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Longitudinal data analysis in support of functional stability concepts for leachate management at closed municipal landfills

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ABSTRACT

Landfill functional stability provides a target that supports no environmental threat at the relevant point of exposure in the absence of active control systems. With respect to leachate management, this study investigates "gateway" indicators for functional stability in terms of the predictability of leachate characteristics, and thus potential threat to water quality posed by leachate emissions. Historical studies conducted on changes in municipal solid waste (MSW) leachate concentrations over time (longitudinal analysis) have concentrated on indicator compounds, primarily chemical oxygen demand (COD) and biochemical oxygen demand (BOD). However, validation of these studies using an expanded database and larger constituent sets has not been performed. This study evaluated leachate data using a mixed-effects regression model to determine the extent to which leachate constituent degradation can be predicted based on waste age or operational practices. The final dataset analyzed consisted of a total of 1402 samples from 101 MSW landfills. Results from the study indicated that all leachate constituents exhibit a decreasing trend with time in the post-closure period, with 16 of the 25 target analytes and aggregate classes exhibiting a statistically significant trend consistent with well-studied indicators such as BOD. Decreasing trends in BOD concentration after landfill closure can thus be considered representative of trends for many leachate constituents of concern.

1. Introduction

Efforts to characterize the behavior of closed municipal solid waste (MSW) landfills have global relevance because despite significant variations in MSW management practices and current reliance on landfills among industrialized countries, there are two important areas of worldwide commonality (Laner et al., 2012). First, the basic design elements of engineered landfills are similar, typically including a waste containment liner system to separate waste from the subsurface environment, systems for the collection and management of leachate and gas, and placement of a final cover after waste deposition is complete. Second, there are thousands of closed landfills and many thousands more operating sites that will close over the next few decades. Post-closure care (also termed aftercare) is a regulatory requirement in almost all industrialized countries and typically includes monitoring of potential emissions (e.g., leachate and gas) and receiving systems (e.g., groundwater, surface water, soil, and air) and maintenance of the final cover, leachate, and gas collection systems. Based on the similarity of design attributes and operational controls in place at MSW landfills during their active service life and after closure, it should be expected that some similarities would also exist in terms of their behavior. This paper presents results from mixed-effects regression modeling using an expansive dataset to determine the extent to which reductions in leachate constituent concentrations can be predicted based on waste age or certain operational practices.

Regulations governing post-closure care (PCC) generally stipulate that an owner of a closed MSW landfill is responsible for its maintenance, monitoring, and condition for 30 years, or for an alternative period as necessary to protect human health and the environment (HHE). Federal guidance in the USA, for example,

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states with respect to leachate management that "concentrations at the point of exposure, rather than concentrations in the leachate collection system, may be used when assessing threats" (U.S. EPA, 1993), where the point of exposure (POE) is defined as the closest property boundary location at which a receptor could be exposed to contaminants and receive a dose via a credible pathway. Demonstrating no unacceptable threat at the groundwater and/or surface water quality POE in the absence of active care therefore provides the foundation for defining when active leachate management can be ended. Recently, a trend toward adopting performance-based standards for PCC has been observed, particularly at the subnational level in USA (e.g., CalRecycle, 2010; WDE, 2012), and different approaches adhering to this concept developed (e.g., van Vossen, 2010; Morris and Barlaz, 2011; Sizirici et al., 2011). Of particular relevance to this study, the Evaluation of Post-Closure Care (EPCC) Methodology described by Morris and Barlaz (2011) defines PCC completion in terms of functional stability, which is defined as a landfill's non-impacting relationship with its receiving environment in the absence of active care, but with some remaining *de minimus* level of control to protect against disturbance of buffer zones or passive barriers (mainly the cover) under a custodial care program (ITRC, 2006). Prior to terminating PCC, functional stability should be demonstrated with respect to all primary control elements in place at a closed landfill (typically, leachate management, landfill gas management, and final cover system) and confirmed based on performance data from PCC monitoring elements (typically, groundwater, surface water, air quality, and/or gas migration monitoring). Demonstrating functional stability in the context of eliminating active leachate management does not require definitive demonstration of organic stabilization within the waste mass, a largely theoretical state of degradation that is difficult to measure (Barlaz, 2012), but instead evaluates potential threats posed by uncontrolled leachate emissions. Such demonstrations help make decisions regarding the necessity of active operation of the leachate collection system (LCS) or whether leachate could be safely managed using a passive system featuring wind/solar operated pumps, low maintenance wetlands, and/or natural biofilters. Full evaluation requires substantial data and rigorous statistical analysis (Gibbons and Bull, 2006). As a precursor to detailed (and potentially expensive) evaluation, however, it is recommended that "gateway" criteria for key indicators are satisfied. Such criteria alone are insufficient to demonstrate functional stability, but are indicative that conditions necessary for functional stability may exist (Morris et al., 2013) such that detailed evaluation is warranted. This paper addresses selection of appropriate indicators, particularly with regard to their predictability in representing long-term leachate quality.

Many longitudinal studies of leachate data have focused on a short list of dissolved organic matter (DOM) indicators, primarily biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total organic carbon (TOC). These have tended to show that BOD will decrease most rapidly after landfill closure, exhibiting relatively low and stable concentrations typical of the long-term stable methanogenic phase of decomposition (Barlaz et al., 2002). Proposed gateway criteria for stable leachate include sustained BOD concentration less than 100 mg/L (Reikes, 2003) or BOD/COD ratio less than 0.1 (Kjeldsen et al., 2002). As waste degrades in a landfill (as measured by BOD in leachate), it has also been shown that the bottommost MSW layers become well decomposed and act as a biofilter with a large attenuating capacity for organics and heavy metals (Shimaoka et al., 1993). Not only does this point to BOD as a suitable indictor of functional stability, it also suggests that the sampling location is important. Given these findings, this study focuses on leachate samples collected from a basal LCS. However, to have broad confidence that demonstrating a significantly decreasing trend in BOD is a suitable surrogate for other constituents of concern, it is important to derive a statistically significant relationship with other commonly detected analytes across a range of leachate datasets. A final objective of this study is thus to update previous findings by evaluating data from a large number of active and closed landfill units of various waste ages to determine whether reductions in leachate constituent concentrations as measured by BOD can be correlated with waste age or operational practices.

2. Background

2.1. Long-term trends in leachate quality

In addition to DOM, MSW leachate typically contains inorganic ions, nutrients, and relatively low concentrations of heavy metals, volatile organic compounds (VOCs), and semi-volatile organic compounds (SVOCs). Leachate generation and composition is governed by the rate of liquids percolation, in-situ physical, chemical, and biological conditions, and the predominant leaching mechanism. These in turn are controlled by waste type and age, landfill design and operational practices, and climate and hydrogeologic factors (Rees, 1980; Christensen and Kjeldsen, 1989; Christensen et al., 1992; Heasman, 1997; Komilis et al., 1999; Mehta et al., 2002; De la Cruz and Barlaz, 2010; Staley et al., 2011). Biodegradation of MSW in landfills typically occurs in a number of sequential phases (Pohland and Harper, 1986), of which the long-term stable methanogenesis phase is of most relevance to this study.

Several reviews of long-term leachate composition have been published (Farquhar, 1989; Robinson, 1995; Kjeldsen and Christophersen, 1999; Christensen et al., 2001; Ehrig and Krumpelbeck, 2001; Robinson and Knox, 2001, 2003; Kjeldsen et al., 2002; Öman and Junestedt, 2008). Many findings demonstrate the predictability of long-term leachate constituent trends, particularly with regard to DOM indicators. For example, Rowe (1995) examined historical leachate data from three landfills and reported that concentrations increase to a peak value and then decrease within a monitoring period of 10–15 years. Statom et al. (2004) evaluated over 12 years of MSW leachate data from one site and found an overall declining trend in major ion chemistry, with data collected after closure capping showing an overall reduction in the amplitude of short-term variations.

Trace organic compounds most frequently present in landfill leachate are the aromatic hydrocarbons, chlorinated solvents, and ketones (Knox et al., 2000; Christensen et al., 2001; Staley et al., 2006). Several processes impact long-term concentration trends in these compounds (Lowry et al., 2008), including volatilization to gas and diffusive loss through cover systems (Foose et al., 2002), sorption to or desorption from waste (Kjeldsen and Grundtvig, 1995; Wu et al., 2001; Saquing et al., 2010), and leaching and degradation (Deipser and Stegmann, 1994; Luthy et al., 1997). Kjeldsen and Christensen (2001) showed that most VOCs will be released in the gas phase, although the release may take several decades.

Amongst inorganic ions and nutrients, ammonia and chloride are of most interest in landfill leachate. Chloride is a conservative parameter and there is no mechanism for ammonia biodegradation under anaerobic conditions (Burton and Watson-Craik, 1998; Price et al., 2003). Both are released in leachate over time. Although the rate of removal could theoretically be increased by flushing the landfill, this would require several pore volumes of water (Beaven and Walker, 1997) and potentially be limited by heterogeneous percolation (Rosqvist et al., 2005).

The fate of heavy metals under various landfill operating and internal biochemical conditions has been extensively researched (e.g., Aulin et al., 1997; Bozkurt et al., 1999; Flyhammer et al.,