more expensive

1.6 Structure of this summary

Chapter 2 describes the regulatory framework. Chapter 3 examines and discusses the main processes occurring in a landfill and controlling these processes. Chapter 4 explains the modelling exercises. Chapter 5 contains descriptions of the three underlying sustainable landfill concepts and the resulting integrated concept. The conclusions are summarised in Chapter 6.

2. Regulatory framework

2.1 Legislation and sustainable landfill

Landfilling is subject to a considerable body of regulations, including both national and European legislation on wastes and soils. An overview of the current regulatory documents (NL and EU) is given in Figure 2.

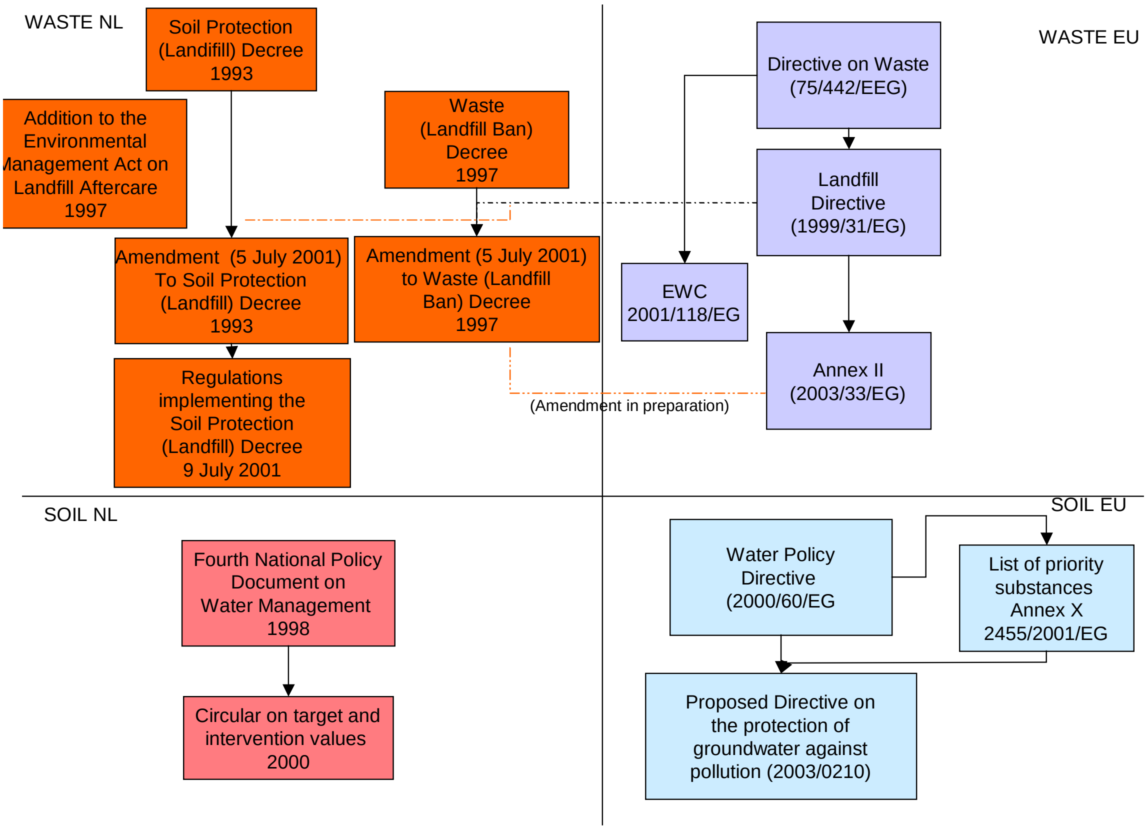

Figure 2 The regulatory framework

European legislation relating to wastes provides a regulatory framework that does not conflict with the characteristics and requirements of sustainable landfill. EU legislation on groundwater quality is under development, which makes it difficult to assess how far sustainable landfill will meet these legislative requirements. The goals of sustainable landfill correspond with those of groundwater policies: no negative impact on environmental quality in the surrounding area. The European Landfill Directive does not require a bottom or top liner at landfills for inert waste.

The goal of sustainable landfill in terms of the European regulatory framework:

> ***Within about 30 years*** *a sustainable landfill permanently meets the emission thresholds for a* ***landfill for inert waste****, and the threshold value for groundwater quality is not exceeded.*

2.2 Acceptance

The acceptable level of leaching is determined by means of a reverse calculation from the groundwater quality objectives, using a standardised model, to derive a ‘source term’ (which describes the emissions in the landfill). The source term ultimately determines whether a waste can be accepted or not. The European Waste Catalogue (EWC) was used to define the source terms. The source term can also be defined as the leachability of the total mix of wastes in the landfill. This does justice to the well-known fact that the wastes react with each other and that these interactions determine the type and level of emissions, not the sum of emissions from each waste. ***Acceptance for sustainable landfill is based on the source term for the waste mix.***

The source term is a dynamic quantity during the landfilling process: as the properties of the wastes going to landfill change over time, so does the waste mix. A key task in sustainable landfill is managing the mix to correspond with the leaching requirements.

2.3 Site engineering

Dutch regulations stipulate the use of top and bottom liners at all landfills. EU legislation is less strict, but includes requirements for the lining of landfills for hazardous and non-hazardous wastes. Bottom liners are compulsory in the Netherlands because the country does not have any ‘impermeable’ subsoils. In some areas of Europe a bottom liner is not required under the provisions of the European Landfill Directive.

Sustainable landfills must have a bottom liner during the operational phase, but this may lose its function when the waste mix has reached a sustainable state.

Additional measures also have to be taken, depending on the nature of the basic waste mix. These may consist of extra drainage (for flushing/leachate recirculation: addition and discharge) or leachate treatment. For gas extraction, systems commonly in use meet the requirements.

A top liner isolates the landfill from the surrounding environment, creating an unstable equilibrium that can only be maintained with considerable effort. A sustainable landfill has no top liner (but it does have a permeable cover) to allow the necessary interaction between the landfill body and its environment.

3. Processes, components and control

3.1 Process and components

Landfills produce a wide range of emissions. The main processes involved are the leaching and transport of contaminants in infiltrated water. Gas emissions are also released from the biodegradation of organic material into water, methane (CH_4) and carbon dioxide (CO_2).

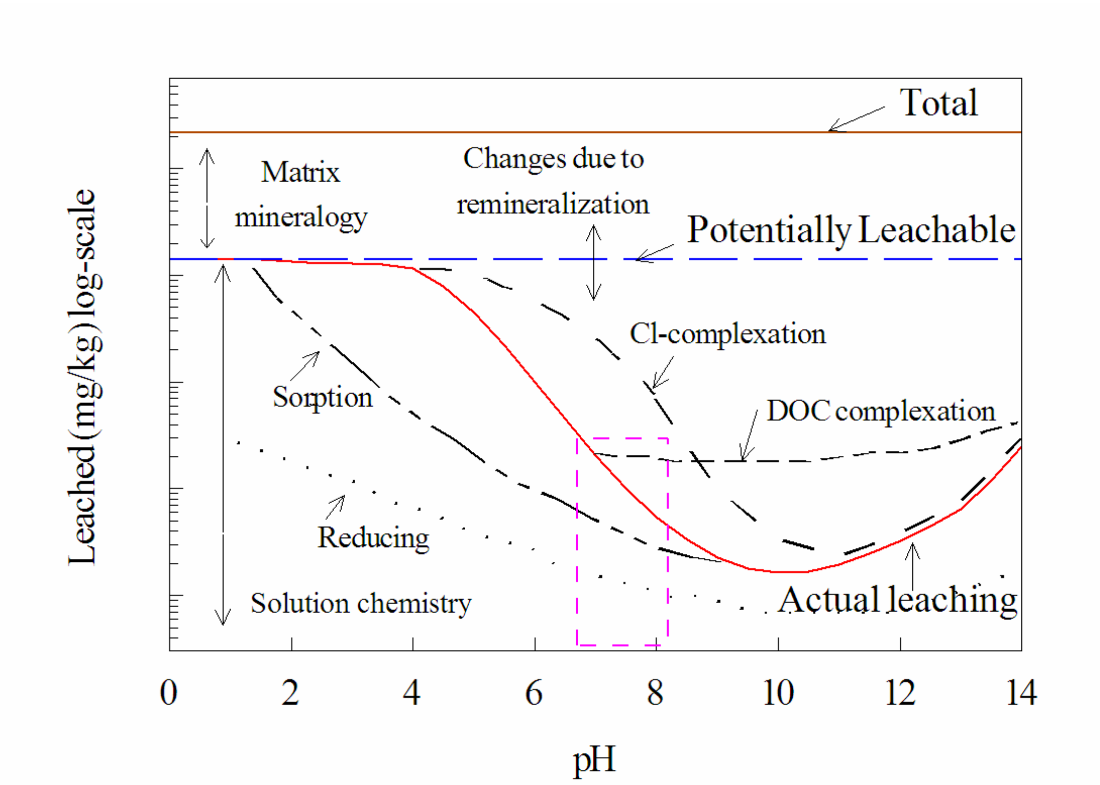

Figure 3 Overview of the processes occurring in a landfill body that have a major influence on the leachability of contaminants to the surroundings

The components that play a role in the internal processes within a landfill are grouped into several categories according to their composition and behaviour.

- ***Organic macrocomponents*** such as biological oxygen demand (BOD), chemical oxygen demand (COD) and organic nitrogen are formed and partly converted to fats, sugars, hemicellulose, cellulose and landfill gas**.** The biological processes are known and well described. The degree of biodegradation depends on a number of factors, such as the composition of the waste, water content and temperature.
- ***Organic microcomponents*** are generally present in the waste upon deposition and may end up in both the landfill gas and the leachate. These components are converted or decomposed under both anaerobic and aerobic conditions.
- ***Metal ions*** are also present in the waste upon deposition. Most of these ions remain immobilised and are not released into the leachate. Mobilisation and immobilisation of metal ions occurs in several processes, which depend on the pH and the extent of degradation of the organic material (see Figure 3).

- ***Oxyanions***, such as sulphate (SO_4^-), carbonate (CO_3^{2-}) and phosphate (PO_4^{3-}), are produced from sulphur and phosphorus precursors. The amounts of oxyanions available for leaching are largely determined by the composition of the waste. The same goes for **salts**, such as chloride (Cl^-).

3.2 Process control

The following factors influence emissions from landfills:

- ***Waste selection:*** (i) prevention: prohibiting certain wastes from landfill, (ii) adding components to stimulate certain processes, (iii) combining wastes in such a way that their interaction reduces emissions.
- ***Pre-treatment:*** This can remove problem components prior to landfilling. Wastes may also he homogenised if required.
- ***Biodegradation:*** Organic components are formed and are also converted during biodegradation. Conversion can be promoted by creating an aerobic environment. Biodegradation also affects metal concentrations in the leachate as dissolved organic carbon concentrations are reduced, thereby mobilising metal ions by complexation.
- ***Immobilisation:*** This can be used as a pre-treatment process for materials that would otherwise not be acceptable for landfilling.
- ***Solubility control:*** The release of metal ions is determined by their distribution between the solid and the liquid phase. This partitioning is mainly determined by the pH, conductivity, redox potential and dissolved organic carbon (DOC) concentrations in the liquid phase (see Figure 3);
- ***Flushing:*** This process removes soluble components from the liquid phase by introducing fresh liquid that does not contain the component in question. To obtain sufficient dilution in the proposed time period the infiltration rate has to be 1,500–3,000 mm per year.

The effects of process control depend on the behaviour of the component in question. These relations are shown in Table 2.

Table 2 *Processes per type of emission component*

Component \ Process	Waste selection	Immobilisation	Biodegradation	Solubility control	Flushing
Organic macrocomponents	X	–	X	x	x
Organic microcomponents	?	–	x	?	X
Metals	X	X	X	X	?
Oxyanions	X	?	x	?	X
Salts	X	x	–	–	X

Legend:

- An 'X' in the table indicates that the component strongly influences the process. This means that the process can be used to minimise or control the release of the component..
- An 'x' indicates that the process has some effect on the component, but this may be a side-effect of the main effect that can be achieved on other components.
- A '?' indicates that the process does not have a clearly defined effect on the component, or the effect is undetermined, and so no prediction is possible.
- A '–' indicates that the process does not have a direct effect on the component in question.

In Figure 3 the field (purple line) at neutral pH represents the final state that can be achieved through waste acceptance, design and management measures.

3.3 Towards an integrated approach

The composition of the waste has a major influence on the additional measures required to control and manage the processes and the emission potential. Strict requirements are placed on the acceptance of wastes which release critical ions (Cl^-, NH_4^+, SO_4^{2-}) into the water percolating through the landfill. Special measures, such as pre-treatment (e.g. Monolith), are needed for waste streams with high concentrations of these critical components, or the landfill site should be in a suitable location (e.g. with brackish groundwater). In this study three types of landfill were distinguished, each of which displays a specific kind of reactive behaviour, which in turn requires different types of measures to control or manipulate the biological and geochemical processes taking place within the landfill body.

Research shows that all landfills will eventually move towards a single end condition (see Figure 4).

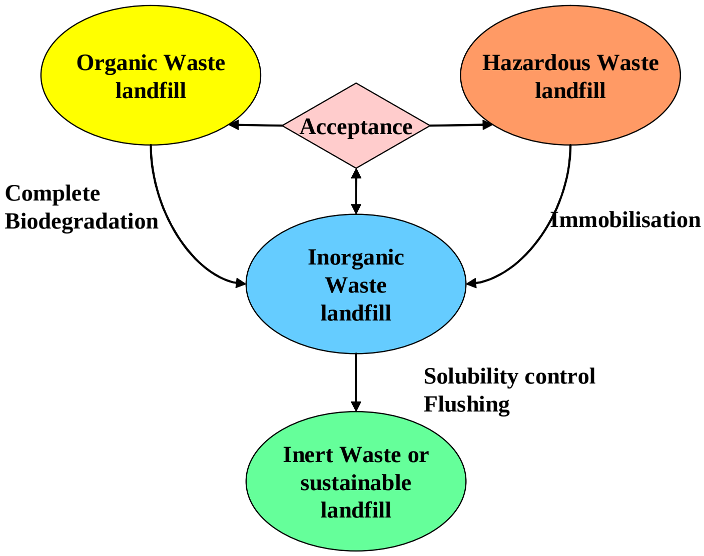

Figure 4 Progression from a landfill containing predominantly organic waste or hazardous waste to a landfill for inert waste, or sustainable landfill

The three types of landfills represent the full spectrum of all landfills. The Sustainable Landfill project investigated these types of landfill on the laboratory scale, the lysimeter scale and the pilot scale. The challenge is to reach the end condition as quickly as possible. The rate at which this end condition is reached can be speeded up by implementing the right package of methods for controlling and manipulating the processes occurring in the landfill.

4. Database and modelling

4.1 Approach to modelling landfill processes

Modelling the processes occurring in landfills allows us to

- predict the emission profile over time,
- predict the effects of pollution control measures, and
- determine the status of an existing landfill.

The Sustainable Landfill project has produced an integrated knowledge base on the processes occurring in landfills, and this information provides the input for the modelling. Modelling the processes occurring in landfills requires that a large number of chemical, biochemical and transport phenomena are taken into account:

- Biochemical conversion of organic materials into dissolved organic matter and the subsequent formation of fatty acids, N_{Ki} and biogas
- Physical chemical speciation: solution and precipitation of metals, anions and salts, and the adsorption of components
- Transport of liquids through pores in the waste
- Transport of gases that are formed through pores in the waste
- Generation and transport of heat that is generated as a result of aerobic and anaerobic reactions in the waste

The modelling approach consists of three sub-models run partly in parallel and partly in series (see Figure 5).

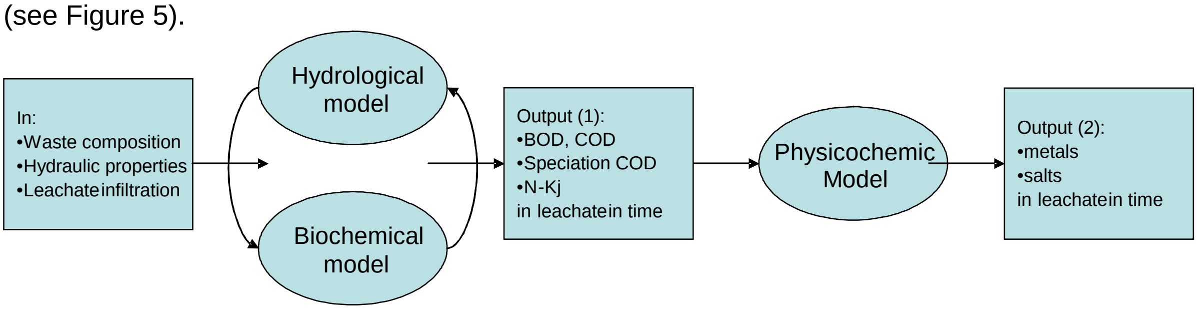

Figure 5 Modelling approach

Gas transport itself is not taken into consideration, but the model does include its impact on hydraulic permeability. The generation and transport of heat is not modelled either because it has little effect on biodegradation under the conditions prevailing in landfills.

4.2 Modelling biochemical transformation

Landfills contain substantial levels of organic carbon in the leachate in the form of BOD, COD and N_{Ki}. Ultimately, BOD and COD in landfill leachate have to meet certain criteria. Moreover, COD correlates with the DOC concentrations. High levels of COD lead to increased DOC and thus to increased concentrations of heavy metals in leachate due to complexation. Therefore, DOC also has to meet certain criteria in order to meet the criteria for heavy metal concentrations in leachate.

The model was developed by elaborating a number of reaction schemes. Several steps in the reaction sequence were distinguished:

- Hydrolysis
- Methanogenesis (methane formation)
- Death of methanogenic biomass (methane-producing bacteria)
- Decay of dead biomass

Further details can be found in Figure 6.

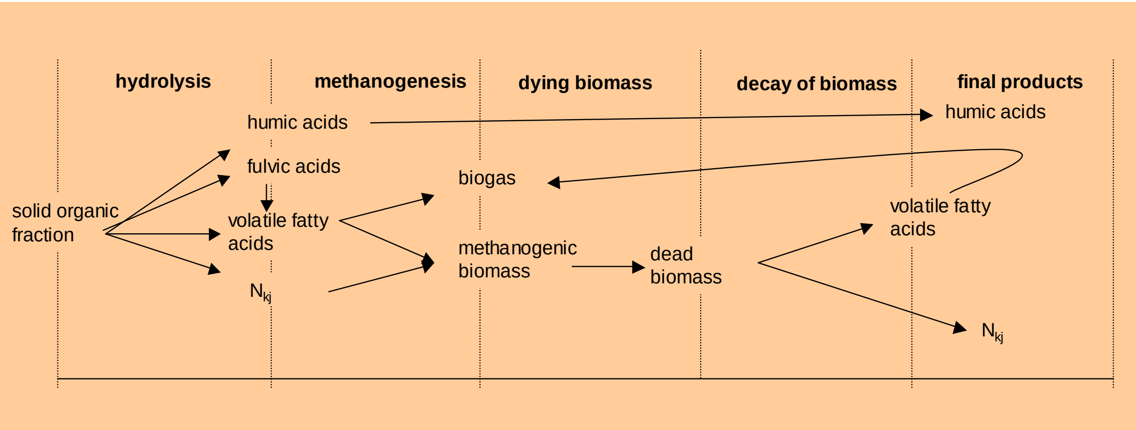

Figure 6 Schematic overview of the biochemical modelling of leachate quality

In reality, the reaction mechanisms are much more complex. This simplified scheme is linked to the model.

4.3 Physical chemical modelling

This model is built up from new and existing databases, models and data on selected solubility controlling minerals. The output of the models consists of:

- a prediction of the total amounts in the water phase,
- understanding of the speciation of each of the elements in the different phases, and
- descriptions of the pH-dependent leaching and the chemical speciation and partitioning in both the solid phase and the liquid phase (leachate).

4.4 Modelling hydrology

It was assumed that the water flow can be described by a triple flow rate concept:

- a stagnant bulk,
- a slow mobile phase, and
- a fast mobile phase.

Compounds are exchanged between the water-dissolved phase and the solid phase. Figure 7 is a schematic representation of the hydrological model. This model was tested using the results of various bioreactor column tests.

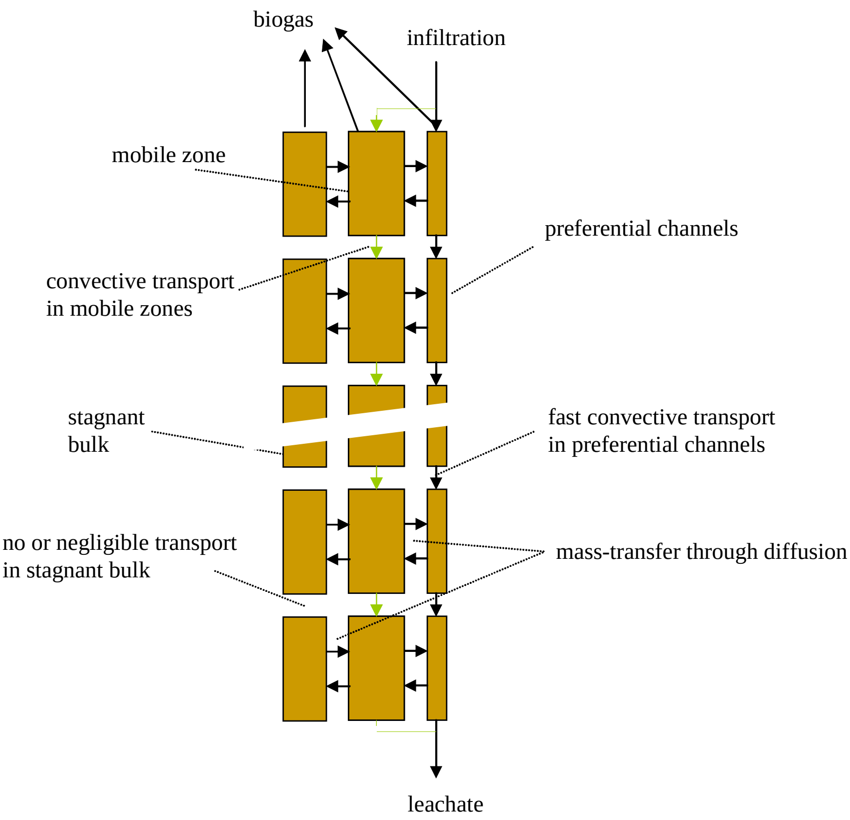

Figure 7 Schematic representation of the water flow in a landfill

4.5 Data interpretation

A database/expert system framework was developed (LeachXS) to process the databases and modelling results, run scenarios and assess the outcomes against the regulations and standards (see also Figure 8).

DATABASE	*MODEL*	*REPORTING*
Leaching		*Excel Spreadsheets*
Scenarios	*LeachXS*	*Reports*
Regulatory		*Other models*
Thermodynamic	*Orchestra*	

Figure 8 Structure of LeachXS

Figure 9 is an example of the model output. The figure contains both the measured data (red dots) and the model predictions (solid black line) of the effect of organic materials on the availability of metals for leaching.

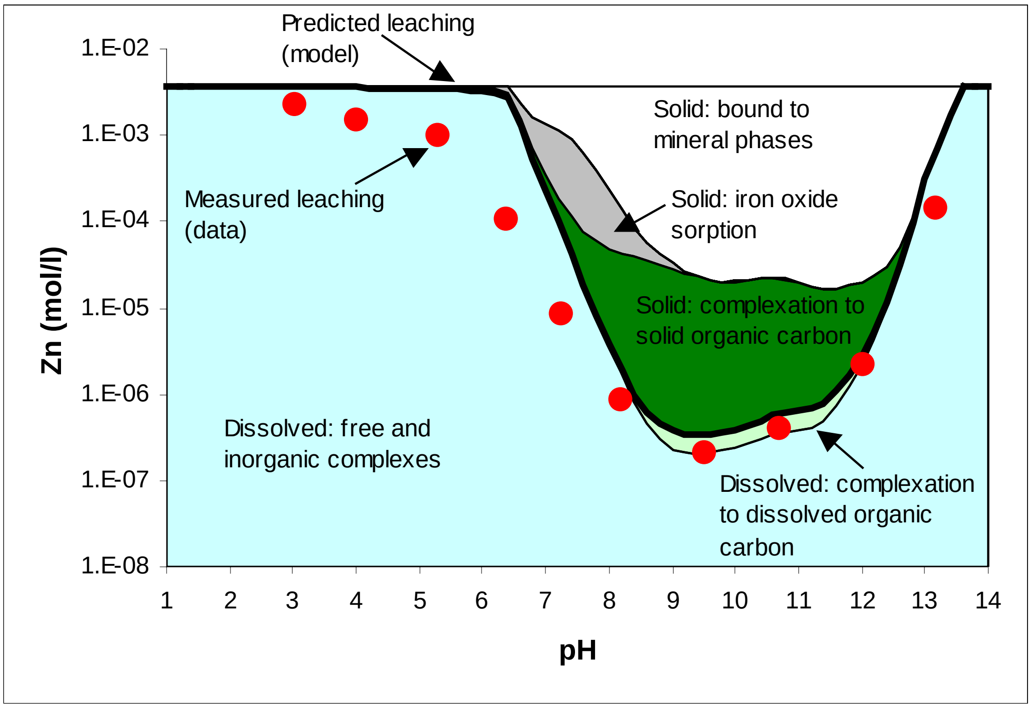

Figure 9 Leachability of Zn in a predominantly inorganic waste mixture

Figure 10 provides an example of how the waste mixture affects leaching. The figure shows the leaching of lead (Pb) and zinc (Zn) as a function of pH. The black line is the pH-dependent leaching predicted by the model. The fact that the line runs close to the data points for most of its length indicates that the processes are described quite accurately. A simulation was also run for a situation in which the available concentration for leaching was raised by a factor of ten. The grey line shows that this has a major effect for Pb (leaching is ten times higher), whereas leaching of Zn under field conditions (pH 7–9) does not change. These results demonstrate that leaching behaviour from waste mixtures can be managed and controlled.

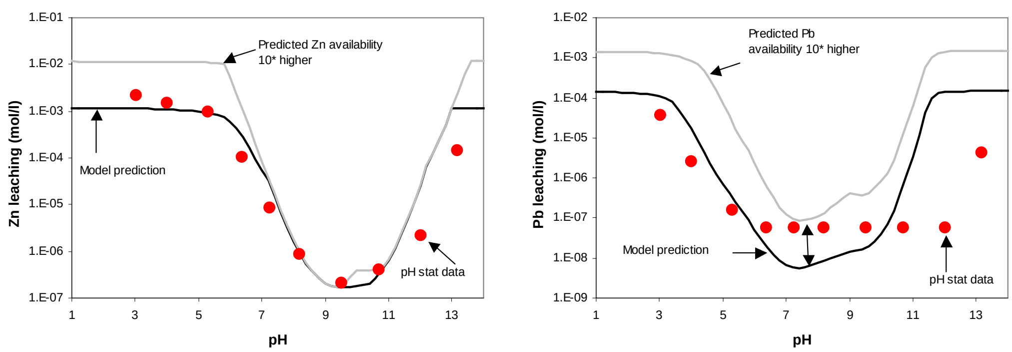

Figure 10 Leaching of Pb and Zn as a function of pH (data points) and the model prediction of leaching behaviour of the waste mixture (black line)

5. Results

5.1 Landfills containing predominantly organic waste

The emission behaviour of waste containing high amounts of organic material is dominated by the breakdown of organic matter. Landfill gas is produced during biodegradation and concentrations of BOD, COD and N_{Ki} in the leachate are high. The high organic matter content leads to high concentrations of metal ions in the leachate (see Figure 11). When biodegradation approaches completion, leachate concentrations are significantly reduced. By the time the degradable organic material in the waste has been stabilised to non-degradable organic matter, the behaviour of the landfill changes into that of a landfill containing inorganic waste.

The objective for organic waste landfills is to achieve full degradation of the organic matter as quickly as possible. The primary control measures needed to ensure complete degradation are waste selection, leachate recirculation and creating the right conditions for aerobic conversion.

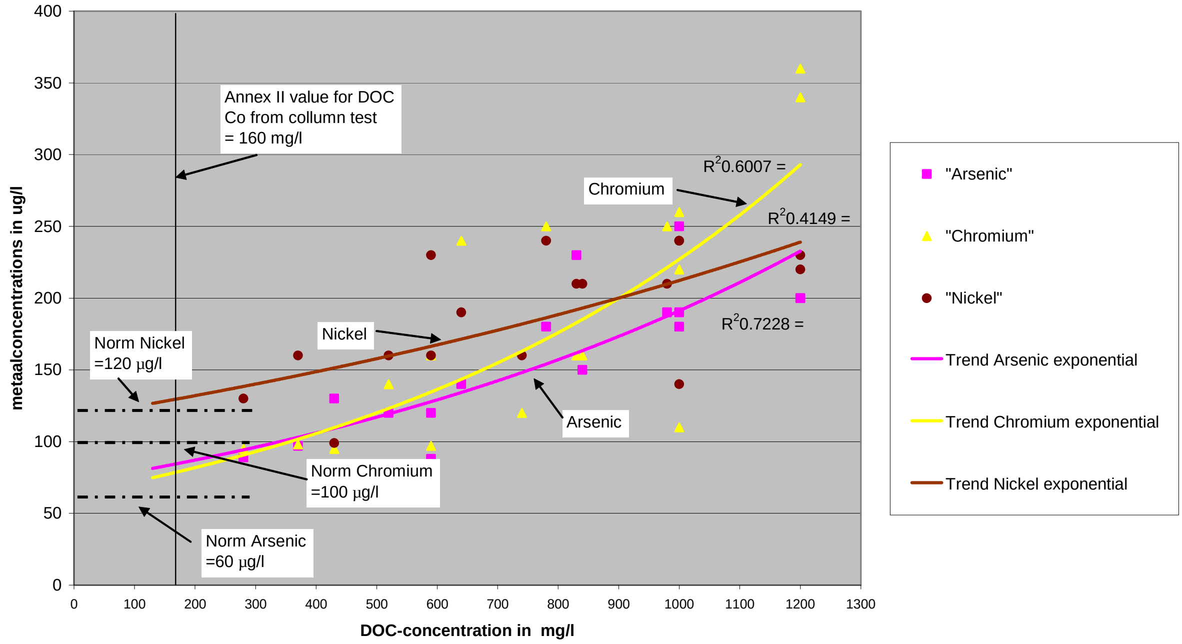

Figure 11 Metal concentrations in leachate versus concentrations of dissolved organic carbon (DOC)

The landfill design for predominantly organic waste is designed to enable control of the biochemical processes (see schematic design in Figure 12).

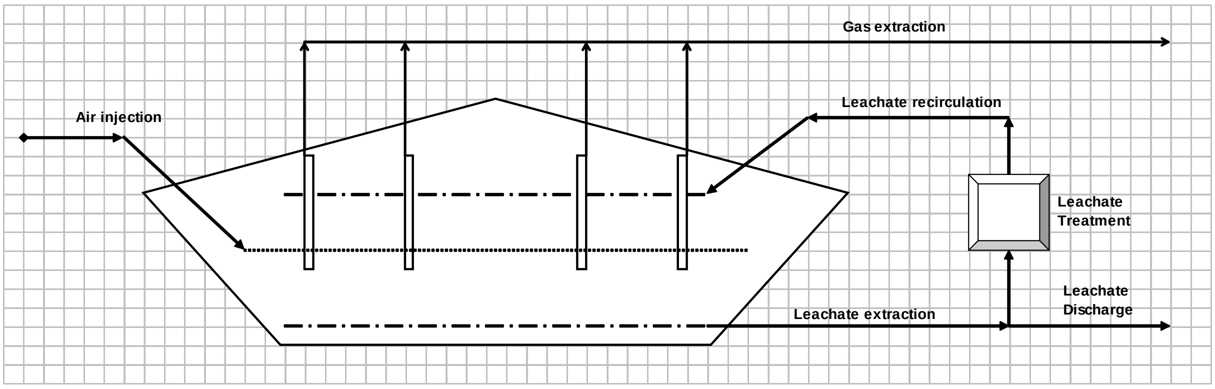

Figure 12 Generalised design for a sustainable landfill (Bioreactor)

5.2 Landfills containing predominantly inorganic waste

For this type of landfill, pH can have a large effect on leaching behaviour. Leaching is determined by the partitioning of contaminants between the solid phase and the leachate. Understanding the factors controlling this partitioning between the two phases during the various stages in the life of a landfill holds the key to controlling leachate quality. pH, conductivity, redox potential and DOC are determined by the major elements (calcite, total organic carbon, sulphur and salts) and the nature of the organic matter in the waste. The interaction of both organic and inorganic contaminants with DOC is crucial in this respect, as the complexed forms are more mobile and in some cases less accessible to microorganisms.

The controlled placement of waste and the structure of the landfill body maintain favourable conditions in the landfill to ensure compliance with European legislation and meet the criterion that the landfill becomes sustainable within 30 years.

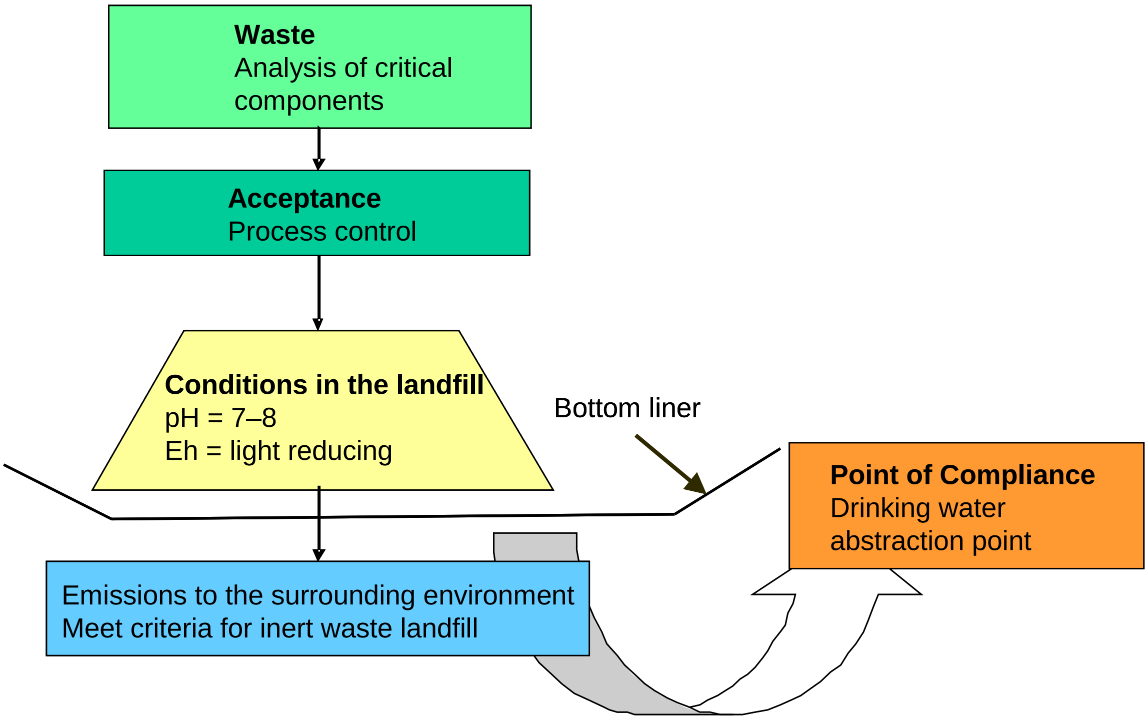

Figure 13 Schematic model for a sustainable landfill containing predominantly inorganic waste

The overall design for a landfill containing predominantly inorganic waste (Figure 13) is no different from an ordinary landfill, but the acceptance policy and placement of waste are geared to controlling the biochemical processes occurring in the landfill body.

5.3 Landfills containing hazardous waste

Leaching from hazardous waste should be limited as far as possible. Therefore, the first objective of sustainable landfill is to modify the leaching behaviour. The major challenge is to ensure that these goals can be guaranteed under conditions far removed from equilibrium with the surrounding environment. To this end the landfill is designed with a natural sealing layer (calcite) and a soil layer for buffering leachate pH. The scenario for stabilised waste is represented by the diagram in Figure 14.

The pilot study demonstrated that a protective layer forms on the surface of the stabilised waste. The limited understanding of this process to date does not allow us to take it into account in the models. It is expected that sufficient information will be obtained in the short term to allow simulation of the leaching behaviour of a Monolith.

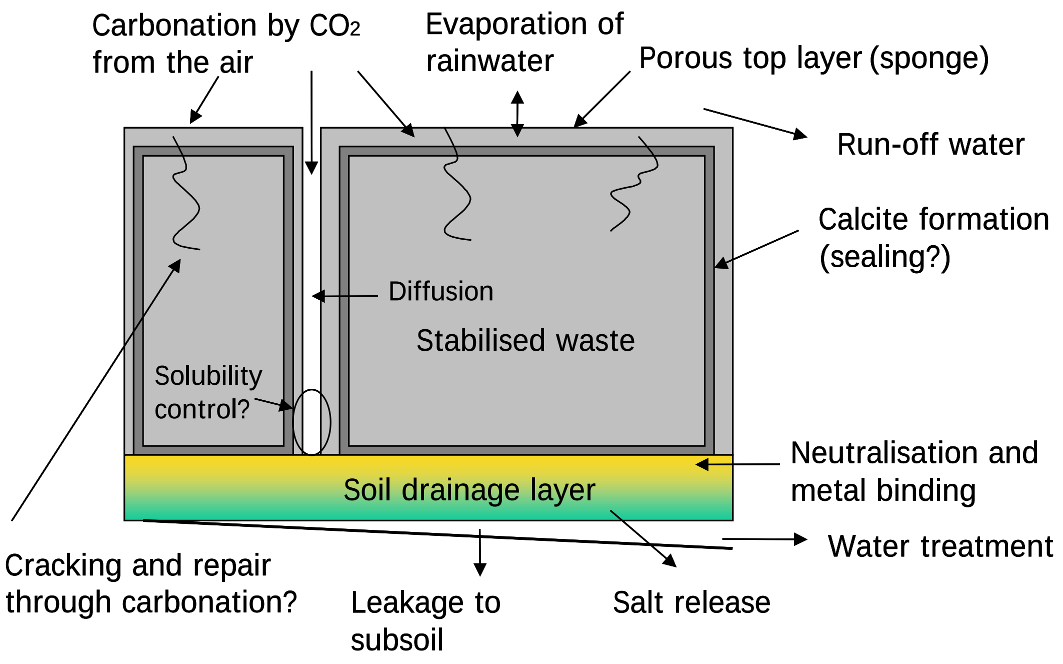

Figure 14 Schematic representation of the Monolith landfill scenario

Figure 15 contains the results for pH-dependent leaching of copper (Cu), molybdenum (Mo), Pb and Zn from stabilised waste, compared with monofill field data, leachate data from the pilot study, run-off data from the pilot study, leached waste cores and lysimeter data, as well as the leaching behaviour predicted by the model.

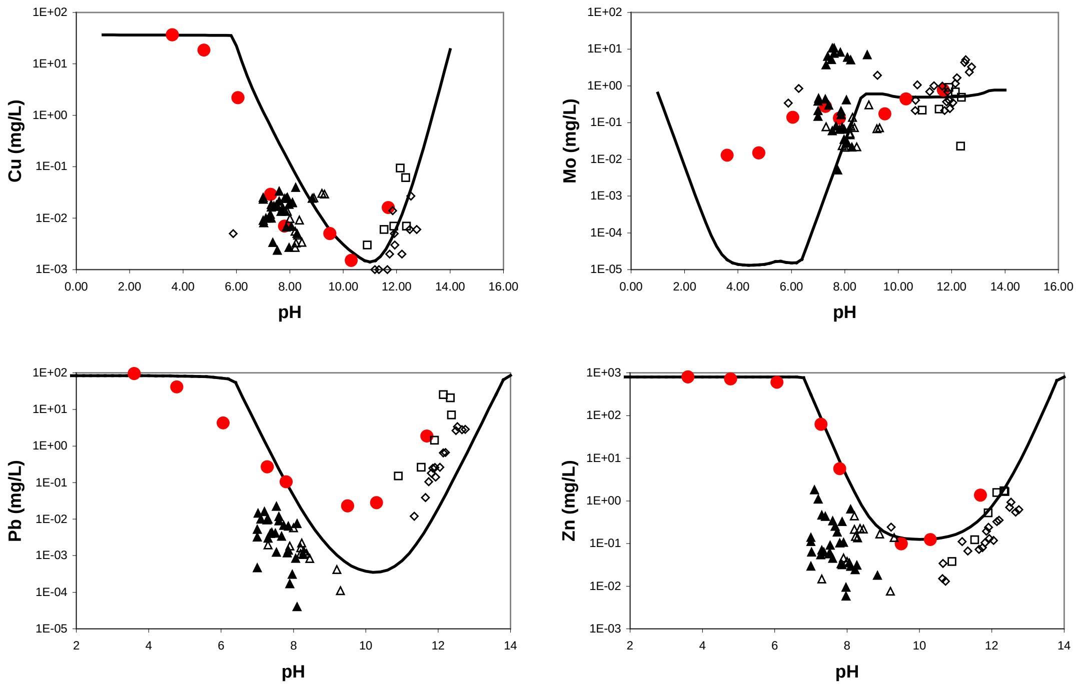

Figure 15 pH-dependent leaching of Cu, Mo, Pb and Zn from stabilised waste (●) compared with monofill data (field scale) and leachate pilot data (▲), pilot run-off data (△), leached waste cores (☐) and lysimeter data (◇). The solid line represents the predicted leaching behaviour by modelling.

5.4 The route to sustainable landfill

The path to a sustainable landfill remains long and without guarantees. Nevertheless, the information obtained and the knowledge gained allow us to formulate design rules and operational procedures that will lead to sustainable landfill. Some questions remain open and these require further research. But resulting alterations or amendments to the concepts are not considered to present any potentially insurmountable problems.

The main steps in the development of a sustainable landfill (see Figure 16) obviously include key decision moments for guiding the process in the right direction. Monitoring of landfill emissions provides data that can be used in the development of any additional measures required to create a sustainable landfill. One limitation is that several process control measures can only be used before landfilling.

The main steps are:

1 ***Site selection:*** Given that the emission criteria depend on the conditions in the surrounding environment, a less permeable base is preferred, and the site should preferably have a relatively high net precipitation (in connection with water for flushing, biodegradation and leaching). A site near the sea can be advantageous with respect to the emission of salts (brackish groundwater).

2 ***Waste selection:*** Managing the types of wastes for deposition (getting the right cocktail) is a key requirement for a sustainable landfill. A basic mixture should be made up from the expected waste arisings that will lead to a sustainable landfill within a period of about 30 years.

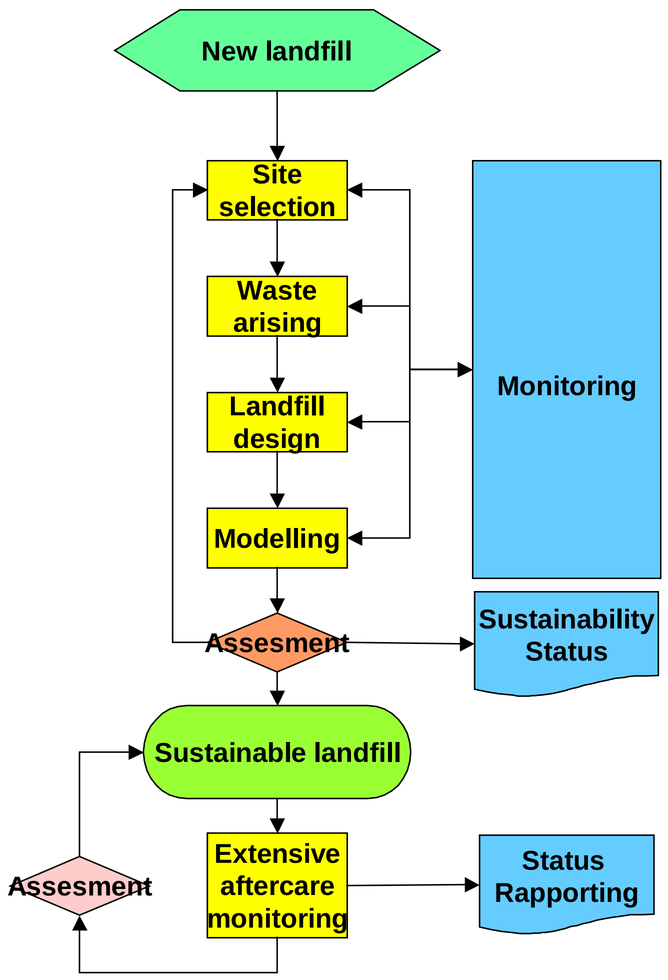

Figure 16 The route to a sustainable landfill

3 ***Landfill design:*** Various engineering techniques will be required depending on the basic waste mixture. A landfill containing organic waste is biologically stabilised as quickly as possible, an important factor being percolation of water through the landfill. Depending on the inclusion of any 'problem wastes', a landfill containing inorganic waste requires special measures for solubility control and immobilisation (metals) or the flow of water through the landfill.

4 ***Modelling:*** Depending on the waste mixture and measures to be taken, the end condition can be predicted by the database/expert system developed during the Sustainable Landfill project (LeachXS). The model results indicate whether and when a sustainable state can be reached; sensitivity analyses are performed by running scenario studies.

5 ***Regulations:*** The sustainable landfill concept has not yet been brought entirely into line with a landfill for inert waste (Landfill Directive) and neither does it conform entirely to the provisions of the Dutch Soil Protection (Landfill) Decree. Given the fact that a bottom liner is required during the active life (the process time) of a landfill (maximum of 30 years), sustainable landfilling practices present no problems.

6 ***Financing:*** The potential aftercare benefits (no top liner for sustainable landfills, see Table 3) depend on whether provisions for sustainable landfills are included in the legislation before this stage has been reached. Landfills for inert waste (Landfill Directive) are assessed on a waste-by-waste basis with separate acceptance criteria for each type of

waste (still partly based on the composition of the waste rather than leaching properties). Sustainable landfilling is based on assessing emissions from the waste mixture as a whole. A cost comparison for the Monolith is not yet available.

Table 3 *Qualitative cost comparison of sustainable versus ordinary landfills*

Measure	Sustainable	
	Bioreactor	Equifill
Top liner	++	++
Pipes	-	-
Operation	--	--
Leachate treatment	--	-
Gas production	+	o
Aeration	--	o
Aftercare funding	(++)	(++)
Total	-	o

'+' reduced costs for the operator

'-' increased costs to the operator above ordinary landfills

It should be possible to convert existing operational landfills into sustainable landfills, although this aspect has not been investigated. The Sustainable Landfill project has developed a unique set of instruments for assessing whether, and how, an existing landfill can be converted into a sustainable landfill. The feasibility of such a conversion depends entirely on the existing process control measures (particularly those that cannot be altered) and the availability of monitoring data. Analysis of the waste input, landfill structure and leachate data over time allows us to make a judgement on the sustainability of an existing landfill. Depending on these data and the time available, in some cases it will be possible to assemble a package of measures that will lead to a sustainable landfill within a specified period of time.

6. Conclusions

The main conclusion is that it is feasible to design and operate a landfill that complies with the standards set out in the Landfill Directive for a landfill for inert waste, based on emissions from the landfill body, through careful selection of the waste input (acceptance) and suitable control measures (pre-treatment, immobilisation, biodegradation, solubility control and percolation/flushing). Work is continuing to find solutions for three problem components: Cl^-, NH_4^+ and SO_4^{2-}. It may be possible to process problem wastes in a Monolith landfill.

The project has shown that in a sustainable landfill:

- total residual emissions are lower than from ordinary landfills;
- emissions are released over a shorter period than from ordinary landfills;
- emissions are more predictable and controllable.

The black box has been opened. The defining processes have been identified. However, some questions remain about the control over these processes (particularly for hydrology).

In this project a sustainable landfill is defined as a landfill body that meets the emission standards required for a landfill for inert waste as defined by the Landfill Directive.

It is expected that sustainable landfills will meet the standards to be set under the proposed European Groundwater Directive, possibly with the exception of Cl^-, NH_4^+, and SO_4^{2-}.

Constructing a sustainable landfill (or cell) involves no extra environmental risks. If the scientific expectations are not borne out in practice, or if the government does not grant the necessary permits, a top liner can always be applied to bring the landfill into compliance with both EU and Dutch legislation. This will involve additional costs and aftercare funds will have to be made available at the end of the operational life of the landfill.

In principle, all wastes are suitable for sustainable landfilling, given the right mixture of wastes and package of control measures. A limited amount of waste that is highly leachable over a long period can in principle be accepted. It is recommended that a bulk mix is compiled that will lead to a sustainable landfill within thirty years. In addition to this bulk mix, specific wastes with anomalous properties can then be accepted if they are neutralised by the bulk mix (buffer). This can be determined by modelling before acceptance.

Sustainable landfill practices do not affect normal landfill operation, although certain aspects have to be adapted. Acceptance (of non bulk waste streams) will take more time, and landfilling itself will have to meet additional requirements (waste placement and landfill structure, compaction, cells, etc.). In general, sustainable landfill requires greater understanding of the processes in the landfill (particularly biochemical and physical processes, hydrology and landfilling techniques); this expertise can be outsourced.

A preliminary cost comparison between ordinary and sustainable landfill shows that a Bioreactor will probably be more expensive than an ordinary landfill, largely because of the additional leachate treatment required. The costs of Equifill are comparable with ordinary landfills. Although the operational costs are higher, aftercare costs are lower.

7. Further information

Besides this summary the following final reports produced for the Sustainable Landfill project are available:

- Final Report (technical) in English, ISBN-10: 90-73573-30-0 / ISBN-13: 978-90-73573-30-7
- Dutch Summary ISBN-10: 90-73573-29-7 / ISBN-13: 978-90-73573-29-1
- Background documents:
  * Bioreactor (in Dutch) ISBN-10: 90-73573-31-9 / ISBN-13: 978-90-73573-31-4
  * Equifill (in Dutch) ISBN-10: 90-73573-33-5 / ISBN-13: 978-90-73573-33-8
  * Monolith (in Dutch) ISBN-10: 90-73573-32-7 / ISBN-13: 978-90-73573-32-1
  * Database (in English) ISBN-10: 90-73573-34-3 / ISBN-13: 978-90-73573-34-5

These reports can be downloaded from the websites www.sustainablelandfilling.com and www.duurzaamstorten.nl.

Articles by researchers on certain aspects of sustainable landfill will be published in several technical journals.

More information can be obtained from the Dutch Sustainable Landfill Foundation. Please contact Jeanne Kok at the Foundation’s secretariat on +31 73 6279444.