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Evaluating landfill aftercare strategies: A life cycle assessment approach

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A B S T R A C T

This study investigates the potential impacts caused by the loss of active environmental control measures during the aftercare period of landfill management. A combined mechanistic solute flow model and life cycle assessment (LCA) approach was used to evaluate the potential impacts of leachate emissions over a 10,000 year time horizon. A continuum of control loss possibilities occurring at different times and for different durations were investigated for four different basic aftercare scenarios, including a typical aftercare scenario involving a low permeability cap and three accelerated aftercare scenarios involving higher initial infiltration rates. Assuming a 'best case' where control is never lost, the largest potential impacts resulted from the typical aftercare scenario. The maximum difference between potential impacts from the 'best case' and the 'worst case', where control fails at the earliest possible point and is never reinstated, was only a fourfold increase. This highlights potential deficiencies in standard life cycle impact assessment practice, which are discussed. Nevertheless, the results show how the influence of active control loss on the potential impacts of landfilling varies considerably depending on the aftercare strategy used and highlight the importance that leachate treatment efficiencies have upon impacts.

1. Introduction

Landfilling has historically been the predominant disposal method for mixed municipal solid waste (MSW) (e.g. Hoornweg and Bhada-Tata, 2012) and is likely to remain so in many countries for the foreseeable future. Landfills often pose a significant pollution risk and contribute to a range of potential environmental and human health impacts via gaseous and liquid (leachate) emission pathways if not properly managed (Christensen et al., 2011). These impacts must be controlled both during the operational phase of a landfill, and post-closure (known as the 'aftercare' period) until they no longer pose an unacceptable risk to the environment.

To counter this pollution risk, modern landfills have been developed over the past few decades into highly engineered containment facilities with a focus on low-permeability capping and multi-barrier artificial lining systems that act to contain and facilitate the collection of leachate and gas produced during the degradation of landfilled waste. However, low infiltration rates caused by low permeability capping impair the degradation of organic matter and result in slow flushing rates of leachate pollutants (e.g. Beaven et al., 2014). This leads to extended aftercare timescales of hundreds, if not thousands, of years before landfills reach a point where no further management or monitoring of emissions is required (Knox, 1990; Knox et al., 2005) – a point commonly known as 'Final Storage Quality' (FSQ) or 'Completion'. A lack of certainty in funding of long-term landfill aftercare leads to an increased risk that active environmental control systems (e.g. leachate pumping/removal and treatment) are shut down or fail (henceforth, 'active control loss') prior to the achievement of FSQ, which may result in potentially significant environmental impacts.

A variety of different approaches are used for the long-term management of landfills (Laner et al., 2012), although real-world examples of practices that reduce the timescale of aftercare are limited. One of the easiest actions that an operator can take to reduce these timescales is to not utilise a low permeability cap, thereby allowing a higher flux of water to enter a site. Perhaps uniquely, based on Rowe (1991) landfill regulations in Ottawa, Canada require the installation of top covers that allow >150 mm infiltration per year (Ministry of the Environment, 2008). More active measures to promote the addition of moisture to the waste mass involve the controlled addition of recirculated leachate or liquids from other sources, such as freshwater or wastewater effluent. Increasing the landfill moisture content has been shown to enhance biodegradation processes in landfills (e.g. Burton et al., 2004; Pommier et al., 2007; Meima et al., 2008) and promote

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organic waste stabilisation, and is at the core of landfill bioreactor technology as adopted, for example, in the USA (e.g. Townsend et al., 1996; Barlaz et al., 2010). Some researchers (e.g. Scharff et al., 2011; Beaven et al., 2014) are therefore encouraging landfill operators to implement such techniques as they may help to alleviate the burden of pollution control on future generations and, considering the uncertainties concerning aftercare funding, minimise the potential environmental impacts of possible active control loss. To this end, the first international field scale accelerated completion trial is due to start in the Netherlands in 2016 (Kattenberg et al., 2013).

Life cycle assessment (LCA) is a systematic tool for quantitatively evaluating the potential environmental and human health impacts of products, processes, and systems over their full life cycle. LCA has become one of the principal decision support tools across all levels of waste management (Thomas and McDougall, 2005) and has been extensively applied to evaluate the potential environmental impacts of landfilling (e.g. Damgaard et al., 2011; Xing et al., 2013; Turner et al., 2016). The majority of these studies have relied on the use of waste-specific LCA models (e.g. EASETECH or WRATE). Such models, which are numerous and diverse (see Winkler and Bilitewski, 2007; Gentil et al., 2010), typically comprise a suite of linkable treatment process models. With regards to landfill modelling, waste LCA models generally adopt simplified approaches that, although suitable for modelling the potential impacts of landfill in the context of integrated waste management systems, are unable to model active control loss or deterioration of engineering systems.

A key issue that must be addressed in LCA studies of landfills is that of sustainability. As leachate emissions occur over extended time periods, they represent an uncertain risk and a burden to future generations. This contradicts one of the core principles of sustainable development, namely that the problems of today should not be passed on to future generations (United Nations, 1987). Furthermore, it is broadly recognised that the efficacy of landfill engineering systems will deteriorate in the long term (Drury et al., 2003; Rowe, 2005). The deterioration or failure/shut down of these control systems may increase the impact on future generations through the release of untreated leachates and landfill gases into the natural environment. Despite this, no previous LCA studies of landfills have considered the potential effect of active control loss on the overall impacts of landfill.

Within this context, the aim of this paper is to present a LCA approach for assessing the potential impacts of alternative landfill aftercare strategies. The model only addresses impacts through the aqueous environment, and does not consider gas emissions, although a future version could do so in principle. A simple mechanistic model for water flow and solute movement is applied to the question: When and for how long does an absence of active control (i.e. managed aftercare) result in a significant increase in the environmental impact of a site (due to liquid contaminants)? This is the first LCA study to consider the effect of active control loss on the potential impacts of landfilling.

2. Methods

An integrated landfill process LCA model and simple mechanistic water flow and solute movement model that is capable of simulating active control loss and deterioration of engineering systems was developed for this study. An overview of the mechanistic model is provided in Fig. 1 and described further in Section 2.2. Fig. 2 illustrates how the mechanistic model is integrated with LCA, which was performed in accordance with the ISO 14040 and 14044 standards (ISO, 2006a, 2006b). According to this framework, an LCA consists of four phases: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation (i.e. presentation and discussion of results).

2.1. Goal and scope definition

The goal of the study was to evaluate the potential impacts of leachate emissions from landfill sites operated with different aftercare strategies, taking into account the effects of potential active control loss. The purpose of the work was twofold: (1) to investigate whether LCA can be used to improve our understanding of the long term impacts of landfilling and (2) to develop an understanding of the potential effects of active control loss on these impacts. The primary audience includes landfill operators and waste regulators in the UK and abroad, as well as the landfill and LCA research communities.

The 'functional unit' was defined as the total amount of leachate generated over a 10,000 year time horizon from a completed landfill site with a surface area of 10,000 m^2 and a depth of 20 m, filled with non-hazardous MSW. These dimensions were selected as they represent a typical landfill cell in the UK. The 10,000 year time horizon was selected to ensure that virtually all emissions from the landfill would be accounted.

The spatial boundary of the system was defined by the boundary of the landfill site, as illustrated in Fig. 1. The 'zero burden assumption' was adopted, whereby environmental impacts from upstream life cycle stages prior to the deposition of waste in the landfill cell were not included (Ekvall et al., 2007). Processes included in the assessed system comprise the generation, movement, and collection of leachate at the site and the treatment of collected leachate. The following processes were excluded:

- Infrastructure, energy, and material use
- Waste transportation
- Landfill gas generation, collection, and utilisation

2.2. Mechanistic flow and transport model

A simple mechanistic flow and mass transport model was used to compile the life cycle inventory of emissions to the environment.

The landfill, parameterised to represent the hypothetical behaviour of a modern engineered landfill in the UK, is simplified as one-dimensional and is modelled from the time at which waste disposal is completed and the site is capped. Water enters the landfill (of depth h_M) at the top, by passing though the cap and entering the waste. The leachate is contained at the base by a hybrid liner – geomembrane (GM) above a compacted clay layer (CCL). The liner is overlain by a drainage layer that, when functioning, allows the leachate to be removed to a control level above the base of the site (h_c). The leachate level in the waste is assumed to change instantaneously depending on the balance between water entering via the cap and leachate removed via the drainage layer and/or by leakage through the liner. The rate of change in leachate levels is related to the drainable (and fillable) porosity (θ_d) of waste, whose water content is assumed never to fall below 'field capacity'.

2.2.1. Cap infiltration

Cap infiltration was modelled based on the performance of a typical flexible membrane liner (FML), as described by Drury et al. (2003). Details of the values assigned to the parameters used to model cap infiltration are provided in Table 1. The infiltration into the waste is via downward flow through the cap (Q_i), which is assumed to be a piecewise linear function.

As the cap degrades, it is assumed that the flow through the cap increases linearly over time from an initial rate, Q_{i-c}. Short-term variations in flow (for instance following a rainfall event) are not

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