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Containment landfills: the myth of sustainability

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Abstract

A number of major problems associated with the containment approach to landfill management are highlighted. The fundamental flaw in the strategy is that dry entombment of waste inhibits its degradation, so prolonging the activity of the waste and delaying, possibly for several decades, its stabilisation to an inert state. This, coupled with uncertainties as to the long-term durability of synthetic lining systems, increases the potential, for liner failure at some stage in the future whilst the waste is still active, leading to groundwater pollution by landfill leachate. Clay liners also pose problems as the smectite components of bentonite liners are subject to chemical interaction with landfill leachate, leading to a reduction in their swelling capacity and increase in hydraulic conductivity. Thus, their ability to perform a containment role diminishes with time. More critically, if diffusion rather than advection is the dominant contaminant migration mechanism, then no liner will be completely impermeable to pollutants and the containment strategy becomes untenable.

There are other less obvious problems with the containment strategy. One is the tendency to place total reliance on artificial lining systems and pay little attention to local geological/hydrogeological conditions during selection of landfill sites. Based on the attitude that any site can be engineered for landfilling and that complete protection of groundwater can be effected by lining systems, negative geological characteristics of sites are being ignored. Furthermore, excessive costs in construction and operation of containment landfills necessitate that they are large scale operations (superdumps), with associated transfer facilities and transport costs, all of which add to overall waste management costs. Taken together with unpredictable post-closure maintenance and monitoring costs, possibly over several decades, the economics of the containment strategy becomes unsustainable. Such a high-cost, high-technology approach to landfill leachate management is generally beyond the financial and technological resources of the less wealthy nations, and places severe burdens on their economies. For instance, in third world countries with limited water resources, the need to preserve groundwater quality is paramount, so expensive containment strategies are adopted in the belief that they offer greatest protection to groundwater. A final indictment of the containment strategy is that in delaying degradation of waste, the present generations waste problems will be left for future generations to deal with.

More cost-effective landfill management strategies take advantage of the natural hydrogeological characteristics and attenuation properties of the subsurface. The 'dilute and disperse' strategy employs the natural sorption and ion exchange properties of clay minerals, and it has been shown that in appropriate situations it is effective in attenuating landfill leachate and preventing pollution of water resources. Operated at sites with thick clay overburden sequences, using a permeable cap to maximise rainfall infiltration and a leachate collection system to control leachate migration, 'dilute and disperse' is a viable leachate management strategy. Hydraulic traps are relatively common hydrogeological situations where groundwater flow is towards the landfill, so effectively suppressing outwards advective flow of leachate. This approach is also best employed with a clay liner, taking

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advantage of the attenuation properties of clays to combat diffusive flow of contaminants. These strategies are likely to guarantee greater protection of groundwater in the long term.

Keywords: Sustainability; Landfills; Containment; Liners; Leachate

1. Introduction

The concept of sustainability with respect to landfill management has been frequently propounded recently (e.g. Derham, 1995; Driessen et al., 1995). As with other environmental issues, the attainment of sustainability in the sphere of waste management has become the common aspiration of legislators, regulators, local government and the waste industry at large. Sustainability, however, is a somewhat nebulous term, often used with a less than complete understanding of its full import. In the context of landfills, it is here defined as '*the safe disposal of waste within a landfill, and its subsequent degradation to the inert state in the shortest possible time-span, by the most financially efficient method available, and with minimal damage to the environment*'. The critical clause of the above definition is the reference to degradation of the waste over the shortest possible time-span, as this not only controls the economics of the waste disposal process, but determines the potential for environmental accidents during the period of activity of the waste. Furthermore, from a purely moral standpoint it is important that this generations waste is rendered inactive as precipitously as possible, so that our waste problems are not left for future generations to deal with.

A sustainable waste management philosophy should encompass the following basic principles:

- Reduction in the generation of waste.
- Waste streaming at source.
- Recycling and reuse.
- Pre-treatment of waste to minimise quantity and volume.
- Landfilling of residual waste.
- Aftercare and rehabilitation of landfills after closure.
- Each generation to deal with all of its own generated wastes.

The latter two principles may be the most problematic, since realisation of both is dependent upon the rapid degradation of waste going to landfill. Current EU landfill management policies and legislation, favour the containment strategy of emission control as an environmental protection measure. However, this is an extremely expensive option which, as will be argued below, is likely to create more environmental problems in the long term, than it supposedly resolves in the short term.

Landfill is critical to most waste management strategies, because it is the simplest, cheapest and most cost-effective method of disposing of waste. In 1989, proportions of waste going to landfill, ranged from about 60% in OECD countries (Stanners and Bourdeau, 1995) to 100% in developing countries. Although in the future, waste minimisation and recycling programmes will reduce waste volumes, and other waste treatment options may be developed, at the end of the day landfills will still be required to accommodate residual wastes (Allen et al., 1997). In the developing world, a general lack of education and social and technological infrastructure mitigates against the initiation of waste reduction programmes or the development of alternative waste treatment options, thus ensuring that in these regions, for the foreseeable future, landfills will continue to be the major method of waste disposal (Allen, 1998).

In developing waste management policies, it is incumbent upon the richer nations to take cognisance of the resources of poorer nations so that universal standards can be applied that are within the technological and financial capabilities of the poorer nations. Pollution transcends national boundaries, and given the recent trend of economic groupings such as the EU to develop standard pollution control legislation, it would seem logical to attempt, where possible, to develop standards that, whilst being acceptable to the more developed nations, are relatively simple and inexpensive to implement, thus making them achievable by third world nations.

In the light of the foregoing, the trend of the more developed nations towards the containment strategy of landfill management, which embodies an expensive highly technological approach to the design and operation of landfills, is critically examined. Evidence and arguments are presented to suggest that this strategy cannot bring about sustainability in landfilling, but on the other hand could lead to serious future environmental degradation of the type that the landfill industry would seek to avoid.

2. The containment strategy

Current EU landfill regulations, now enacted into law by all member states, have made the installation of artificial lining systems and impermeable cappings mandatory for all landfills, except for sites possessing a suitable in situ low permeability ($<10^{-9}$ m s^{-1}) natural liner, which can also ensure complete containment of landfill emissions. Thus containment is now the only permissible landfill management strategy within the EU. Other landfill management strategies, such as hydraulic traps and 'dilute and disperse', which take advantage of the natural characteristics and properties of the subsurface, and which, in appropriate circumstances, could be developed and operated at a fraction of the cost of a containment landfill, will not in future even be considered by planners, since, under current legislation, they will no longer be granted a licence. Thus the EU has favoured, to the exclusion of all other strategies, an expensive purely technological approach to landfill management, at the expense of cheaper natural solutions.

The new EU regulations are based on the premise that artificial lining systems can wholly contain all leachate produced during degradation of landfill waste, and so provide complete protection to all groundwater, i.e. the concentrate and contain method of leachate control (Gray et al., 1974). However, due to unremitting leakage problems, the requirement to contain all leachate within the landfill, has necessitated the design of more and more elaborate liner systems, so that now it is standard to install composite two, three, or four layer multibarrier clay-membrane systems (Tchobanoglous et al., 1993; Cossu, 1994, 1995). These typically consist of sheets of synthetic membrane, most commonly high density polyethylene (HDPE), interlayered with clay mineral material, usually the smectite-rich bentonite or a bentonite-enriched soil (BES). Two layer systems consist of a sheet of HDPE overlying a 1 m thick mineral layer, three layer systems are composed of a 1 m thick mineral layer sandwiched between two sheets of the synthetic membrane, whilst four layer systems are represented by two sheets of membrane alternating with two 1 m thick mineral layers. Leak detection and leachate collection systems are also generally built into the lining designs. Daily covering of the waste with a clay-rich soil, in order to reduce wind-blown litter, odours, birds, vermin, flies and visual intrusion, is a further requirement. On closure of the landfill, an impermeable capping is installed to prevent infiltration of rainwater. The cap commonly consists of a sheet of flexible membrane such as HDPE, or a sufficiently thick layer of clay-rich soil with a permeability of at least 10^{-9} m s^{-1} (Cossu, 1995). A landfill gas collection system is usually installed immediately beneath the capping material, and completed cells are generally landscaped, to ensure that virtually all rainwater runs off the surface.

The effective functioning of such a complex containment system is dependent on the careful design and engineering of each site, strict quality control during installation of the liner system, excessive care during waste disposal operations, and high levels of maintenance throughout the operational life of the landfill. Thus the containment strategy employs a purely engineering solution to leachate management, representing a high cost technological approach, not only involving major expense in construction, but also costly levels of maintenance (Mather, 1995).

3. Flaws in the containment strategy

High levels of confidence have been accorded the containment principle of landfill management. Unfortunately, these may be severely misplaced. There are a number of fundamental flaws in the containment approach, some of which have serious long-term environmental implications, but which have tended to be either ignored or played down. The main problems are discussed below.

3.1. Durability of artificial liner systems

The long-term durability of artificial landfill liners is as yet unproven. Landfill waste degradation is a long-term process, and even under wet conditions, stabilisation of waste to an inert state ('final storage quality') has not occurred in most landfills 20 years after completion and capping (Belevi and Baccini, 1989). However, landfill liner systems have only been in use for about 30 years, so their long-term performance is uncertain. Thus, apart from the leakage problems, which have plagued them from the outset, and have led to the development of more and more complex lining systems, the uncertain long-term durability of these lining systems is of major concern.

Furthermore, numerous recent studies have drawn attention to some of the deficiencies associated with artificial lining systems, particularly the synthetic membranes. The behaviour of such synthetic materials (e.g. CPE, PVC, EPDM, PP and HDPE) subjected over long time-scales to the corrosive effects of leachate, and to the elevated temperatures generated by the exothermic processes operating within landfills, is extremely uncertain. The polymer membranes (e.g. HDPE) are generally regarded as being more chemically and biologically resistant than other synthetics (Cossu, 1995). However, HDPE membranes have been shown to be prone to stress cracking (Rollin et al., 1991; Thomas and Woods-DeSchepper, 1993) and are also known to crack under cold conditions (Thomas and Kolbasuk, 1995; Thomas et al., 1995). Nonwoven textiles such as PET and PP appear to be highly prone to ageing during exposure to the natural elements, leading to severe embrittlement (Cazzuffi et al., 1995), and PVC is known to degrade when exposed to gasoline products (Surmann, et al., 1995). Bituminous membranes (e.g. SPS) may also be sensitive to stress cracking, and have been shown to be subject to ageing, particularly at elevated temperatures (Duquennoi et al., 1995).

The synthetic membranes are also highly prone to damage (Artieres and Delmas, 1995; Colucci and Lavagnolo, 1995), particularly due to poor dumping practices, or failure of the membranes near welded seams (Surmann et al., 1995). Furthermore, extreme care and favourable weather conditions are essential during installation of these lining systems, because they are susceptible to failure if strict quality controls are not adhered to during installation (Averesch, 1995). Thus, apart from their high costs of purchase and installation, and the need for long-term maintenance, the durability of synthetic liners remains highly suspect.

Mineral layers within the liner system, typically consisting of bentonite clays, which are predominantly composed of expansive smectite group minerals, are usually situated below the synthetic membranes. Thus they are supposedly isolated from the landfill leachate. These layers necessitate emplacement and compaction at optimum moisture contents (Mundell and Bailey, 1985; Daniel, 1987; Majeski and Shackleford, 1997), and even if this is adhered to, they will tend to desiccate under the elevated temperatures generated within landfills. Indeed bentonitic mineral layers have been shown to be susceptible to severe dessication cracking due to inaccessibility of moisture (Meggyes et al., 1995; Holzlöhner and Ziegler, 1995), and elevated temperatures (Holzlöhner, 1994). Furthermore, in the event of failure or leakage of the synthetic membrane, chemical interaction between organic substances and bentonite lead to an increase in permeability (Fernandez and Quigley, 1985; Alther, 1987). Similarly, interaction between inorganic pollutants and smectitic clays in mineral liners can lead to cracking (Wagner, 1988), also increasing the permeability of the clay layers. Also, sorption of heavy metal ions within the intermediate layer of the smectite may result in the loss of swelling potential and plasticity as well as to significant volume changes in the smectite (Wagner, 1994). Joseph and Mather (1995) have further shown that the method of emplacement of the mineral liner in "lifts" can create horizontal migration pathways which can connect with vertical migration pathways of the desiccation type. Thus, in the event of failure of the synthetic membrane, the mineral layers in the lining system may have a significantly reduced potential to inhibit leachate migration.

Ultimately, the key to the containment method of leachate control, i.e. the effectiveness of composite artificial liner systems in preventing leachate migration from the landfill, will be almost solely dependent on the performance of the synthetic membrane member(s). It is unlikely that any synthetic membrane is completely free of defects (Christensen et al., 1994), regardless of quality control and, whilst leakage may be minimal initially, it is the long-term durability of the membrane(s) over periods of tens or possibly even hundreds of years, under conditions that are ultimately unpredictable, that leaves grounds for concern. In the light of the 'precautionary principle', the wisdom of placing such long-term reliance on an as yet unproven technology is short-sighted, and may ultimately be to our detriment.

3.2. Problems with clay liners

Clay liners are in common use, particularly in North America, but are employed solely with a containment function, permeability being the critical property, and attenuation properties being of little importance. Various types of clay liner have been experimented with (Farquhar, 1994), including in situ clay deposits; swelling clay (usually bentonite); sand-swelling clay mixtures (ranging up to 15% w/w bentonite); and remoulded and compacted clay. In situ clay deposits may not require remoulding and compaction provided large scale permeability is not adversely affected by weathering, root penetration or continuous inclusions of coarser materials (Williams, 1988; Quigley et al., 1988).

Bentonite or bentonite-bearing mixtures have been predominantly used as clay liners in the past. Bentonites are composed of the highly unstable smectite mineral montmorillonite, which has Na and Ca end-members, the former having the greater swelling potential and higher activity (Velde, 1992; Cancelli et al., 1994). Replacement of Na in the montmorillonite by Ca, due to reaction with MSW leachate, results in shrinkage of the clay, development of cracks, increased permeability and lower activity (Hoeks et al., 1987; Madsen and Mitchell, 1989)). The extent to which this occurs, depends on the degree of incompatibility between the clay liner and the leachate (Farquhar and Parker, 1989), which will be a function of the leachate composition and the Na:Ca ratio of the montmorillonite. For instance, European bentonites with greater substitution of Ca and Mg as opposed to Na are less susceptible to Na replacement, and thus less prone to shrinkage and increase in permeability (Hoeks et al., 1987; Madsen and Mitchell, 1989). Furthermore, hydraulic conductivities of the same sand-bentonite mixture have been shown to be two orders of magnitude higher for leachate than for water (Hoeks et al., 1987). Thus, bentonite and sand-bentonite liners appear not to perform a containment function well in the longer term.

Compacted clay liners consisting mainly of non-swelling clays do not suffer to a major extent from the problem of reaction with MSW landfill leachate, provided the swelling clay content is kept to a minimum (Gordon, 1987; Farquhar and Parker, 1989). In fact liner permeability often decreases with time due to sealing by precipitate formation, solids accumulation and biomass growth along the upper surface of the liner and into any pre-existing cracks and fissures (Quigley and Rowe, 1986; Daniel, 1987; Farquhar and Parker, 1989). So compacted liners are the most versatile type of clay liner as far as containment is concerned.

However, as indicated earlier, hydraulic conductivity of clay liners is critically dependent on moisture content and degree of compaction. The nature of this dependence is an increased density with compaction effort and also a non-linear dependence of density on moisture content resulting in an optimum moisture content to produce maximum density (Farquhar, 1994). This dependence is specific to the clay mixture being tested, and cannot be applied to other soils, so equivalent data sets must be generated for each liner material being considered. Thus, in order to comply with hydraulic conductivity specifications in landfill design regulations, each liner must be rigorously tested, with placement necessitating optimum weather conditions, standardised compaction effort, strictly controlled moisture content and very careful compaction techniques. Adverse weather conditions, which delay completion of the placement process can have serious ramifications in terms of liner performance. Overall, regardless of whether an in situ or cheap local source of clay is available, the testing and correct installation of clay liners performing a containment function is costly.

Furthermore, field testing of the hydraulic conductivity of clay liners is notoriously difficult to perform, and laboratory test values do not correlate well with field values, often being of the order of one to two orders of magnitude less than field measurements (Daniel, 1987; Williams, 1988). This primarily stems from the high hydraulic gradients of several hundred under which laboratory test are performed, compared with normal field hydraulic gradients of less than 1.0. Such high gradients generate unnatural flow conditions, which adversely affect hydraulic conductivity leading to errors (Quigley et al., 1988). Other problems with laboratory tests are the size of the samples, which are insufficiently large to account for field heterogeneities such as cracks, or their insufficient duration to account for long term interactions between the liner and the leachate (Farquhar, 1994). The only correct hydraulic conductivity is that exhibited by the liner in place, determined by seepage measurements in the field using large-scale infiltrometers. However, these are expensive and take several months to complete.

Thus, natural clay liners, whilst probably more durable and certainly cheaper and more environmentally friendly than synthetic liners, may not perform a purely containment function as adequately as might be hoped over the longer term, due to problems of chemical interaction with leachate, difficulties in placement and in precise determination of hydraulic conductivity. However, in the event of failure of clay liners, attenuation properties of the clays can mediate, to a greater or lesser extent, groundwater contamination by the leachate.

Furthermore, it has now been recognised that the dominant mechanism of contaminant migration may be diffusion and not advection, (Rowe, 1994b). Consequently, and this applies both to synthetic and natural materials, even if the liner system performs to expectation, and leakage is minimal, migration of contaminants through the liner by diffusive processes, may still occur. Therefore, complete containment of all contaminants emitted by landfill waste may be a fallacy. However, migration of contaminants through natural clay liners may be mitigated by the attenuation properties of the clays.

3.3. Unsuitability of sites

As a consequence of the over-reliance placed in liner technology, frequently little attention is paid to local geological/hydrogeological conditions in the choice of sites for landfills. Indeed, not only are the most suitable sites from a geological/hydrogeological perspective ignored, but often sites are selected regardless of negative geological factors. In fact, misplaced trust in the containment concept is so absolute, that the geological/hydrogeological characteristics of any proposed site are generally seen as no more than the basis for an elaborate engineering plan, based on the attitude that any site can be engineered for landfilling (O'Sullivan, 1995).

For example, landfills are frequently sited in pre-excavated holes such as quarries and gravel pits, chosen because a hole already exists, thus reducing the cost of site development. Rocks forming the floors and sides of quarries are typically highly fractured due to blasting operations, so generally present little barrier to leachate migration. Similarly, gravel provides little natural attenuation to migrating leachate. In such quarry sites, the lining system is often placed almost directly against the bedrock, commonly with only a very minimal thickness layer of gravel or soil beneath it, primarily as protection for the liner. Quarry sites selected may even be filled with water, and thus must be temporarily drained to lower the local water table in order to install the lining system and emplace the refuse.

At one such site in Ireland, bedrock of highly karstified limestone, is first quarried for road metal down to the level of the water table, creating a hole which is then lined and used as a landfill site. The site is coastal, occupying part of a small peninsula, which juts into a tidal lagoon, the mudflats of which are used for oyster farming. The limestone bedrock forms part of a major limestone syncline, representing an important regional aquifer. Not only is there the potential to pollute an ecologically sensitive area, in the event of leakage or liner failure, but widespread contamination of groundwater in this regionally important aquifer is also a serious risk. However, although from a geological/hydrogeological perspective it represents the worst possible scenario, the site is generally regarded as a very satisfactory site on the basis that, because of its seclusion, it has attracted little local opposition apart from the owner of the oyster farm.

The fact that, at this and many other such sites, there is no underlying geological barrier to control leachate migration in order to give secondary protection to the groundwater in the event of liner failure seems to have been of little importance in selecting the site. Indeed at some sites, overburden with a high attenuation potential has been stripped away during site development. Clearly the need for a secondary natural geological barrier to leachate migration is regarded as unnecessary, thus placing total reliance on artificial lining systems. In view of the leakage problems and uncertainties as to the long-term durability of artificial liners outlined above, this represents at best a naïve and somewhat ill-advised trust in such liners.

3.4. Impact on landfill waste degradation rates

Encapsulation of waste inhibits waste degradation and considerably prolongs the activity of the waste. The most critical flaw in the current containment landfill ethos, is the misconception that encapsulation of landfill waste within artificial liner systems will, by minimising leachate and gas production, protect the environment (Joseph and Mather, 1993). In fact the opposite is more likely to be the case. By isolating the waste from the natural agents of degradation, particularly water (i.e. keeping the waste dry), rates of degradation within the waste will be minimised, thereby prolonging the activity of the waste and inhibiting its stabilisation to an inert state. Stabilisation of waste results from degradation processes which, whether they occur over a period of decades or centuries, involve the production of the same amount of leachate and gas (Joseph and Mather, 1995). Permanently isolating the waste, with the resultant long-term threat to the environment, will necessitate an infinite period of monitoring (Carter, 1993; Stegmann, 1995). Furthermore, prevention of rainwater infiltration, designed to minimise the production of leachate, leads to the generation of a highly concentrated, toxic leachate, which in contact with the artificial membrane over a long time-span, may have an extremely corrosive effect on the membrane, leading to its degradation.

It is clear that there is a fundamental flaw in the reasoning that has led to the current landfill legislation. On the one hand, encapsulation of waste in landfills within artificial lining systems reduces the potential for environmental pollution by leachate in the short and medium term. On the other hand, however, minimisation of the production of leachate resulting from the 'dry entombment' of the waste, inhibits its degradation, delaying its stabilisation to an inert state. Given the uncertainty regarding the durability of artificial lining systems over a long time-span, it also increases the potential for environmental pollution in the long term.

Recognition of this paradox has led to the concept of accelerated waste decomposition (AWD) (Harris et al., 1994) by enhancement of microbial degradation processes — the 'bio-reactor landfill' concept (Campbell, 1992; Blakey et al., 1995). Microbial communities are complex and only poorly understood and, given the heterogeneity of waste and the variety of environmental conditions which exist within landfills, it is not surprising that there is much uncertainty regarding microbiological processes and the optimal conditions for their enhancement. It would appear unlikely that control of microbial processes within landfills can be achieved within the foreseeable future, for the 'bio-reactor landfill' concept to become a reality (Blakey et al., 1995).

What has become clear from waste degradation research, is the critical importance of moisture content in promoting microbial activity. In order to increase moisture content, some method of periodic flushing of the waste with water, referred to as 'below cap irrigation', must be accomplished, one solution being recirculation of leachate (Barber and Maris, 1984). This, however, requires installation of sophisticated below cap irrigation systems, and problems of efficiency of recirculation remain. It seems somewhat ludicrous that on the one hand ingress of rainwater to the waste is inhibited by capping, whilst on the other expensive below cap irrigation systems must be built into the landfill design to accomplish what could be achieved naturally.

3.5. Aftercare

Long term post-closure maintenance and monitoring of landfills may be financially unacceptable. The new EU regulations and national legislation of member states holds landfill operators responsible for aftercare and monitoring of landfills after completion and capping, and require the license holders to post bonds to cover financial aspects of the discharge of their responsibilities under the terms of the license. Furthermore, the licensee will not be able to surrender the license until the regulatory agency is satisfied that the facility concerned is not causing, and is unlikely to cause future environmental pollution. This aspect of landfill regulations has major implications for landfill operators, in that the landfill operators, be they local authorities or private contractors, will be responsible for the landfill for as long as the waste is active and has a potential to cause pollution. Thus a scenario of long-term, largely unpredictable, maintenance and monitoring costs following completion and capping of the landfill (after revenue earnings have ceased) looms for landfill operators

(Mather, 1995). It therefore becomes incumbent on landfill operators to ensure that the rate of degradation of waste in landfills is optimised in order to reduce the time-scale of their liability.

The threat of long-term liability also has serious implications both for landfill operators and regulatory agencies. Should the liner system fail before the waste is stabilised to an inert state, leading to leachate or gas migration and environmental pollution, then under the 'polluter pays' principle, the landfill operator will be liable. The economic ramifications of this for landfill operators, given the unpredictability of the costs of mitigation of environmental damage possibly decades into the future, would seem an unacceptable risk, regardless of long-term liability insurance cover. Furthermore, legal difficulties in enforcing such a principle several decades or even centuries into the future, may be daunting, and pose a major problem for regulatory agencies.

3.6. Financial and social costs

The containment strategy employs a costly high technology engineering solution, which puts severe constraints on the economics of the landfill operation. Because of the high cost of preparation of the site and purchase and installation of the lining system, it has become uneconomic to develop small landfills, and the trend is now towards huge superdumps serving large catchment areas. Due to their remoteness from the source of much of the waste arising, these superdumps generate further costs, as waste has to be transported often over great distances, with the inevitable pressure on road networks and the potential for en route traffic accidents and waste spillages. In order to reduce the volumes of waste being transported, construction of a series of transfer stations where waste is compressed and baled, are an essential additional component of the superdump landfill management strategy. All of this adds to the overall costs of the landfilling operation.

Furthermore, local communities typically feel threatened by such superdumps, which generates intense resistance to the siting of such dumps (the NIMBY syndrome), compounded by the fact that little of the waste is of local origin. This invariably gives rise to an adversarial and often acrimonious relationship between advocates and opponents of any given superdump, leading to costly review and licensing procedures, commonly involving court proceedings. The loss of social harmony within communities confronted by the prospect of a superdump in their backyard is a cost that cannot be quantified.

The hugely increased costs associated with the use of artificial lining systems as opposed to in situ natural liners is illustrated by the case of a small landfill in the south-west of Ireland. Ballygyroe in north County Cork is situated upon 21–30 m of very low permeability red lateritic clay (1×10^{-9} m s^{-1}), representing a tropical weathering profile, which overlies Old Red Sandstone bedrock. Opened in 1990, following a court order to close the existing landfill, as a stop gap measure whilst the most suitable site in this administrative district was sought, this landfill was initially operated employing a cellular system using the in situ overburden as a natural clay liner, at a cost of IR£ 100,000 per annum.

Eventually it was concluded that this was the best site available, and a licence was subsequently sought from the Irish EPA which, despite the geological evidence of the suitability of the natural clay overburden as a liner, insisted on the installation of an artificial lining system. A cellular system is still in operation, but the cells have had to be increased in size, and slopes considerably reduced in order to accommodate the lining system, with significant loss of landfilling space. The annual cost of operation of the landfill is now in excess of IR£ 1,000,000, a tenfold increase. Sadly, this landfill, an example of an optimum natural landfill site, and probably the best site in Ireland, is to close due to an injunction obtained by opponents, but it would inevitably have been forced to close anyway, as the operational costs make it uneconomic to run, given that the largely rural area it serves, supports a rather sparse population of only 70,000. A further negative impact of the increased costs of operation of the Ballygyroe landfill, is that high charges of IR£ 300 per truck load of refuse, now levied to private refuse collectors or private individuals delivering waste to the landfill, is likely to have the effect of encouraging illegal dumping.

3.7. Impact on third world economies

A frequently unappreciated ramification of current waste management policies is their impact on third world economies. The high technology containment strategy embraced by the richer western nations is generally beyond the financial and technological resources of poorer nations. Given the difference in operational costs in installing an artificial liner as opposed to using a natural geological barrier, as illustrated above, the promotion by the EU and other western nations, of a containment strategy based on artificial lining systems, must have a profoundly detrimental impact on the economies of poorer developing countries, placing unnecessary demands on their very limited financial resources.

Groundwater is a critical resource to many third world nations, particularly those with arid climates and thus limited surface water supplies. In addition, poor sanitation infrastructure in many third world countries tends to make surface waters particularly prone to pollution, so groundwater may be the only reliable source of good quality drinking water. The need to preserve the quality of groundwater is a strong motivation to third world nations to follow a landfill management policy which gives greatest protection to groundwater from contamination by landfill leachate. That third world governments are misled into believing that the expensive containment strategy is the safest, most cost-effective approach, is an indictment on western self-interest, since it is the western nations who mainly manufacture and supply the expensive landfill lining systems.

In at least one developing nation, South Africa, opposition to unlined landfills has arisen, due to the mistaken belief that since the richer western nations are pursuing this approach, then it must be the best available technology, i.e. the BATNEEC principle. This is an unfortunate development, because there is a strong likelihood that most third world nations possess numerous sites, which have adequate geological/hydrogeological characteristics to enable the pursuit of landfill management strategies that make use of the natural attributes of the site. In the more overcrowded nations of Western Europe, the shortage of sites with adequate natural geological barriers may, in many instances, make the use of landfill liners an unavoidable necessity. On the other hand, in developing countries with less infrastructure, it is probable that there exist numerous sites with suitable natural liners, both for containment or 'dilute and disperse', or sites with natural hydraulic traps. Identification of such sites will allow developing nations to pursue more cost-effective landfill management strategies, and western technology would perhaps be better channelled into supporting the achievement of such aims.

3.8. Failure of this generation to deal with all its generated waste

The most serious ramification of the current containment policy of landfill management is that the present generations waste problems will be left for the next generation to deal with. A fundamental consequence of encapsulating landfill waste and significantly reducing the degradation rate, is that this generations waste will still be active and posing problems certainly for the next generation, and even perhaps for several future generations. Given that future waste production is unlikely to decrease, and waste management problems are also unlikely to diminish, it seems morally indefensible that, in addition to having to deal with their own waste problems, future generations may have to deal with waste problems created by this generation.

4. Alternative natural landfill management strategies

Natural solutions, which employ the hydrogeological characteristics of the subsurface and the attenuation properties of subsurface materials, are totally ignored in current landfill management strategies. Indeed, as indicated above, no provisions have been made in EU regulations for landfill management strategies other than containment, and in fact the current legislation for most member nations based on these regulations prohibits other strategies. The advantage of using natural in situ geological/hydrogeological barriers is that the natural infiltration and percolation characteristics of the subsurface are not disrupted, and little or no maintenance costs are involved. Such natural barriers do not encapsulate waste and inhibit its degradation, provided the natural characteristics of the barrier are appropriately employed. Two types of natural leachate management solution are available, namely 'dilute and disperse' and hydraulic traps.

4.1. Dilute and disperse

The 'dilute and disperse' principle of leachate management, defined by Gray et al. (1974), has been largely superseded by the containment strategy. It relies both on the natural low permeability and also the attenuation characteristics of geological barriers in the subsurface to control groundwater pollution by landfill leachate. This method of leachate management employs the natural confinement potential of primarily low permeability clay-rich overburden and, to a lesser extent, bedrock to impede the migration of leachate from the landfill, whilst at the same time attenuating and purifying it by processes of filtration, sorption and ion exchange. Such natural processes are in continuous and effective operation in the purification of groundwater, which under normal circumstances requires no treatment for use as household water supply.

The dilute and disperse principle has been militated against by current legislation that requires all leachate emanating from the landfill to be collected and treated (Mather, 1995). These regulations have been introduced despite the fact that field and laboratory studies (e.g. DOE, 1978), have highlighted the effectiveness of natural processes in attenuating leachate concentrations. The conclusion reached was that, in appropriate situations, the dilute and disperse method would be effective enough to prevent the pollution of water resources, and could be used as a leachate management strategy. More recent studies (Warith and Yong, 1991; Batchelder and Mather, 1998; Batchelder et al, 1998) have confirmed the capacity of clay-rich overburden and mudrocks to attenuate leachate. The dilute and disperse principle of leachate control has been unfairly maligned, much of the criticism being that it represents no control whatsoever and relies on, largely unknown, subsurface characteristics at any individual site. However, failure of this approach has stemmed largely from the fact that at numerous landfill sites where the strategy was employed, no adequate geological/hydrogeological investigation was undertaken. Thus, many selected sites were totally inappropriate for this method of leachate management, due to the absence of a suitable geological barrier to attenuate the leachate.

Natural geological barriers, may be defined as low permeability clay-rich geological units (hydraulic conductivity $<10^{-7}$ m s^{-1}), which can perform the function of an attenuating layer, enabling leachate to percolate slowly downwards, simultaneously undergoing attenuation by filtration, sorption and exchange processes with the clays in the unit. Extremely low permeability geological units (hydraulic conductivity $<10^{-9}$ m s^{-1}) cannot fulfil a 'dilute and disperse' function, as they perform in a similar manner to artificial or natural lining systems, providing complete containment of all emissions. Similarly, geological units with higher permeability (hydraulic conductivity $>10^{-7}$ m s^{-1}), do not provide sufficient confinement to leachate, so are also unsuitable for a 'dilute and disperse' role. The optimum permeability for 'dilute and disperse' is of the order of 10^{-7}–10^{-9} m s^{-1}, although in situ geological units just outside that range, could have their hydraulic conductivity modified by addition of fine sand in the case of extremely low permeability natural units, or clay in the case of higher permeability units. In most instances, it would probably be necessary to partially excavate the natural barrier layer in order to remove stones, homogenise it and remould it, and any modification of hydraulic conductivity by addition of sand or clay could be undertaken prior to re-emplacement.

The suitability of any individual barrier layer for 'dilute and disperse' is a function not only of its permeability, but also of its attenuation potential, which is dependent principally on the proportion of clay minerals and iron and manganese oxides present in the deposit, and also the types of clay minerals present, due to the variable sorption and cation exchange capacities (CEC) of the various clay mineral groups. Of the major clay mineral groups, the least activity (sorptive capacity) and also the lowest CEC are possessed by the kandites. The illites have higher activities and CEC, followed by the sepiolite-palygorskites, followed by the vermiculites, whilst the smectites have the highest CEC and sorptive capacities due to their ability both to adsorb ions on to their external surfaces and also to absorb ions between their lattice sheets (Velde, 1992). Interactions between leachate and clay liners include ion exchange, adsorption–desorption, particle size reduction, mineral dissolution and clay mineral disordering and collapse (Batchelder and Mather, 1998; Warith and Yong, 1991). High swelling clays such as the smectites are more prone to mineral transformations and collapse than mixed clay mineral assemblages and the low swelling illite and kaolinite clay groups (Batchelder and Mather, 1998). Furthermore, clay-rich overburden and mudrock, can buffer acid leachates, leading to precipitation of heavy metals (Batchelder et al, 1998), which displace Na^+, Ca^{2+} and Mg^{2+} on clay mineral surfaces by cation exchange mechanisms (Mohamed et al, 1994).

If improvement of the attenuation characteristics of the barrier layer is necessitated, options may be intermixture with local clay-rich material or enhancement with imported bentonite. However, although the montmorillonite component in bentonite has the highest sorption and CEC of the common clay minerals (Velde, 1992; Cancelli et al., 1994), employment of bentonite-based mineral layers in artificial lining systems is not based on these properties, but rather, as has been pointed out earlier, on its very high swelling capacity.

The minimum thickness requirement of an attenuating layer should be dependent on its hydraulic conductivity, so that provided the attenuation potential of the layer was sufficiently high, the limiting permeability could be related to layer thickness. In order to ensure that a geological barrier would, on its own, give sufficient protection to the environment, stringent geotechnical requirements regarding the nature, thickness, hydraulic conductivity and attenuation potential of the barrier would need to be specified. Furthermore, rigorous site investigation and field and laboratory testing of the permeability and attenuation properties of the geological unit would be a primary requirement of any application for a landfill licence.

Wagner (1994) has introduced the concept of a double mineral base layer (DMBL). This consists of an 'active' layer with a high content of highly active smectite clays (bentonite) and/or carbonate, performing an attenuation function through processes of sorption and ion exchange, above an 'inactive' layer composed predominantly of more stable clay minerals such as kaolinite, which performs a confinement function, but undergoes minimal reaction with the leachate. The presence of the inactive layer beneath the attenuation layer impedes downward movement of leachate maximising the reaction time between the active layer and the leachate. As pointed out by Wagner (1994), this arrangement may represent a better option than a single attenuating layer, as the two functions of confinement and attenuation may be mutually exclusive, since the sorption and ion exchange processes in clays lead to a gradual reduction in swelling capacity and consequent increase in permeability. The two layers could be developed simultaneously from natural in situ clay deposits, by excavation of the natural material, separation of the excavated soil into two piles and treatment of them separately, adding kaolinite to one to create the inactive confining layer, and smectite to the other to form the active attenuation layer. Organic material could also be added to the active layer to enhance its sorption/ion exchange properties and so improve its attenuation potential. Care would be required in placement of the inactive layer to ensure a suitably low hydraulic conductivity, whereas the hydraulic conductivity of the active layer would not be so critical. Such a DMBL liner design could represent a type of 'dilute and disperse' leachate management solution, provided the hydraulic conductivity of the inactive layer was sufficient to allow slow migration through it of the attenuated leachate leaving the active layer.

More rapid stabilisation of waste in such 'dilute and disperse' landfills could be achieved by allowing unrestricted ingress of rainwater into the waste, thus promoting biochemical and microbial degradation processes. In addition a more dilute and therefore less toxic leachate will be produced. Therefore it would be highly advantageous if the capping consisted of a permeable material, whilst pretreatment of the waste by shredding could improve rainwater percolation and access to the waste.

The main danger of uncontrolled rainfall infiltration into the landfill is the build up of leachate head, particularly after periods of heavy rainfall. This would increase the rate of leachate migration through the attenuation clay layer below the landfill, and potentially lead to hydraulic failure of the attenuating layer and resulting groundwater pollution. The solution to this problem is to install an efficient drainage and leachate collection system above the attenuating layer, which could control the leachate head in order to prevent shock loading of the receiving environment. The collected leachate could be stored in leachate ponds and recirculated to the landfill surface during periods when the leachate head is low, so that the leachate collection system would perform the

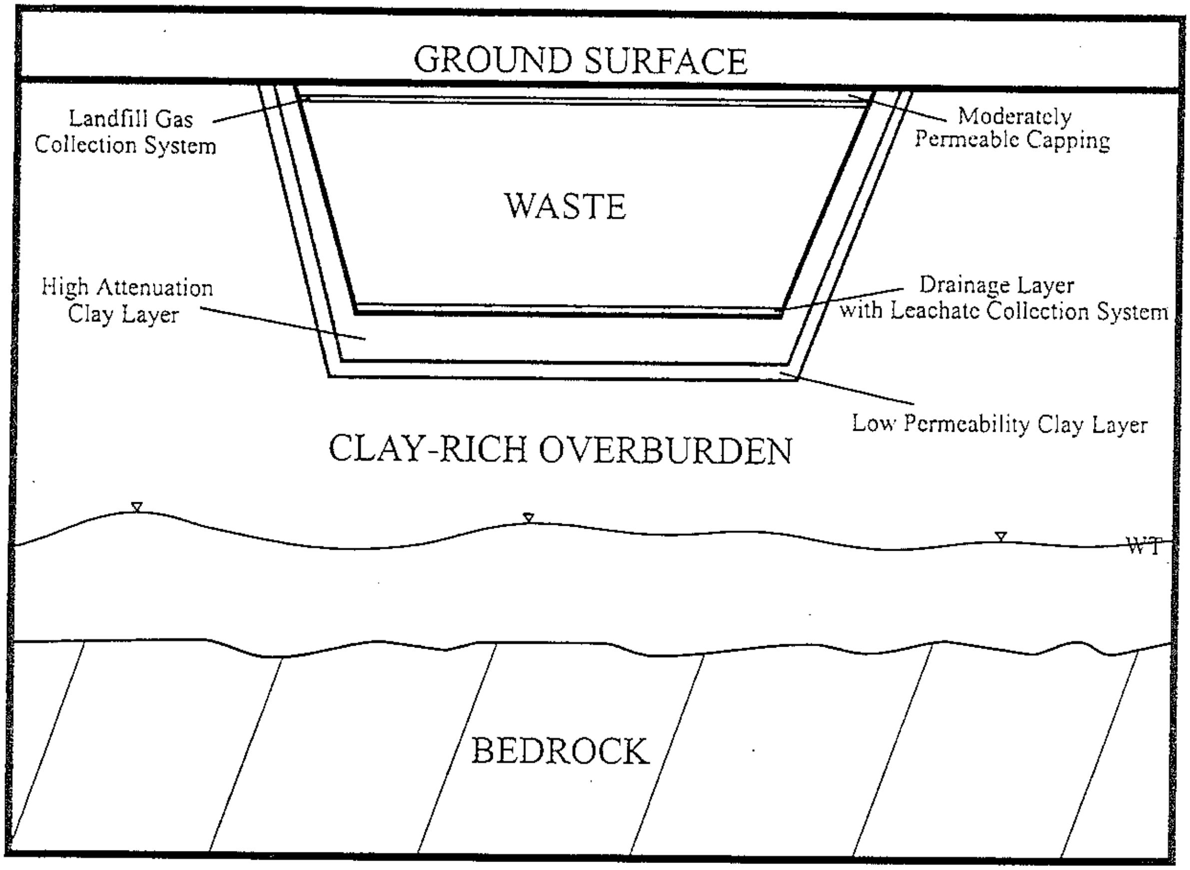

Fig. 1. Attenuation landfill with double mineral base layer (DMBL), consisting of a kaolinite-enriched 'inactive' clay layer overlain by a smectite-enriched 'active' clay layer. A drainage layer with a leachate collection system to control the rate of leachate migration overlies the DMBL, to prevent shock loading of the DMBL. A landfill gas collection layer overlies the waste and the capping consists of moderately permeable soil to allow ingress of rainwater.

function of controlling the rate of leachate migration from the landfill. The final mass release to the sensitive environment should be at a rate which gives rise to no hazard and does not cause unacceptable damage to the environment (Knox, 1989). Fig. 1 depicts a simplified schematic diagram of the elements of an attenuation landfill.

4.2. Hydraulic traps

Hydraulic traps, the other type of natural solution, are hydrogeological situations where, instead of leachate migrating outwards from the landfill into the surrounding subsurface, the groundwater surrounding the landfill migrates into the landfill. This reversal of the migration path not only suppresses outwards advective flow of leachate from the landfill, but the addition of ingressing groundwater to the leachate produced within the landfill dilutes it, rendering it less harmful. It is necessary to collect the diluted leachate and dispose of it, otherwise the build-up of leachate plus ingressed groundwater would ultimately overtop the landfill.

Natural hydraulic traps are quite common and usually associated with hollows, often containing lakes or swamps. It is also possible to artificially create a hydraulic trap, by siting the landfill within a pit excavated in the subsurface to a depth below that of the local water table, and controlling the leachate head within the landfill, so as to maintain it at a lower level than that of the water table in the surrounding ground. This creates a negative hydraulic head

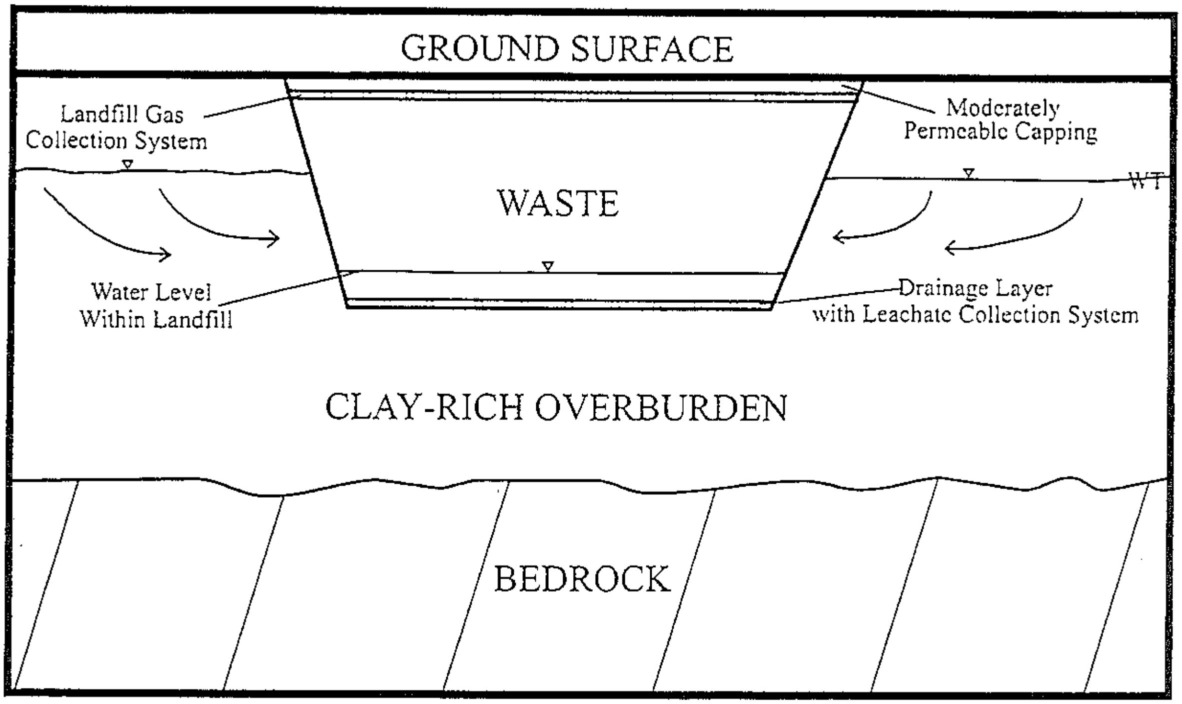

Fig. 2. Hydraulic trap landfill excavated to below the local water table within low permeability clay-rich overburden. Groundwater migrates towards the landfill, and the water level within the waste is maintained at a lower level than the local water table by the leachate collection system. The landfill gas collection system and the capping are similar to that for the attenuation landfill.

towards the landfill, which thus acts as a sump towards which groundwater will migrate, so counteracting leachate migration from the landfill. Water-filled quarries represent examples of holes below groundwater level, but the permeability of the surrounding rocks make this type of hydraulic trap unsatisfactory, since they must be drained to enable waste to be emplaced, temporarily lowering the local water table. During this period, leachate can migrate outwards into the surrounding groundwater.

Most landfills employing hydraulic traps, be they natural or artificially created (Rowe, 1988), are lined with a synthetic lining system, so no cost benefit is derived from the hydraulic trap. Whilst lining may be advantageous to reduce ingress of groundwater from the surroundings during emplacement of the waste, the whole advantage of the hydraulic trap is that leachate cannot migrate outwards regardless of whether the landfill is lined or not, so lining the landfill renders the hydraulic trap superfluous. Clay-rich overburden would behave as a natural barrier to groundwater movement, impeding ingress of groundwater during waste emplacement activities, but still allow operation of the hydraulic trap, both during the operational phase of the landfill, and after waste emplacement has ceased.

Although the negative hydraulic head induced by a hydraulic trap suppresses advective flow of leachate from the landfill, diffusional flow may, in response to a concentration gradient, result in migration of contaminants outwards from the landfill against the hydraulic gradient (Barone et al., 1989). Furthermore, Rowe (1994a) has pointed out that diffusion of contaminant can even take place through synthetic landfill liner membranes. However, the clay layers in the lining system have the potential to attenuate contaminants, provided they are of sufficient thickness. Natural clay-rich overburden will also perform an attenuating role with respect to diffusing contaminants, and will be much more effective in this regard than an artificial lining system. Thus an artificial liner system gives no added protection in a hydraulic trap situation, and is less suitable than a natural clay-rich geological barrier. Fig. 2 illustrates the elements of a hydraulic trap landfill.

5. Conclusions

Flaws in the current containment strategy, outlined above, are:

- leakage problems and major uncertainties as to the long-term durability of synthetic landfill lining systems;
- chemical interaction of many clay liners, particularly bentonite liners, with landfill leachate, leading to an increase in hydraulic conductivity with time.
- the inability of either synthetic or natural liners to suppress diffusive transport of contaminants which, rather than advection, is the dominant contaminant transport mechanism
- the total reliance placed on the lining system, with little account taken of geological/hydrogeological characteristics of sites being selected, and commonly no secondary geological barrier to protect groundwater in the event of liner failure;
- encapsulation of waste in a synthetic lining/capping system, so inhibiting waste degradation and thus prolonging the activity of the waste, possibly for many decades;
- the financial burden of long-term, post-closure maintenance and monitoring of landfills;
- the failure to take advantage of natural hydrogeological solutions to leachate migration, or the natural filtration, sorption and ion exchange properties of clay-rich overburden in order to attenuate leachate;
- excessive costs in development and operation of containment landfills, making the whole strategy uneconomic and financially unsustainable;
- the unsuitability of such a high-technology, high-cost waste management strategy to the financial and technological resources of the less developed third world nations;
- the present generations waste problems being left for future generations to deal with.

The alternative landfill strategies can be represented as, on the one hand, high technology solutions offering favourable short-term protection to the environment, but less certainty of long-term protection, possibly resulting in serious environmental pollution in the long-term, as opposed to natural solutions, which offer possibly less guarantee of environmental protection in the short term, but less likelihood of serious long-term environmental pollution. Earth scientists (e.g. Mather, 1995; Allen, 1998) favour the latter approach, whereas the engineering community, in the belief that an engineering solution is superior to a natural approach, have promoted the current policy — which is being followed without due regard to long-term cost or environmental impact.

The containment strategy employs a purely technological approach to the management of leachate, ignoring the potential of natural solutions based on the confinement and attenuation properties of the subsurface. High technology engineering solutions to pollution control are usually expensive and rarely completely successful, and frequently have negative impacts, the tendency being that the more sophisticated the solution, the greater the cost and maintenance that they entail (Mather, 1995). A much more sensible and cost effective approach typically involves some form of enhancement of natural processes by the integration of a cheap, simple technology.

The containment approach has led to increasingly more complex technologies being applied to overcome each succeeding problem. The fundamental flaw in the strategy is that dry entombment of waste inhibits its degradation, so prolonging the activity of the waste and delaying, possibly for several decades, its stabilisation to an inert state. Given the uncertainty regarding the durability of artificial lining systems over long timespans, the potential for environmental pollution in the long term is significant. Furthermore the costs of construction and operation of containment landfills are excessive, and the post-closure maintenance and monitoring costs are ultimately unpredictable. If a universal approach to pollution control is to be adopted, a strategy relying on complex technologies, beyond the financial and technological resources of the less advanced nations, is unlikely to succeed.

Landfill management options are curtailed by the inflexibility of the current EU landfill regulations and national legislation of member states, which not only makes a containment approach mandatory to the exclusion of all other strategies, but militates against the use of natural geological liners in the form of clay-rich overburden. The current legislation reflects the triumph of the engineering solution over the natural solution in landfill management strategies and represents an extreme approach to the protection of groundwater.

Finally, it should be pointed out that the current regulations render protection of all groundwater as a mandatory requirement, regardless of whether the groundwater being protected constitutes a material resource or not. Not all groundwater can be regarded as a substantive resource, since a real resource only exists where it is readily available and extractable in sufficient quantity at an acceptable cost. Groundwater only constitutes a resource provided the porosity and hydraulic conductivity of the subsurface are sufficient to provide an adequate supply at a sufficient yield for the purpose for which the groundwater is being sought, which at the lowest common denominator could represent the household supply to a single dwelling. Commonly, subsurface characteristics do not fulfil these requirements, so in many areas groundwater cannot be regarded as a resource. If the groundwater does not constitute a resource, then protection of such groundwater becomes a very costly and futile exercise.

In the light of the foregoing, the conclusion that must be reached, is that many of the problems associated with containment are insurmountable, and that the containment strategy and sustainability in landfilling are incompatible. It is therefore hard to conceive of sustainability in landfilling ever being achieved via the containment approach, and conversely it can be argued that if sustainability is to be attained, the containment strategy becomes untenable.

References

Allen, A.R., 1998. Sustainability in landfilling: containment versus dilute and disperse. In: Moore, D.P., Hungr, O. (Eds.), Engineering Geology: A Global View from the Pacific Rim. 8th Congress of the International Association of Engineering Geologists, Vancouver, Canada, vol. IV, pp. 2423–2431.

Allen, A.R., Dillon, A.M., O'Brien, M., 1997. Approaches to landfill site selection in Ireland. In: Marinos, P.G., Koukis, G.C., Tsiambaos, G.C., Stournaras, G.C. (Eds.), Engineering Geology and the Environment. Balkema, Rotterdam, pp. 1569–1574.

Alther, G.R., 1987. The qualification of bentonite as a soil sealant. Engng. Geol. 23, 177–191.

Artieres, O., Delmas, P., 1995. Puncture resistance of geotextile-geomembrane lining systems. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, pp. 213–224.

Averesch, U., 1995. Specific problems in the construction of composite landfill liner systems. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, pp. 115–130.

Barber, C., Maris, P.J., 1984. Recirculation of leachate as a landfill management option: benefits and operational problems. Q. J. Engng. Geol. Lond. 17, 19–29.

Barone, F.S., Yanful, E.K., Quigley, R.M., Rowe, R.K., 1989. Effect of multiple contaminant migration on diffusion and adsorption of some domestic waste contaminants in natural clayey soil. Can. Geotech. J. 26, 189–198.

Batchelder, M., Mather, J.D., 1998. Mineralogical and chemical changes in mineral liners in contact with landfill leachate. Waste Manag. Res. 16, 411–420.

Batchelder, M., Mather, J.D., Joseph, J.B., 1998. The stability of the Oxford Clay as a mineral liner for landfill. J. Chart. Inst. Water Environ. Manag. 12, 92–97.

Belevi, H., Baccini, P., 1989. Long-term assessment of leachates from municipal solid waste landfills. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 89, Second International Landfill Symposium, Porto Conte, Sardinia, p. 8.

Blakey, N., Archer, D., Reynolds, P., 1995. Bioreactor landfill: a microbiological review. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 1. CISA, Cagliari, pp. 97–116.

Campbell, D.J.V., 1992. Implications of site design and operational factors on the optimisation of landfills as bioreactors. Biowaste 92, Copenhagen, 9 pp.

Cancelli, A., Cossu, R., Malpei, F., Offredi, A., 1994. Effects of leachate on sand-bentonite mixtures. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Landfilling of Waste: Barriers. E & FN Spon, London, pp. 259–293.

Carter, M.J., 1993. The impact of landfill on groundwater. In Second Annual Groundwater Pollution Conference, London: IBC Technical Services, 15 pp.

Cazzuffi, D., Corbett, S., Rimoldi, P., 1995. Compressive creep test and inclined plane test for geosynthetics in landfills. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, pp. 477–491.

Christensen, T.H., Cossu, R., Stegmann, R., 1994. Principles of landfill barrier systems. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Landfilling of Waste: Barriers. E & FN Spon, London, pp. 3–10.

Colucci, P., Lavagnolo, M.C., 1995. Three years field experience in electrical control of synthetic landfill liners. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, pp. 437–452.

Cossu, R., 1994. Engineering of landfill barrier systems. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Landfilling of Waste: Barriers. E & FN Spon, London, pp. 11–23.

Cossu, R., 1995. The multi-barrier landfill and related engineering problems. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, pp. 3–26.

Daniel, D.E., 1987. Earthen liners for land disposal facilities. In:

Woods, R.D. (Ed.), Geotechnical Practice for Waste Disposal '87. Geotechnical Special Publication, ASCE, vol. 13, pp. 21–39.

Department of the Environment (DOE), 1978. Cooperative Programme of Research on the Behaviour of Waste in Landfill Sites. London: HMSO. 169 pp.

Derham, J., 1995. The engineering of (a sustainable) landfill. The Role of Groundwater in Sustainable Development, Proceedings of 15th Annual Groundwater Seminar, Portlaoise, International Association of Hydrogeologists (Irish Group), 9 pp.

Driessen, J.H.A., Moura, M.L., Korzilius, E.P.A., 'van der Sloot, H.A., 1995. The sustainable landfill. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 1. CISA, Cagliari, pp. 15–24.

Duquennoi, C., Bernhard, C., Gaumet, S., 1995. Laboratory ageing of geomembranes in landfill leachates. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, pp. 397–404.

Farquhar, G.J., 1994. Experiences with liners using natural materials. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Landfilling of Waste: Barriers. E & FN Spon, London, pp. 37–53.

Farquhar, G.J., Parker, W., 1989. Interactions of leachates with natural and synthetic envelopes. In: Baccini, P. (Ed.), Lecture Notes in Earth Sciences, Volume 20: The Landfill, Reactor and Final Storage. Springer, Berlin, pp. 174–200.

Fernandez, F., Quigley, R.M., 1985. Hydraulic conductivity of natural clays permeated with simple liquid hydrocarbons. Can. Geotech. J. 22, 205–214.

Gordon, M.E., 1987. Design and performance monitoring of clay-lined landfills. In: Woods, R.D. (Ed.), Geotechnical Practice for Waste Disposal '87. Geotechnical Special Publication, ASCE, vol. 13, pp. 500–514.

Gray, D.A., Mather, J.D., Harrison, I.B., 1974. Review of groundwater pollution from waste disposal sites in England and Wales, with provisional guidelines for future site selection. Q. J. Engng. Geol. 7, 181–196.

Harris, R.C., Knox, K., Walker, N., 1994. A strategy for the development of sustainable landfill design. Proceedings of the Institute of Wastes Management (UK), pp. 26–29.

Hoeks, J., Glas, H., Hofkamp, J., Ryhiner, A.H., 1987. Bentonite liners for isolation of waste disposal sites. Waste Manag. Res. 5, 93–105.

Holzlöhner, U., 1994. Moisture behaviour of soil liners and subsoil beneath landfills. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Landfilling of Waste: Barriers. E & FN Spon, London, pp. 247–258.

Holzlöhner, U., Ziegler, F., 1995. The effect of overburden pressure on dessication cracking of earthen liners. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, pp. 203–212.

Joseph, J.B., Mather, J.D., 1993. Landfill - does current containment practice represent the best practice? In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 93, Fourth International Landfill Symposium, vol. 2. CISA, Cagliari, pp. 99–107.

Joseph, J.B., Mather, J.D., 1995. Landfill regulation: The need for a scientific framework. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, pp. 141–148.

Knox, K., 1989. Practice and trends in landfills in the UK. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Sanitary Landfilling: Process, Technology and Environmental Impact. Academic Press, London, pp. 533–547.

Madsen, F.T., Mitchell, J.K., 1989. Chemical effects on clay fabric and hydraulic conductivity. In: Baccini, P. (Ed.), Lecture Notes in Earth Sciences, Volume 20: The Landfill, Reactor and Final Storage. Springer, Berlin, pp. 201–251.

Majeski, M.J., Shackleford, C.D., 1997. Evaluating alternative water content – dry unit weight criteria for compacted clay liners. In: Marinos, P.G., Koukis, G.C., Tsiambaos, G.C., Stournaras, G.C. (Eds.), Engineering Geology and the Environment. Balkema, Rotterdam, pp. 1989–1995.

Mather, J.D., 1995. Preventing groundwater pollution from landfilled waste - is engineered containment an acceptable solution? In: Nash, H., McCall, G.J.H. (Eds.), Groundwater Quality. Chapman & Hall, London, pp. 191–195.

Meggyes, T., Holzlöhner, U., August, H., 1995. Improving the technical barrier for landfills. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95. Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, pp. 89–102.

Mohamed, A.M.O., Yong, R.N., Tan, B.K., Farkas, A., Curtis, L.W., 1994. Geo-environmental assessment of a micaceous soil for its potential use as an engineered clay barrier. Geotech. Test. J. 17, 291–304.

Mundell, J.A., Bailey, B., 1985. The design and testing of a compacted clay layer to limit percolation through a landfill cover. In: Johnson, A.I., Frobel, R.K., Cavalli, N.J., Petersson, C.B. (Eds.), Hydraulic Barriers in Soil and Rock. ASTM STP874ASTM, Philadelphia, pp. 246–262.

O'Sullivan, S., 1995. Landfill studies: the role of the hydrogeologist. The Role of Groundwater in Sustainable Development, Proceedings of 15th Annual Groundwater Seminar, Portlaoise: International Association of Hydrogeologists (Irish Group), 6 pp.

Quigley, R.M., Fernandez, F., Rowe, R.K., 1988. Clayey barrier assessment for impoundment of domestic waste leachate (Southern Ontario) including clay-leachate compatibility by hydraulic conductivity testing. Can. Geotech. J. 25, 574–581.

Quigley, R.M., Rowe, R.K., 1986. Leachate migration through clay below a domestic waste landfill, Sarnia, Ontario, Canada: chemical interpretation and modelling philosophies. In: Lorenzen, D., Conway, R.A., Jackson, L.P., Hamza, A., Perket, C.L., Lacy, W.J. (Eds.), Hazardous and Industrial Waste Testing and Disposal. ASTM STP933, vol. 6. ASTM, Philadelphia, pp. 93–103.

Rollin, A., Mlynarek, J., Lafleur, J., Zanescu, A., 1991. An investigation of a seven years old HDPE geomembrane used in a landfill. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 91, Third International Landfill Symposium. CISA, Cagliari, pp. 667–678.

Rowe, R.K., 1988. Contaminant migration through groundwater: the role of modelling in the design of barriers. Can. Geotech. J. 25, 778–798.

Rowe, R.K., 1994a. Design options for hydraulic control of leachate diffusion. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Landfilling of Waste: Barriers. E & FN Spon, London, pp. 101–113.

Rowe, R.K., 1994b. Diffusive transport of pollutants through clay liners. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Landfilling of Waste: Barriers. E & FN Spon, London, pp. 219–245.

Stanners, D., Bourdeau, P., (Eds.), 1995. Europe's environment: the Dobris assessment. European Environment Agency, Copenhagen.

Stegmann, R., 1995. Concepts of waste landfilling. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 1. CISA, Cagliari, pp. 3–12.

Surmann, R., Pierson, P., Cottour, F., 1995. Geomembrane liner performance and long term durability. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, pp. 405–414.

Tchobanoglous, G., Thiesen, H., Vigil, S.A., 1993. Integrated Solid Waste Management: engineering principles and management issues. McGraw-Hill, New York, 978 pp.

Thomas, R.W., Kolbasuk, G.M., 1995. Lessons learned from a cold crack in an HDPE geomembrane. In: Giroud, J.P. (Ed.), Geosynthetics: Lessons Learned from Failures. Industrial Fabrics Association International, pp. 251–254.

Thomas, R.W., Kolbasuk, G., Mlynarek, J., 1995. Assessing the quality of HDPE double track fusion seams. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.). Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, pp. 415–427.

Thomas, R.W., Woods-DeSchepper, B., 1993. The environmental stress crack behavior of coextruded geomembranes and seams. In Proceedings of the Fifth International Conference on Geotextiles, Geomembranes and Related Products, Singapore, 945–948.

Velde, B., 1992. Introduction to Clay Minerals: Chemistry, Origins, Uses and Environmental Significance. Chapman & Hall, London, 198 pp.

Wagner, J.-F., 1988. Migration of lead and zinc in different clay rocks. International Symposium on Hydrogeology and Safety of Radioactive and Industrial Hazardous Waste Disposal, IAH, Orléans, Doc. B.R.G.M. No. 160: Orléans, pp. 617–628.

Wagner, J.-F., 1994. Concept of a double mineral base liner. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.). Landfilling of Waste: Barriers. E & FN Spon, London, pp. 91–99.

Warith, M.A., Yong, R.N., 1991. Landfill leachate attenuation by clay soil. Hazard. Waste Hazard. Mater. 8, 127–141.

Williams, C.E., 1988. Containment applications for earthen liners. In: Dietz, J.D. (Ed.), Proceedings of the 1987 Specialty Conference on Environmental Engineering. ASCE, New York, pp. 122–128.