

A Phased Water Balance Screening Model for Landfill Leachate Management Planning

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Marcus Holden

Holden Environmental Ltd

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Abstract

Landfill leachate management plans require a water balance capable of predicting the volume of leachate produced over time and demonstrating that extraction, storage, treatment and disposal capacity are adequate. In practice, many assessments remain static: they apply a single infiltration rate to a fixed area, compare an annual average with a nominal outlet capacity and do not represent the changing surface condition of an operational landfill or the recovery of an inherited leachate inventory. This paper presents a transparent monthly screening model that links a staged filling and capping programme to rainfall-derived infiltration, separates new leachate generation from existing mobile storage, and constrains recovery by the sustainable capacity of each part of the leachate-management chain. A worked anonymised application comprises nine scenarios formed from three operational programmes and three open-waste infiltration assumptions. In the central case, accelerated completion and capping reduced average new leachate generation from approximately 50 m³/day to 18 m³/day. The model also showed that a high installed pumping rate does not demonstrate control where treatment, storage or disposal capacity remains lower. The method is intended for screening, option appraisal and operational planning. It does not replace a calibrated hydrological model, hydrogeological risk assessment, measured leachate levels or engineering judgement. Its principal value is that it makes the assumptions, programme dependencies, bottlenecks and consequences of delay explicit within an auditable LMP framework.

Keywords landfill; leachate; water balance; management plan; infiltration; capping; capacity; scenario analysis

1 Introduction

A landfill leachate management plan must do more than describe pumps, wells and treatment equipment. It must show how much leachate the site is likely to produce, how the quantity changes as the landfill develops, how existing stored leachate will be recovered, and whether the complete management system can maintain levels below the applicable action and compliance limits. Current Environment Agency guidance explicitly requires an appropriate water balance calculation to predict leachate production over time and adequate provision for extraction, storage, treatment and disposal based on that calculation [1–3].

The difficulty is that an operational landfill is not hydrologically static. Areas pass from active waste placement to temporary cover and then to permanent restoration. Previously capped surfaces may be opened to accommodate revised landforms. Construction programmes slip. The proportion of rainfall entering exposed waste varies with working practice, compaction, gradients and temporary drainage. At the same time, the site may be carrying a substantial mobile leachate inventory represented by elevated heads within the waste. A single annual number cannot represent those interactions adequately.

This paper describes a monthly, phased water balance screening model developed to support practical LMP preparation. It combines established infiltration assessment with an operational mass balance. The result is a tool for testing programmes and capacity decisions, not a claim of precise prediction.

2 The management question

The core management question is not simply how much leachate rainfall may generate. It is whether the site can reduce and then maintain leachate storage under credible wet-weather and programme conditions. That requires four questions to be answered together:

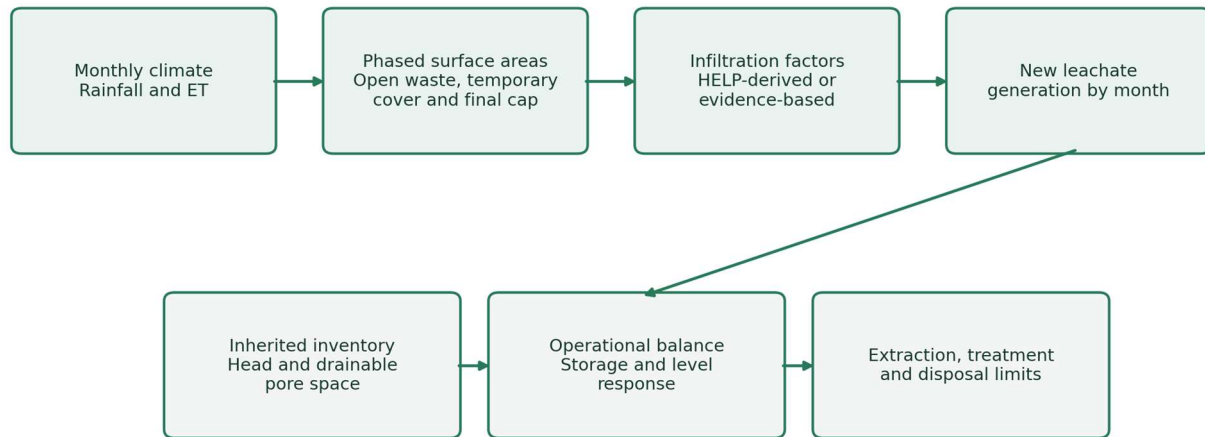
- How does rainfall-derived leachate generation change as the areas of exposed waste, temporary cover and permanent cap change?
- How large is the mobile inventory associated with existing leachate head, and how uncertain is that estimate?
- What is the sustainable rather than nominal capacity of extraction, reception storage, treatment and final disposal?
- Which filling, capping or infrastructure interventions deliver the greatest and quickest reduction in risk?

A useful model therefore needs to represent both generation and recovery. It must also preserve the distinction between verified measurements, design information, working assumptions and sensitivity cases. This is important because a numerical output can otherwise imply a level of knowledge that the underlying site records do not support.

3 Model architecture

The model operates at a monthly time step. Each month is assigned a plan area for each hydrological surface class. The classes can be expanded where needed, but the minimum practical set is open waste, temporary cover, final cap and open water. Future or unconstructed cells are retained within the phasing schedule but do not generate leachate until they enter the operational footprint.

Figure 1 Model structure and information flow



The model separates rainfall-derived generation from the recovery of pre-existing leachate inventory.

Model component	Purpose	Typical evidence
Monthly climate series	Represents rainfall and, where used, evapotranspiration or effective rainfall	On-site gauge, Met Office station or defensible long-term series
Surface schedule	Tracks hydrological condition as filling and capping progress	Survey, restoration plan, cell sequence and operator programme
Infiltration parameters	Converts rainfall to drainage entering the waste or collection system	HELP runs, cover design, field evidence and sensitivities
Inherited inventory	Represents mobile leachate already stored above the drainage horizon	Measured heads, affected area and drainable pore-space range
Removal chain	Constrains recovery by the lowest sustainable capacity	Pump tests, lagoon freeboard, treatment records, consent and tanker availability
Scenario outputs	Shows storage trajectory, clearance time, reaccumulation and capacity margin	Monthly calculation and exception reporting

4 Monthly generation calculation

For each month, rainfall-derived leachate generation is calculated separately for every surface class. The conceptual formulation is:

$$Q_{gen,t} = \sum_{i=1}^n A_{i,t} P_t f_{i,t} + Q_{other,t} - \Delta S_{unsat,t}$$

Equation 1

where $Q_{gen,t}$ is new leachate generation during month t ; $A_{i,t}$ is the plan area of surface class i ; P_t is monthly rainfall; $f_{i,t}$ is the fraction of rainfall contributing to leachate for that class; $Q_{other,t}$ represents other external inputs such as direct inflow or imported liquids; and $\Delta S_{unsat,t}$ represents a change in retained moisture where this is explicitly modelled. Consistent units are used so that the result is expressed as a monthly volume.

The infiltration fraction may be based on HELP output or another defensible assessment. HELP is well suited to evaluating rainfall, runoff, evapotranspiration, drainage and liner or cover performance [4,5]. It does not, by itself, represent pump availability, lagoon constraints, treatment outages, consent limits or operator response. Those operational elements are therefore applied in a separate mass balance.

5 Representing the operational programme

The surface schedule is the defining feature of the approach. Rather than assuming a fixed percentage of the site is capped, the model converts the operational programme into monthly areas. A working phase may begin as future area, move to exposed waste during filling, remain under temporary cover after completion and then transfer to permanent cap following construction and quality assurance. Where overtipping requires existing cap to be removed, that area is returned to the appropriate open or temporarily covered class for the relevant period.

The programme should be plausible rather than optimistic. In the worked application, an operator programme was expressed as six-month stages over 42 months and interpolated monthly. Permanent capping followed area completion after an assumed construction and approval interval. Separate scenarios represented a slower current-permit programme and completion by a planning deadline. This allowed the hydraulic benefit of operational acceleration to be quantified rather than merely asserted.

6 Open waste and temporary cover

Open waste is normally the most uncertain surface class. Rainfall may be shed from trafficked or compacted gradients, retained within recently placed waste, evaporated, or transmitted to the collection system. A single value should not be presented as fact. The worked application therefore used three open-waste rainfall-entry assumptions of 60%, 75% and 100%. The 60% case was adopted as the central screening case, with the higher cases showing sensitivity to wetter or less controlled conditions.

Temporary cover should not automatically be treated as either open waste or permanent cap. Its performance depends on material, thickness, placement, cracking, drainage and maintenance. A 300 mm compacted clay temporary cover was assessed using HELP, producing a screening infiltration fraction of approximately 17% of rainfall for intact cover. The parameter is explicitly conditional: damaged or poorly drained cover should be represented by a higher value or a separate degraded-cover class.

7 Existing inventory and head recovery

A rainfall balance only estimates new generation. It does not show the effort required to remove leachate that is already stored within the waste. The model therefore introduces a separate initial mobile inventory. A simple screening relationship is:

$$V_{head} = A_h n_d h \quad \text{and} \quad h_t = \frac{V_t}{A_h n_d}$$

Equation 3

where V_{head} is mobile leachate volume, A_h is the hydraulically affected plan area, n_d is drainable pore space and h is representative leachate head above the drainage horizon. The calculation is deliberately presented

as a range because both effective area and drainable pore space are uncertain. In the worked application, the midpoint assumption for a 3 m starting head produced an indicative mobile inventory of approximately 27,600 m³. Sensitivities at 2 m and 4 m were retained to show the proportional effect of the starting condition.

This relationship is a storage screening calculation, not a substitute for a hydrogeological model. It assumes an effective connected mobile volume. Perched water, heterogeneous waste, blocked drainage, inter-cell bunds and poor well connectivity may cause measured levels and recoverable volume to behave differently. The inventory should be reconciled progressively against measured levels and abstraction data.

8 Capacity constrained mass balance

The monthly storage balance is calculated as:

$$V_t = \max[0, V_{t-1} + Q_{gen,t} + Q_{in,t} - Q_{out,t}]$$

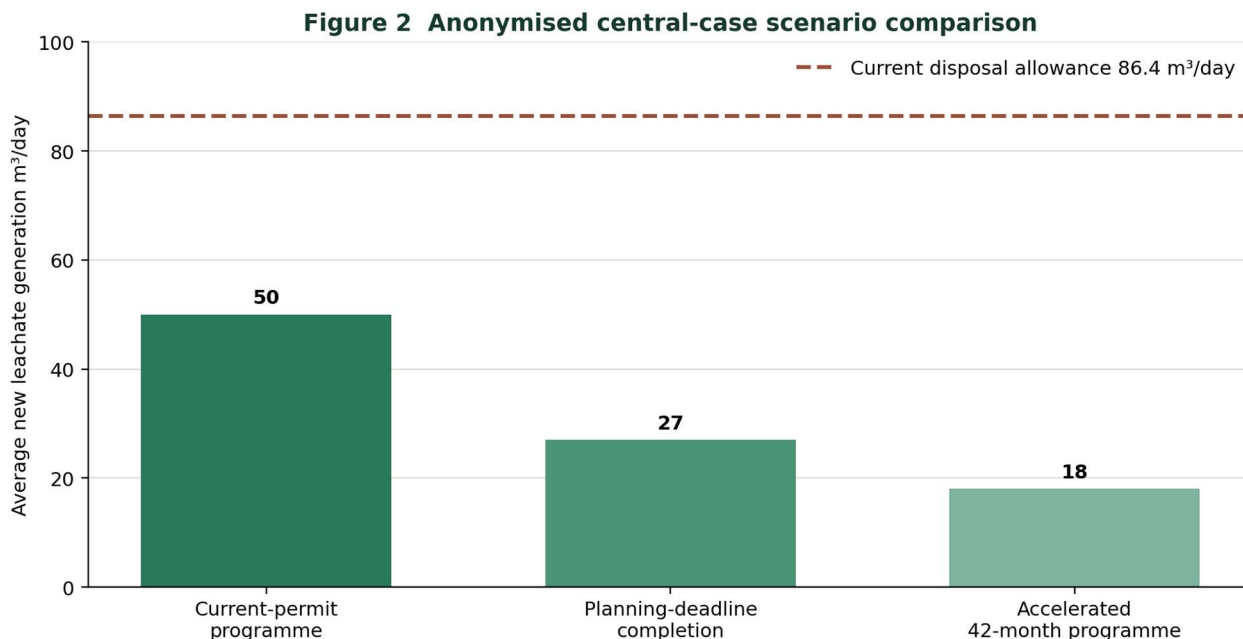
Equation 2

where V_t is mobile inventory at the end of the month, $Q_{in,t}$ includes defined transfers into the control volume, and $Q_{out,t}$ is the actual removable volume. $Q_{out,t}$ is constrained by the lowest sustainable capacity in the management chain. A pump array capable of moving 48 m³/hour does not provide that removal capacity if treatment and disposal can sustain only 86.4 m³/day. Similarly, a higher sewer consent does not solve the problem if biological treatment, reception storage or transfer pumping cannot operate at the same rate.

The model distinguishes installed, consented and demonstrated capacity. Nominal equipment ratings are useful for identifying gross hydraulic constraints, but the operational scenario should use evidenced sustainable throughput and allow for downtime. Where evidence is absent, the capacity remains provisional and is tested as a sensitivity.

9 Worked anonymised application

The worked application combined three filling and capping programmes with three open-waste rainfall assumptions, producing nine monthly scenarios. The central 60% open-waste case gave the following average new leachate generation rates. Values have been rounded and the site has been anonymised.



Programme scenario	Average new generation	Indicative clearance of 3 m inventory at 86.4 m ³ /day	Subsequent central-case response
Current-permit programme	about 50 m ³ /day	about 20 months	Later wet-period reaccumulation up to about 2,320 m ³
Planning-deadline completion	about 27 m ³ /day	about 15 months	Minor later reaccumulation of about 92 m ³
Accelerated 42-month programme	about 18 m ³ /day	about 14 months	No later reaccumulation in the central case

At an illustrative overall removal capacity of 200 m³/day, the inherited inventory cleared in approximately six months under all three programmes. This comparison is not a recommendation to adopt that capacity without design work. It shows that the time required to regain control is governed by both starting inventory and the margin between sustainable removal and ongoing generation.

The analysis produced two useful management conclusions. First, earlier capping acts as a hydraulic intervention and can reduce ongoing load materially. Second, treatment and disposal were more important to recovery time than installed pump nameplate capacity. Those conclusions are difficult to see from an annual balance or equipment schedule considered in isolation.

10 Using the model within an LMP

The model is most useful when embedded in the LMP rather than appended as an unexplained spreadsheet. The LMP should state the control volume, surface classifications, programme, climate series, infiltration basis, starting inventory and capacity constraints. It should then translate the outputs into actions, responsibilities and review triggers.

LMP function	How the model supports it
Demonstrating adequacy	Compares monthly generation and inherited inventory with sustainable extraction, storage, treatment and disposal capacity.
Setting actions	Links specified level, storage or capacity thresholds to pumping, tankering, treatment recovery, temporary covering or accelerated capping.
Planning construction	Quantifies the leachate consequence of delayed filling, delayed capping or cap removal.
Testing contingencies	Runs wet infiltration, reduced treatment availability, sewer restriction, plant outage and tankering scenarios.
Prioritising evidence	Identifies which uncertain input most affects the management decision and therefore needs measurement first.
Maintaining the plan	Provides a repeatable monthly update process using rainfall, survey, level, abstraction and discharge data.

The model should be updated when the active area, cover condition, programme, treatment configuration or disposal consent changes materially. A routine monthly comparison of modelled generation, measured abstraction and observed leachate levels provides a basic calibration loop. Persistent divergence is evidence that the conceptual model or one of its operating assumptions needs revision.

11 Data hierarchy and uncertainty

The model is transparent only if its inputs are classified. A practical hierarchy is: verified site measurement; approved design or consent value; operator programme; engineering assumption; and sensitivity value. Each assumption should have an owner, evidence source and review date. Missing information should remain visible rather than being filled with false precision.

The most influential uncertainties are commonly the extent and condition of temporary cover, open-waste infiltration, representative starting head, drainable pore space, hydraulic connectivity and sustainable

treatment throughput. Monte Carlo analysis may be added where probability distributions are justified, but a small number of clearly explained scenarios is often more useful for an operational LMP than a statistically elaborate model built on weak input data.

12 Limitations

The model is a screening and decision-support method. It should not be described as a calibrated predictive model unless site data demonstrate calibration and validation. In particular, it does not independently resolve unsaturated flow, perched leachate, preferential pathways, transient pump drawdown, clogging, spatial variation in head, liner leakage or groundwater interaction. HELP-derived infiltration remains dependent on the assumed profile and climate data. The simple head-volume relationship assumes an effective connected drainage domain.

The calculated clearance date is conditional on capacity being continuously available. Biological treatment instability, lagoon constraints, maintenance, consent quality limits and tanker logistics can all reduce effective throughput. The LMP must therefore include operational records and contingency actions rather than treating the model output as a guarantee.

13 Conclusions

A phased monthly water balance provides a stronger basis for leachate management planning than a static annual estimate. By linking the changing landfill surface to rainfall infiltration, separating new generation from inherited inventory, and limiting removal to the sustainable capacity of the complete management chain, the method answers the practical question of whether and when control can be achieved.

The anonymised application showed that an accelerated 42-month filling and capping programme reduced average central-case generation from approximately 50 m³/day to 18 m³/day and avoided later reaccumulation under the modelled conditions. It also demonstrated that nominal pump capacity was not the controlling constraint. The value of the model lies less in a single forecast than in its ability to expose assumptions, compare interventions, identify bottlenecks and create a measurable management pathway.

Used properly, the model turns the water-balance section of an LMP from a compliance calculation into an operational decision tool. Its outputs should be updated against rainfall, survey, abstraction, discharge and leachate-level data so that the plan becomes progressively better grounded in actual site performance.

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