PRACTICAL APPLICATION OF HAZARDOUS WASTE CO-DISPOSAL WITH MUNICIPAL REFUSE AT THE COASTAL PARK LANDFILL BIOREACTOR

VOLUME 2

by

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EXECUTIVE SUMMARY – VOLUME 2

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1. INTRODUCTION

The co-disposal of hazardous wastes with general wastes in sanitary landfills has been practised in many overseas countries, especially in drier areas which have a perennial water deficit. However, different approaches to co-disposal have led to quite different experiences and attitudes, with the result that different perceptions of the values and dangers of the co-disposal practice have developed. The major perceived problem with the disposal of special wastes on a landfill is the possible generation of a more polluting leachate.

The co-disposal of hazardous wastes with general wastes in sanitary landfills in South Africa has not been widely implemented to date, due to various reasons. To investigate details of the process, a research project was negotiated between the Cape Metropolitan Council and the Water Research Commission with the objective of developing practical operational criteria for the landfill co-disposal of selected hazardous wastes with general wastes. This could assist smaller landfill operators where only general waste landfills occur and where small volumes of special wastes must be disposed of.

2. FULL-SCALE LANDFILL CELL STUDIES AT COASTAL PARK

The Coastal Park landfill, constructed in 1985 without a containment liner, is situated on the False Bay coastline above the Cape Flats aquifer, with an average separation of 2 m between the base of the waste pile and the water table, forming a "buffer" zone. It was envisaged that the calcareous sand in this buffer zone and encroaching sea water would attenuate leachate discharged from the site.

2.1 Location and Construction of Experimental Landfill Cells

Five experimental cells were constructed in which hazardous wastes could be co-disposed and from which leachate could be collected for monitoring. Cell 1 was constructed during March 1986 (control). Cells 2, 3, 4 and 5 were constructed in a line during August 1987, each with a 14 x 14 m HDPE sheet at the base draining via a pipe to a collection sump. The sheets were overlain with 2 m of sand and 2 x 2,5 m layers of refuse was placed above the sand. The final surface was covered with a 500 mm layer of sand. Every effort was made to simulate the usual sanitary landfill procedures when placing the refuse.

2.2 Hazardous Wastes Applied to the Experimental Landfill Cells

The following types of special waste were applied to the surface of the cells during the period August 1988 to July 1995.

a) Cell 2: Metallic waste: Copper, Chromium, Arsenic in the form of CCA.
b) Cell 3: Tracer substance: LiBr and NaCL (Control cell).
c) Cell 4: Phenolic wastes: such as effluent from the Cape Gas Works.
d) Cell 5: Nitrogenous wastes: such as digested waste-water sludges and urea.

3. RESULTS OF FULL-SCALE STUDIES AT COASTAL PARK

3.1 Leachate Flow

The most striking finding of these studies was the small amount of leachate that found it's way to the base of the cells, on average 2,5% of the annual rainfall. It would appear that rain water was absorbed and mostly held by the landfilled-general wastes, subsequently being drawn back to surface by capillary action, where it evaporated during the course of each year.

3.2 Seasonal Effects

Seasonal variations in leachate flow rate were evident to varying degrees in all cells. There was an average lag of two months between early winter rainfall peaks and leachate peaks, but late in the rainy season the response to rainfall was more immediate.

3.3 Lack of Breakthrough

There was no evidence of breakthrough of any of the applied hazardous waste chemicals or soluble tracer salts over a period of 7 years. The total masses of chemicals found in the leachates were a very small percentage of the applied amounts and sampling of the wastes underlying the cells showed that most of the co-disposed substances had remained within the waste.

4. EXTENSION OF THE RESEARCH

To more fully utilize the experimental cells, a proposal was submitted by the Cape Metropolitan Council for an extension of the current project at the Coastal Park landfill to research the effects of increasing the moisture absorption capacity of the waste body by increasing its height.

The Water Research Commission subsequently approved an extension of 2 years to the contract term of the project (1998 – 1999). When it became apparent that the processes being studied were of a rather long term nature, the contract period was extended and eventually ended in March 2004. This allowed a full five year period of study and observation.

The extended project entailed raising the surface of that section of the Coastal Park landfill where the underlined cells 2 to 5 are located, by an additional 7.5 m of waste. The objectives of the extended project were:

a) to study if and by how much the ultimate rate of leaching of this section of the landfill would be affected by the increased height;
b) to study the variation of quantity and quality of the resultant outflow of leachate, as the 5 m of refuse already in place are squeezed by the additional overburden load, and;
c) to study the amounts and rates of settlement, both of the existing 5 m of refuse and of the 7.5 layer placed over it.

5. FINDINGS OF EXTENDED RESEARCH

5.1 Leachate Flow Rates

The leachate flow from the experimental section of landfill was down to 21 mm/y at the end of the experiment. This is not only within the maximum leakage rate through a liner, permitted for municipal solid waste landfills by the South African Minimum Requirements (1994) of 30 mm/y, but is of a similar order to measured leakage rates reported for geomembrane linings, of up to 16 mm/y. The results also illustrate that apart from a small portion of the infiltration that appears to transit and exit the waste by flow through macro- pores and channels, most of the infiltration is stored in micro pores and then re-evaporated.

5.2 Water Balance Studies

There are clear indications, both from the water balance study and the leachate quality study that the landfill is slowly drying out, and this may eventually stop the leachate flow, just as the flow from measuring Cell 1 has already stopped. This process has been assisted by the reduced rainfall over the period covered by the experiment.

5.3 Settlement

Measurements of the settlement of the original landfill and of the raising have provided useful information on the volume compressibility of the waste. These parameters are quite similar to those calculated for landfills in other parts of the world.

5.4 Leachate Quality

The study has also yielded useful information on changes in leachate quality as a result of raising the landfill. Chemical Oxygen Demand has increased continuously since 1996. This may be caused by leachate from the fresh waste of the raising percolating through the 13 to 18 year old waste of the original landfill, or it may result from an increase in concentration of the leachate as the landfill has dried out, or from a combination of both effects. Similar comments apply to the observed increase in chromium in the leachate.

5.5 Chemical Loading

An examination of the chemical loading carried by the leachate shows that loading has been heavily influenced by the rate of leachate flow, reaching a peak when the leachate flow was highest and then declining as the leachate flow reduced. However, the chemical loading at the end of the experiment is several times higher than it was before the supplemental watering of the observation cells in 1996.

6. RECOMMENDATIONS FOR FUTURE RESEARCH

The experiment was formally brought to an end after 5 years, but it would obviously be beneficial to continue observing leachate flow and quality as well as settlement of the waste on a longer term basis.

During the five years that the experiment has been in progress, the remainder of the original landfill area has been temporarily capped and a new lined section has been constructed and taken into use. A study of the water balance for the new section has been started, and it would be interesting and valuable to observe how the behaviour of the unlined and lined sections of the landfill compare as time progresses.

7. PAPERS EMANATING FROM THIS PROJECT

Several informal presentations of the experimental data have been made during the 5 year course of the experiment, but no formal papers have been published.

A formal paper has now been prepared which will be submitted to the international journal "Waste Management". A paper has been submitted to the (IWMSA) local conference Wastecon held at Sun City in October 2004.

8. CONTRIBUTIONS TO CAPACITY BUILDING, TECHNOLOGY TRANSFER AND LANDFILLING PRACTICE

8.1 Capacity Building

Four technicians, who have assisted with the day-to-day operation of the experiment, have been trained in the practice of precise sampling, operation and record keeping.

8.2 Technology Transfer

Presentations of preliminary findings of the experiment and descriptions of the behaviour of the raised landfill have been given on several occasions to audiences composed of civil engineers and members of the Southern African Institute for Waste Management. Papers based on the final findings will be published both in South Africa and abroad.

8.3 Landfilling Practice

It is possible that the findings will impact on the contents of the new revision of the Minimum Requirements for Waste Disposal by Landfill.

9. REFERENCE

Novella P.H., Ballard R.H., Stow J.G., Ross W.R., Blight G.E., Vorster K., 1999. Practical application of special waste co-disposal with municipal refuse at the Coastal Park landfill bioreactor, vl, WRC Report No. 606/1/99.

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- This project was guided by a Steering Committee constituted as follows:

Ms APM Moolman	:	Water Research Commission (Chairperson)
Prof GE Blight	:	University of the Witwatersrand
Mr GE McConkey	:	Department of Water Affairs and Forestry
Mr P Novella	:	City of Cape Town (Project Leader)
Mr JG Stow	:	City of Cape Town
Mr R Mee	:	City of Cape Town
Mr JM Ball	:	Jarrod Ball & Associates (Waste Management Consultants)
Dr WR Ross	:	Ross Consultancy
Ms W Kloppers	:	Department of Water Affairs and Forestry
Ms SG Matthews	:	Water Research Commission (Committee Secretary)

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1. INTRODUCTION

In semi-arid climatic regions, the potential for evaporation from the Earth's surface may exceed rainfall, year on year although actual evaporation cannot exceed average annual rainfall. If there are clearly defined wet and dry seasons, there may be short periods of seasonal water surplus. Figure 1 shows, for example, the long term mean atmospheric water balance of rainfall and potential evaporation for Cape Town, South Africa. There is a small water surplus in the May to June period. For the rest of the year water deficient conditions prevail. More detailed information on the components of the atmospheric water balance is given later in the paper.

Because of the large excess of potential evaporation over rainfall, landfills in such climates are known to produce little or no leachate even if the landfill capping layers are pervious and almost all precipitation infiltrates (see, e.g. Fourie, Blight and Pinheiro, 1999, Zornberg, et al., 1999 and Blight and Fourie, 1999). If the capping layer is pervious, water can be stored by capillarity in the capping and the landfilled waste, during the wet season, and then be re-evaporated and evapotranspired during the ensuring dry season. If the moisture storage capacity of the waste body is large enough, the entire annual rainfall infiltration could theoretically be stored and re-evaporated, and under these circumstances, the landfill would produce no leachate. If this can be proved true by means of a large-scale field experiment, it could have very beneficial financial consequences, for if a landfill can be shown to produce no leachate, or only an acceptably small quantity of leachate, there is good reason for allowing the expensive underliner, usually required, to be dispensed with.

Supporting evidence had been advanced by Fourie, Blight and Pinheiro (1999), who investigated six long-established unlined landfills in South Africa that are located in both water deficient and water surplus climatic zones. The saturated infiltration rates for the base strata on which these landfills rest, range from 0.3 m/year to 63 m/year. The soils at the toes of the landfills, downstream with reference to the direction of ground-water flow, were sampled to a depth of 2.5 m. Analysis of the samples showed that only slight and localized contamination of the soil had occurred, even at the two landfills located in water surplus climatic zones. This is a strong indication that all, or almost all of the annual rainfall is being stored in the waste during the wet season and re-evaporated during the dry season.

The case that is considered in his paper is that of the Coastal Park Landfill in Cape Town. The landfill is situated 500 m from the sea on permeable beach deposits of sands and silty sands, and the section being studied has no underliner. In 1986, the year the landfill was commissioned, an underlining was not legally required. Water balance studies undertaken in 1985 had indicated that little or no leachate would be produced, and as the aquifer under the landfill is appreciably saline and does not constitute a usable water resource, an underliner was not considered necessary by the local authority. However, a landfill liner has been required since 1994 (Anon, 1994).

Table 1 shows the annual mean values of leachate flow, rainfall and American Standard A-pan evaporation for the landfill for the periods 1987 to 1995 and 1996 to 1997. Reasons for the difference between the two periods will be explained below. However, note that from 1987 to 1995, leachate averaged only 2% of rainfall. The leachate flows were measured by means of five lysimeters or measuring cells constructed beneath the landfill as described below. The sand on which the landfill is built was used for intermediate and top cover layers. Because the sand is pervious (k exceeds 5 m/day), there is almost no runoff and virtually the entire rainfall infiltrates into the waste. Hence the figures for rain in Table 1 can, with little error, be taken to represent infiltration into the landfill.

2. SOME EFFECTS OF RAISING THE HEIGHT OF A LANDFILL

But the effects of raising the height of a landfill are by no means as simple as might appear from the reasoning set out above.

The moisture absorbtion capacity of a landfill is the maximum moisture content that can be held by capillarity in the voids of the landfilled waste. Theoretically, if a landfill is at its moisture absorbtion capacity, the addition of one litre of water at the surface will, in the absence of evaporation, result in one litre of leachate emerging from the base. For this to happen, the waste must be in equilibrium with its suction-water content relationship. This has been demonstrated for a dump of power station ash in an experiment reported by Blight and Roussev (1995). In this experiment, a 30 m high ash dump was sampled for moisture content in June 1987, October 1993 (the end of the dry season) and April 1994 (the end of the wet season). The suction-water content relationship for the ash was established in the laboratory (Fourie and Papageorgiou, 1995). Figure 2 shows the suction-water content curve superimposed on the three sets of water content versus depth relationships. Even though power station ash is a reasonably uniform product, its properties are still variable, but Figure 2 shows that there was a reasonable correspondence between the laboratory curve and the field measurements. In other words, the ash dump was close to being at its moisture absorbtion capacity and was not leaching to the ground-water to any appreciable extent.

Landfilled waste is much less homogenous than power station ash. Nevertheless, it is possible to measure a suction-water content relationship in the laboratory and to make super-positions on field measurements like that shown in Figure 2. An example is shown in Figure 3 (Blight, 1997). In this case the waste was contained in a lysimeter 3 m deep, buried in a landfill (Roussev, 1995), with the lysimeter separated from the surrounding waste by flexible geomembrane walls. The scatter in water content measurements is large, but there is some correspondence between the laboratory suction-water content curve and the water content-depth data.

Another apparent problem is the belief that water can only be drawn to the surface, to evaporate, from a limited depth of a metre or two. Field measurements in landfills have, however, disproved this (Blight, Ball and Blight, 1992, Blight 1997). Water content profiles measured at the ends of the wet and dry seasons have demonstrated that evaporative drying can occur down to at least 15 m. Experiments on lysimeters have shown similar effects. In an experiment by Roussev (1995) the rate of evaporation from a waste-filled lysimeter 3 m deep over a period of 295 days averaged 0.16 mm per m depth per day, while from a similar lysimeter 5.5 m deep the rate of evaporation averaged 0.22 mm per m depth per day. Thus there is no doubt that during an extended dry season, evaporation can remove water from waste down to depths of many metres.

Landfilled waste is inherently heterogeneous and flow of leachate through the waste mass will occur simultaneously through macropores in coarse waste and (at a slower rate) through micropores in finer waste. The dual flow characteristics have been well documented and explored by Bengtsson, et.al (1994), Powrie and Beaven (1999), Rohrs, et.al (2001) and others. The considerations relating to moisture absorbtion capacity will probably apply to the micro-pored waste in a landfill. Even though the moisture content of the waste may be below the theoretical moisture absorbtion capacity, infiltration could still penetrate the waste and emerge from the base via flow through the macropores. Hence it may not be possible completely to stop the generation of leachate by increasing the height of a landfill.

Finally, raising the height of a pre-existing landfill will have the effect of compressing both the old and the new waste, thus driving leachate out at the base of the landfill. It should therefore be expected that raising a landfill will initially increase the leachate flow. It is only once most of the compression has occurred that the leachate flow can be expected to subside and eventually slow to zero or to what may be considered an acceptably low value.

3. THE MEASURING CELLS

Before this experiment was undertaken, the measuring cells had been used for another experiment and this prior usage, as it happened, had an important influence on the height raising experiment.

Table 1 shows that leachate exiting Coastal Park averaged 12 to 15 mm per year over a period of observation of nine years from 1987 to 1995. To put this figure into perspective, Koerner (2001) has reported leakage rates from landfills lined with undamaged composite geomembrane/compacted clay systems of up to 8 mm per year, and of up to 16 mm/y for undamaged geomembrane systems. Hence the leakage from the Coastal Park landfill was on a par with that from a lined landfill. In 1995, the landfill was only 5 m high, and yet the moisture absorption capacity combined with evaporation from the waste was sufficient to hold or evaporate 98% of infiltrating rainfall (Table 1). Thus it was tempting to conclude that a small increase of moisture absorption capacity, created by raising the height of the landfill, should be sufficient to stop the leachate flow completely. If there is no leachate in the long term, there can be no need for an underliner. The experiment at Coastal Park was designed to test this hypothesis by constructing a raised section of the landfill over four of the five observation cells.

The first observation cell (Cell 1) had been installed to detect and measure leachate flow quantity and quality. The remaining four cells, constructed about 200 m away from Cell 1, were constructed as part of an experiment to test if hazardous water-soluble substances could safely be co-disposed with domestic refuse. This experiment and its results have earlier been described by Blight (1996) and Ballard (1997) and in a South African Research Commission Report (Novella,et al, 1999).

Each cell consists of a plastic (HDPE) geomembrane liner measuring 15 m x 15 m which is buried at a depth of 2 m below the original ground surface at the landfill site. The site is underlain by approximately 20 m of fine silty sand and the depth of the regional water table varies seasonally from 2 m below natural ground level at the end of the wet season to 3 m at the end of the dry season. Each liner was laid with its edges turned up by 0.5 m all round to form a lined impervious basin of $200m^2$ plan area. Each basin is graded to a corner from which a pipe leads to a collecting and measuring sump. In this way, all liquid percolating out of the bottom of each lysimeter can be recovered, its quantity or flow rate measured and chemical analyses made for leachate quality assessment. Figure 4 shows the layout of the lysimeters in both section (above) and plan (below).

After replacing the 2 m of sand excavated to place the geomembranes, waste was landfilled and compacted to a depth of 5 m, in two 2.5 m lifts. The two lifts of waste were separated by a 0.2 m layer of sand intermediate cover. After covering the surface of the 5 m of waste with a 0.3 m cover-layer of sand, the area of landfill directly above each geomembrane was surrounded by a low bund of clay. The water-soluble substances disposed on the surfaces of the various cells are indicated in the lower part of Figure 4.

It was somewhat surprising to find that the water-soluble substances did not ever appear in the leachate collected from the cells (see Blight, 1996). In desperation, in 1996, an attempt was made to flush phenol from Cell 4 by flooding the surface of the cell with the equivalent of more than twice the annual rainfall, over a 6 month period. The leachate flow from Cell 4 increased by a factor of 9 as a result (see Table 1). The flows from every other cell in the set of four were also affected, with that from Cell 2, 48 m away from Cell 4, increasing by a factor of 1.5, and that from Cell 5, 15 m away by a factor of 4.1.

Absolutely no phenol was detected in the leachate from Cell 4, but the failed experiment showed that horizontal flow occurs very strongly in the waste when water is applied to the surface. The lateral flow and resultant overall increase in leachate flow exerted an appreciable influence on the raising experiment that was to follow, by upsetting the state of near-equilibrium that existed at the end of 1995.

4. THE EXPERIMENTAL RAISING AND ITS EFFECT ON SETTLEMENT AND LEACHATE FLOW

It was decided to raise the height of the test section of the landfill in two stages. In the first year (1998/99) an additional 5 m would be added, and this would be repeated in the following year (1999/2000). The test section would be in the form of a compacted waste berm covering Cells 2 to 5, about 300 m long, 90 m wide at the base and 40 m wide at the crest. Because of the difficult working conditions on the landfill, it was decided to keep the instrumentation simple. A major difficulty with instrumentation existed because of the presence of scavengers on the landfill who tend to appropriate anything and everything with a potential scrap value. Observations were to be made of the following variables.

- Levels of original waste surface
- Levels of surface of first 5 m raising
- Levels of surface of second 5 m raising
- Time domain reflectometry (TDR) measurements of water content of waste
- Leachate flow rates
- Leachate chemical analysis (COD, pH, ammonia, chloride, copper, chromium, arsenic)
- Density and composition of in situ compacted waste

The basic instruments would be the engineer’s level and tacheometer with water contents of the waste being measured in situ by TDR probes buried in the waste.

Unfortunately, the first ten TDR probes that were buried in the waste embankment were dug out and stolen during the next night and it was decided to abandon this part of the experiment. It was expected that flow rates of leachate would increase as additional overburden was added to the existing waste. It was also decided to analyse the leachate to observe any changes in quality as the raising proceeded. Not much difference was expected at first, although a concern had been voiced that leachate expressed from the test cells might contain raised levels of copper, chromium and arsenic. When the freshly added waste started to generate acidic leachate, there might be a lowering of the pH in the original waste with the result that metals might be remobilized and emerge in the leachate.

The raising experiment was started on 25 November 1998, with the placing of the first 2.5 m lift of waste and was ended 5 years later, although measurements of settlement and leachate flow and quality are still being made.

As a result of holdups caused mainly by labour problems, it was eventually decided to limit the raising to three lifts of 2.5 m each. Final profiles of the raised portion are shown in Figure 5. A set of experimental evaporative covers was installed on the crest of the raising, but these are not described in this paper. (Preliminary results of the cover experiment have been reported by Blight, et al, 2003.)

The full records of settlement and leachate flow rate for Cells 2 to 5 are shown graphically in Figure 6. Table 2 shows selected numerical values of settlement for the original landfill surface between 0 to 690 days, 0 to 820 days and 0 to 1825 days (5 years). (Day 690 marks the start of the third 2.5 m lift, and day 820 was when work on the experimental covers was started). The settlements are given both as a percentage of the original thickness of the waste, and as millimeters of settlement.

The settlement versus time graphs show the initial quick compression giving way to slow settlement which continues to increase as the waste decomposes and, as a result, slowly compresses. Application of the 5 m first raising and the 2.5 m second raising caused the settlement to accelerate for the periods from 60 to 240 days and 700 to 750 days and thereafter the settlement rate started progressively reducing. Unfortunately, because of a misunderstanding between the project leader and the field staff, compounded by the introduction of staff new to the project, settlement measurements for the surface of the first 5 m raising were made impossible from day 840 onwards and only measurements on the original landfill surface and the final surface of the combined 7.5 m total raise were possible after this. At the end of the experiment (5 years after the start) the lost settlement slabs were exhumed and leveled to establish their final settlement. The final settlements are shown on Figure 6 at a time of 5 years.

It is interesting to note that the waste above each cell behaved differently. In particular, Cell 5 showed the least settlement under the first 2.5 m lift of the raising, but the underlying waste then appeared to yield, and under the second 2.5 m lift, settled to an extent similar to the other cells.

The building of trial "store and evaporate" landfill cap sections on the top of the raised landfill, but to one side of the test sections, accelerated the settlement slightly, but this effect died away in a short time.

Table 2 also records the leachate flow rates at the start of the experiment (day 0) and also the flow rates in 1995, prior to the application of water to Cell 4. It will be seen that the leachate flow rates at day 0 (25 November 1998) had not subsided to their 1995 levels, but were still only slightly less than the flow rates in July 1996 (46 mm/y in 1998 as compared with 12 mm/y in 1995). The fact that the lower 5 m of waste was surcharged with water from the earlier experiments was obviously going to affect the results of the raising experiment.

Figure 6 also shows the leachate flow rates. As the surface above each cell was raised by the first 2.5 m, the flow rate increased sharply, except for Cell 5, which showed almost no increase in flow rate. As the second 2.5 m lift came on, the leachate flow rates increased further for all cells and then gradually declined. The flow rates from Cells 2, 3 and 4 were back almost to the starting values after 690 days. That from Cell 5, however, was still double its initial value, although slowly declining.

Imposition of the third 2.5 m raising caused only a slight increase of the leachate flow rates. Building of the experimental cap sections caused a further (very slight) increase in the leachate flow rates.

Since shortly after day 820, leachate flow rates have slowly declined to their average value at day 1825 of 21 mm/y. This is still above the value in 1995, but there are indications that within the next 4 to 5 years, the leachate flow will decrease further. Apart from the slow decline in flow rate shown in Figure 6, another indication comes from the overall water balance of the raised landfill section that will be described later in the paper. Also, the leachate flow from Cell 1 (which was not affected by the raising experiment) ceased on day 750 and has not restarted. These all indicate that the landfill is slowly drying out.

5. IN SITU DENSITY, WASTE COMPOSITION AND COMPRESSION PARAMETERS.

5.1 In Situ Density and Waste Composition

The original 5 m high landfill layer as well as the 5 m first raise and the 2.5 m second raise were sampled by digging a hole with an approximate volume of l m^3 in each of the layers.

The bulk density was measured by filling the material excavated from each test hole into the load body of a weighed small truck, and then weighing the truck and its contents. A 100 kg sample, as close to being representative as possible, was then taken for water content and waste composition determination. The truck was emptied and refilled loosely with dry sand, striking the sand off level with the rim of the load body, for which the volume had been measured, and then weighing the full truck. Sand from the known volume and weight on the truck was then shovelled loosely into the test hole to fill it level with the surrounding surface. The truck was then weighed again to determine the weight and hence volume of the sand used to fill the hole. Hence the bulk density could be calculated.

The water content samples were weighed and then spread out on plastic sheets in a locked dry shed, allowed to air-dry for six months and then reweighed. Hence the air-dry water content was determined. The air-dry samples were then sieved through a 3 mm mesh sieve to separate the various waste components, and each class of component was then weighed. The results of the compositional and geotechnical measurements are shown in Tables 3 and 4. In these tables, the parameters of void ratio e, degree of saturation S_r and gas-filled void height (=(1 – S_r) x height of waste) have been calculated by assigning solids densities to each of the waste components (see Table 3) and calculating the composite solids density of the waste according to the percentage by mass of each component present.

The initial gas-filled void heights were fairly large and even the original landfill, which has settled an average of 1.4 m after 5 years still has a calculated gas-filled void height of about 1.6 m, assuming that leachate has not accumulated in this layer.

The various components of the waste proved to be reasonably consistent from sample to sample and even, as shown in Table 3 and 4, from the original landfill (13 years older than the raises) to the 1st and 2nd raises. An interesting feature of the waste analyses is that metals and glass are almost absent. This may be a result of the activities on the landfill of the scavengers (who were mentioned earlier).

5.2 Compression Characteristics of Waste

The compression of the waste (Figure 6) is strongly time-dependent, as a result of conventional compression (shown by the increase in leachate flow rate), creep of the organic and plastic components, and decomposition of the organic components. Figure 7 shows the compression of the original landfill and the raisings in the form of void ratio versus applied pressure curves. These are shown for the original and new waste at 30 days, 0.5, 1, 2 and 3 years after loading. The slopes of chords to these compression curves have been summarized in Figure 7 as values of the volume compressibility:

$$m_v = de/dp(1 + e_o) \qquad \text{(units: } m^2/kN) \qquad (1)$$

(Where de/dp is the slope of the chord to the compression curve and e_o is the initial void ratio. In simple terms, m_v is the compressional strain undergone by the waste after a particular time, per unit of applied stress).

In Figure 7 the load increments for the original (5 m) landfill represent the full weights of the 5 m raising (52 kPa) and the total 7.5 m raising (88 kPa). For the 5 m raising, 26 kPa represents the weight of the lower 2.5 m of the raising. For the combined 7.5 m raising 44 kPa represents half of the weight of the raising.

The values of m_v recorded on Figure 7 have been compared in Table 5 with values calculated for settlement versus time curves published for four landfills of similar age to Coastal Park, situated in various parts of the world (Brazil, Colombia, Spain and England). Table 5 shows that, although on the high side, values of m_v for Coastal Park are similar to values calculated from time-settlement curves measured on comparable landfills in other parts of the world. In fact, considering possible differences in waste composition, degree of compaction and climate, the correspondence is good.

6. VARIATIONS IN LEACHATE QUALITY

Figures 8a, 8b and 8c summarize the leachate quality measurements of leachate samples taken between 1995 and the end of the experiment (November 2003):

The results of the measurements are all rather scattered, but clear trends are discernable over the 9 years spanned by the results, even though no measurements were made in 1997 and in early 1998.

6.1 Chemical Oxygen Demand (COD)

COD increased continuously over the period of observation, for all cells (Figure 8a). The lowest CODs have been recorded for Cell 2, with Cells 5, 4 and 3 showing successively higher values. Comparing with Figure 6, this is the exact reverse of the order in which the settlements of the original landfill increase, and may indicate that the refuse over the various cells contains increasing quantities of organic matter, in the order 2, 5, 4, 3. Even with the scatter in the measurements, the correspondence between COD and settlement is quite clear.

It is not known why the COD of the leachate from all cells has increased with time. One possible explanation is that leachate formed in the fresh waste of the raising layers is gradually percolating down through the old waste of the original landfill, increasing the COD as it does so. If this is so, it shows that a small proportion of infiltrating rain will always find its way out of the base of the landfill, even though the remainder may be stored and re-evaporated in the upper part of the landfill. In other words, because of the macro-flow properties of the waste, it is not possible to store and re-evaporate all infiltration, a small proportion will probably always leach through the base.

6.2 Ammonia

Ammonia levels rose between the ends of 1996 and 1998 when the experiment was started (Figure 8b). From 1999 to the end of 2003, ammonia in the leachate tended to be fairly constant. Cell 5 showed the lowest levels of ammonia, followed by Cells 2, 3 and 4. Thus the indication is again that the waste over Cells 3 and 4 had the highest organic content. The change in order between Cells 2 and 5 may indicate that the organic matter over Cell 2 was more of animal origin and that over Cell 5 more of vegetable origin.

6.3 pH values (not graphed)

pH values have remained in a range from 7.8 to 8.3 throughout the duration of the experiment. The highest pH values have been measured on leachate from Cell 2, followed in descending order by Cells 3 and 5, with Cell 4 the lowest. Trends are not very clear, but the cell with the lowest pH (Cell 4) is also that with the highest ammonia.

6.4 Chloride (not graphed)

Average values of chloride in the leachate increased gradually from just over 4000 mg/L in 1999 to about 4500 mg/L at the end of 2003. The leachate from Cell 3 has consistently contained the most chloride, but this should not be surprising as Cell 3 was dosed with lithium and sodium chloride as tracers.

6.5 Chromium

Chromium values have been erratic, but the trend appears to be for increasing values (Figure 8c). Most of the chromium may have originated from Cell 2 which was dosed with CCA (see Figure 4), yet if anything, the leachate from Cell 2 has had the lowest chromium values. The trend for chromium to increase with time may show an increasing mobility for metals, however this is not supported by decreased levels of pH.

6.6 **Arsenic** (not graphed)

Arsenic has remained below the detection limit of 50 μg/L throughout most of the period of the experiment. Right at the end of 2003, however, values of 60 to 90 μg/L were measured, which may mean that the trend for arsenic is similar to that for chromium.

6.7 **Copper** (not graphed)

Copper values have consistently remained low, at just above the detection limit of 25 μg/L.

Thus the main trends shown by the leachate analyses have been for increasing values of COD and chromium.

7. RELATIONSHIP BETWEEN LEACHATE QUALITY, SETTLEMENT AND LEACHATE FLOW RATE

The correlations between the settlements of the original 5 m high landfill and the final raised top surface, and the COD of the leachate have been graphed for conditions in mid-2003 and are shown in Figure 9a. In Figure 9a, the numbers 2, 3, 4, 5 represent the data points for the corresponding observation cells. For the original 5 m high landfill, the correlation is positive, but for the final top surface it is negative. Hence, interesting though the correlations may be, they probably have no useful meaning.

Figure 9b shows the variation of the chemical loading of the leachate (i.e. concentration in g/L multiplied by flow rate in $L/m^2/y$ to give loading in $g/m^2/y$) for COD, Ammonia and Chromium. Comparing the curves for the loadings with those for the flow-rates (Figure 6) it is obvious that the chemical loadings are largely dependent on the rates of leachate flow. It is also clear from Figure 9b that leachate expressed by raising a landfill can enormously increase the pollution load exiting from the base of the landfill. In this case, the COD loading of $23g/m^2/y$ (230 Tons/ha/y) rose to a peak of 500 $g/m^2/y$ (5000 Tons/ha/y). Even if the leachate flow rate eventually declines to the initial rate of 12 mm/y, the increasing concentrations shown in Figure 8a will result in a loading of at least 80 $g/m^2/y$ (800 Tons/ha/y) which is 3.5 times the loading at the end of 1995. It is therefore very important to realize that it is not only the flow rate of leachate escaping from a landfill that decides the potential for causing ground water pollution, but that the chemical loading is more important.

8. THE WATER BALANCE FOR THE LANDFILL TEST SECTION

Changes in the water balance for the Coastal Park landfill can be written as:

$$\Sigma(R - L) = \Sigma E + \Delta S \qquad (2)$$

Where $\Sigma(R - L)$ = cumulative difference between rainfall and leachate flow

ΣE = cumulative evaporation from landfill surface

ΔS = change in water stored in landfilled waste as a result of infiltrating rain, evaporation and leachate flow.

At Coastal Park early rainfall measurements were made via a rain gauge mounted at the position of Cell 1. This was later replaced by an automatic tipping gauge mounted at the Park site office, about 200 m from the experimental site.

A term for runoff does not appear in equation (2). This is because the landfill cover layer is formed of the local sand which, as explained earlier, is sufficiently pervious to allow all but intense rainfalls to infiltrate completely.

Leachate flow (L) has been measured since 1989 via the five test cells, as described earlier. The leachate receptacles are emptied daily and the volume of their contents measured. Leachate flow rates are then calculated for each weekly total flow.

Evaporation (E) from the landfill surface has been measured by means of a series of surface energy balance measurements made at various times of the year. The theory and practice of the method has been set out in detail by Blight (1997, 2002). Figure 10a shows the results of ten sets of energy balance measurements made at Coastal Park, while Figure 10b shows the cumulative evapotranspiration derived from Figure 10a. It should be noted that the estimated annual evapotranspiration of 620 mm is close to the average annual rainfall quoted in Table 1.

The initial quantity of water stored in the waste was measured via the sampling program described earlier, and initial quantities of storage (S) are listed in Table 4.

The water balance for the experimental raising is shown graphically in Figure 11 for the experimental period of five years, i.e. from 25 November 1998 to 25 November 2003. Figure 11a shows the accumulation of rainfall (ΣR), evaporation (ΣE_B at a rate of $\dot{E}_B = 620 mmy^{-1}$) and leachate (ΣL). According to equation (2) the changes in storage are given by

$$\Delta S = \Sigma(R - L) - \Sigma E_B \qquad (2b)$$

It will be seen from Figure 11a that the cumulative leachate flow increased at 200 days, reflecting the increased flow rates shown in Figure 6, and caused by compression of the original landfill under the superimposed weight of the first 5 m raising. Based on an annual evaporation of 620 mm, cumulative changes in storage have been negative throughout the five year period, indicating that the water stored in the landfill is progressively decreasing with time.

Leachate ceased to flow from cell 1 in December 2000 and flow has not restarted since. Cell 1 was not affected by the raising experiment and this may confirm the conclusion that the landfill is drying out.

Figure 11b shows the changes in the total water stored in the landfill, including the increases in storage caused by the two stages of the experimental raising (also based on an annual evaporative loss of 620 mm per year).

During the five years of the experiment, the annual rainfall was (1999) 510 mm, (2000) 390 mm, (2001) 440 mm, (2002) 370 mm and (2003) 350 mm for an average of 412 mm/y. This is considerably less than the 620 mm/y recorded for 1996/97. As shown by Figure 11b, there was a reservoir of water stored in the waste that was sufficient to supply a depletion rate of 620 mm/y, although it is likely that depletion has taken place at a lesser rate. If, to allow for the lesser rainfall, a rate of evaporation from the raising ($\dot{E}_B$) of 400 mm/y is assumed (i.e. slightly less than the average annual rainfall during the period of the experiment) the calculated rate of depletion of water from the landfill would be reduced from an average of 280 mm/y to only 20 mm/y, but remains a depletion. Note in Figure 11a that the line representing $\dot{E}_B$ = 400 mm/y almost coincides with the ΣR line at the end of each dry season and hence is completely possible. Thus it is clear that the water storage in the raising is being depleted, year by year, but the actual rate of depletion is not known with certainty.

9. SUMMARY AND CONCLUSIONS

9.1 The main objective of the experiment, to stop the leachate flow, has not yet been realized, and may never be realized completely. Nevertheless, the declining leachate flow from the experimental section of landfill was down to 21 mm/y at the end of the experiment. This is not only within the maximum leakage rate through a liner, permitted for municipal solid waste landfills by the South African Minimum Requirements (1994) of 30 mm/y, but is of a similar order to measured leakage rates reported for geomembrane linings, of up to 16 mm/y. (Koerner, 2001). The results also illustrate that apart from a small portion of the infiltration that appears to transit and exit the waste by flow through macro pores and channels, most of the infiltration is stored in micro pores and then re-evaporated.

9.2 There are clear indications, both from the water balance study and the leachate quality study that the landfill is slowly drying out, and this may eventually stop the leachate flow, just as the flow from measuring Cell 1 has already stopped. This process has been assisted by the reduced rainfall over the period covered by the experiment.

9.3 Measurements of the settlement of the original landfill and of the raising have provided useful information on the volume compressibility of the waste. These parameters are quite similar to those calculated for landfills in other parts of the world.

9.4 The study has also yielded useful information on changes in leachate quality as a result of raising the landfill. Chemical Oxygen Demand has increased continuously since 1996. This may be caused by leachate from the fresh waste of the raising percolating through the 13 to 18 year old waste of the original landfill, or it may result from an increase in concentration of the leachate as the landfill has dried out, or from a combination of both effects. Similar comments apply to the observed increase in chromium in the leachate.

9.5 An examination of the chemical loading carried by the leachate shows that loading has been heavily influenced by the rate of leachate flow, reaching a peak when the leachate flow was highest and then declining as the leachate flow reduced. However, the chemical loading at the end of the experiment is several times higher than it was before the supplemental watering of the observation cells in 1996.

9.6 During the five years that the experiment has been in progress, the remainder of the original landfill area has been temporarily capped and a new lined section has been constructed and taken into use. A study of the water balance for the new section has been started, and it will be interesting to see how the behaviour of the unlined and lined sections compare.

10. RECOMMENDATIONS FOR FUTURE RESEARCH:

10.1 The experiment was formally brought to an end after 5 years, but it would obviously be beneficial to continue observing leachate flow and quality as well as settlement of the waste on a longer term basis. It is recommended that the City of Cape Town continue will this monitoring on a longer term basis.

10.2 During the five years that the experiment has been in progress, the remainder of the original landfill area has been temporarily capped and a new lined section has been constructed and taken into use. It would be of value to record the behavour of the lined section of the site and compare any differences that may occur in practice with the experimental results.

10.3 A study of the water balance for the new section has been started, and it would be interesting and valuable to observe how the behaviour of the unlined and lined sections of the landfill compare as time progresses.

11. ARCHIVING OF DATA

11.1 Report will be archived at the Water Research Commission offices

11.2 Field results will be held at the University of Witwatersrand, Department of Civil Engineering

11.3 Background information and all raw data for volume 1 and 2 have been archived at City of Cape Town, Waste Management Department.

11.4 All scientific and analytical data will be held at the Scientific Services Department of the City of Cape Town.

11.5 Organisational contacts for information on this project

Water Research Commission can be contacted via:	**www.wrc.org.za**
City of Cape Town can be contacted via:	**www.capetown.gov.za**
University of Witwatersrand can be contacted via:	**www.wits.ac.za**
Wasteman Group (Pty) Ltd can be contacted via:	**www.wasteman.co.za**

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TABLE 1: ANNUAL MEAN VALUES FOR LEACHATE, RAIN AND A PAN EVAPORATION* AT COASTAL PARK LANDFILL

	1987 to 1995 Average Annual Rain: 691 mm/y A-pan evaporation: 1618 mm/y			1996 to 1997 Average Annual Rain: 620 mm/y A-pan evaporation: 1756 mm/y		
	Leachate			Leachate		
	mm/y	mm/day	% of rain	mm/y	mm/day	% of rain
Cell 1	24.8	0.068	3.6	26.7	0.073	4.3
Cell 2	21.9	0.060	3.2	33.6	0.092	5.4
Cell 3	8.9	0.024	1.3	27.1	0.074	4.4
Cell 4	12.5	0.034	1.8	113.3	0.310	18.3
Cell 5	5.2	0.014	0.8	21.5	0.058	3.5
Mean (1 to 5)	14.7		2.1	44.4		7.2
Mean (2 to 5)	12.1		1.8	48.9		7.9

Supplemental wetting, Cell 4: 1 485 mm over January-July 1996

* A-pan = American standard evaporation pan

TABLE 2: SETTLEMENTS AND LEACHATE FLOW DATA FOR FIRST AND SECOND RAISES OF COASTAL PARK LANDFILL

Part	Cell No	2	3	4	5	Mean 2 to 5
1	Settlement:% original 5m high fill (mm)					
	0-690 days(0=25 Nov 1998)	16	20	19	17	18
	0-820 days	19	24	23	21	22
	0-1825 days(25 Nov 2003)	26(1326)	32(1601)	31(1545)	27(1357)	29(1457)
2	Settlement:% 5m raising(mm)					
	210-690 days	10	10	9	11	10
	210-820 days	18(910)	16(800)	14(700)	18(900)	16(827)
	210-1825 days(25 Nov 2003)	26(1350)	21(1059)	24(1201)	26(1350)	24(1240)
3	Settlement:% 7.5m Raising (mm)					
	690-1825 days	13(956)	10(754)	11(811)	11(848)	11(842)
4	Flow rate in 1995 mm/y	22	9	12	5	14
5	Flow rate: mm/y					
	Day 0	55	44	69	15	46
	Day 640	40	36	55	18	37
	Day 840	58	47	69	42	54
	Day 1825	29	24	23	9	21

TABLE 3: COMPOSITION OF WASTE

Component	Original	1st Raise	2nd Raise	Component Solid Density kg/m^3
	% by dry mass			
Sand, stones, bricks, concrete	51	77	62	2650
Paper and cardboard	13	9	10	1800
Plastic	9	6	10	1000
Metals	3	Trace	2	7000
Glass	3	Trace	1	2700
Organics, textile, leather	21	8	15	1800
Solid density of waste kg/m^3	2155	2492	2360	2336 Average

TABLE 4: GEOTECHNICAL PARAMETERS OF WASTE

Source of Waste	Original	1st Raise	2nd Raise	Overall Average
Bulk density kg/m^3	940	1030	1165	1045
Water content % dry mass	37	18	37	31
Dry density kg/m^3	686	873	850	803
Void ratio e	2.1	1.9	1.8	1.9
Degree of saturation S_r%	37	24	55	39
Thickness of lift m	5	5	2.5	
Gas-filled void height m	2.1	2.5	0.6	Total 5.2
Initial storage of water S mm	1270	780	780	2830

TABLE 5: COMPARISON OF COMPRESSIBILITY OF COASTAL PARK LANDFILL WITH COMPRESSSIBILITIES OF A SAMPLE OF OTHER LANDFILLS

Reference and name of landfill	Height of Landfill m	Age Years	m_v m^2/kN $\times 10^{-3}$
Watts & Charles (1999). Brogborough	11	6	3.8
Machado et al (2002). Bandeirantes	58	7	0.5 – 1
Rodriques & Velandia (2002). Don Juana	20	3	1.6
Pereira et al (2002). Valdemingomez	35	6	1.0
Coastal Park	5-12.5	13-18	2.2-4.6

13. FIGURE CAPTIONS

Figure 1 Atmospheric water balance for Cape Town, South Africa

Figure 2 Comparison of water content-depth measurements in a dump of power station ash with laboratory suction-water content relationship for the ash

Figure 3 Comparison of water content-depth measurements in a lysimeter of municipal solid waste with laboratory suction-water content relationship for the waste

Figure 4 Arrangement of observation cells (or lysimeters) at Coastal Park landfill

Figure 5 Transverse and longitudinal profiles of raised portion of landfill (vertical scale exaggerated)

Figure 6 Records of settlement and leachate flow during the 5 year duration of the raising experiment

Figure 7 Compression characteristics of waste

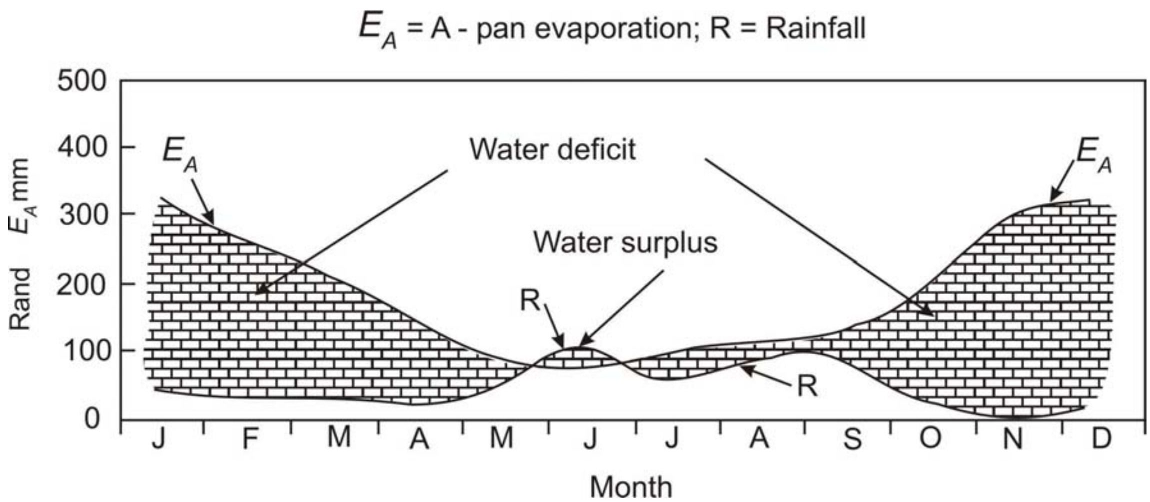
Figure 8 Variation of leachate quality before and during raising experiment:
(a) Chemical Oxygen Demand (COD)
(b) Ammonia
(c) Chromium

Figure 9(a) Correlations between settlement of original landfill surface and final raised surface and Chemical Oxygen Demand of the leachate

Figure 9(b) Variation of chemical loading of leachate for COD, Ammonia and Chromium before and during raising experiment

Figure 10 Evaporation from landfill surface assessed by surface energy measurements
(a) Rates of evaporation through year
(b) Cumulative evaporation through year

Figure 11 Water balance for raised part of landfill during experiment
(a) Changes in water storage as a result of rain infiltration, leachate exfiltration and evaporative losses
(b) Changes in total water stored in landfill



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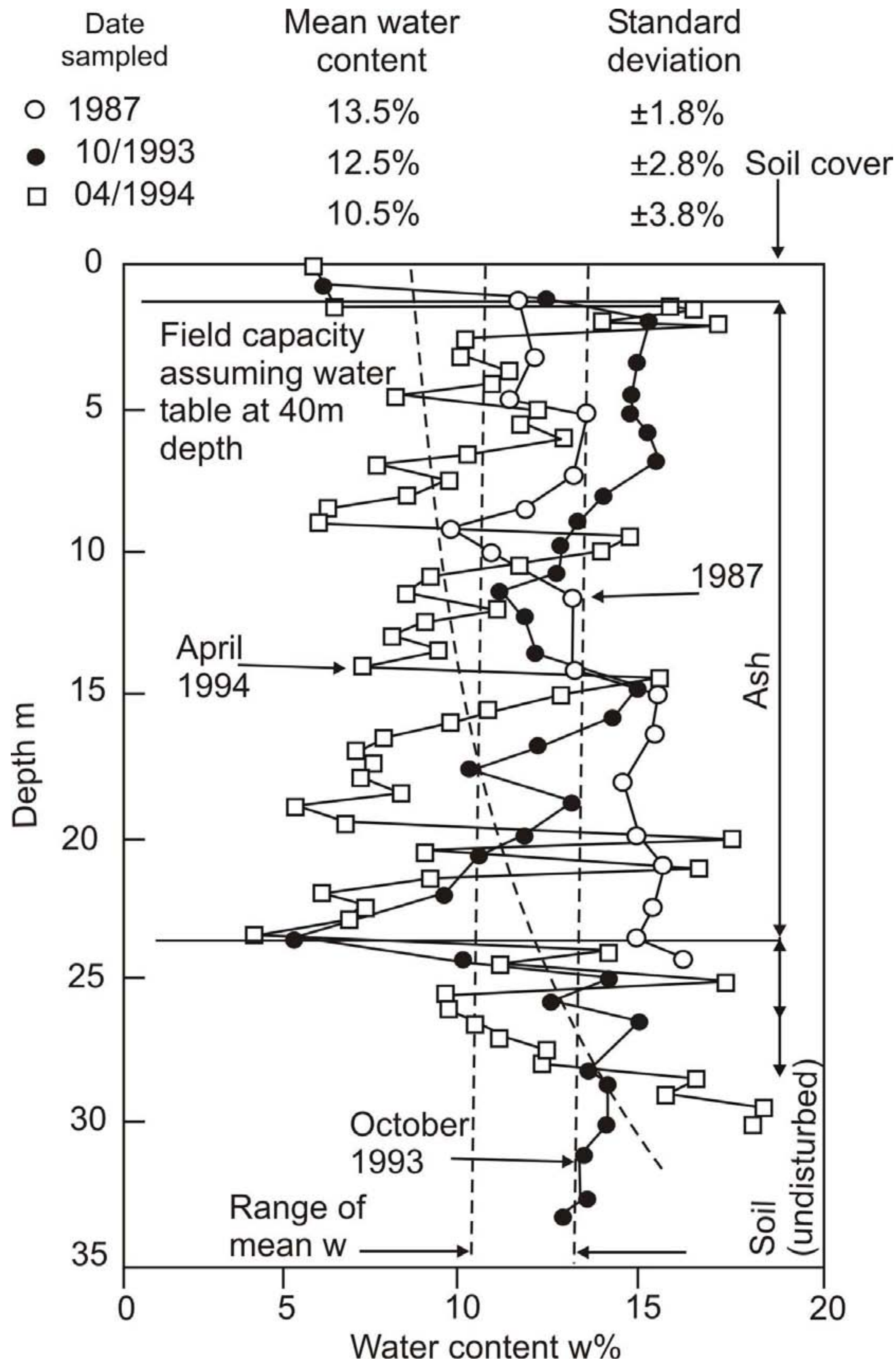


Figure 2 Comparison of water content-depth measurements in a dump of power station ash with laboratory suction-water content relationship for the ash

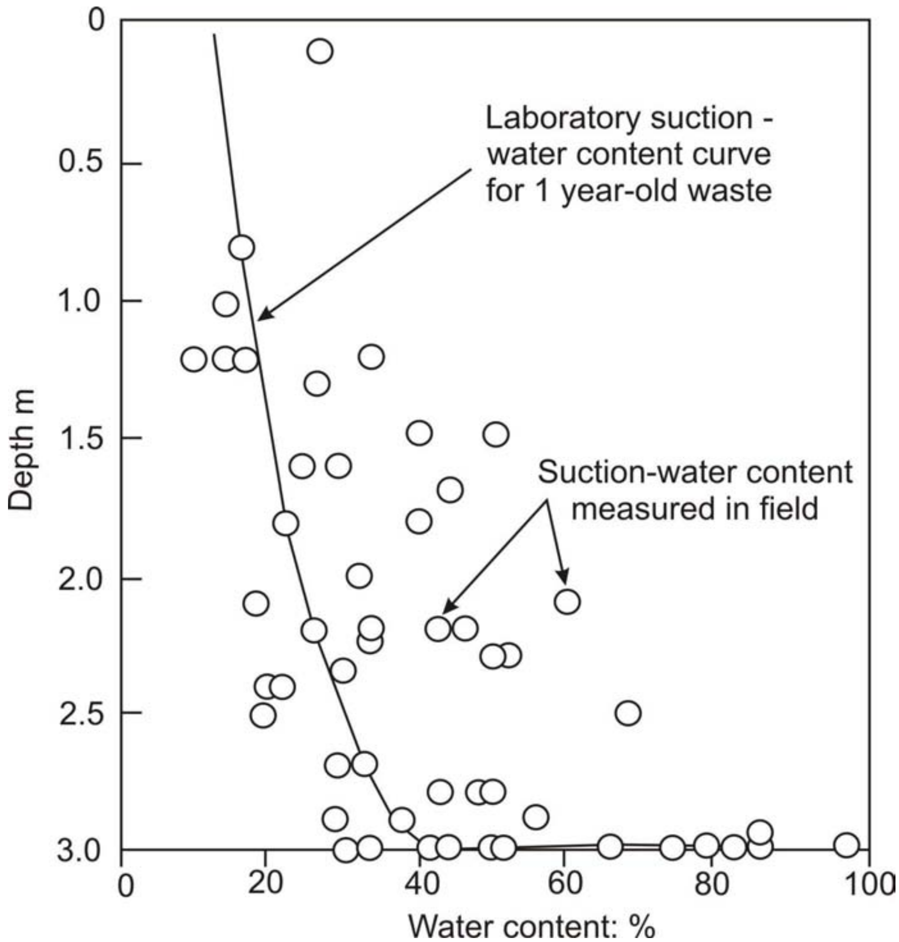
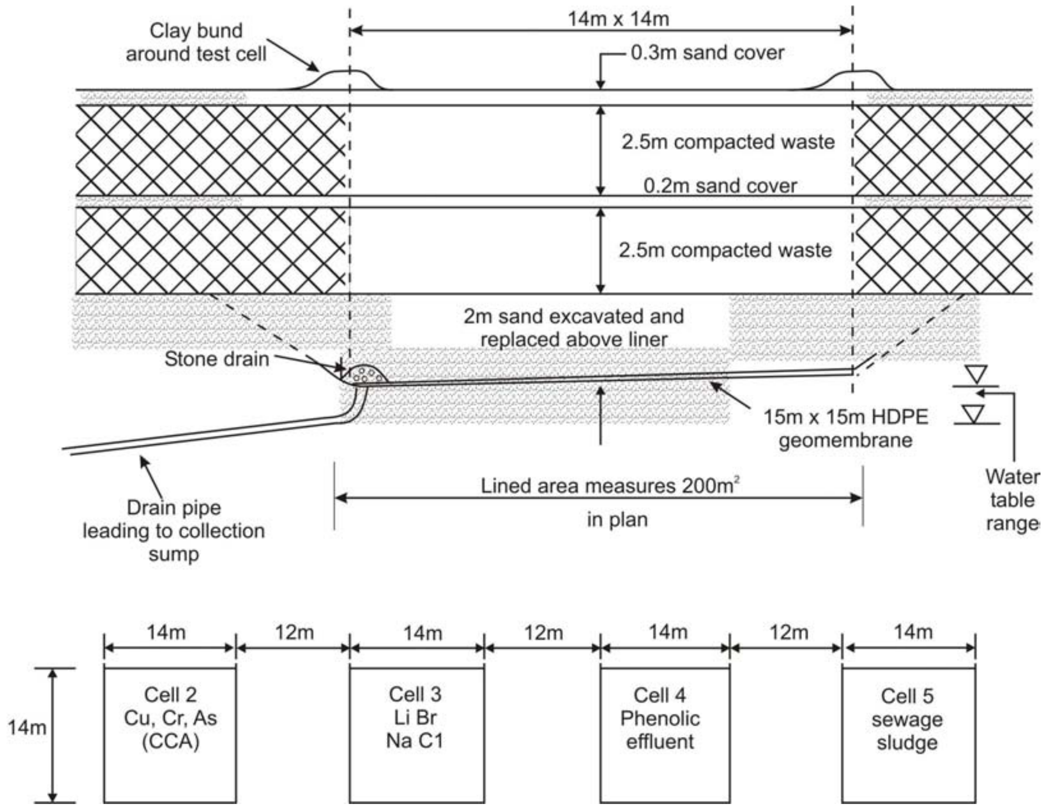


Figure 3 Comparison of water content-depth measurements in a lysimeter of municipal solid waste with laboratory suction-water content relationship for the waste



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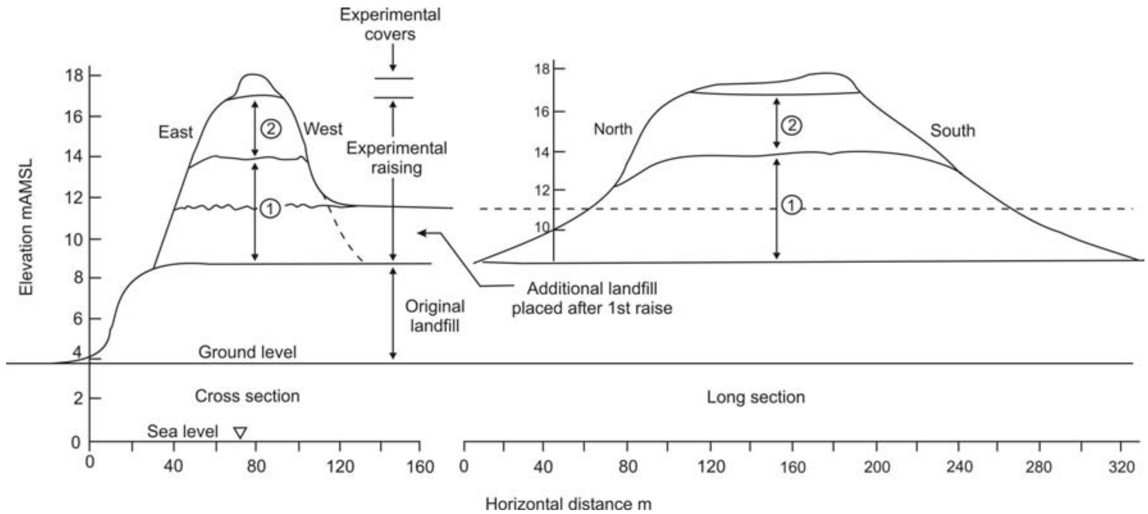

Figure 5 Transverse and longitudinal profiles of raised portion of landfill (vertical scale exaggerated)

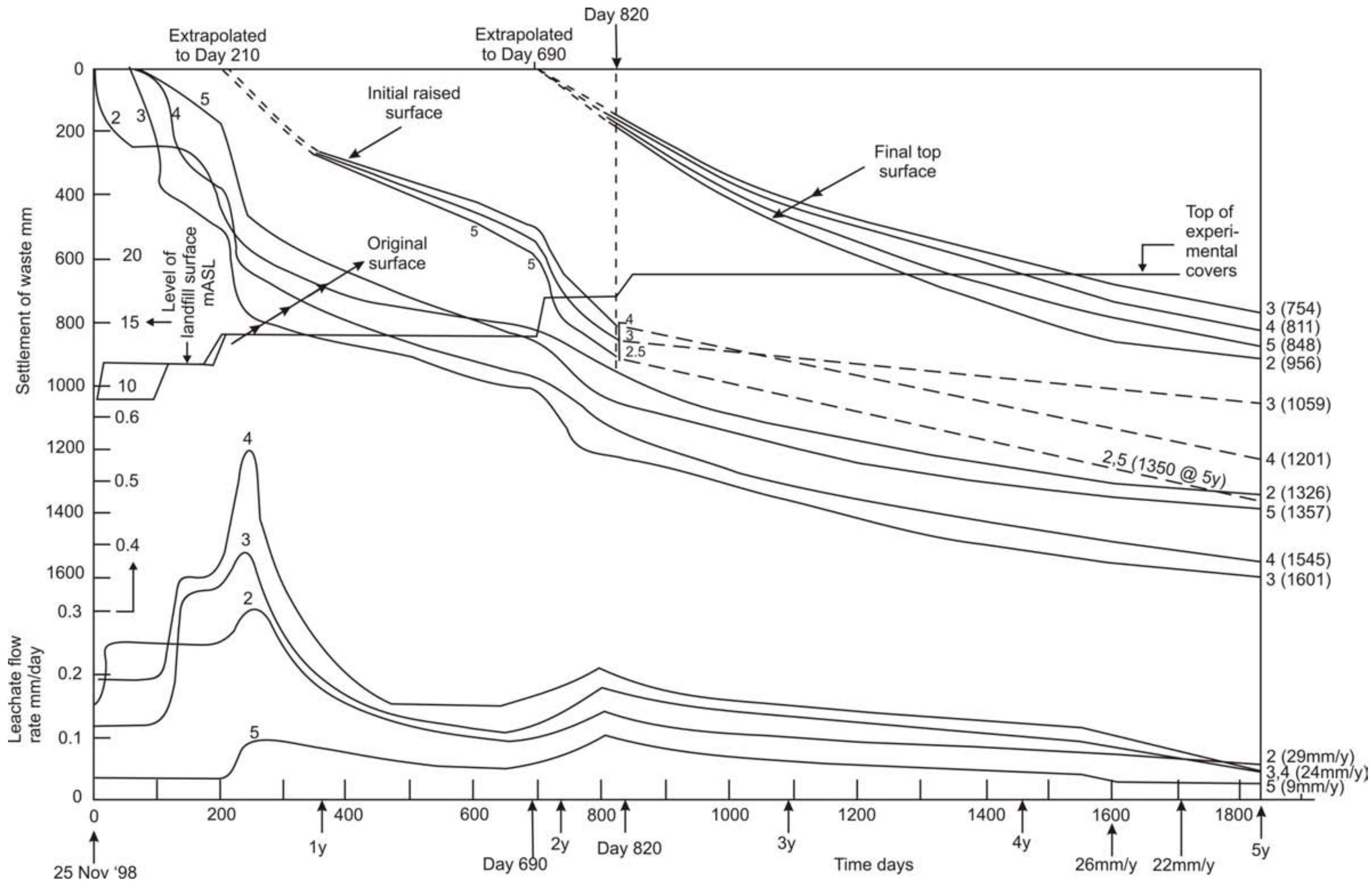

Figure 6 Records of settlement and leachate flow during the 5 year duration of the raising experiment

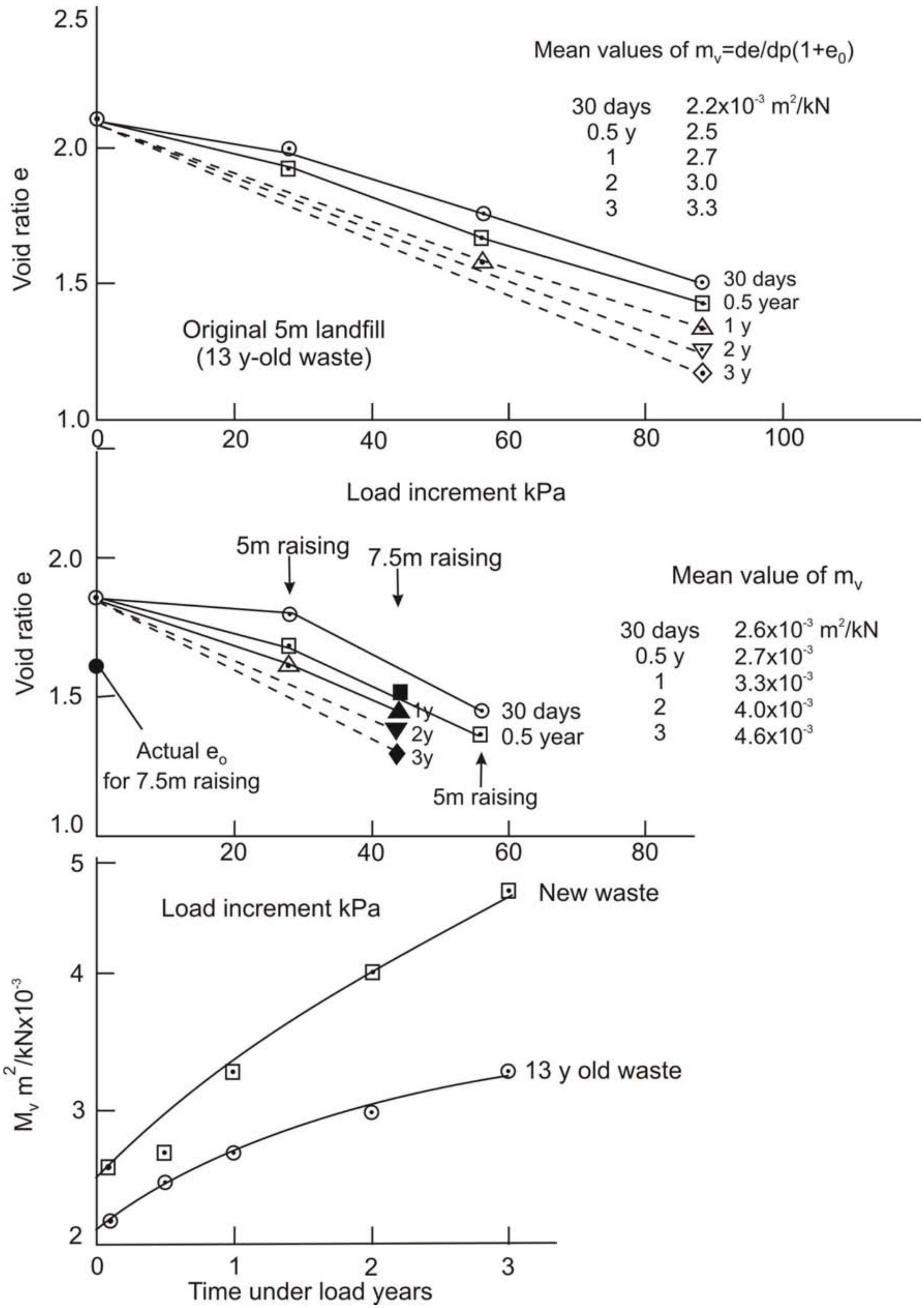

Figure 7 Compression characteristics of waste

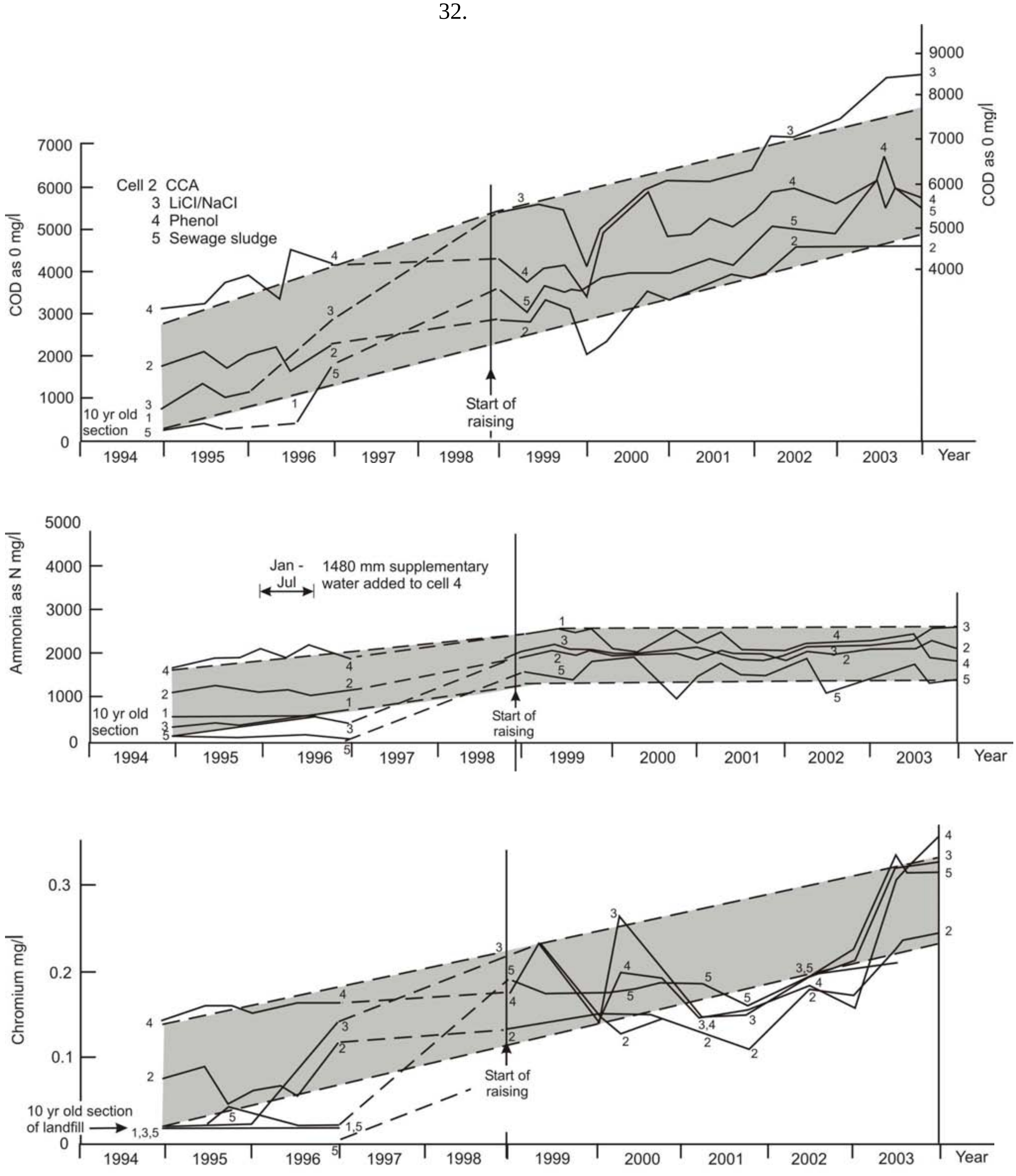

Figure 8 Variation of leachate quality before and during raising experiment:
(a) Chemical Oxygen Demand (COD)
(b) Ammonia
(c) Chromium

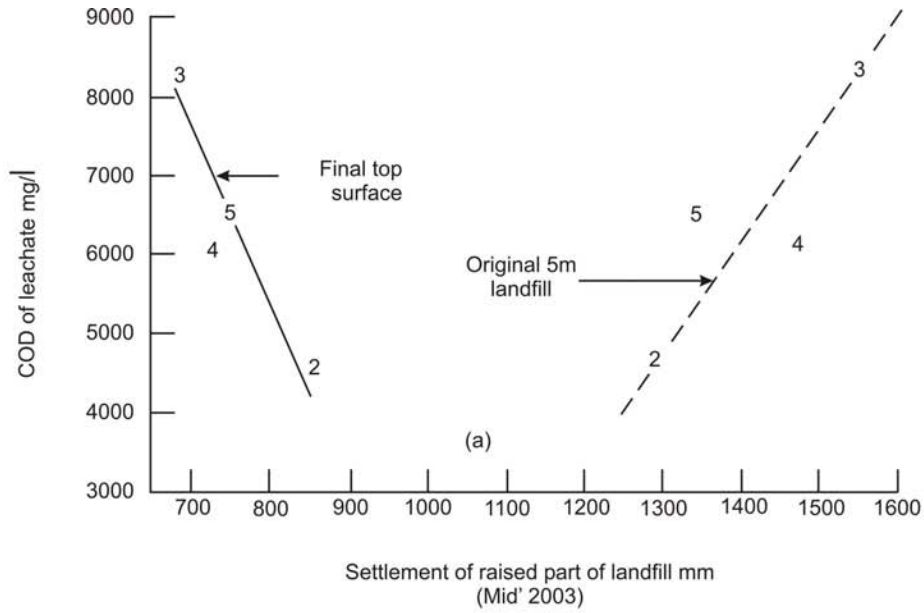

Figure 9(a) Correlations between settlement of original landfill surface and final raised surface and Chemical Oxygen Demand of the leachate

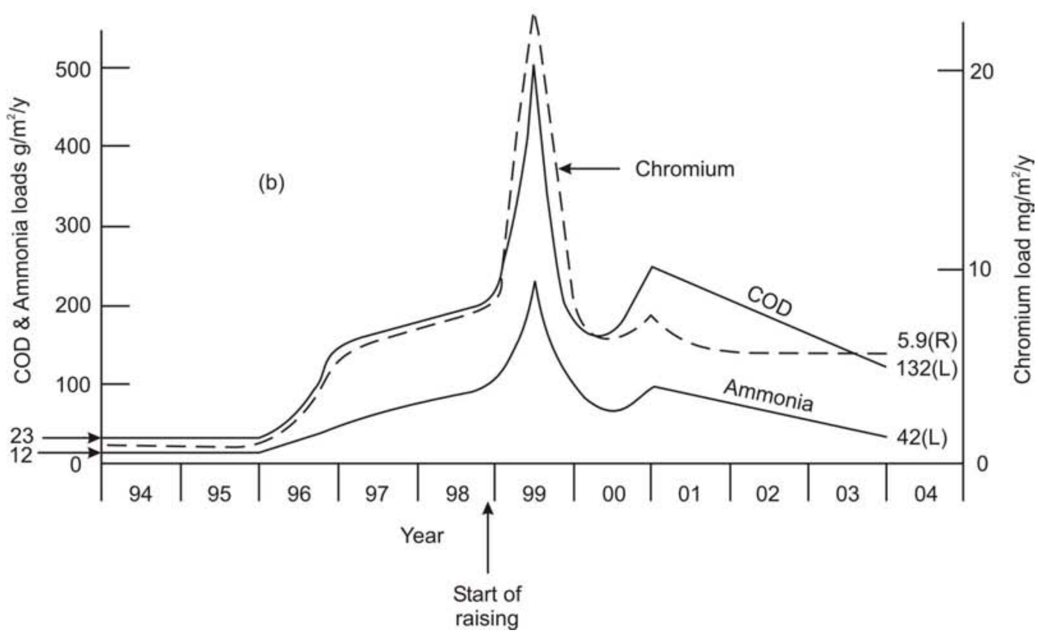

Figure 9(b) Variation of chemical loading of leachate for COD, Ammonia and Chromium before and during raising experiment

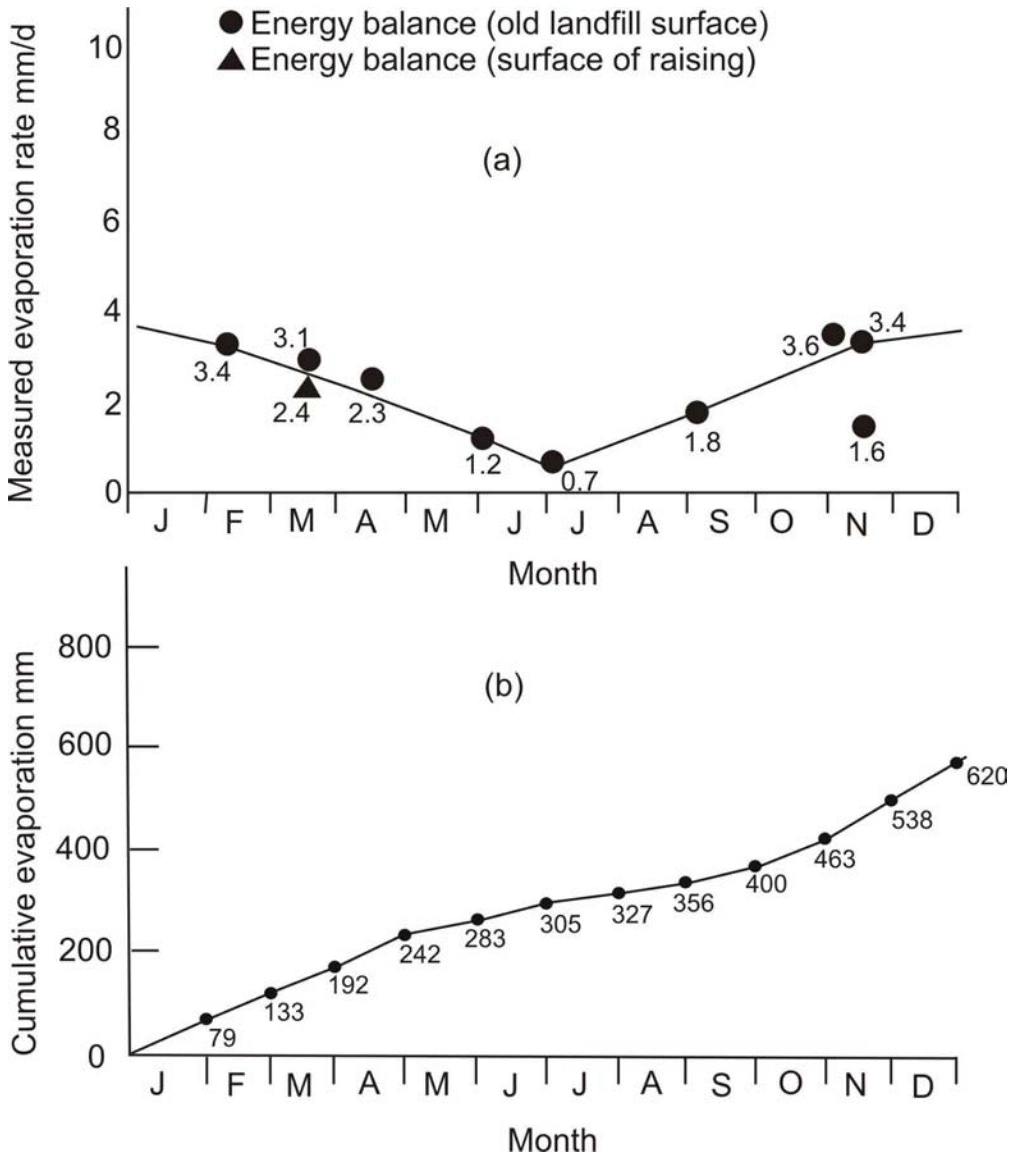

Figure 10 Evaporation from landfill surface assessed by surface energy measurements
(a) Rates of evaporation through year
(b) Cumulative evaporation through year

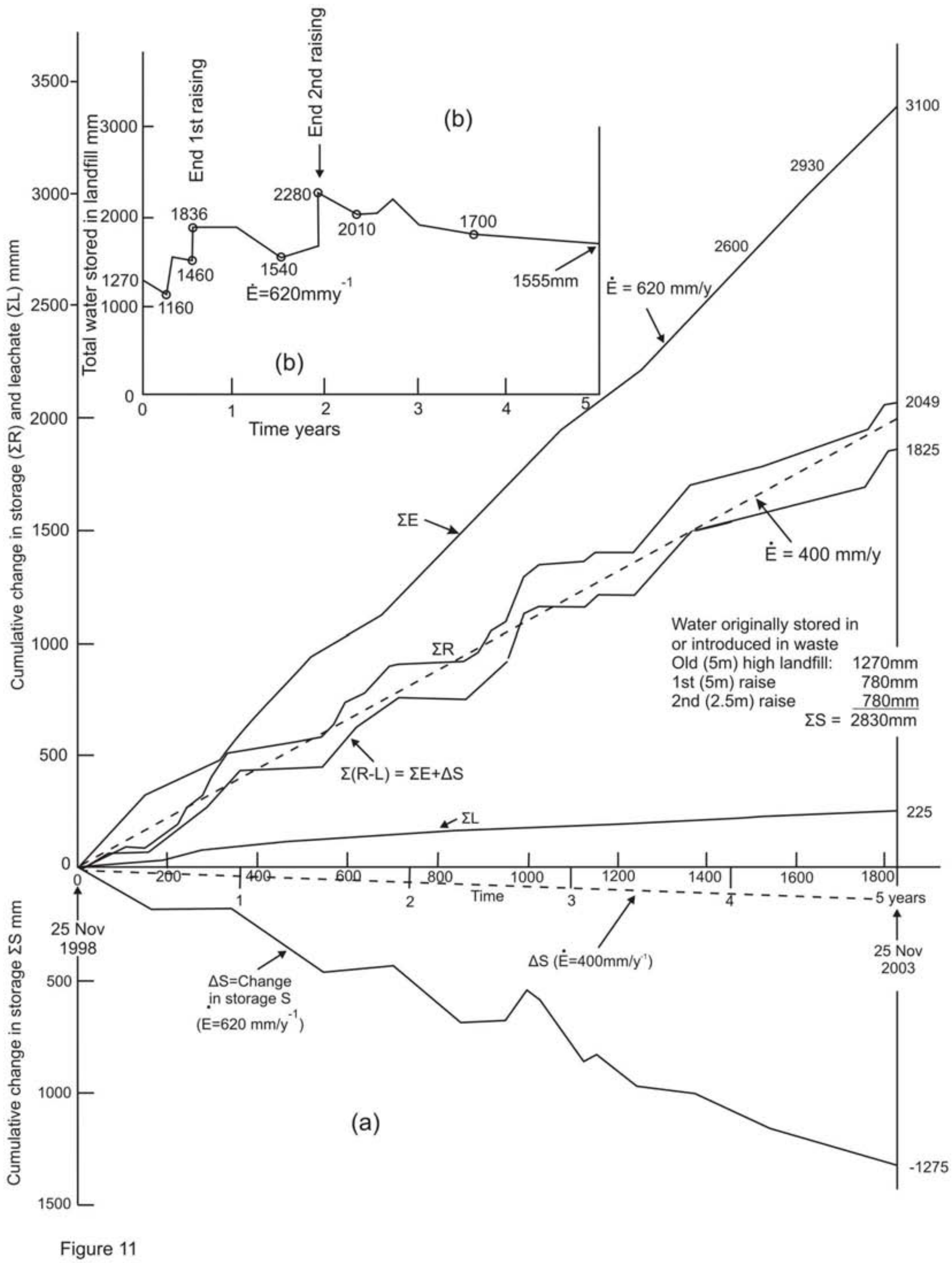

Figure 11 Water balance for raised part of landfill during experiment

(a) Changes in water storage as a result of rain infiltration, leachate exfiltration and evaporative losses

(b) Changes in total water stored in landfill