AN EMPIRICAL ANALYSIS OF GAS WELL DESIGN AND PUMPING TESTS FOR RETROFITTING LANDFILL GAS COLLECTION

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By

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ABSTRACT

Retrofitting a landfill with a gas collection system is an expensive and time consuming endeavor. Such an undertaking usually consists of longer-term extraction testing programs and the installation of deep, large diameter extraction wells. Installation and longer-term testing of these wells can be expensive, and yet, few, if any, documented field studies have been reported in the literature to evaluate the necessity of longer-term extraction tests and expensive well designs.

Therefore, the aims of this thesis are as follows:

1) The primary goal of this work was to evaluate the performance of landfill gas extraction wells to the various aspects of their design and construction.
2) A secondary goal was to evaluate the performance of the gas wells using various short-term and longer-term testing methodologies.

Accordingly, several different short-term and longer-term pumping tests were carried out on the landfill gas extraction wells which were constructed to varying design specifications. As well, the efficacy of two different longer-term pumping methodologies was compared to determine if one method of longer-term extraction proved superior to another. In order to interpret these results, it was necessary to select a measure for the efficiency of a particular landfill gas extraction well that was appropriate yet simple. The parameter principally used for this purpose in this study is the specific capacity which was determined for each well.

Following the completion of the short- and longer-term pumping tests, three important conclusions were reached. Firstly, it appeared that construction well specifications had no impact on the efficiency of the extraction wells. Further, there was no significant difference in pneumatic response of the extraction wells between short-term and longer-term testing programs.

Lastly, the constant pressure type longer-term extraction test (opposed to constant flow type test) showed lower levels of oxygen ingress into the waste mass and landfill gas, and resulted in an overall higher gas extraction rate.

ACKNOWLEDGMENTS

I’m pleased to acknowledge the guidance and mentorship provided to me by Dr. Ian Fleming. Dr. Fleming’s enthusiasm for continued education and knowledge was both a valuable resource and inspiration from which I drew to complete this research. Ian also always provided thoughtful and sincere advice and commentary with only the best intentions for my own benefit at heart. They sometimes fell on deaf ears throughout the course of my studies and work, but they have not gone without recognition and appreciation.

Thank you, Dr. Fleming.

A great amount of thanks also must be given to the City of Saskatoon for providing a site to host this project and to Brad Chapple of AMEC Earth and Environmental who contributed a signification amount of effort and time in the construction of the demonstration system.

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Thank you.

DEDICATION

I dedicate this thesis to all my family and friends who supported me in my endevour of higher learning. I’d like to especially thank my loving wife for the motivation, patience, and understanding required in marriage to a graduate student. And, last but certainly not least, to my beautiful daughter Bronwyn.

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CHAPTER 1
INTRODUCTION

Modern waste disposal sites are commonly designed to meet or exceed health and environmental regulation standards, for example through fitting with engineered liner systems, leachate collection systems, and cover soils. Waste sites are also often engineered with gas extraction systems for the collection of methane gas that is produced from degradation of the organic fraction of the waste. The methane (an energy gas) collected is commonly used to generate electrical energy or processed and used in combustion engines and furnaces.

While the level of engineering in newer landfills is typically high, many older landfill sites built according to dated technologies and practices are still currently in operation. These sites pose challenges to the engineers and environmental scientists who attempt to retrofit them with modern technology and processes for methane collection, as this endeavour is both technically demanding and expensive. In order to be economical and viable, retrofit systems must produce a methane yield that supersedes the costs of construction of the extraction system and longer-term operation.

Although the rate of gas production is largely dependent on the nature of the waste and the moisture levels within it, a couple of technically and economically challenging aspects of methane extraction systems are the construction and testing of the extraction wells. Gas wells can be costly due to expensive materials and drilling programs associated with the commonly recommended deep wells with large diameters, and longer-term (time consuming) extraction testing programs which are often undertaken to determine site specific well-field designs and requirements.

Two important questions therefore arise regarding these assumptions:

1) Will expensive, deep, and larger-diameter wells consistently out-perform cheaper, shallower, and smaller-diameter wells?
2) Are longer-term extraction tests absolutely necessary for determining pneumatic response and behavior in the ambient waste around an extraction well for the design of the well-field?

Surprisingly, these simple considerations have not yet been addressed and documented with a carefully controlled field testing program.

The aims of this thesis are thus as follows:

1) The primary goal of this work was to attempt to relate the performance of the landfill gas extraction wells to the various aspects of their design and construction.
2) A secondary goal was to evaluate the performance of the gas wells and extraction system using various short-term and longer-term testing and extraction methodologies.

Accordingly, several different short-term and longer-term pumping tests were carried out on the landfill gas extraction wells that had been constructed to varying design specifications. A large amount of care and forethought was used in designing the extraction system so that the analysis of the results could be simpler. For example, a larger header-pipe was used to reduce head losses and keep upstream pressures the same at each wellhead. Also, identical well-heads were used for each construction well and were calibrated for each well construction configuration in the gas analyzer unit.

In order to interpret these results, it was therefore necessary to select an appropriate (and simple) measure (or measures) for the efficiency of a landfill gas extraction well. The parameters used for this purpose in this study were the specific capacity (SC) and radius of influence (ROI). SC is defined as the gas flow [L^3T^{-1}] per unit of vacuum [$ML^{-1}T^{-1}$] applied to the wellhead. In simple practice, this is defined as the slope of a flow vs. pressure "drawdown" for the various pumping rate "steps" in a step-drawdown pumping test. The ROI is the radial distance from an extraction well in which there is a measureable impact from pumping. More precisely, it is the radius at which the change in pressure in the drawdown curve is equal to zero. For this thesis, the definition used to calculate the ROI was first proposed by Gardner et al. (1990), who suggested an allowable pressure gradient differential between 0.5 mPa/m and 1.3 mPa/m using a line of best fit from pumping tests results.

A more efficient gas well can then be defined as requiring little energy input (small applied vacuum) for a given flow (ie: large specific capacity) with a larger ROI. Likewise, a less efficient well is one that requires a greater amount of energy input (large applied vacuum) for a given flow rate (ie: small specific capacity) and has a small ROI.

Specific capacity and ROI of an extraction well largely depend on the properties of the surrounding waste. Most importantly, specific capacity and ROI depend on the pneumatic conductivity at the ambient volumetric water content prevailing in the waste. However, a rigorous analysis of municipal waste pneumatic permeability and time dependent behaviors of refuse which may affect gas extraction pumping are outside the scope of this research (although they are discussed in Chapter 2) as this research was primarily focused on documenting and testing any correlations or relationships between the construction specifications of a well assuming that the ambient properties of the waste surrounding each well are the same.

This assumption may seem simplistic; however, if the efficiency of a well is dominated by ambient waste properties, and effects of construction specifications on well performance are too slight to be discernible, designing expensive, deep, and larger-diameter wells for landfill gas extraction systems seems impractical and uneconomical.

Likewise, if short-term pumping test results showed similar pneumatic responses as longer-term tests, longer-term testing programs to determine the pneumatic behavior of the ambient waste, for assisting in well-field design, would also be seem impractical and uneconomical.

CHAPTER 2
BACKGROUND

This chapter reviews research conducted to date on the hydraulic and pneumatic transport properties of municipal solid waste (MSW) with regards to landfill gas (LFG) extraction/collection wells. An important part of an efficient and cost effective design for a gas extraction system is accurately determining the pneumatic and hydraulic properties of the waste to optimize well spacing, the number of wells required, and the required capacity of pumps and/or blowers.

In the case of groundwater flow and pumping tests, there are several well known methods/models that are used to determine the characteristics of an aquifer. For example, Cooper and Jacob (1946) is commonly used for determining storativity and transmissivity of non-equilibrium radial flow in a confined aquifer. For this method, a straight line is fitted through the variable flow rate drawdown data over logarithmic time scale. Jacob (1947) first described two components for calculating well losses of pumping a groundwater well by plotting the drawdown over flow vs. flow (Equation 1).

$$S = BQ + CQ^2 \tag{1}$$

Where S is drawdown, B is the linear aquifer loss coefficient and C is a non-linear well loss coefficient. By dividing drawdown by flow, a straight line is produced where the aquifer loss is the y intercept and well loss is the slope of the line.

For LFG extraction, determining the hydraulic and pneumatic properties of the waste is not as simple as in groundwater well hydraulics. The hydraulic/pneumatic behaviour of municipal solid waste is extremely complicated and difficult to accurately model due to the nature and properties of the waste and changes in the waste over time.

Subsection 2.1 of this chapter reviews the various types of gas wells used for LFG extraction. Subsection 2.2 briefly synthesizes research characterizing polyphasic flow within porous media. Subsection 2.3 describes extraction well performance analysis and design, including the radius of influence, interactions between the extraction wells, and the use of pumping tests and field trials in the design of gas extraction systems and extraction wells in MSW. Finally, subsection 2.4 reviews gas extraction models which suggest how the specifics of well construction specifications may affect gas extraction.

2.1 Gas Extraction/Collection Systems

Gas extraction/collection systems are generally characterized by a network of vertical or horizontal wells connected to a large pump by way of a “header” pipe. A negative pressure is created in the header pipe by the pump, which in turn creates a pressure differential in the LFG wells to draw out the gas from the pore space in the refuse.

2.1.1 Gas Wells

Vertical wells are generally the preferred well type for MSW gas extraction systems (Townsend et al., 2005) because they are cost effective and easy to implement after the placement of waste and cover systems. Vertical wells are also less vulnerable to damage due to the differential settlement of MSW over time. Vertical gas wells are typically constructed with a half-slotted, half-solid pipe in a borehole that is drilled to a slightly larger diameter to allow for the emplacement of a highly permeable surrounding material, such as a fine uniform screened and washed gravel (pea-gravel), to mitigate clogging of the well-screen and provide a larger screen surface area. The area around the solid section of pipe is in-filled with a grout or bentonite plug/seal and auger cuttings from excavation of the borehole. The preferred pipe material types used for vertical wells are high-density polyethylene (HDPE) or polypropelene (PP) due to their flexibility and resistance to fracturing during settlement of the refuse. Polyvinyl chloride (PVC) pipe is also sometimes used; however, it is usually more brittle and susceptible to fracturing. Figure 2-1 shows a typically constructed vertical gas extraction well.

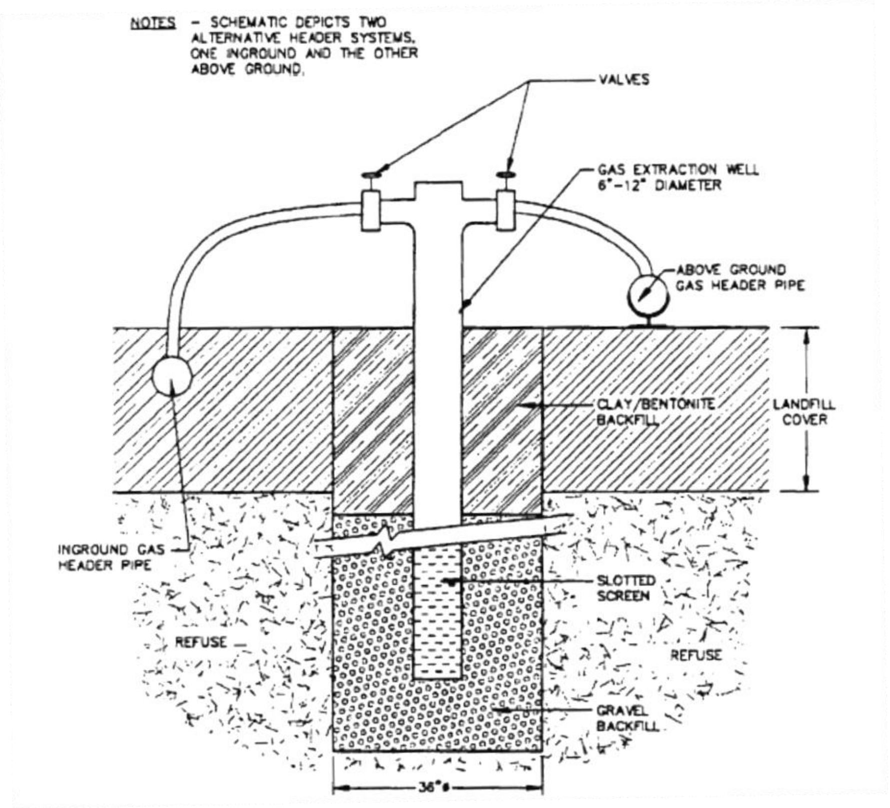


Figure 2-1. Typical vertical well for gas extraction in MSW (McBean et al., 1995).

Horizontal wells consist of a perforated pipe placed in the refuse during deposition. Such wells can be retrofitted by means of a directional drill; however, this procedure can prove to be extremely challenging and is often expensive (Cox et al., 2006). Horizontal wells might be used instead of vertical wells if local authorities or bylaws enforce gas collection early in the construction and deposition stages. Otherwise, and in general, vertical wells are more effective

(Townsend et al., 2005). Horizontal wells are constructed in a similar fashion to leachate collection systems, which can, in the early stages of landfill operation, serve a dual function by also collecting landfill gas (Townsend and Miller, 1997). Horizontal wells can prove more advantageous than vertical wells for vapour extraction in the vadose zones of contaminated soil due to the larger screen size (Zhan and Park, 2002); however, horizontal wells are less desirable due to the layering of landfill refuse and daily covers as well as the extreme settling and volume change of the landfill over its lifetime. This means that gas extraction with a horizontal well might not be as effective throughout the entire depth and lifespan of the landfill.

2.2 Polyphase Fluid Flow in Municipal Solid Waste

Full characterization of LFG flow in municipal solid waste is nearly impossible due to the complex nature of the refuse, interactions of the fluids and gases within the MSW matrix, and the evolution of the MSW over time. MSW is a polyphasic medium, the heterogeneity of which is not only mechanical but also hydraulic and pneumatic (re transport of liquids and gases) and biochemical. To characterize fluid and gas flow within MSW, parameters must be selected to effectively capture the essential aspects of the waste while simultaneously acknowledging their approximate nature. Some important considerations for fluid flow in MSW that may not be applicable to flow in the vadose zone are the constant generation of gases due to biochemical reactions, the evolution of porosity with time due to solids loss from biodegradation and mechanical settling, and the complex interfacial interactions of all the components of LFG and the liquids within the MSW.

Another factor usually not considered is the dual porosity nature of MSW. A dual porosity model (Mooder and Mendoza, 2000) of flow is one that describes flow through media with two distinct overlapping and interacting domains within a single heterogenous matrix. Mooder and Mendoza conceptualized MSW as a combination of loose waste and refuse contained in semi-intact garbage bags. In their model, the primary channel (described as the volume between the semi-intact garbage bags) is the primary conductive domain and the bags of refuse are a secondary, “storative domain” represented as “porous spheres”. The two domains are coupled using transfer coefficients to represent the resistance to fluid or mass migration across the garbage bag interface. Moisture movement is characterized by rapid flow through the loose waste and gradual water transfer into the garbage bags.

Active gas control systems are in common use at MSW landfills. The design of these systems requires a good understanding of the polyphasic LFG flow, defined as the flow of two or more fluids in a porous matrix that differ in their thermodynamic state and/or chemical composition. Polyphasic fluid dynamics in porous media is a non-linear phenomenon that is very complicated to model mathematically (Knudsen and Hansen, 2006; Nastev et al., 2001; Martin et al., 1997; and others). This is especially true for landfills due to their highly heterogeneous and time-dependent structure and properties (Durmusogulu et al., 2005). Richards (1931) and was the first to model flow in a polyphasic system. His model assumed that Darcy’s law is independently valid for the two phases, and that the volume-averaged velocities are proportional to the respective pressure gradients and effective permeability. His work resulted in the concept of relative permeability, which is the ratio of the effective permeability of the fluid of interest to the absolute permeability of the medium. Problems with generalizing Darcy’s Law for a polyphasic system arise with the assumption that fluid phases interact with each other in the same way that they interact with the porous media (solids). This assumption is too simplistic as it does not take into account the effects of viscous coupling between the non-wetting and the wetting phases or the partial dissolution of some of the gas components into the wetting phase. With such a simple generalization, models depend more on empirical correlations and coefficients for a wider range of operating and design conditions.

Other models that attempt to solve the polyphase problem have used variations of percolation and homogenization. Percolation models study slow polyphase flow in a porous medium by capillary forces; this type of model has been studied both theoretically (Broadbent and Hammersley, 1957; de Gennes and Guyon, 1978; Chandler et al., 1982; Wilkinson and Willemsen, 1983; Guyon et al., 1984) and experimentally (Lenormand, 1981). In a percolation type model, flow is induced through a random network by the capillarity (Fatt, 1956; Singhal and Somerton, 1977), and the displacement of the fluids is considered as a sequence of the states of equilibrium. Homogenization theory is derived by macroscopic functions and is obtained by asymptotic developments (Ene and Sanchez-Palencia, 1975) or by averaging local values. The averaging methods can be divided into two groups: the first consists of volume-averaging methods (Whitaker, 1969, 1973, 1986 I,II, and III); Gray and O'Neill, 1976; Hassanizadeh, 1980), which are based on the concept of a representative elementary volume (REV) that implies spatial indifference and time invariance; the second group involves weight function methods, pioneered by Matheron (1965) and developed by Marie (1965, 1967, 1982).

2.3 Flow to Extraction Wells in Municipal Solid Waste

Migration of gas in a landfill was first modeled in only a single dimension, where the refuse was assumed to be a heterogeneous and non-deformable medium, and steady state conditions were reached instantaneously (Findikakis and Leckie, 1979). Although these assumptions oversimplified gas flow in MSW, Findikakis and Leckie's model was one of the pioneering papers used in modeling gas phase flow to an extraction well in MSW.

Gas extraction modeling describes the production and movement of landfill gas through a single gas extraction well or network thereof. Modeling gas extraction to wells aids in understanding of effects of various parameters on the efficiency of extraction. Extensive analytical solutions for polyphasic flow to wells in the vadose zone (McWhorter, 1990; Baehr and Hult, 1991; and others) have been developed for problems with vapour extraction in soils affected by sub-surface contamination. However, several important and challenging aspects of flow to gas collection wells in MSW, such as the time-dependent physical properties of refuse, are not as problematic for wells in the vadose zone in soil remediation applications. These aspects are related to the variations of gas storage, and include compression and mechanical settlement, porosity enlargement from degradation of the organic matter, cover soil and oxygen ingress, dissolution of gas from the leachate, and, most importantly, gas generation.

An analytical solution for steady state gas flow around multiple extraction wells in MSW was first developed with assumptions that the landfill is rigid (not susceptible to settling or porosity changes from degradation of the organic matter) and gas generation/storage is constant (Young, 1989). Young developed a two-dimensional model (assuming no change in the pressure profile along the length of the well) incorporating Darcy's Law that describes the transport of a single species in a non-isotropic porous medium with constant gas generation and impermeable boundaries (representing a liner and final cover) with an arbitrary number of horizontal gas wells. However, this solution is limited to newer landfills constructed with low permeability covers and liners and is not valid for permeable boundary conditions.

More recent analytical solutions (Arigala, 1995; Townsend et al., 2005) improve on Young's model by incorporating a first-order gas generation term (Equation 2) similar to that described in Findikakis and Leckie (1979) and El-Fadel et al. (1995).

$$\alpha_j(t) = CA_j\lambda_j e^{-\lambda_j t};\ \ j = 1, 2, 3, \qquad (2)$$

where C = total capacity for gas production (mass of total gas produced per volume of MSW deposited); A_j = fraction of the MSW corresponding to component j; and λ_j = reaction rate constant corresponding to that exponent. The overall gas production rate is thus:

$$\alpha(t) = \sum_{j-1}^{3} \alpha_j(t), \qquad (3)$$

Arigala (1995) modeled various numbers of vertical wells represented by line sinks (Figure 2-2) with permeable boundary conditions. This approach was more flexible for applications to older landfill sites, closer to real field conditions, and able to gauge the effects of cover soil on the collection efficiency of the wells. Townsend et al. (2005) modeled the effects of waste permeability and waste thickness on the collection efficiency of two horizontal gas collection zones.

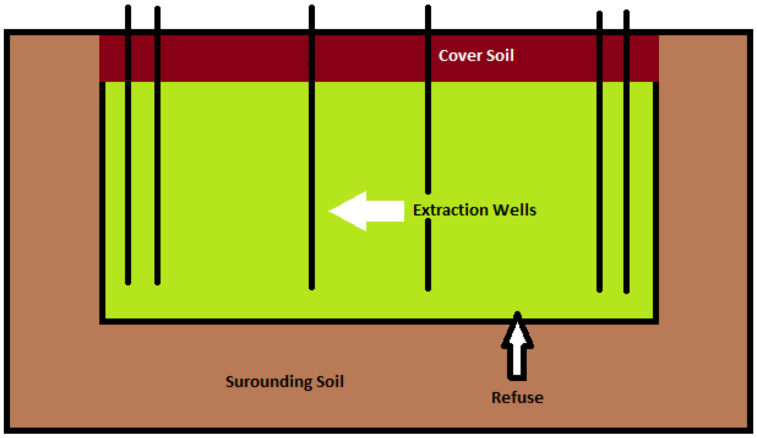


Figure 2-2. Model cross section (Arigala, 1995).

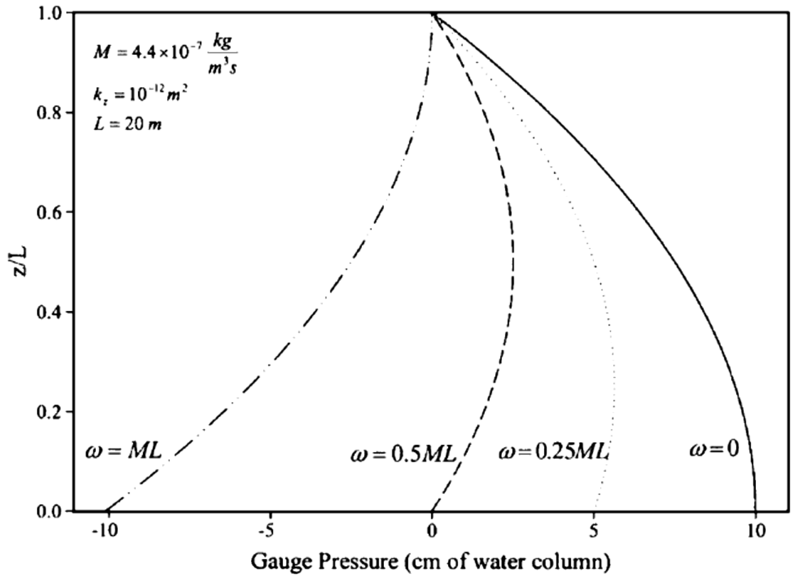


Figure 2-3. Pressure distribution of various scenarios and combinations of extraction through the Leachate Collection System (LCS) alone and LCS plus surface geomembrane (Townsend et al., 2005).

These models assumed constant gas phase permeability with depth and that leachate perched over the collection system would not interfere with the gas collection efficiency of the bottom extraction zone. These assumptions are clearly flawed; however, this analytical model is simple and provides reasonable estimates of the extraction pressures required for horizontal collection systems as well as the collection efficiency, and thus informs gas collection strategies for horizontal collection wells (Figure 2-3).

Several numerical solutions have been formulated to analyze gas flow around gas extraction wells in MSW (Martin et al., 1997; Nastev et al., 2001; Chen et al., 2003; and others). Martin et al. (1997) proposed a simple numerical model for a manually controlled extraction well that analyzed the effects of air concentration on the concentration of biogas. Air ingress and its effects on methane concentration was also modeled by Nastev et al. (2001), who devised a solution for axi-symmetric gas flow around a single active gas well using the finite difference method with a TOUGH2-LGM simulator. A TOUGH2-LGM simulator was also used to model the radius of influence of a gas extraction well by Vigneault et al. (2004), who considered waste thickness, generation of landfill gases, and concentration of CH4 in the landfill gas as variables affecting the radius of influence of the well (Figure 2-4).

A numerical solution for passive gas flow to a single vertical well, gauging the effects of parameters such as final cover thickness, cover soil permeability, age of the waste since final cover soil deposition, and well depth (Figure 2-5 (a) through (d)), was also modeled with the finite difference method by Chen et al. (2003).

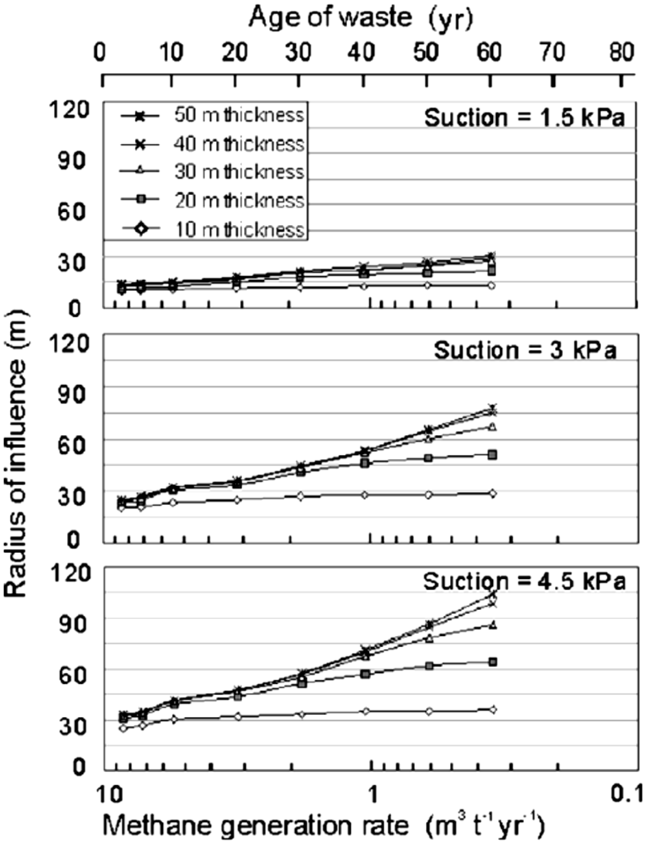


Figure 2-4. Effects of methane generation rate on the radius of influence of a MSW extraction well (Vigneault et al., 2004).

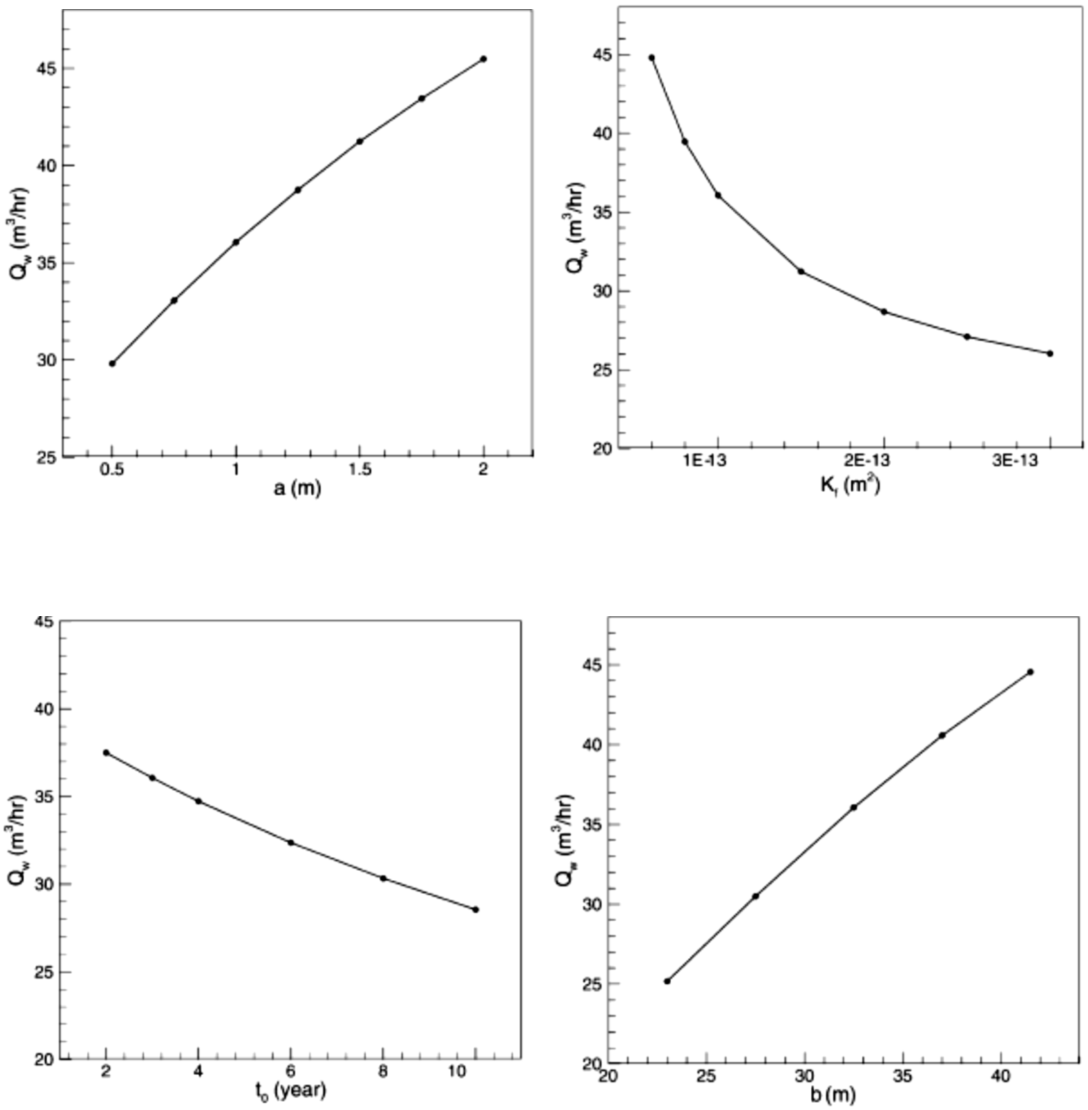


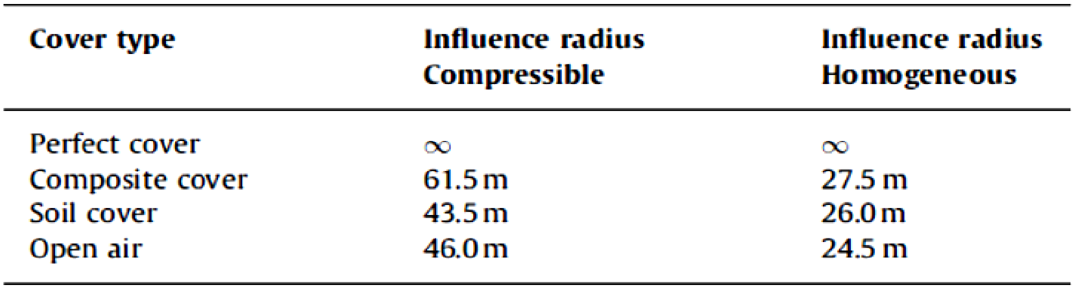
Figure 2-5. Gas flow vs. (a) final cover thickness, (b) cover soil permeability, (c) age of the waste since final cover soil deposition, and (d) well depth (Chen et al., 2003).

Chen's and Vigneault's numerical models have several important and practical implications regarding construction specifics on the cover soil and well. In general, their findings suggest that deeper wells placed in older and thicker wastes with thicker, less permeable covers, will result in the higher gas flows over larger areas (suggests reduced SC and large ROI).

However, results from these models still have limited applicability and should be used carefully due to fundamental errors in the assumptions that gas generation is constant (Young, 1989) and that landfills are homogeneous, rigid, and have a constant porosity (Young, 1989; Arigala, 1995; Townsend et al., 2005; Martin et al., 1997; Nastev at al., 2001; Chen et al., 2003). The pneumatic and hydraulic properties of MSW are also complicated by its heterogeneity (Durmusogulu et al., 2005), the evolution of the pore space with time due to mechanical settling and biochemical degradation (Liu et al., 2006; Hettiarachchi et al., 2007; Tinet and Oxarango, 2010; Yu et al., 2009; Stoltz et al., 2010), complex polyphase interfacial interactions (Sanchez et al., 2010), and the dual porosity nature of MSW (Mooder and Mendoza, 2000).

The effects of mechanical settling coupled with gas generation, transport, and changes in the MSW pores were first modeled numerically based on the mass balance of gas (Hettiarachchi et al., 2007) and Fredlund and Rahardjo's (1993) theory of linear unsaturated soil consolidation (Liu et al., 2006). Both of these models assume that variation in the porosity of the MSW during compression is the sum of the consolidation that occurs due to changes in effective stress and enlarged void volume from the biochemical degradation. Neither model considered changes in gas phase storativity due to variations in the dissolved fraction of each gas component. Yu et al. (2009) formulated an analytical model of gas flow to a vertical extraction well that took into account time-dependent compressibility, dissolution of the gases, and porosity enlargement from biodegradation. They assumed that all deformation occurred in the vertical direction, that the gases follow Boyle's ideal gas law, and that dissolution obeys Henry's law. Gas pressure and velocity distributions to extraction wells can be very sensitive to the time-dependent compressibility of the refuse (Tinet and Oxarango, 2010), which also improves overall well collection efficiency as defined by the gas wells influence radius (Table 2-1). However, these models still assume that all of the void space formed due to biochemical degradation will translate into mechanical settlement. This assumption is questionable and has yet to be thoroughly examined. Overall, considerable improvements have been made in the last 20 to 30 years regarding the accurate description of the pneumatic behaviour of gas extraction to extraction wells in MSW. However, such models are complicated and may be impractical to implement.

Table 2-1. Influence radii for different cover types (Tinet and Oxarango, 2010).



Cover type	Influence radius Compressible	Influence radius Homogeneous
Perfect cover	∞	∞
Composite cover	61.5 m	27.5 m
Soil cover	43.5 m	26.0 m
Open air	46.0 m	24.5 m

2.3.1 Radius of Influence

The radius of influence (ROI), for a gas extraction well has been defined in several different ways. The most common definition is the radius at which the change in pressure is equal to zero, and this has been used as a single parameter relating gas yields to applied suction (Lofy, 1983). ROI has also been defined in numerical models as the radial volume surrounding a well in which recovery rate of the generated methane in the radial volume is 90% (Vigneault et al., 2004). However, this definition requires one to first know the gas production rate of the refuse. Gardner et al. (1990) noted that defining the ROI as the point of zero pressure change produces results that appear excessive, and instead suggested that a more realistic determination of ROI, depending of site-specific characterizations, was an allowable pressure gradient differential between 0.5 mPa/m and 1.3 mPa/m using a line of best fit from pumping tests results.

Several papers have established the shape and extent of the zone surrounding an extraction well or series of extraction wells (Lofy, 1983; Young 1989, Vigneault et al., 2004). The shape and extent of the ROI is hypothesized to be primarily impacted by the amount of vacuum applied, extraction rate, permeability of the waste, permeability and thickness of the final cover, and well characteristics such as length of the screen and the amount and type of perforations. However, these assumptions may also be too simplistic as the ROI may be influenced by other factors (e.g., the availability of the gas, ratio of gas extraction to gas generation rate, transportation of liquids to the well due to applied vacuum, in-situ moisture content). Moreover, construction of practical gas extraction systems involves many wells that will invariably interact with one another. Therefore, the ROI for any given well is also dependent on other wells in the surrounding area. Young and Gay (1995) analyzed these interactions using a term they coined the yield reduction coefficient (YRC). They demonstrated that wells interact with each other, as reflected in the value of the YRC variable, depending on variables such as the distance from each other (Figure 2-6), depth of the well perforations, horizontal and vertical permeability of the refuse (Figure 2-7), length of the perforated section, and radius of the effective screen of the well.

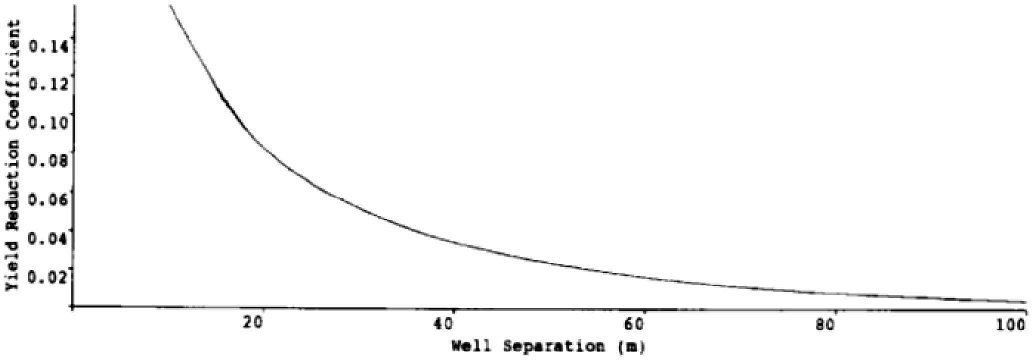


Figure 2-6. YRC vs. well spacing (Young and Gay, 1995).

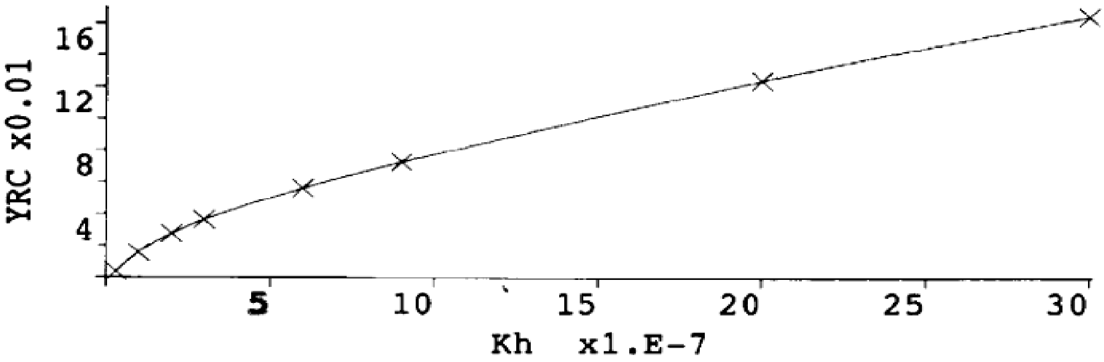


Figure 2-7. YRC vs. horizontal permeability (Young and Gay, 1995).

They also proposed a cap parameter L, which reflected the properties of the final cover and was defined as

$$L = \frac{lK_v}{K_l}, \tag{4}$$

Where l is the cap thickness, Kv the vertical permeability, and Kl the vertical gas permeability

(Figure 2-8).

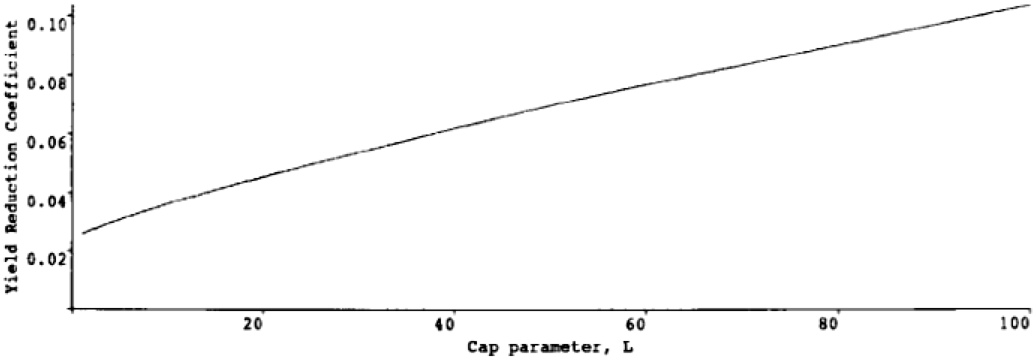


Figure 2-8. YRC vs. cap parameter (Young and Gay, 1995).

2.3.2 Pumping Tests

Pumping Tests in groundwater wells are typically carried out to determine the following:

1) Performance characteristics of the well.

2) Hydraulic parameters of the aquifer.

The most typical pumping test carried out for these purposes in groundwater wells are step-drawdown tests (Driscoll, 1986). Step-drawdown tests can also be useful in a network analysis of landfill gas wells to characterize the pneumatic and hydraulic properties of the ambient municipal waste for the purpose of gas extraction system design. A step-drawdown pumping test for a landfill gas extraction well is similar to groundwater pumping tests (Gardner et al., 1990; Nastev et al., 2001; Yu et al., 2009), however, no standard pumping test method exists for landfill gas wells. It is traditionally thought that pumping tests used to estimate the ambient pneumatic properties of the waste and also the maximum sustainable yield of methane gas extraction (the highest possible extraction rate of methane gas without oxygen ingress into the waste), should be run for extended periods of time (2 weeks or longer) while monitoring gas composition, extraction rates, and pressures in the MSW. These longer-term pumping tests and trials are expensive and time consuming to construct and perform, however, they are a commonplace requirement for system design due to the complexity of wastes pneumatic behaviours, and the difficulty of modeling wastes pneumatic properties. And yet, it has been cautioned (Walter, 2003) that well efficiency estimates which rely on the gas production rate cannot be accurately measured by pumping trials as they tend to over- or under-estimate the rates depending on the accuracy of the measured radius of influence.

2.4 Well Construction Specifications and Extraction Efficiency

Well efficiency of a groundwater well has been traditionally defined as the ratio of the actual specific capacity at the designed well yield to the maximum specific capacity possible – calculated from formation characteristics and well geometry (Mogg, 1968). Using this method, it is possible to identify the amount of head loss attributed to natural head losses in the formation and those caused by a poorly designed/constructed well. An efficient well has therefore been defined as having a 0.7 to 0.8 specific capacity design to max possible specific capacity ratio (Driscoll, 1986).

There is no similar calculation for determining the efficiency of a landfill gas well. However, landfill gas extraction wells are still typically designed to some minimum specifications. For example, McBean et al. (1995) shows a typically constructed gas well as having a borehole diameter of 0.90 m with a minimum casing diameter of 0.15 m to 0.30 m (Figure 2-1). It has also been suggested that some construction specifications of the landfill gas well will affect gas extraction. For example, Gardner et al. (1990) proposed that screen length may have a measureable impact on extraction well effectiveness as defined by its radius of influence. Chen (2003) hypothesized that well depth is a contributing factor to gas flux in the well and Gamliel and Abdul (1992) suggested that such a relationship is linear.

Other authors have suggested that construction specifications of the gas extraction wells will also have predictable and measureable impacts on each other. For example, Young and Gay (1995) showed, through modeling the gas well interactions of two neighbouring wells, that the length of the perforated screen will increase that wells susceptibility to be influenced by an adjacent well but will not necessarily be itself an influence on the other nearby wells. They also suggest that placement of a well near low permeable boundaries will reduce the wells influence on neighbouring wells but increase the influence of the neighbouring wells on it. They also suggest that the effective radius of the well screen may also increase its YRC (influence on nearby wells). However, the effects of these well construction characteristics on well extraction efficiency as defined by its ROI and SC has yet to be thoroughly and empirically examined in a full-scale documented trial.

CHAPTER 3
METHODOLOGY

This chapter outlines the design and methodology of research that aims to 1) assess the effects of variations in well construction and specifications on landfill gas well performance and 2) evaluate short- and longer-term pumping test methods that are used to estimate gas well efficiency, pneumatic conductivity of the waste, and sustainable gas yield from a landfill gas extraction well-field. The trials were field based and conducted at the Spadina landfill, located in the City of Saskatoon, Saskatchewan. A site plan showing the location of the demo area and the design of the extraction system is shown in Figure 3-1.

3.1 Site Background

Saskatoon's Spadina landfill commenced waste filling in 1955 and is located in the southwest part of Saskatoon, approximately 500 m from the South Saskatchewan River and the Queen Elizabeth Power Plant. Based on information provided by the City of Saskatoon, the landfill currently holds approximately four million tonnes of waste on a 31 hectare footprint and has a depth of approximately 35 m from the crest.

The older portion of the landfill was constructed as a “non-engineered” dry cell, meaning that it was not designed with barrier or leachate collection systems. It was situated on glacial till with an overlying shallow surficial aquifer comprised of stratified deposits (terrace sands) of the Quaternary-age Saskatoon Group. The surficial sands allow for considerable groundwater movement and are a pathway for leachate to seep into the groundwater and migrate to the South Saskatchewan River located to the south of the landfill. As a mitigation measure, groundwater interception trenches were constructed so that impacted groundwater could be collected and pumped to holding ponds or to the wastewater treatment plant (Singh and Fleming, 2004).

Figure 3-1. Site Plan (contours provided by the City of Saskatoon).

3.2 Field Design and Construction

This project involved drilling and construction of ten (10) vertical LFG extraction wells in the Spadina landfill. The older region of the landfill where the wells were drilled was trapezoidal in shape with a total area of approximately 12,500 m^2. It was split into two sections, referred to as the East Header (EH) and West Header (WH) collection areas, respectively.

3.2.1 Gas Extraction Wells

Vertical gas wells consist of several components/sections. Typically, a half solid-half slotted pipe inserted into an augered hole and backfilled with 0.5 cm (¼ inch) screened crushed stone (pea-gravel) with a bentonite seal placed over the screened interval to mitigate oxygen ingress during pumping.

3.2.1.1 Gas Extraction Well Installation

Gas wells were installed in the Spadina landfill from 2004 to 2007 using various sizes of solid and hollow stem continuous flight augers (CFA). Five (5) different drilling strategies were attempted to determine the most effective for the installation of the vertical extraction wells.

1. For gas wells (GW) 01-04, 02-04, 03-04, 08-07, and 09-07, the desired drilling depth was reached with a single pass of a 15 cm (6 inch) solid stem CFA. Provided that the hole remained open after withdrawal of the auger, the 5 cm well casing was placed and pea-gravel poured into the annulus around the casing to a depth of approximately 7.5 m (25 ft) below ground surface (BGS). The annular space around the solid well casing was then sealed with bentonite chips that were placed immediately overlaying the top of the pea-gravel and extending all the way to surface. Once the bentonite chip seal was hydrated, a wellbore seal was then placed around each of the wells and covered with the final cover soil material.

2. For gas well 05-06, the desired drilling depth was reached in a single pass with a 15 cm (6 inch) solid stem CFA. The 10 cm well casing was then placed into the hole by pushing with the derrick of the drilling rig. This was required due to natural squeezing of the sides of the borehole around the well casing, which was close to the same diameter. No pea-gravel was added for screening and the annular space around the casing was sealed, for the uppermost part of the well, using backfill from the final cover. A geomembrane wellbore seal was also installed at surface.

3. Gas well 06-07 was drilled to desired drilling depth in a single pass with a 25 cm (10 inch) hollow-stem auger from surface. The 10 cm well casing and pea-gravel were inserted into the hole on the inside of the auger. After the casing and screen material were placed, the augers were carefully removed from the hole. The annular space around the casing was then filled to surface with bentonite chips and the wellbore seal installed at surface.

4. Gas wells 04-07 and 10-07 were first drilled to desired drilling depth in a single pass with a 15 cm (6 inch) solid stem CFA. The holes were then widened with a 20 cm (8 inch) hollow stem CFA. After a single pass with the 20 cm hollow-stem auger, the wells were constructed in the same manner as described in method 3.

5. Gas well 07-07 was drilled to its desired drilling depth in a single pass with a 15 cm (6 inch) solid-stem CFA, then gradually widened by re-drilling with consecutively larger (20 and 27.5 cm) augers. Once drilled to the desired depth at the desired borehole diameter (27.5 cm), the well was constructed in the same manner as described in method 3.

These different strategies were investigated to determine the most efficient method for drilling in municipal waste due to the extreme heterogeneity of wastes properties and as well as maximize the number of wellbores that could be drilled on a limited budget. It was also necessary to devise different drilling strategies for holes that were difficult to drill or that collapsed once the augers were removed, rather than risk damage or excessive rental costs for drilling and excavation equipment. The construction methodology and gas well specifications for each well are provided in Table 3-1 and Table 3-2.

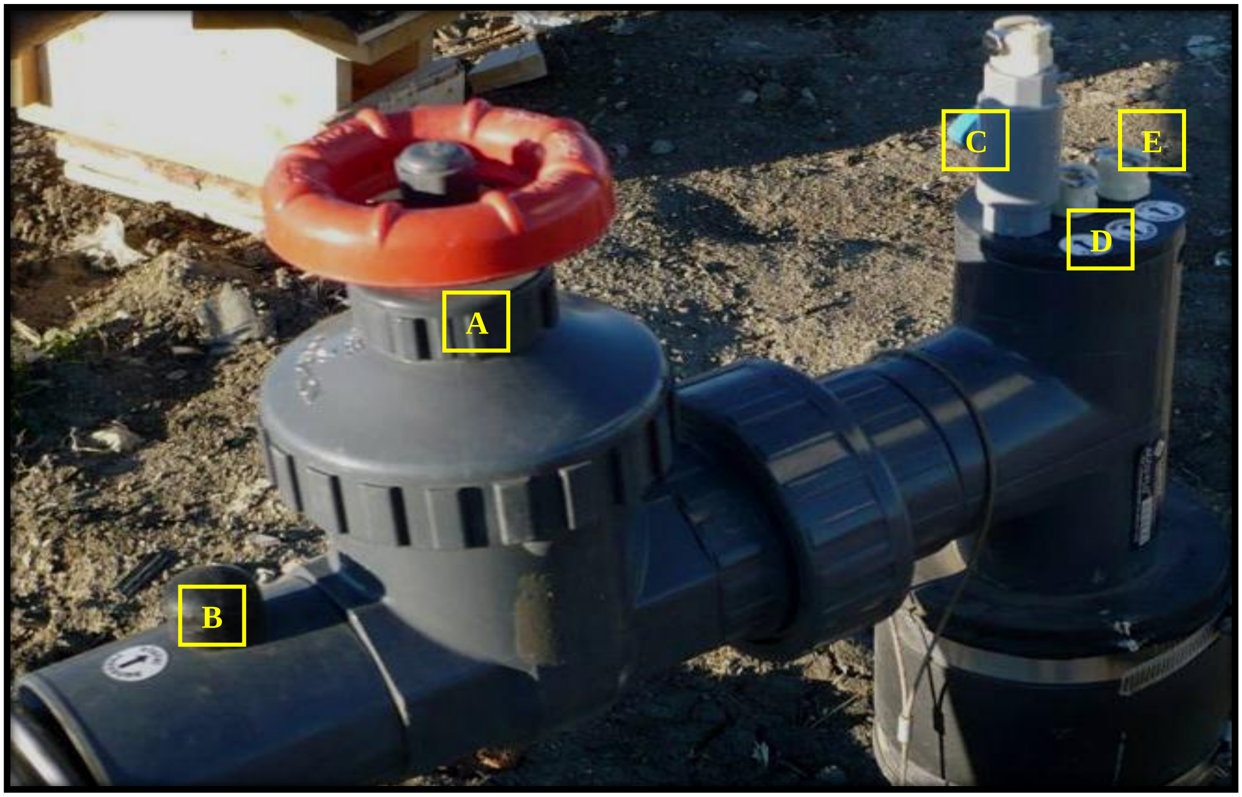
Table 3-1. Gas well construction methodology.

LFG Wells	Year Drilled	# Passes to Drill	Pass 1	Pass 2	Pass 3
GW01-04	2004	1	15 cm SS	N/A	N/A
GW02-04	2004	1	15 cm SS	N/A	N/A
GW03-04	2004	1	15 cm SS	N/A	N/A
GW04-07	2007	2	15 cm SS	20 cm HS	N/A
GW05-06	2006	1	15 cm SS	N/A	N/A
GW06-07	2007	1	25 cm HS	N/A	N/A
GW07-07	2007	3	15 cm SS	20 cm HS	27.5 cm HS
GW08-07	2007	1	15 cm SS	N/A	N/A
GW09-07	2007	1	15 cm SS	N/A	N/A
GW10-07	2007	2	15 cm SS	20 cm HS	N/A

Table 3-2. Gas well construction specifications.

LFG Wells	Depth (m)	Pipe Diam. (cm)	Borehole Diam. (cm)	Gravel Pack (Y/N)	Solid Int. (m)	Slotted Int. (m)	Gravel Screened int. (m)
GW01-04	24	5	15	Y	0 – 8.33	8.33 – 24.00	6.00 – 24.00
GW02-04	25.5	5	15	Y	0 – 8.40	8.40 – 25.50	9.00 – 25.50
GW03-04	21.8	5	15	Y	0 – 7.50	7.50 – 21.75	6.00 – 21.75
GW04-07	12	5	20	Y	0 – 7.73	7.73 – 12.00	6.60 – 12.00
GW05-06	23.4	10	15	N	0 – 9.14	9.14 – 23.40	9.14 – 23.40
GW06-07	14.4	10	25	Y	0 – 5.84	5.84 – 14.40	5.40 – 14.40
GW07-07	18.3	10	27.5	Y	0 – 9.74	9.74 – 18.30	8.40 – 18.30
GW08-07	13.5	5	15	Y	0 – 7.80	7.80 – 13.50	7.50 – 13.50
GW09-07	17.1	5	15	Y	0 – 8.55	8.55 – 17.10	8.10 – 17.10
GW10-07	20.7	10	20	Y	0 – 9.29	9.29 – 20.70	8.40 – 20.70

The gas extraction wells were constructed with slightly different specifications for the purpose of evaluation. Each well was fitted with a 5 cm (2 inch) wellhead assembly (Photograph 3-1).



Photograph 3-1. Wellhead assembly: (A) wellhead control valve; (B) downstream well pressure sample port; (C) temperature probe access port; (D) dynamic pressure measurement port (fitted to calibrated pitot tube for measurement of well flow); and (E) upstream wellhead static pressure port.

A PVC geomembrane was wrapped around the casing near the surface and spread over an approximate 3 by 3 m area and backfilled to help reduce ingress of oxygen into the well as a result of short-circuiting immediately adjacent to the well casing. This is particularly important if the annular seal around the casing is imperfect or if desiccation cracking occurs in the cover in the vicinity of the well. Notably, this well seal does not prevent oxygen ingress; however, it helps to reduce the negative effects associated with a poor soil cap by lengthening the path of flow around each wellbore. A wellbore seal is pictured below in Photograph 3-2.

Photograph 3-2. Geomembrane wellbore seal (PVC geomembrane).

3.2.1.2 Costs of Gas Well Construction

The cost for each individual gas well was estimated by averaging the drilling time on a unit (per metre) basis and multiplying the total depth of the drilled well by the number of passes used to achieve the well diameter. For example, if the unit rate of drilling each metre was averaged at \$50/m, drilling a 30 m deep by 27.5 cm diameter well (which would have been drilled in 3 passes) would cost approximately \$4500 (not including materials). The cost of drilling was then added to the cost of the materials used for a given well. The materials for each wellhead and wellbore seal were not added as these costs were the same for each well.

3.2.2 Gas Probes

Gas probes were constructed for the purpose of monitoring the LFG pressure and composition with respect to distance from the well (or wells) undergoing testing during single well step-drawdown testing and system LFG extraction testing. The installation specifications and cross-section for the gas probes are very similar to the gas wells (Figure 3-4), except that they have a shallower depth of penetration, shorter screen length, and the top is fitted with a cap and ball-valve with a single connection port rather than a wellhead. Construction specifications of the four (4) gas probes are provided in Table 3-3.

Table 3-3. Gas probe specifications.

LFG Probes	Depth (m)	Screened Interval (m)	Borehole Diam. (cm)	Pipe ID (cm)	Pipe Wall Thickness (mm)
GP01-04	12	6 - 12	15	5	4
GP02-04	12	6 - 12	15	5	4
GP03-04	12	6 - 12	15	5	4
GP04-07	10.5	6 - 10.5	15	5	4

3.2.3 Gas Collection Header Design

The gas collection header was built using 20 cm (8 inch) HDPE pipe with a wall thickness of approximately 13 mm (1/2 inch). This large pipe size was selected to make things simpler for the purposes of analysis, as pressure losses in the header pipe and in the well casings could be minimized. To satisfy this assumption, the Darcy-Weisbach equation (Equation 5) was used to calculate the expected pressure loss due to gaseous flow:

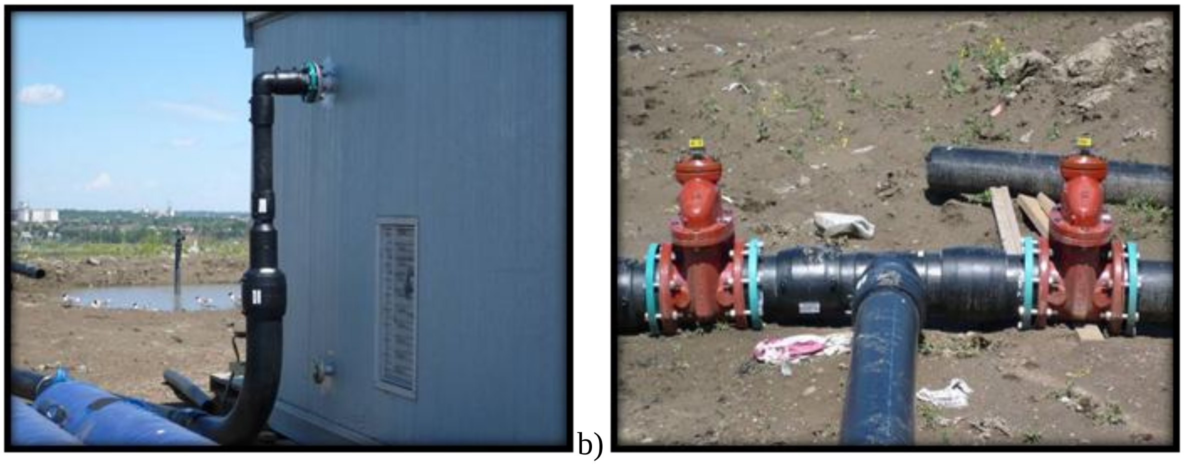
$$h_f = f\frac{L}{D}\frac{V^2}{2g}, \tag{5}$$

Where hf is the head loss due to friction (m), L is the length of the pipe (m), D is the hydraulic diameter of the pipe (m), V is the average velocity of the fluid flow (m/s), g is the local acceleration due to gravity (m/s^2), and f is a dimensionless coefficient called the Darcy friction factor. The pipe flow was assumed to be laminar and the gas was assumed to be ideal (i.e., no volume or temperature changes in the gas itself during flow). This calculation also assumed no elevation differences along the given length of pipe (L). With this method, the losses in pressure due to friction/viscous effects were calculated to be approximately 0.002 and 0.107 kPa for a 300 m long section of 20 cm header pipe and 24 m section of 5 cm well casing, respectively. The flow rate used was 0.56 m^3/min (20 standard cubic feet per minute (scfm)) at an initial pressure head of 5 kPa. These pressure changes represent ~0.04 and 2.1%, respectively, and thus the initial assumption of negligible pressure losses was considered reasonable.

In addition, and perhaps more importantly, the oversized header pipes (fitted with large header control valves) allowed the header vacuum to be used to control the rate of gas extraction from the wellfield under conditions in which, when each wellhead valve was fully opened, the wellhead vacuum could be maintained essentially constant for all extraction wells in the wellfield. Thus it was possible to evaluate the effect on the overall LFG extraction rate of varying the method of controlling the vacuum at each wellhead (i.e. variable wellhead vacuum by adjusting individual wellhead control valves vs. spatially uniform wellhead vacuum using the oversized header system). Trials were carried out using both of these approaches and the results are discussed below.

Photograph 3-3 shows the pumphouse inlet (a) and the header control valves (b) for the EH and WH collection areas. The WH and EH areas were separated close to the blower unit by large

(20 cm) gate valves. These valves were installed so that the pressure on each side of the header system could be controlled independently.



a) b)

Photograph 3-3. Pumphouse inlet and header control valves.

3.3 Pumping Tests

Two (2) different types of pumping tests were carried out for the purpose of this study: short-term and longer-term. These pumping tests were performed to compare the results of short and longer-term extraction on LFG collection wells and to compare the collection well construction specifications to pneumatic performance (defined by the collection wells specific capacity and radius of influence). A total of four (4) well-field extraction tests were carried out and one (1) round of individual (short-term) step-drawdown tests performed. The pumping test procedures are described below in the order in which they were performed. In brief,

1. A pumping test was carried out with all control valves set to fully open and the blower set to its maximum capacity to determine the maximum possible extraction rate of the well-field;

2. A pumping test was carried out to evaluate the previously estimated total sustainable gas yield of 5,663 L/min (200 scfm), which is approximately 566 L/min (20 scfm) per well. This rate is based on the welled volume of the gas wells and an approximate gas production rate of 3 to 5 m^3/T/year.

3. Individual step-drawdown pumping tests were carried out for each extraction well;

4. A longer-term system extraction was conducted with a constant system static pressure on both EH and WH and flow controlled at each individual well control valve (A in Photograph 3-1); and

5. A second longer-term system extraction test was conducted with individual control valves set to fully open and the total flow controlled with the main control valves.

The entire system was first checked for leaks prior to any testing of the wells. In the leak test, all individual wellhead valves were closed to ensure a sufficient seal when system was pressurized. A pressure was applied to the system by turning on the main pump. The main control valves were closed and the pump was turned off. The header network was then monitored over the course of two (2) hours for losses of vacuum is the pressure gauges installed near the main control valves and at the far ends of both the EH and WH. It was assumed the gas collection header system had no leaks if the pressure remained constant for a minimum of one (1) hour.

3.3.1 Pumping Test for Maximum Rate of Extraction

This pumping test was the first performed on the system. The pump was set to its maximum pumping capacity and all wells were set to fully open. Flow rates, well pressures, and system pressure were recorded over the course of approximately 24 hours. The procedure followed for this test is briefly described below.

1. All individual wellhead control valves were set to fully open.

2. The pump was turned on and set to maximum pumping capacity.

3. Flow rate and gas composition were monitored at each well and gas probe.

4. The test was completed once significant air ingress was observed, as indicated by oxygen in the gas composition readings. Individual wellhead control valves were adjusted to lower flow rates before the next extraction test was started.

3.3.2 Well-Field Extraction Testing at Estimated Sustainable Yield (5.7 m^3/min)

Well-field extraction testing was carried out to evaluate the estimated sustainable yield of gas extraction in the study area. The estimated rate of yield was ~0.57 m^3/min (20 scfm) at each gas well, for a total system extraction rate of ~5.7 m^3/min (200 scfm). The procedure followed for this test is described below.

1. Vacuum pressure in the system collection header on both the EH and WH was set to approximately 5 to 7.5 kPa (20 to 30 inH_2O) by adjusting the pump and the main control valves.

2. Each gas extraction well was then adjusted to produce roughly 0.57 m^3/min (20 scfm), allowing for slight variations due to changes in barometric pressure and ambient air temperature. Flow rate adjustment was an iterative process, as adjustments for individual wells had a measureable impact on the pressures and flows of every other well in the system and, consequently, the total system pressure.

3. After setting the pressures and flows, extraction wells and probes were carefully monitored with respect to pressure, gas composition, and flow rate changes.

4. Once oxygen was detected in the landfill through close monitoring of the gas wells and probes, all wells were shut-in and the pump turned off. The extraction wells and monitoring probes were monitored during recovery.

3.3.3 Step-Drawdown Pumping Tests

Step-drawdown tests were performed for each individual well in the gas collection system to measure specific capacity, which was used in this research as a simple surrogate for the pneumatic conductivity and extraction well efficiency (ROI). Using the variation in measured specific capacity and ROI to evaluate the effect of varying the design/construction of gas wells presupposes similar pneumatic conductivity (air permeability) of the waste at the various well locations and no significant spatial variation in the gas generation rate of the waste. This assumption is at least partially valid as McBean et al. (1984) found isotropic effects of pumping gas in MSW.

Each test consisted of three to four 2-hour intervals, during which a constant pumping rate was maintained. During each test, the nearby probes and extraction wells were monitored to assess the degree of lateral influence of the wells in the testing area and to calculate the radius of influence for each extraction well at various flow rates.

After measurement of the wellhead pressure (assumed equal to wellbore pressure) at three or four flow rates, the specific capacity was determined from the slope of the best-fit line. Using customary units (wellhead vacuum measured in inches of water-column and flow rate measured in scfm), the units of the specific capacity are scfm per inH_2O. This could also be expressed in metric units (m^3/s per kPa); however, using units of scfm per inH_2O maintains consistency with the units used in the commonly available instruments for taking measurements in the field.

The procedure used for step-drawdown pumping test is described below.

1. All individual control valves were closed so there was no flow in the system. The static pressure in the gas well to be tested and in nearby gas probes and monitoring wells was measured.

2. The header line vacuum pressure was set at an arbitrary but easy to work with value typically within the range of 5 to 7.5 kPa (20 to 30 inH_2O).

3. The flow in the well being tested was adjusted to a low (approximately 5-10 scfm) flow rate.

4. Fluctuations in pressure in the pumping well and in the nearby gas probes and monitoring wells were monitored and recorded. It was also necessary over the course of each successive step to periodically adjust the wellhead control valve to maintain the flow at the target rate.

5. If little to no change in pressure or flow was evident over a 1-2 hour period, the flow rate was increased and maintained at the next flow rate. Monitoring of the nearby probes and extraction wells was repeated with the procedure described in stage 4.

6. For each step in the test, the flow rate in the testing well was increased by approximately 10 scfm and stages 4 through 5 were repeated for three (3) or preferably four (4) flow steps.

7. After the final step in the test, the well was shut-in by quickly closing the wellhead control valve. The extraction well undergoing the test, and the probes and other nearby extraction wells, were then closely monitored during recovery of pressures.

The step-drawdown data were used to characterize the flow capacity and pneumatic efficiency of each gas well in terms of its specific capacity. The specific capacity of a well is defined as the change in flow rate divided by the increment of static pressure (or vacuum) as measured at the well. For the range of flow rates, depths, and diameters of gas wells considered in this study, it was assumed that pressure losses from the screen to the wellhead (refer to section 3.3.6) were sufficiently low for the wellbore vacuum to represent the vacuum applied at the wellscreen (i.e., a boundary condition for the production rate and area of influence of the well).

3.3.4 Longer-Term System Pumping Tests

Two different methodologies were used for longer-term extraction testing. The first was a constant flow rate test in which a constant system flow rate was established by adjusting the individual wellheads and allowing fluctuations in system pressure. Flow rates in a given well were decreased if oxygen levels were above ~0.5% or found to be continually rising during extraction. The pressure in the header was first set at 5 to 7.5 kPa (20 to 30 inH_2O) vacuum. Each well was then adjusted to yield a flow rate of 10 to 15 scfm with a small allowance for fluctuations due to changes in atmospheric temperature and pressure. Throughout these tests, the gas probes were closely monitored.

After approximately 6 weeks, the extraction methodology was changed to a constant pressure test. Each flow control valve on the wells was set to fully open, and a small amount of vacuum held constant in the header using the large main system control valves. In the constant pressure method, the flow at the wells was allowed to vary. A low vacuum of approximately 0.75 kPa (approximately 3 inH_2O) was set in the header. The valves at the wells were then set to fully open, and flows monitored on a semi-regular basis. This testing method was also maintained for approximately 6 weeks, with close monitoring of the probes and gas concentrations within the landfill.

3.4 Extraction Test Monitoring Equipment

This study employed a gas extraction monitor (GEM) 2000 purchased from CES Landtec (Photograph 3-4). This monitor was selected due to its capacity for real time monitoring and storage of specific gas concentrations (CO_2, CH_4, and O_2) as well as static and dynamic well pressures and temperature. The GEM 2000 had the capability to automatically correct for barometric pressure and could be calibrated in advance for each of the wellheads. The GEM's onboard memory could store data that was recorded in the field and transfer the data directly to a Microsoft Excel™ spreadsheet for data analysis by connecting the GEM to a laptop computer.

Photograph 3-4. Gas Extraction Monitor (GEM) 2000.

CHAPTER 4
RESULTS

The complexity of the experimental design and, consequently, the large amounts of time and effort to design and construct the network (wells and header system) for this project, allowed the benefit of conducting a more simple and straightforward network analysis of the resulting data. This chapter presents the results of the gas extraction pumping tests carried out at Saskatoon's Spadina landfill. The results were analyzed to compare the efficiency and performance of the landfill gas extraction wells to their construction methods and specifications. Also evaluated and compared were the short- and longer-term pumping test methods to estimate the ambient pneumatic behaviors of the wells (measured by specific capacity) and extraction performance of the system (oxygen ingress measured at the wells and probes, and total extracted flow of LFG).

4.1 Gas Well Construction Methods

In this study, each gas well was constructed with different specifications, including the size of pipe, the diameter of the wellbore, the length and diameter of the screen, and depth of placement. The difficulty of drilling and the estimated time and costs associated with the drilling of landfill gas extraction wells were somewhat unpredictable. This is covered in detail in section 4.5. However, the wells with wellbores larger than 15 cm diameter were, in general, more time consuming, more difficult to drill, and more likely to damage equipment during drilling. However, it was observed that the drilling difficulty was lessened, although the total well construction time significantly lengthened, by using multiple passes with ever-increasing drill bit sizes to gradually widen the borehole to achieve the desired wellbore diameter.

The total cost of drilling the seven wells came to approximately \$26,900. Only \$2,900 of this value represented the cost of the materials. Thus, the costs of construction and installation of landfill gas extraction wells were overwhelmingly due to the costs of drilling and not the cost of the materials.

4.2 Short-Term Test Methods and Well Performance Results

The following section presents data gathered from the short-term extraction pumping tests. The short-term tests carried out included a 24 hour maximum flow test of the entire well-field, a 200 hour well-field extraction test at an estimated longer-term sustainable pumping rate of 0.57 m^3/min (20 scfm) per well, and individual well step-drawdown tests.

4.2.1 24-hour and 200-hour extraction tests

A pumping test was carried out for the entire well-field to determine the maximum possible extraction rate with the control valves set to fully open and the blower set to its maximum capacity. This maximum extraction pumping test was carried out for approximately 24 hours immediately following the completion of construction of the header system. The total system flow at maximum extraction was measured at approximately 9.85 m^3/min (348 scfm) with an average system pressure of approximately 2.25 kPa (-9 inH_2O).

Immediately following the initial 24 hour maximum rate extraction test, each well was adjusted to yield a gas flow of approximately 0.57 m^3/min (20 scfm); this was a hypothesized rate for the sustainable yield of a single extraction well in the study area. During these first two pumping tests, oxygen levels in the wells were carefully monitored (Figure 4-1).

Oxygen levels in the majority of the wells rapidly increased during the maximum flow test and appeared to steadily decline following test completion and transition to the 200 hour (0.57 m^3/min/well) extraction test, with some wells fluctuating around 0.1-0.2 %. The exception was GW05-06 (shown in Figure 4-1 with a 0.1 multiplier), which was turned off after 42 hours

(18 hours after the completion of the full flow extraction test) due to excessive and rapidly increasing oxygen levels even after several adjustments to lower flow rates. Landfill gas composition was also monitored by probes during the course of the two initial short-term system extraction tests (Figure 4-2).

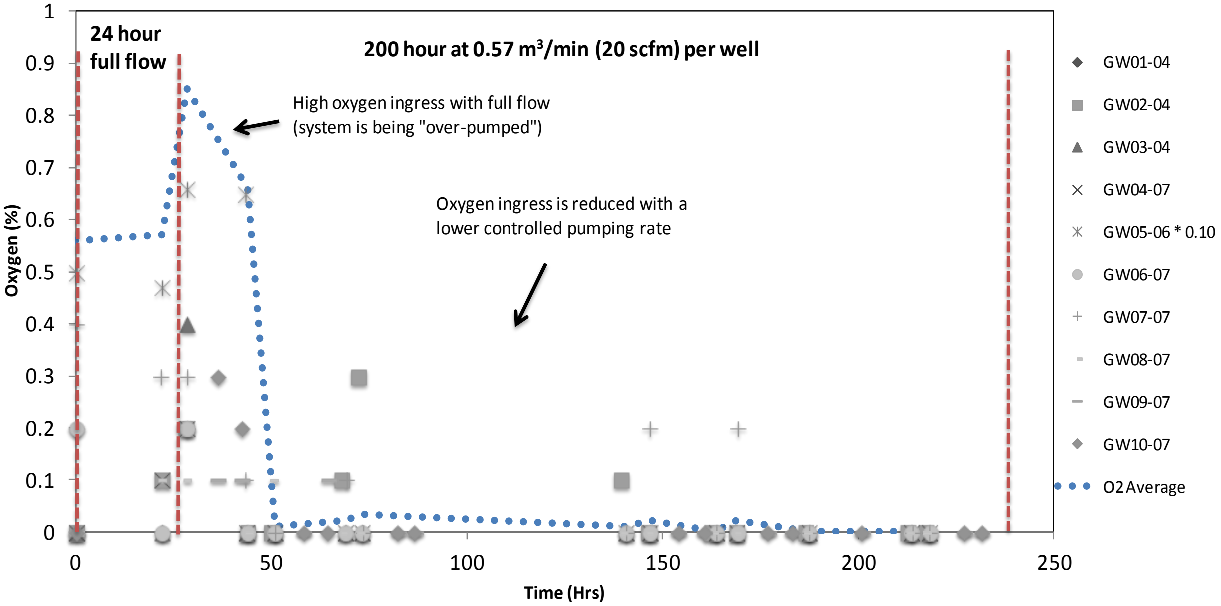


Figure 4-1. Gas well oxygen levels during short-term extraction pumping tests.

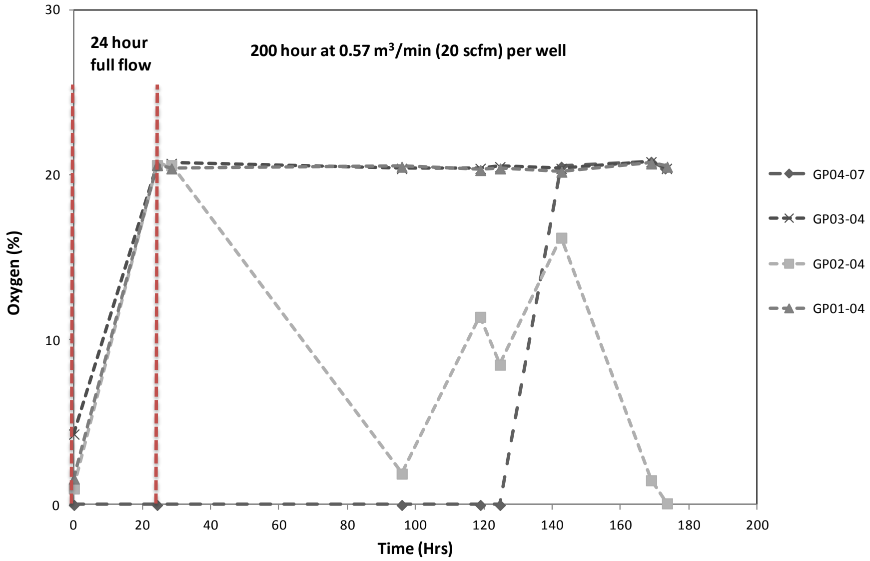


Figure 4-2. Oxygen levels recorded in gas probes during 24 hour and 200 hour extraction testing.

The general reduction in oxygen levels that was observed in the wells following the 24 hour maximum flow extraction test, as seen in Figure 4-1, was not fully corroborated by gas composition readings taken from the probes during the same time period as seen in Figure 4-2. Probe readings indicated that the refuse gas composition at shallower depths underwent a more rapid change to near atmospheric gas concentration levels and remained at these gas concentrations levels during the entire period of initial short-term extraction testing. The gas composition readings from the probes also appear to exhibit a delay in the ingress of atmospheric gases between the EH (GP01-04, GP02-04, and GP03-04) side of the collection area and the WH (GP04-07) side. This could be due to several reasons. First, the soil cover on the EH side of the collection area is, on average, more desiccated, thinner, or otherwise "weaker". Second, the ingress of atmospheric gas from GW05-06 had a greater measureable impact on the entire surrounding area. And lastly, the difference in gas composition between the WH and EH sides may accounted for in the difference in the total flow and extraction pressures on both sides, respectively. Table 4-1 summarizes the average well static pressures and flow rates along with well construction specifications.

Table 4-1. Construction details and initial performance measurements for wells (near-constant system pressure measurements show the effect of the oversized header system).

LFG Well	Depth	Pipe Diam.	Hole Diam.	Gravel Pack	Screened (gravel) Interval	Full Flow	Wellhead static pressure at full flow	Wellhead static pressure at 0.57m^3/min	System pressure at 0.57m^3/min
	(m)	(mm)	(mm)		(m)	(m^3/min)	(kPa)	(kPa)	(kPa)
GW01-04	24	51	152	yes	6.00 – 24.00	1.39	-2.09	-0.65	-5.03
GW02-04	26	51	152	yes	9.00 – 25.50	0.51	-2.44	-2.14	-5.1
GW03-04	22	51	152	yes	6.00 – 21.75	0.51	-2.34	-2.02	-5.05
GW04-07	13	51	203	yes	6.60 – 12.00	1.5	-1.94	-0.62	-5.08
GW05-06	24	102	152	no	9.14 – 23.40	0.62	-2.29	Shut Off	-
GW06-07	15	102	254	yes	5.40 – 14.40	0.93	-2.29	-1	-5.05
GW07-07	19	102	279	yes	8.40 – 18.30	0.45	-2.22	-2.49	-5.05
GW08-07	14	51	152	yes	7.50 – 13.50	1.42	-2.07	-0.5	-5.05
GW09-07	17	51	152	yes	8.10 – 17.10	1.53	-1.87	-0.15	-5.15
GW10-07	21	102	203	yes	8.40 – 20.70	0.99	-2.24	-0.95	-5.00

This table above provides a quick comparison and summary of the most important details of well construction and the results of the initial testing. Interestingly, but not unexpectedly, there appears to be no trend or correlation found in Table 4-1 between well performance, as measured by total well flow with respect to pressure, and well construction specifications.

4.2.2 Step-Drawdown Pumping Tests

Step-drawdown pumping tests were carried out to evaluate the gas yield of each well at various suction pressures. The resulting data were then used to calculate the specific capacity of each extraction well and to establish the well's radius of influence. For most wells, three different suction pressures were applied for intervals averaging 1.5 to 2 hours each. The tests were started at lower suction pressures/flow rates and were successively increased by intervals ranging between 0.14 and 0.42 m^3/min (5 to 15 scfm) per step. At the completion of the test, the well was quickly shut-in and the "recovery" of its pressure monitored. The results of the step-drawdown tests performed on all ten (10) wells are shown below in Figure 4-3 though Figure 4-12.

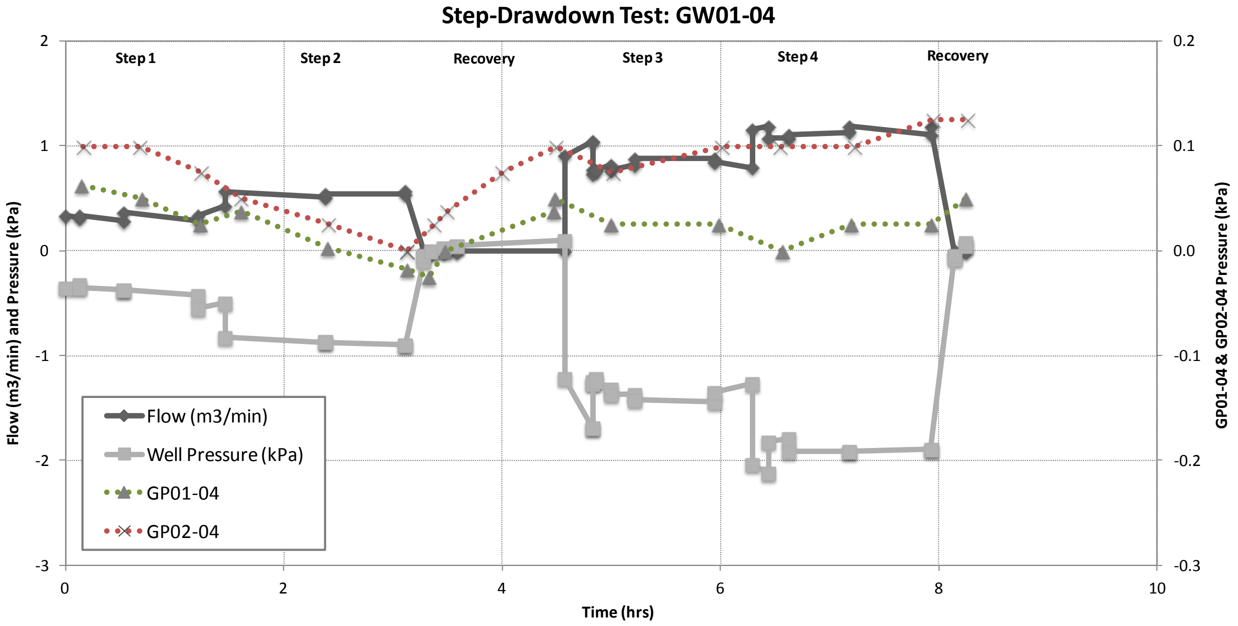


Figure 4-3. Step-drawdown test: GW01-04.

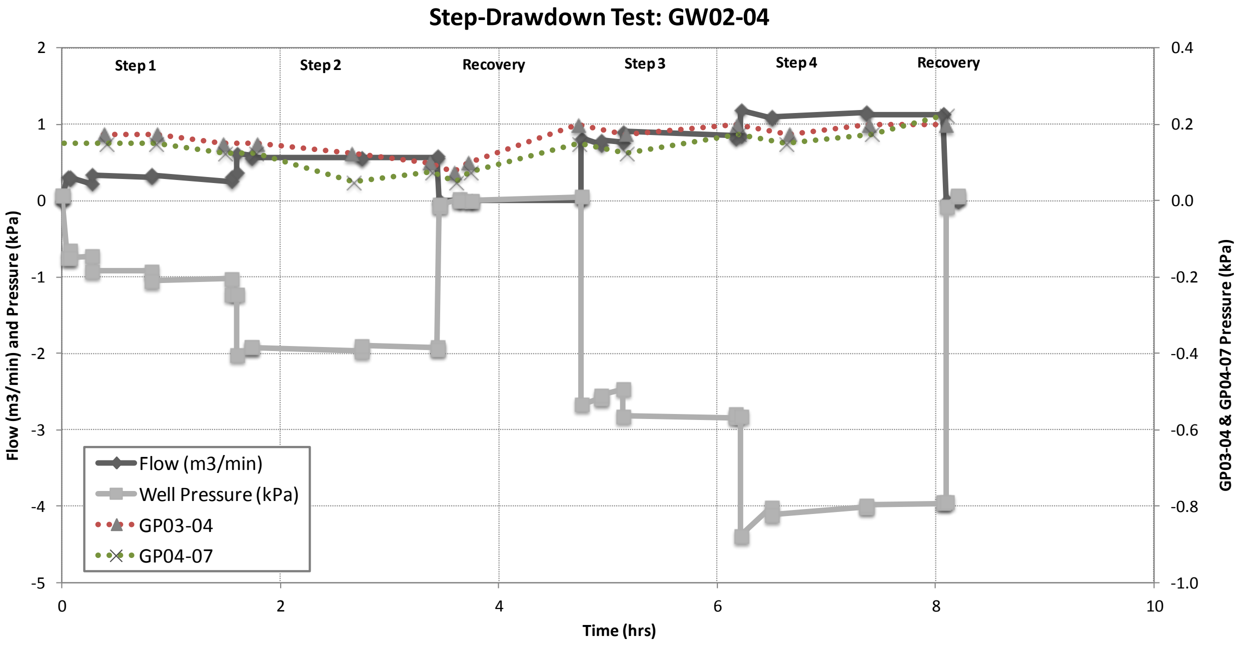


Figure 4-4. Step-drawdown test: GW02-04

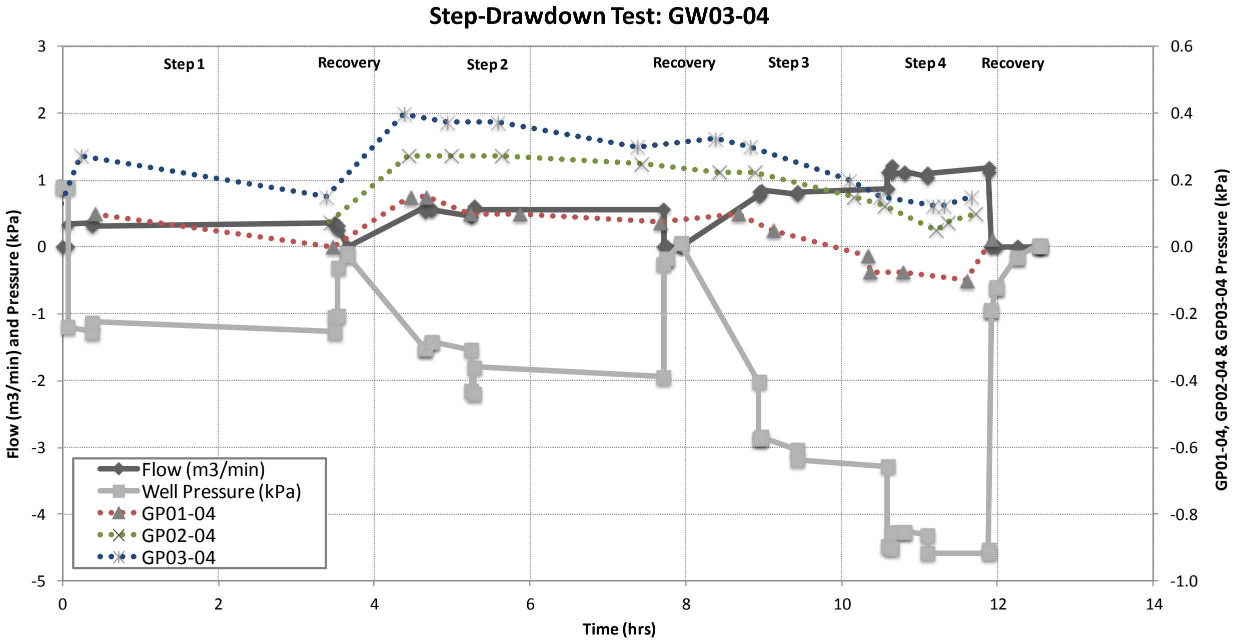


Figure 4-5. Step-drawdown test: GW03-04.

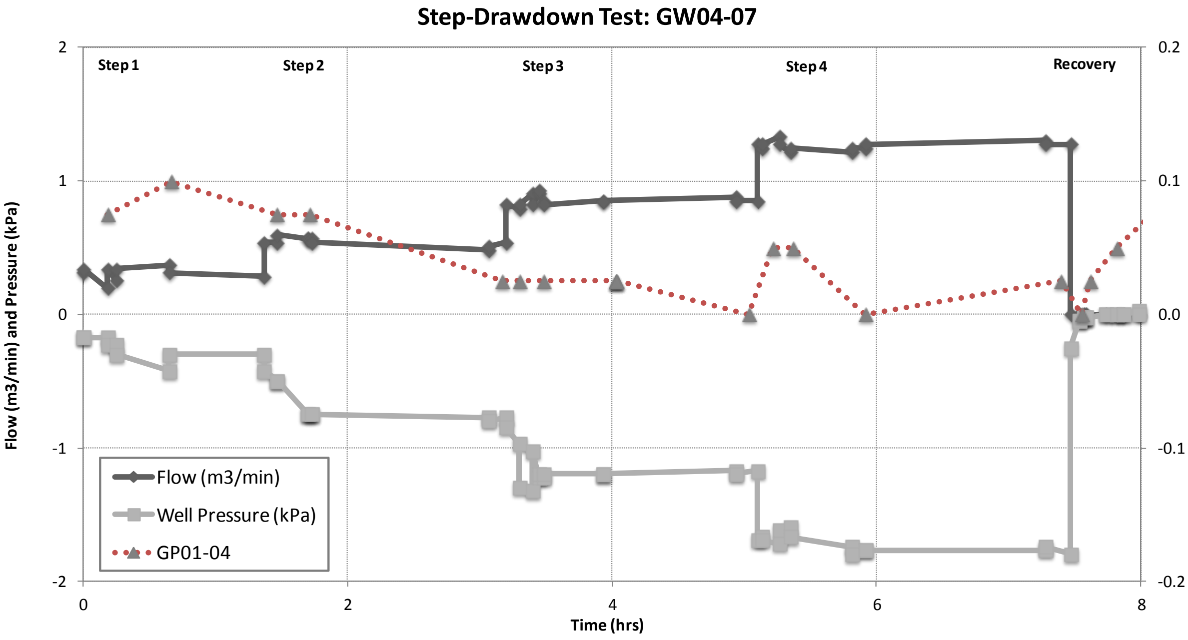


Figure 4-6. Step-drawdown test: GW04-07.

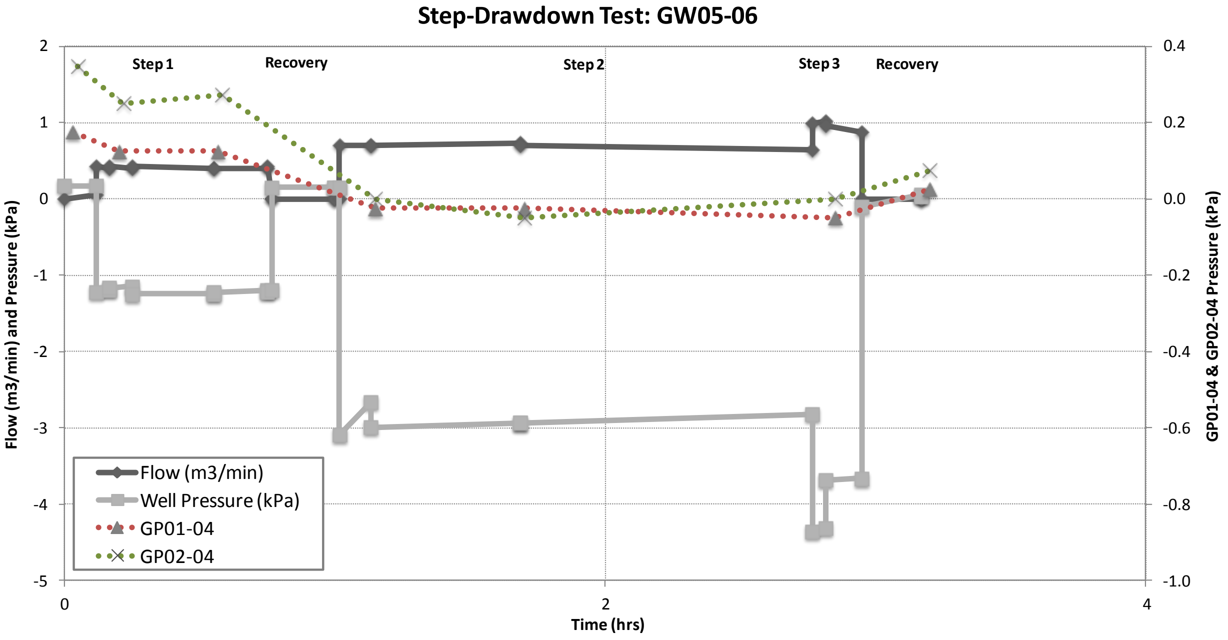


Figure 4-7. Step-drawdown test: GW05-06.

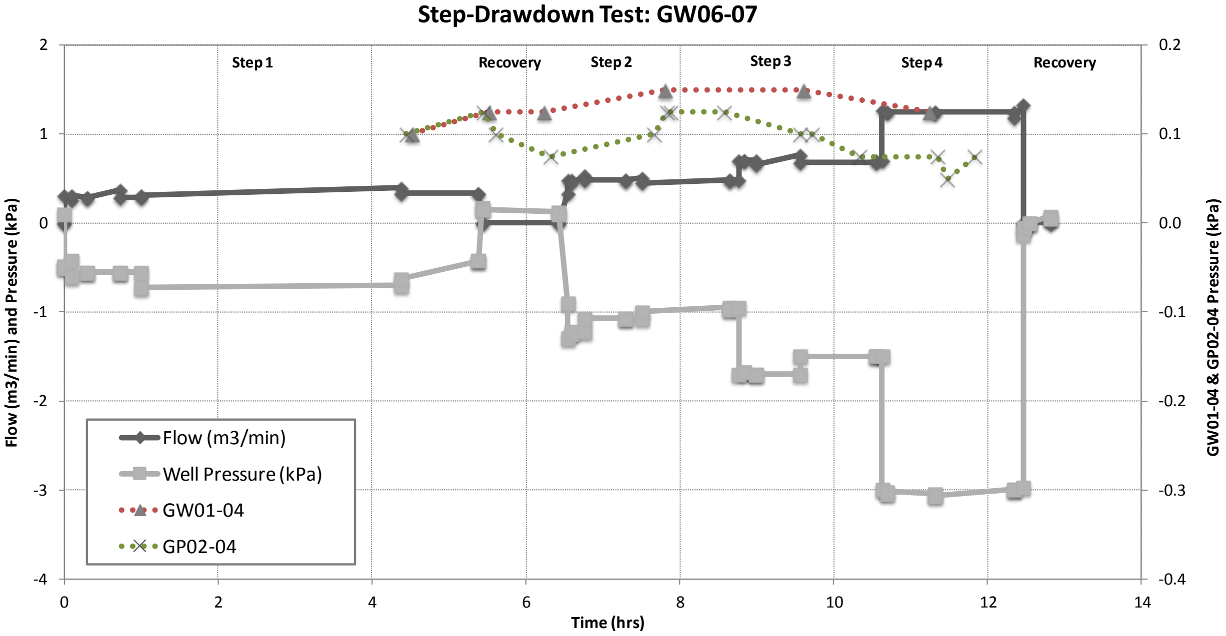


Figure 4-8. Step-drawdown test: GW06-07.

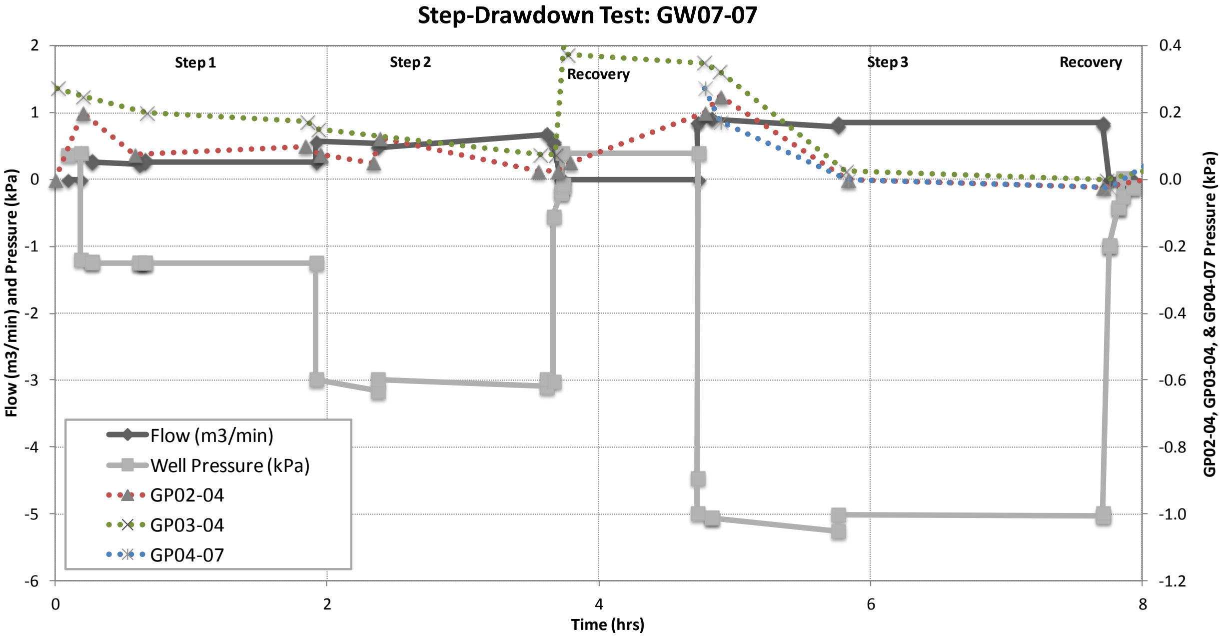


Figure 4-9. Step-drawdown test: GW07-07.

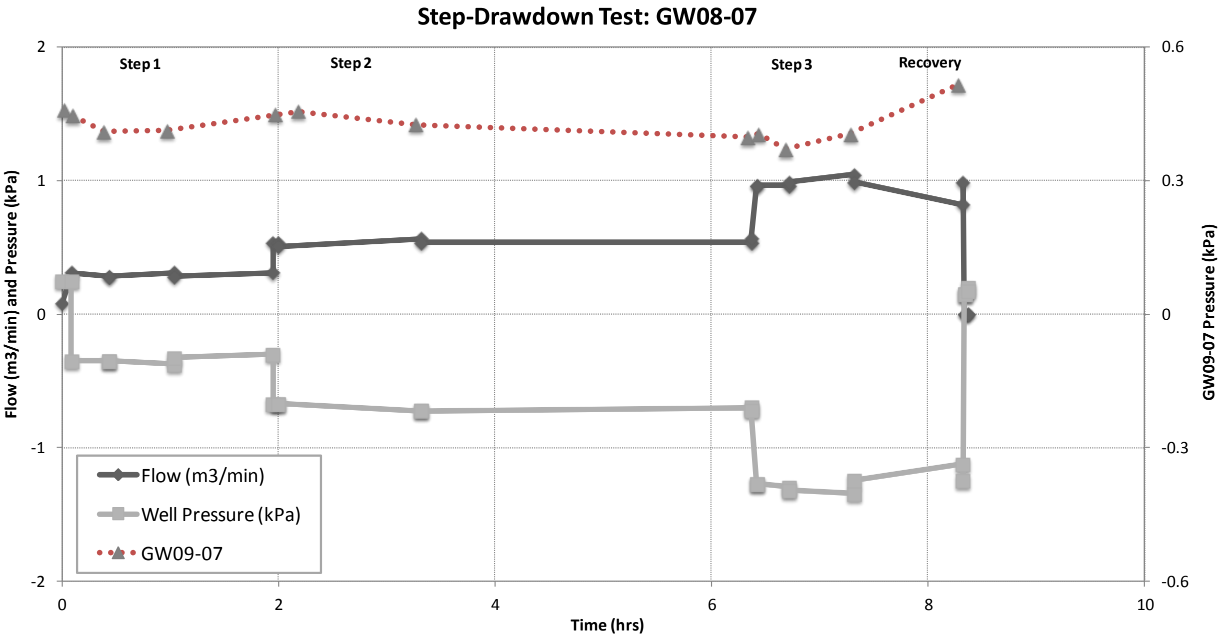


Figure 4-10. Step-drawdown test: GW08-07.

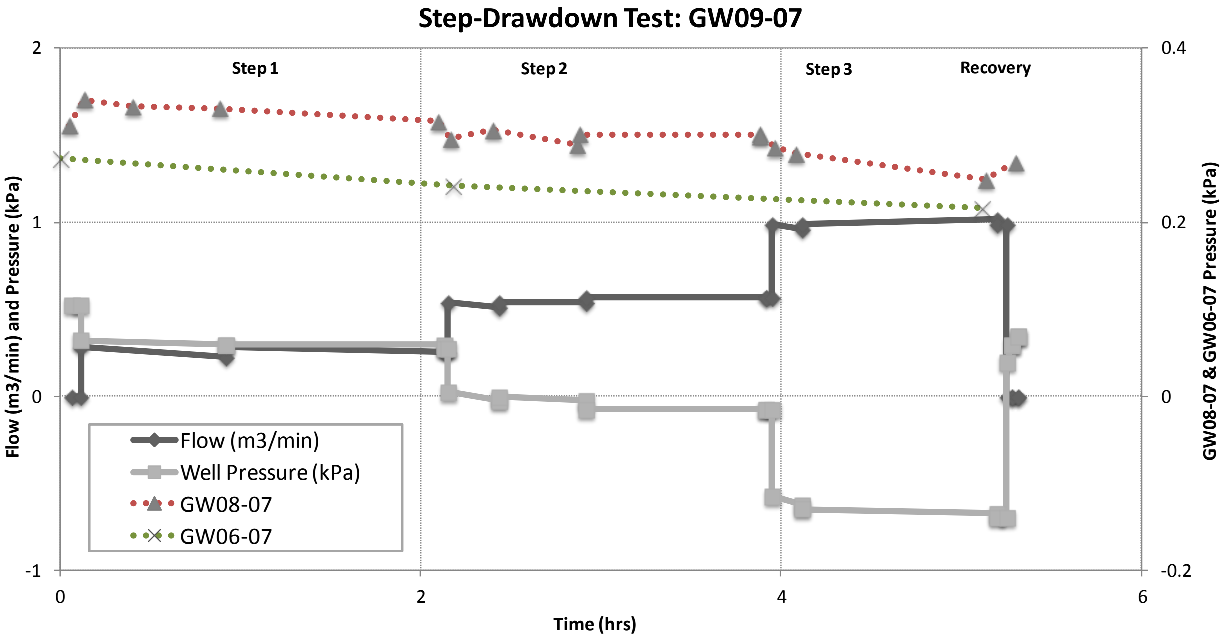


Figure 4-11. Step-drawdown test: GW09-07.

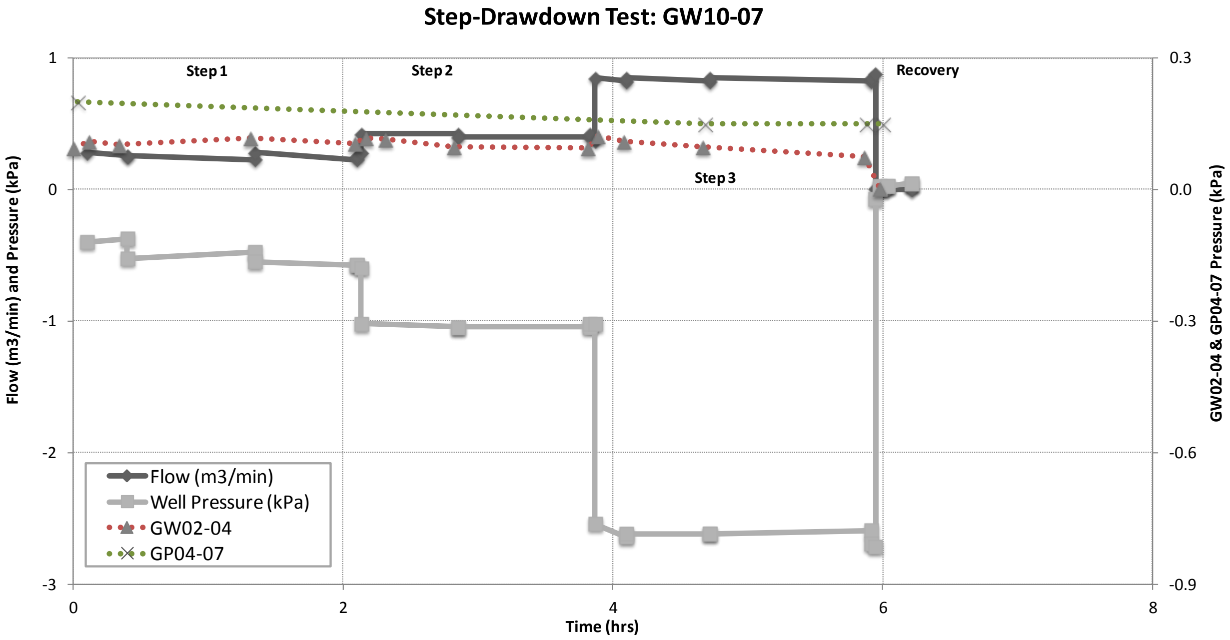
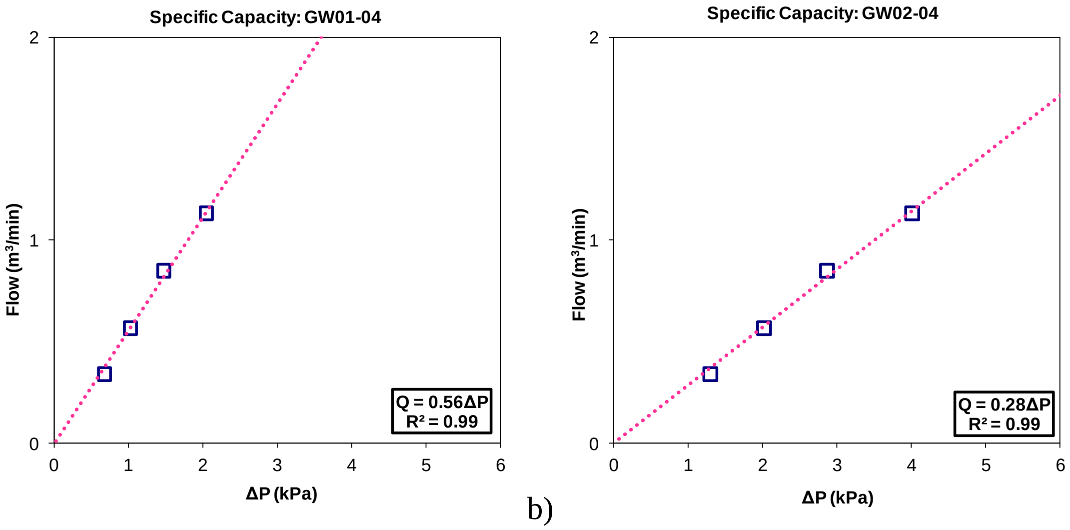
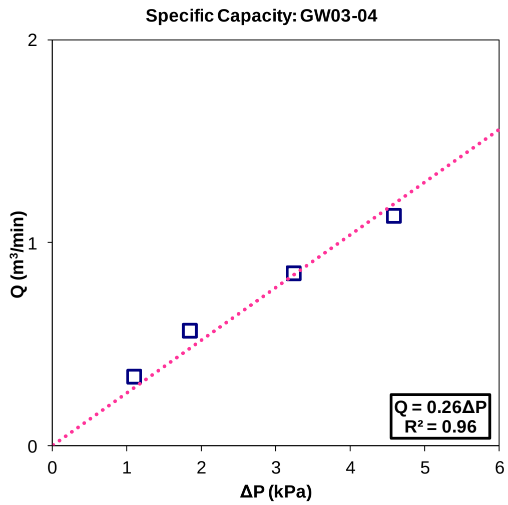


Figure 4-12. Step-drawdown test: GW10-07.

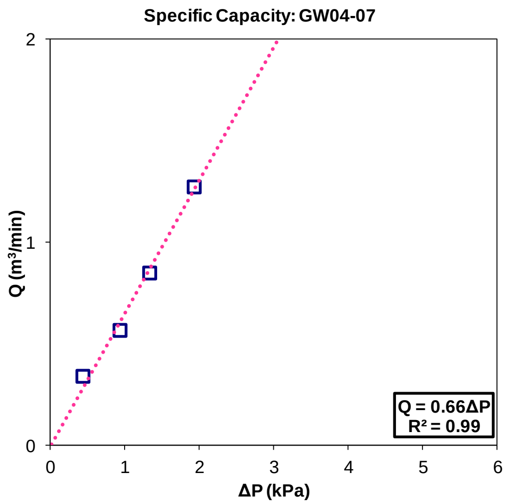
Specific capacity (S.C.) was calculated with the data obtained from each step-drawdown test. S.C. is defined as the change in flow rate divided by the increment of static pressure (or vacuum) as measured at the well. The specific capacity plots for the above step-drawdown tests are shown below in Figure 4.13 (a) through (j).



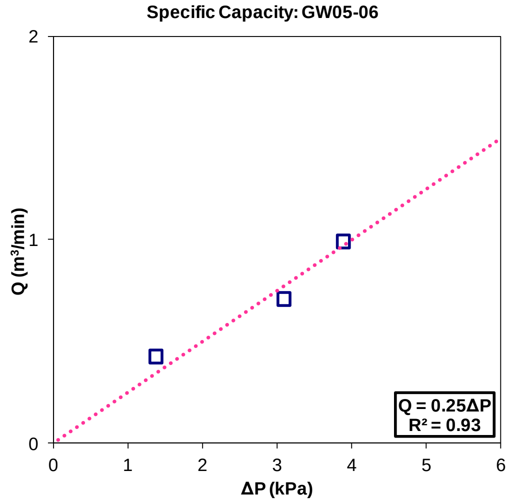
a) b)


Specific Capacity: GW03-04
Q (m³/min)
ΔP (kPa)
0
1
2
0
1
2
3
4
5
6
Q = 0.26ΔP
R² = 0.96

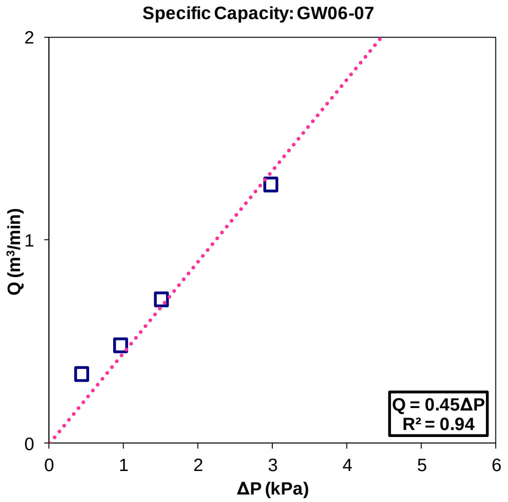
c)


Specific Capacity: GW04-07
Q (m³/min)
ΔP (kPa)
0
1
2
0
1
2
3
4
5
6
Q = 0.66ΔP
R² = 0.99

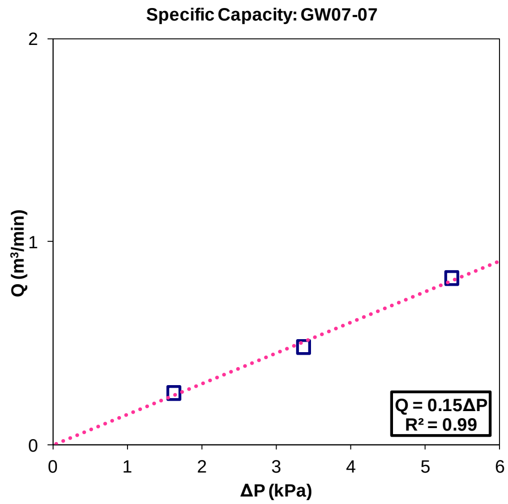
d)


Specific Capacity: GW05-06
Q (m³/min)
ΔP (kPa)
0
1
2
0
1
2
3
4
5
6
Q = 0.25ΔP
R² = 0.93

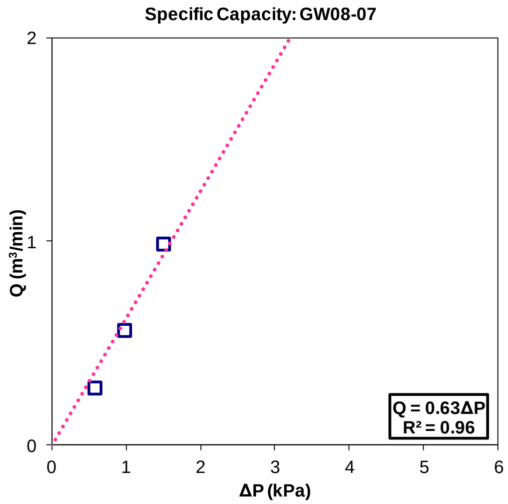
e)


Specific Capacity: GW06-07
Q (m³/min)
ΔP (kPa)
0
1
2
0
1
2
3
4
5
6
Q = 0.45ΔP
R² = 0.94

f)


Specific Capacity: GW07-07
Q (m³/min)
ΔP (kPa)
0
1
2
0
1
2
3
4
5
6
Q = 0.15ΔP
R² = 0.99

g)


Specific Capacity: GW08-07
Q (m³/min)
ΔP (kPa)
0
1
2
0
1
2
3
4
5
6
Q = 0.63ΔP
R² = 0.96

h)

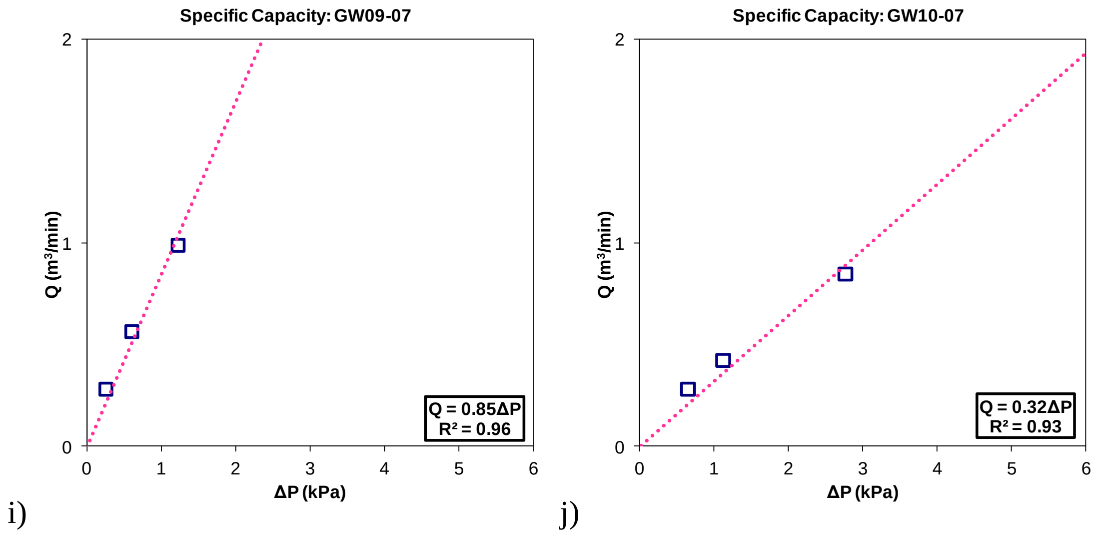


Figure 4-13. Specific capacity calculated from step-drawdown tests for wells (a) GW01-04, (b) GW02-04, (c) GW03-04, (d) GW04-07, (e) GW05-06, (f) GW06-07, (g) GW07-07, (h) GW08-07,(i) GW09-07, and (j) GW10-07.

A summary of the specific capacity values calculated from the results of step-drawdown pumping tests is provided in

Table 4-2. Apparent specific capacity (S.C.) for each extraction well.

Gas Well	S.C. scfm per inH_20	S.C. m^3/min per kPa
GW01-04	4.91	0.56
GW02-04	2.50	0.28
GW03-04	2.28	0.26
GW04-07	5.77	0.66
GW05-06	2.20	0.25
GW06-07	3.95	0.45
GW07-07	1.33	0.15
GW08-07	5.51	0.63
GW09-07	7.46	0.85
GW10-07	2.84	0.32

For a single well analysis in groundwater applications, estimation for transmissivity, storativity, and effective well radius can be made using the Cooper and Jacob (1946), and Jacob (1947) methods. However, these methods are not appropriate for the analysis of the data obtained in LFG well step-drawdown pumping tests as the data does not fit with a logarithmic time scale as used in these solutions. For LFG wells, the data is linear (hence the straight line fit with flow and pressure change) meaning that the application of Jacob's (1947) method for well loss produces a graph with a flat horizontal line. This is important for a two reasons. First, it demonstrates that groundwater well hydraulics is just an analogue for LFG well pneumatics and should not be used for calculating LFG well properties. Second, a linear line in the plots of specific capacity may indicate that well losses in LFG wells at the flow rates that were produced in this study may be considered negligible.

4.2.3 Radius of Influence (ROI)

For this study, the radius of influence was defined as the distance to which the pressure gradient differential was between 0.5 mPa/m and 1.3 mPa/m using a line of best fit (Figure 4-14 through Figure 4-24) from the step-drawdown pumping test results. As described in Chapter 2, this method was originally proposed by Gardner et al. (1990) based on observations that defining ROI at the point of where the pressure gradient is zero often produced results that appeared excessive. Therefore a small non-zero radial pressure gradient of 0.5 mPa/m and 1.3 mPa/m was used to estimate respectively the maximum and minimum extent of the influence of a pumping well (i.e. the maximum and minimum ROI).

A power function was used to draw a line of best fit for the drawdown profile for each well. This function was selected for its best fit to the data, and due to the poor fit when attempting to use groundwater hydraulics theory (Cooper and Jacob, 1946; Jacob, 1947) for LFG wells. The drawdown profiles for each well are shown below in Figure 4-14 through Figure 4-23.

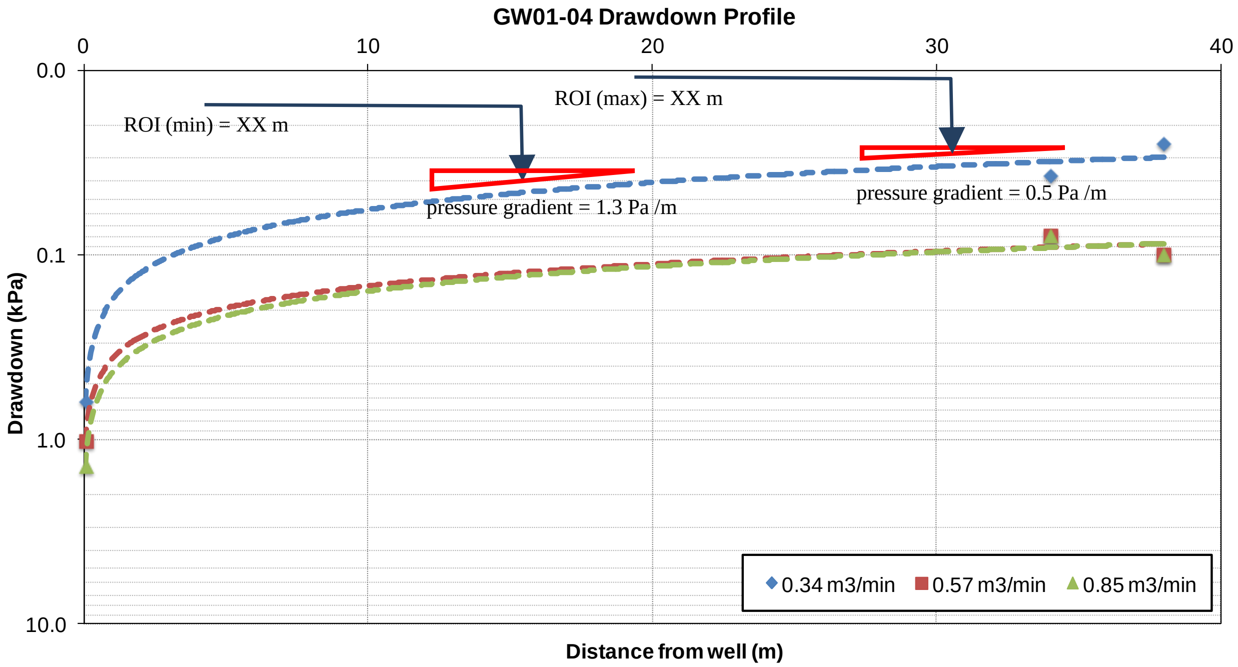


Figure 4-14. Drawdown profile for GW01-04 showing the use of Gardner et al. (1990) method to evaluate the radius of influence (ROI).

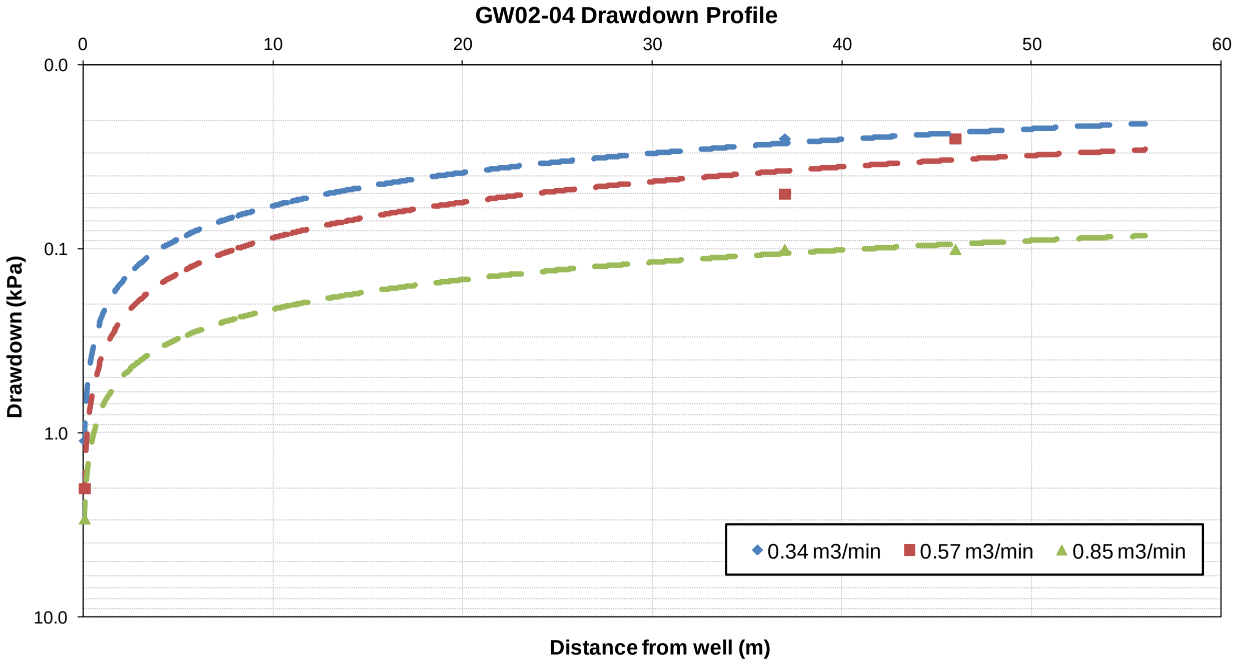


Figure 4-15. Drawdown profile for GW02-04.

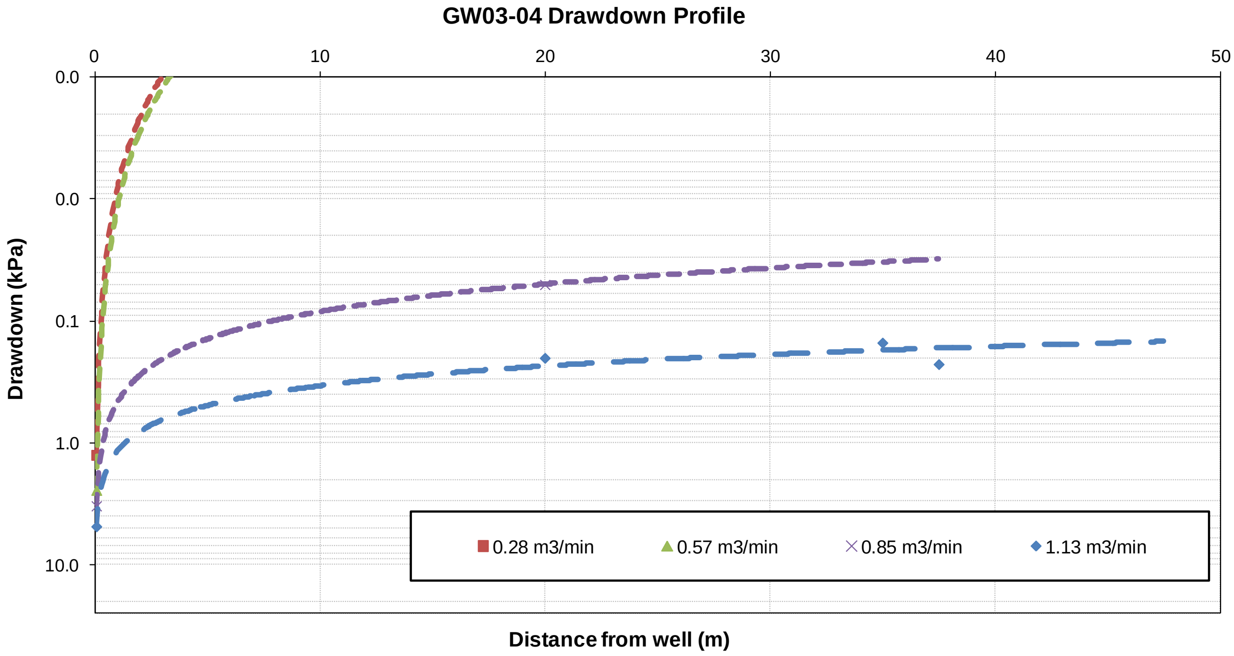


Figure 4-16. Drawdown profile for GW03-04.

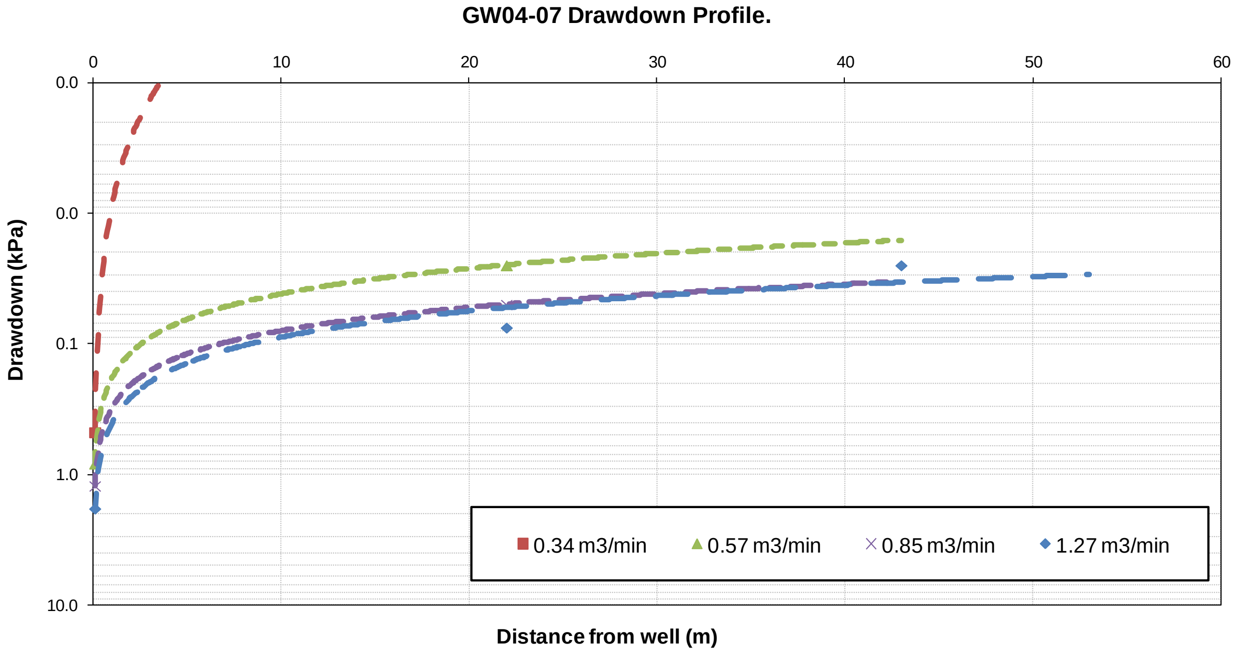


Figure 4-17. Drawdown profile for GW04-07.

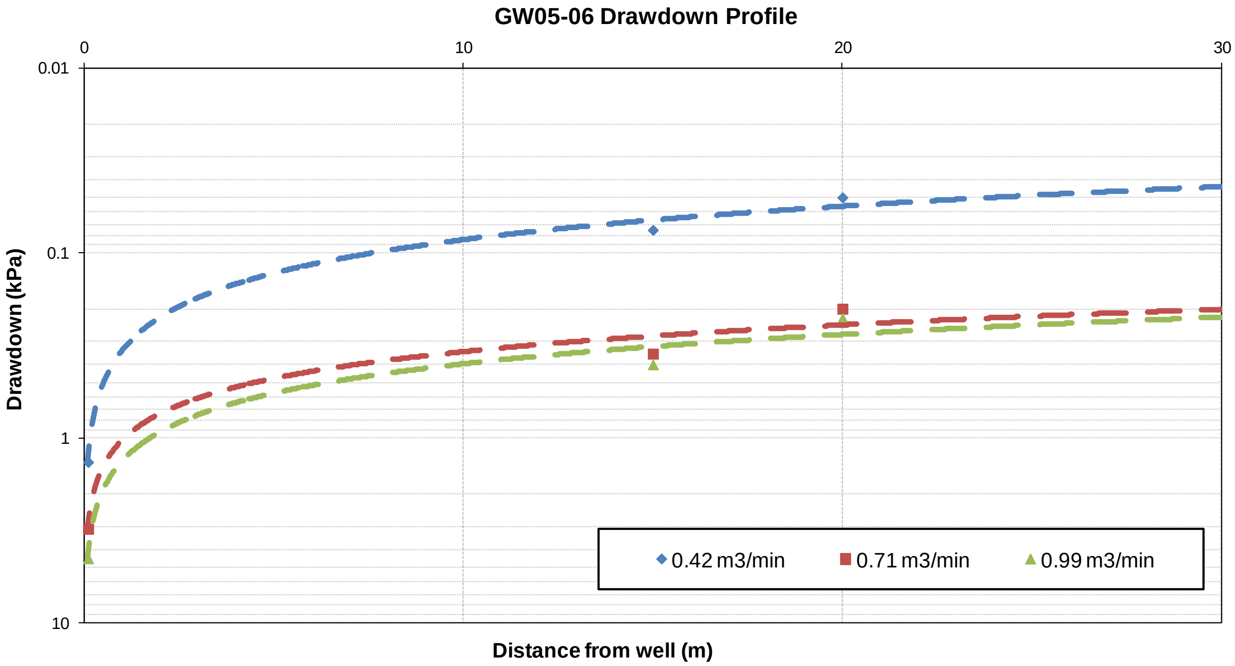


Figure 4-18. Drawdown profile for GW05-06.

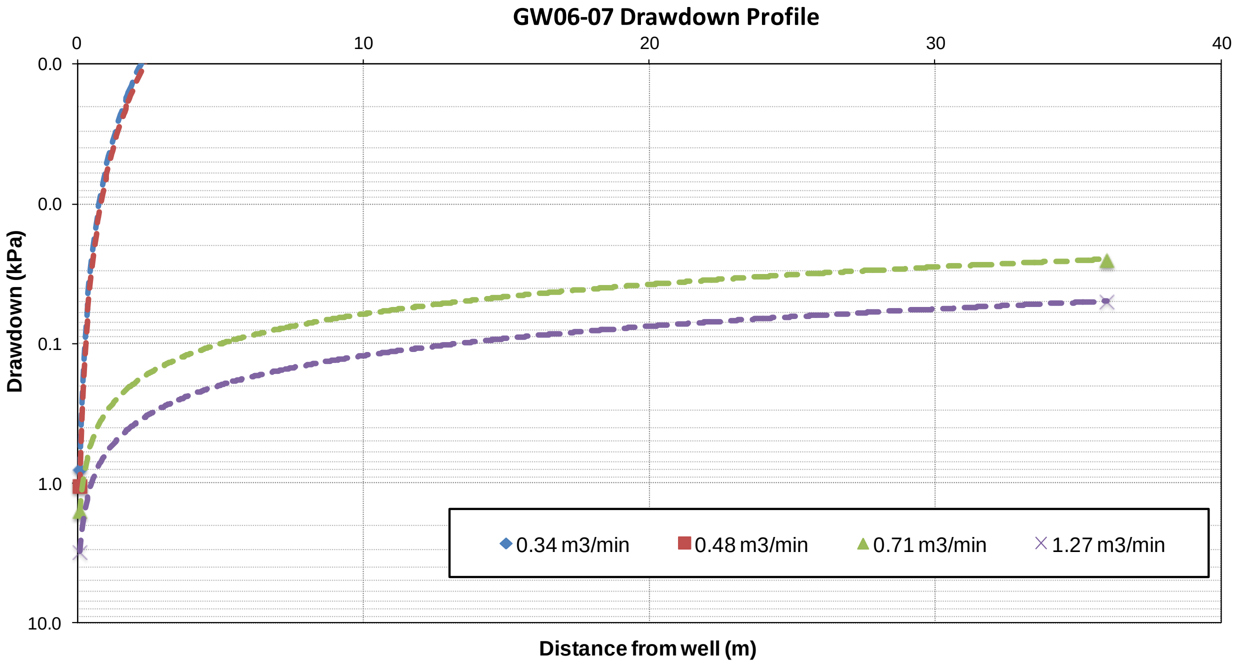


Figure 4-19. Drawdown profile for GW06-07.

Figure 4-20. Drawdown profile for GW07-07.

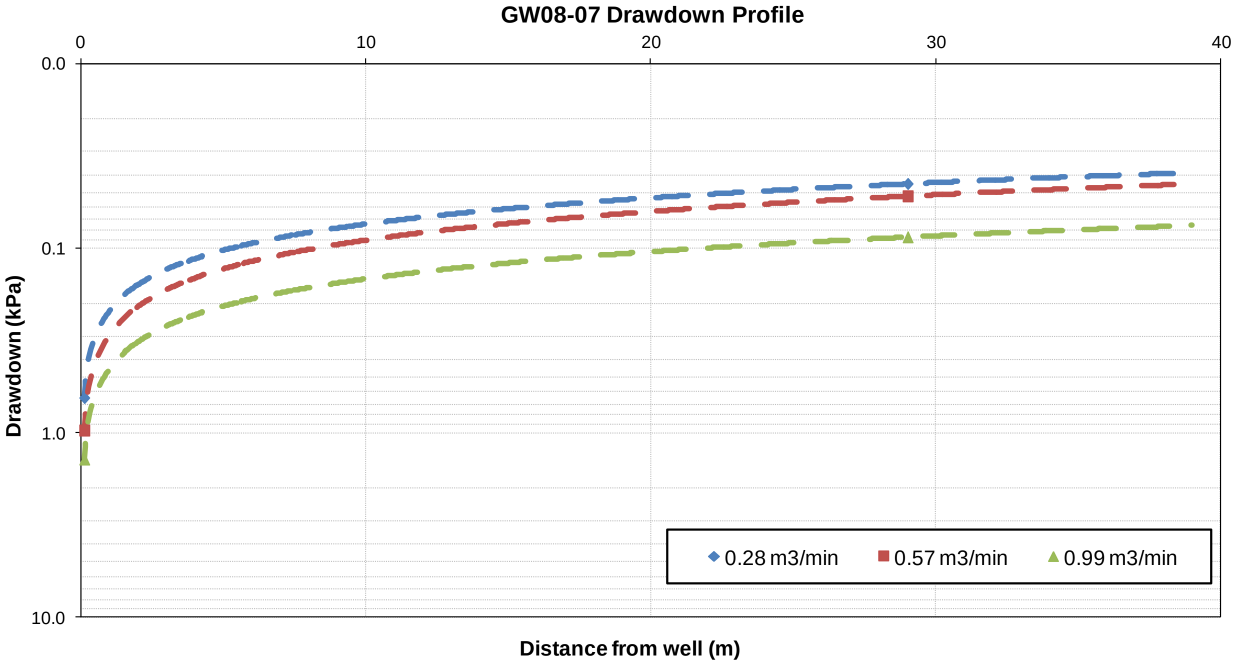


Figure 4-21. Drawdown profile for GW08-07.

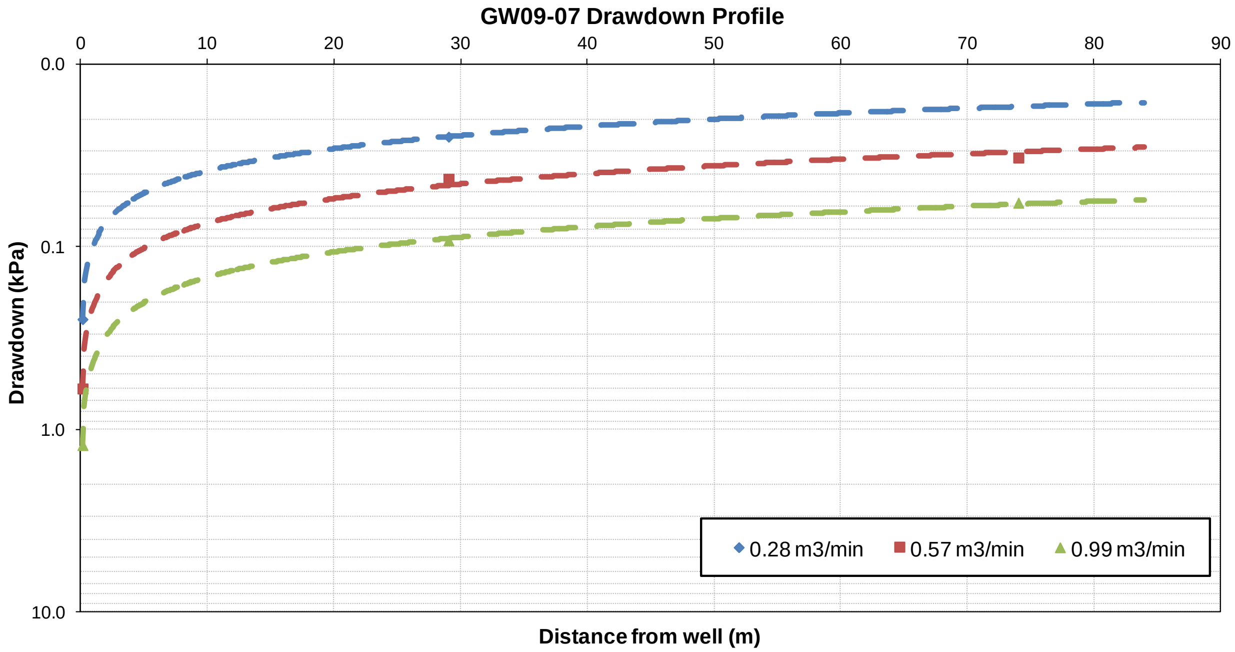


Figure 4-22. Drawdown profile for GW09-07.

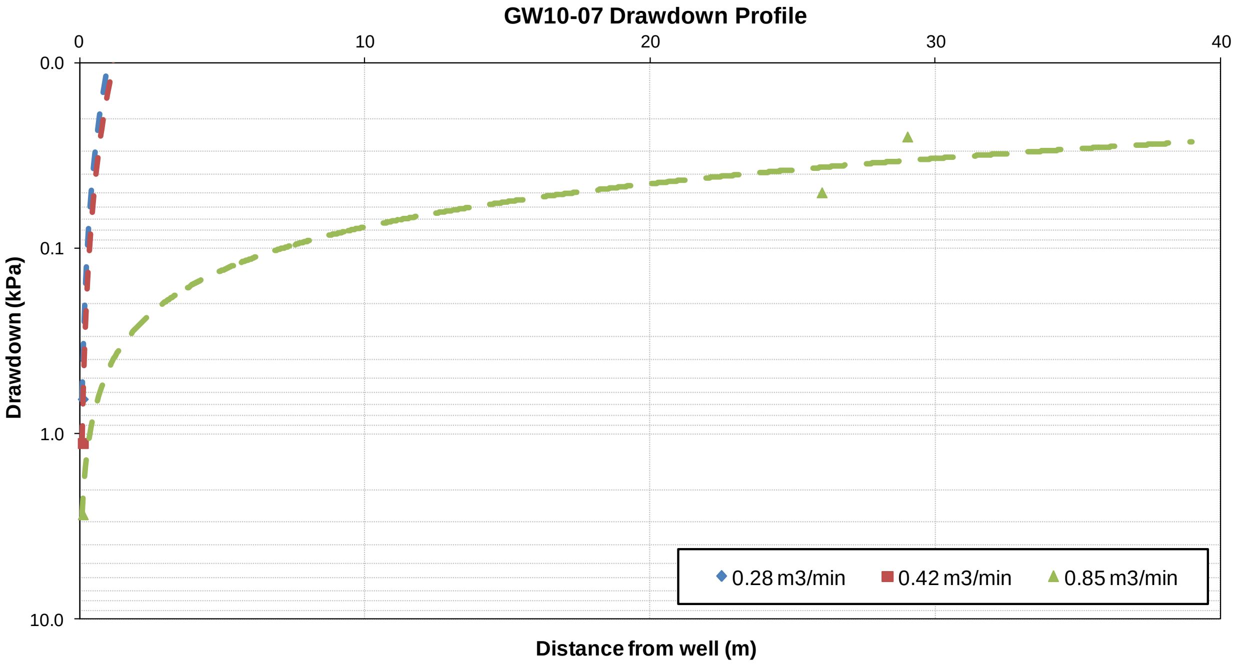


Figure 4-23. Drawdown profile for GW10-07.

By differentiating the equation for the line of best fit (power function) and using the pressure gradient differentials noted above, minimum and maximum radii of influence were calculated for each well and well flow rate (Table 4-3).

Table 4-3. Calculated ROI for each well and well flow rate from step-drawdown testing data.

Gas Well	Flow		ROI min (m)	ROI max (m)	ROI avg. (m)
	scfm	m^3/min			
GW01-04	12	0.34	18	35	26.5
	20	0.57	30	60	45
	30	0.85	35	65	50
GW02-04	10	0.28	12	25	18.5
	20	0.57	25	45	35
	30	0.85	40	80	60
GW03-04	10	0.28	<5	<5	<5
	20	0.57	<5	<5	<5
	30	0.85	25	45	35
	40	1.13	55	105	80
GW04-07	12	0.34	<5	<5	<5
	20	0.57	16	30	23
	30	0.85	25	40	32.5
	45	1.27	25	45	35
GW05-06	15	0.42	25	45	35
	25	0.71	55	105	80
	35	0.99	60	115	87.5
GW06-07	12	0.34	12	25	18.5
	17	0.48	20	40	30
	25	0.71	32	60	46
	45	1.27	32	60	46
GW07-07	10	0.28	32	60	46
	20	0.57	50	90	70
	30	0.85	60	115	87.5
GW08-07	10	0.28	20	36	28
	20	0.57	25	45	35
	35	0.99	32	60	46
GW09-07	10	0.28	12	25	18.5
	20	0.57	20	40	30
	30	0.85	32	60	46
GW10-07	10	0.28	<5	<5	<5
	15	0.42	<5	<5	<5
	30	0.85	25	40	32.5

4.3 Longer-Term Extraction Testing

Longer-term extraction tests were carried out to provide information on the sustainable yield of extraction and rates of gas production of the testing area; data were also compared to the results of the short-term pumping tests. Two (2) different methods for longer-term extraction testing were performed. The first was a “constant flow” type test in which a constant flow was maintained at each well by adjusting each individual wellhead but allowing for slight variations of pressure in the header. The flow rates measured in each well as well as oxygen levels recorded in the probes for both testing procedures are shown in Figure 4-24.

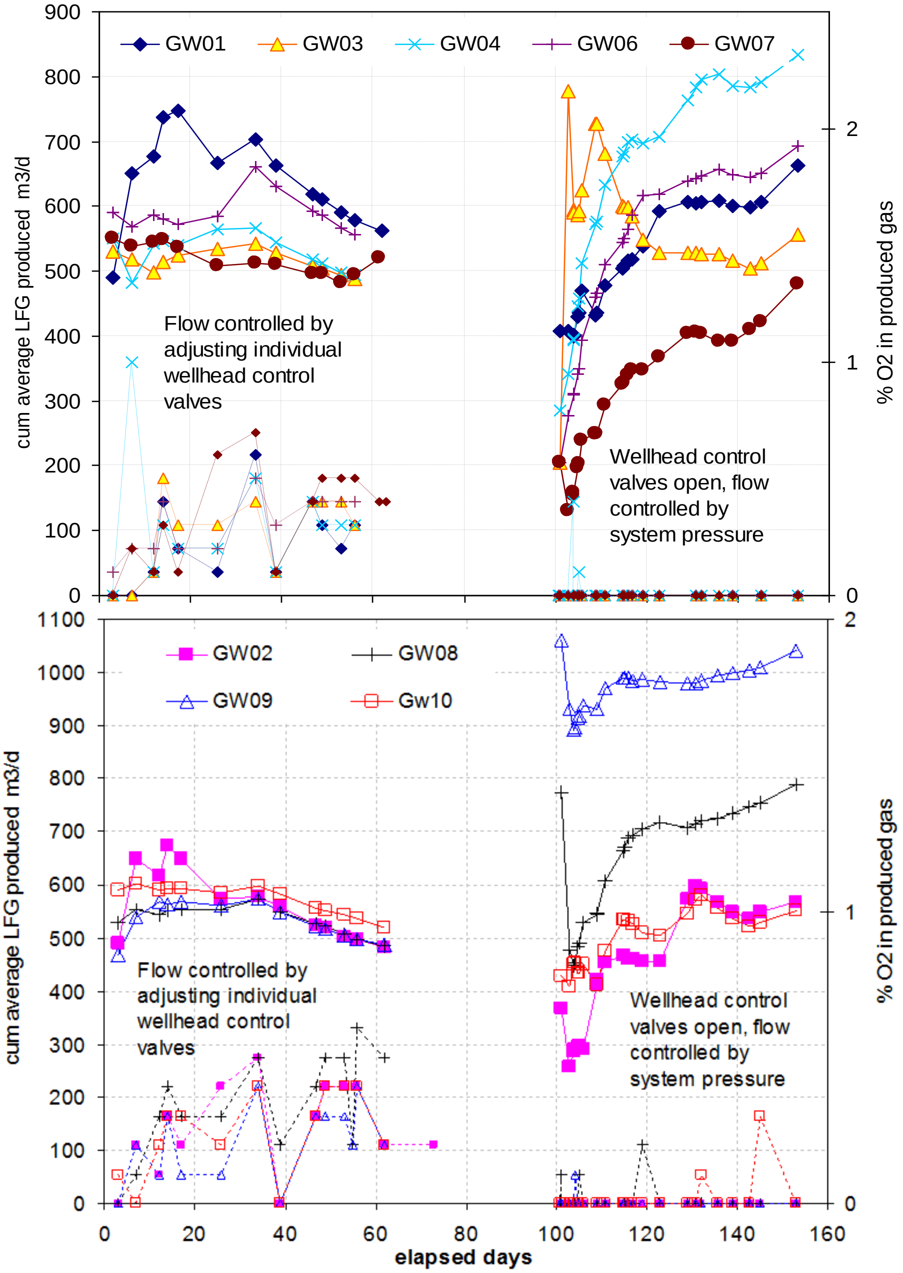


Figure 4-24. Pumping rates and O_2 levels in individual wells in the (a) West Header and (b) East Header. (solid lines represent pumping rates, dashed lines represent O2 concentrations in extracted LFG)

Note: GW05-06 was not part of the longer-term extraction testing due to significant oxygen ingress recorded at this well even at low flow rates.

Any significant changes, due primarily to fluctuations in temperature and barometric pressure, prompted a series of readjustments at the wellheads to maintain constant flow rates. Well flow rates were lowered by small increments if oxygen readings in the well or nearby probes were above 0 %. The second test type was a "constant pressure" method in which the individual wellhead valves were fully opened and system pressure was rigidly maintained at approximately 0.75 to 1.0 kPa (3 to 4 inH_2O) using the main header valves. The system pressure was maintained by the main header valves near the blower, and this level of uniformity in wellhead vacuum was rendered possibly by the provision of the oversized header pipe and header control valves as discussed in Chapter 3, above. The flow from the entire wellfield was allowed to fluctuate in the wells depending on the amount of oxygen in the gas readings.

Figure 4-24 presents interesting results from the longer-term tests. While the flow was controlled to approximately 600 m^3/day per well using the individual wellhead control valves, it is apparent that ingress of air occurs and the flow rates decline over time. During the second stage of testing, all individual wellhead control valves were opened fully and the vacuum in the header maintained at a relatively low -1 kPa. Because the header pipes were oversized, the wellhead vacuum at all wells was maintained at this target. This approach yielded greater gas flows with less oxygen in the gas produced and apparently less air ingress into the waste mass. The effect is clearly evident in Figure 4-25, which presents the total wellhead flow as well as oxygen concentration measured downhole in gas probes.

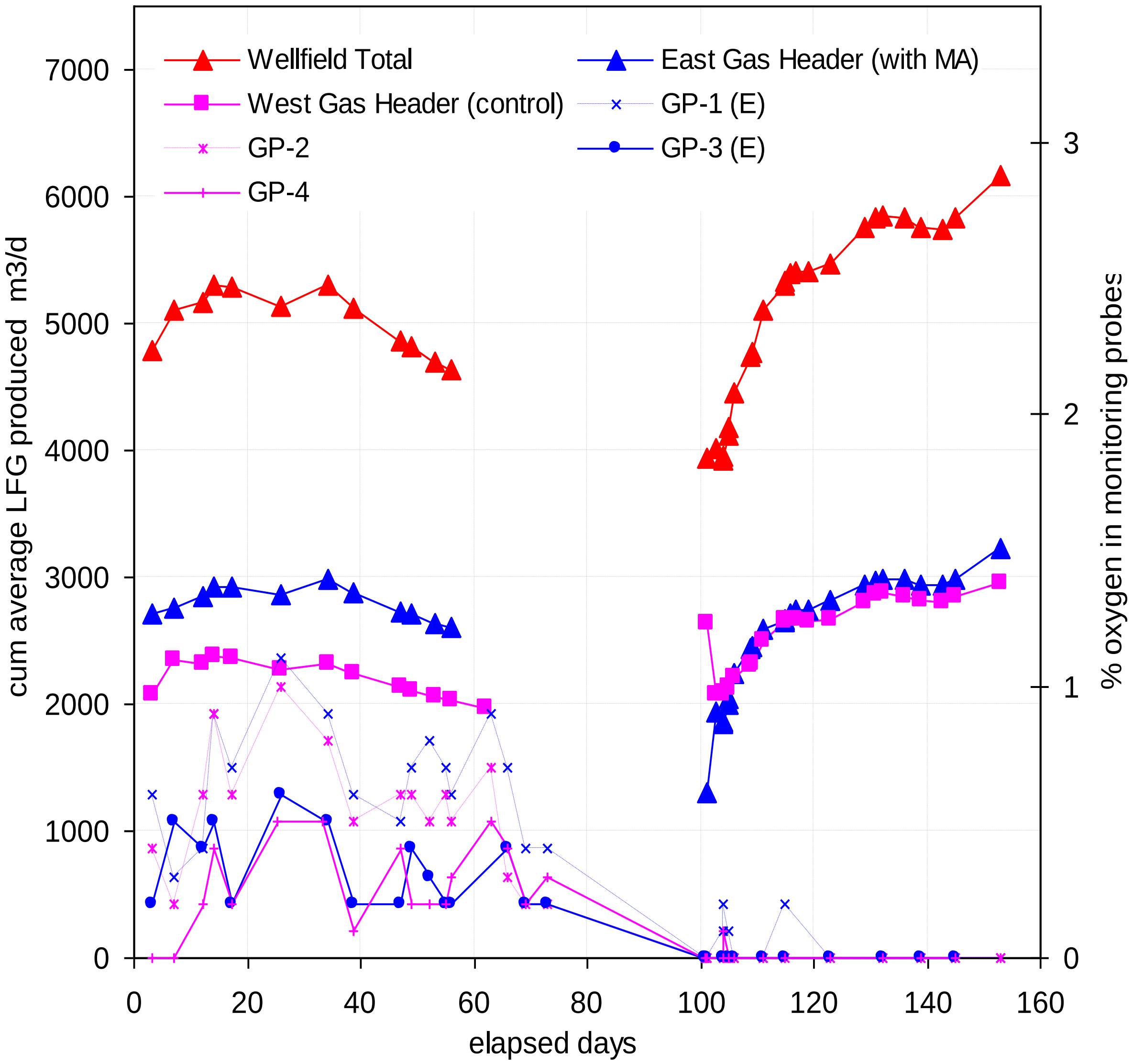
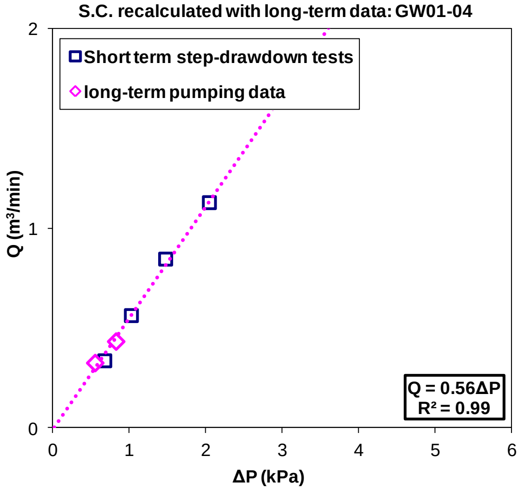


Figure 4-25. Total well-field flow with oxygen ingress.

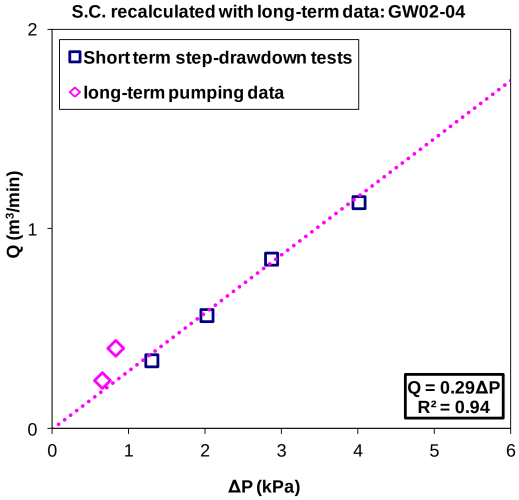
This finding is potentially a very important one as it could suggest that controlling well-field flows with the header valves at lower system pressures is preferable to controlling flow with the individual wellhead valves. This might suggest that instead of opting to save money on designing systems with smaller header pipes, but spending more money on expensive well heads and larger blower units, it would be wiser to spend more on larger header pipes and save on blower unit costs and operations, as well as avoiding the cost of expensive well-heads.

4.4 Comparison of Short- and Longer-term Pumping Tests

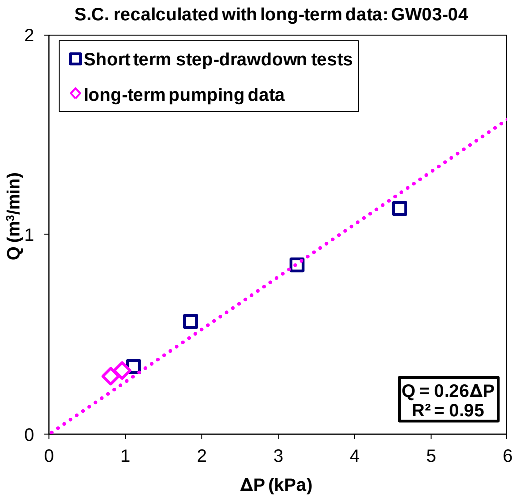
The results of the short- and longer-term pumping tests were compared to assess the reliability of a short-term testing program for predicting longer-term gas well performance with regard to pneumatic efficiency for gas extraction. Data points were taken from the longer-term extraction tests by using the average longer-term equilibrium flow over average drawdown for each test and each gas well. The S.C. of each well was then recalculated incorporating the points from the longer-term tests (Figure 4-26 (a) through (i)). If the short-term pumping tests are a good representation of well performance (pneumatic efficiency) over longer periods, then the calculated specific capacity should theoretically not change from the value determined in the short term step-drawdown pumping tests.



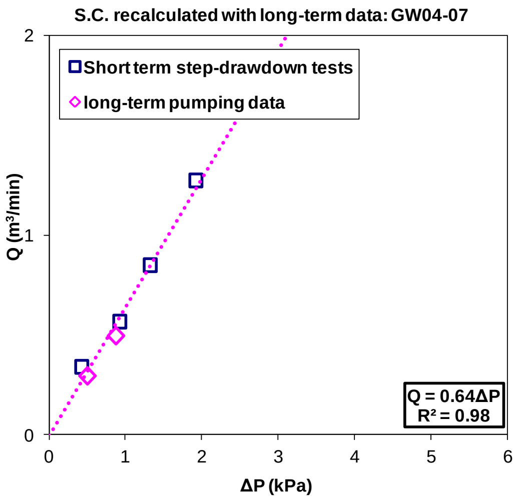
a)



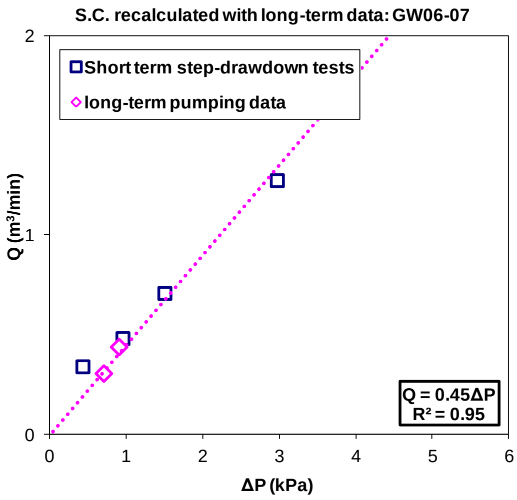
b)


S.C. recalculated with long-term data: GW03-04
Short term step-drawdown tests
long-term pumping data
Q = 0.26ΔP
R² = 0.95
Q (m³/min)
ΔP (kPa)
0
1
2
0
1
2
3
4
5
6

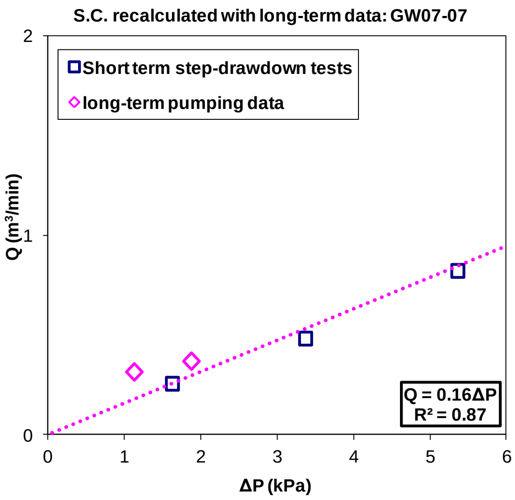
c)


S.C. recalculated with long-term data: GW04-07
Short term step-drawdown tests
long-term pumping data
Q = 0.64ΔP
R² = 0.98
Q (m³/min)
ΔP (kPa)
0
1
2
0
1
2
3
4
5
6

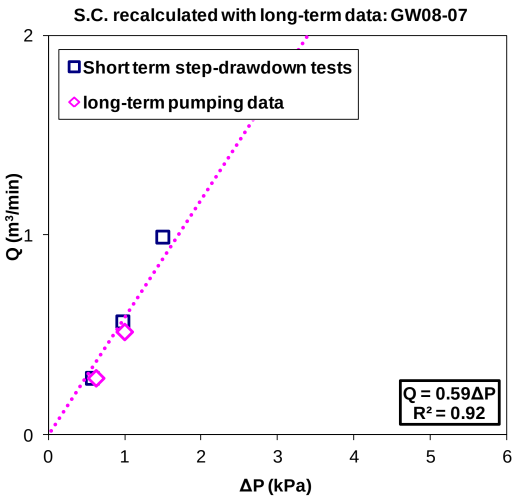
d)


S.C. recalculated with long-term data: GW06-07
Short term step-drawdown tests
long-term pumping data
Q = 0.45ΔP
R² = 0.95
Q (m³/min)
ΔP (kPa)
0
1
2
0
1
2
3
4
5
6

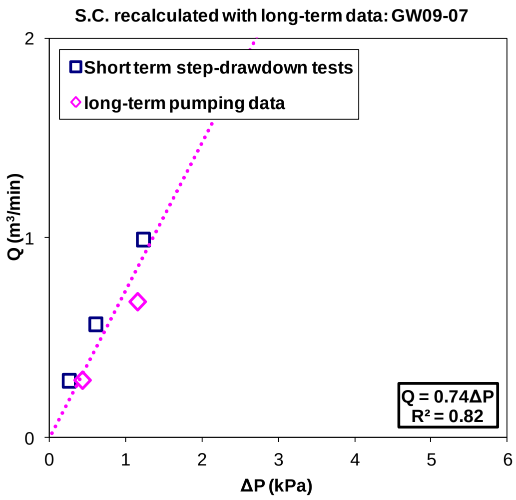
e)


S.C. recalculated with long-term data: GW07-07
Short term step-drawdown tests
long-term pumping data
Q = 0.16ΔP
R² = 0.87
Q (m³/min)
ΔP (kPa)
0
1
2
0
1
2
3
4
5
6

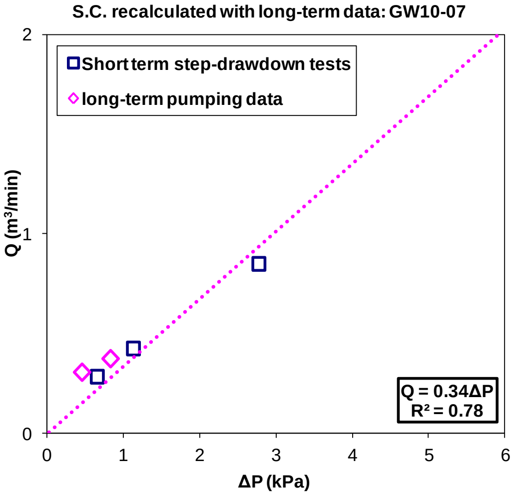
f)


S.C. recalculated with long-term data: GW08-07
Short term step-drawdown tests
long-term pumping data
Q = 0.59ΔP
R² = 0.92
Q (m³/min)
ΔP (kPa)
0
1
2
0
1
2
3
4
5
6

g)


S.C. recalculated with long-term data: GW09-07
Short term step-drawdown tests
long-term pumping data
Q = 0.74ΔP
R² = 0.82
Q (m³/min)
ΔP (kPa)
0
1
2
0
1
2
3
4
5
6

h)



i)

Figure 4-26. Specific capacity recalculated incorporating data points obtained from longer-term testing results for wells (a) GW01-04, (b) GW02-04, (c) GW03-04, (d) GW04-07, (e) GW06-07, (f) GW07-07, (g) GW08-07, (h), GW09-07, and (i) GW10-07.

It is important to note that several of the graphs above do appear as though there may be a significant difference in the ambient pneumatic behaviour between short-term and longer-term tests if a new line is fitted with only the two longer-term data points through the origin. However, fitting a line with only two data points would make for greater uncertainty in the analysis. Therefore, it was decided that combining the short-term and longer-term data to recalculate specific capacity provided a more consistent and reliable analysis of the data. This seems reasonable as when new lines are graphed with only the two points from longer-term tests, most of the new plots still show insignificant deviation in the originally calculated specific capacity values from short-term testing alone.

A summary of the results showing the % change in the specific capacity values is provided in Table 4-4 .

Table 4-4. Change in S.C. with the incorporation of longer-term testing data points.

Device ID	S.C.		S.C. recalculated with long-term data		% Change
	scfm per inH2O	m^3/min per kPa	scfm per inH2O	m^3/min per kPa	
GW01-04	4.91	0.56	4.90	0.56	0.2%
GW02-04	2.51	0.29	2.55	0.29	1.6%
GW03-04	2.28	0.26	2.31	0.26	1.3%
GW04-07	5.77	0.66	5.67	0.64	1.7%
GW05-06	2.20	0.25	-	-	-
GW06-07	3.95	0.45	3.97	0.45	0.5%
GW07-07	1.33	0.15	1.39	0.16	4.5%
GW08-07	5.50	0.62	5.19	0.59	5.6%
GW09-07	7.46	0.85	6.51	0.74	12.7%
GW10-07	2.84	0.32	2.98	0.34	4.9%

No significant changes in the specific capacity values for each well were observed after incorporating the longer-term testing data. This finding is potentially important as it suggests that quick and easy step-drawdown tests may provide information that is just as useful for the design of a well-field and well spacing as data from expensive and time-consuming longer-term testing.

4.5 Effect of Well Specification on Extraction Performance

At the outset of the study, gas extraction well construction specifications were hypothesized to have little or no significant effect on pneumatic efficiency. This hypothesis was supported in a quick analysis of the results from the short-term extraction testing conducted at the beginning of the field trials as briefly discussed in Section 4.2. The hypothesis is examined in greater detail in this section by comparing aspects of the extraction well construction specifications as a function of the well costs (in time and materials) to their short-term apparent S.C. and average ROI (Figure 4-27).

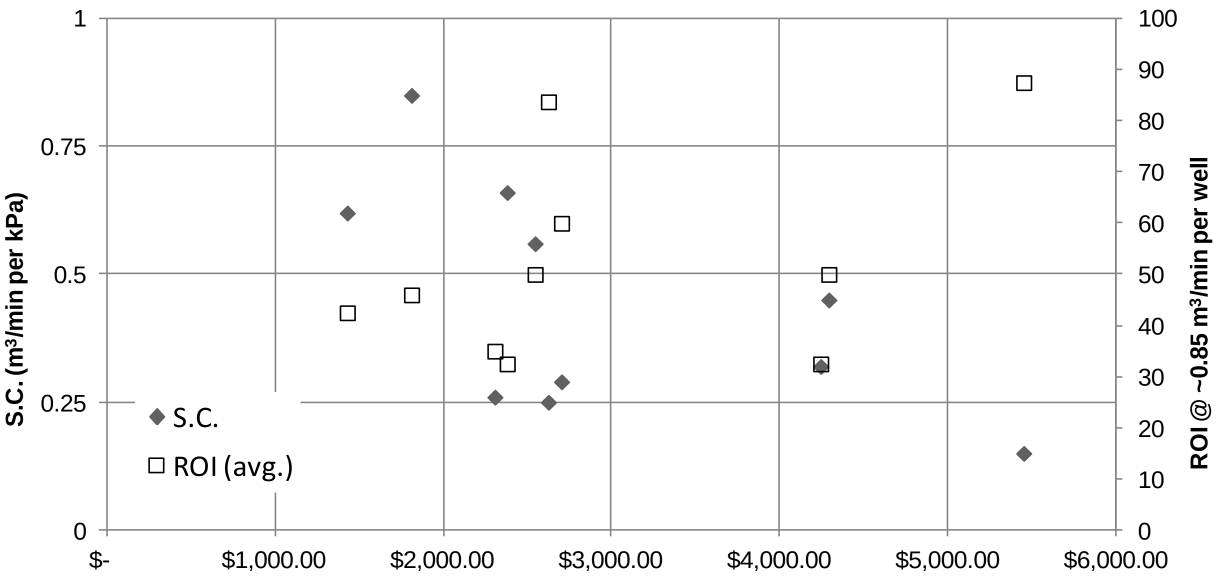


Figure 4-27. Well performance related to construction cost of well.

The cost of drilling and materials for an individual well ranged from less than \$1,500 to \$6,000 (CAD). An important observation based on Figure 4-27 is that there is no clear benefit to constructing a well with a larger diameter or longer wellscreen; no relationship between the well cost, construction specifications, and the productivity (as measured by S.C.) of the wells was evident. In other words, the method of construction and details of well design were found to have little to no effect on well performance. This is not an unexpected finding, but to date this has not been clearly demonstrated in any published field studies in which these factors have been measured and compared. The results indicate no systematic effect on well performance related to the amount of effort (expressed as cost) expended in well construction. This finding is important for retrofitted LFG systems as wells costing less than \$2,000 appear to be just as effective (or more effective) as those costing up to three (3) times more in construction effort and materials. However, this analysis does not consider the performance of the wells over an extended period of time. The longest period for testing in this program was approximately 110 days. Considering the expected lifetime for permanent extraction wells in bio-reactors or other retrofitted systems (years), well screen clogging or well maintenance may become relevant factors for well performance.

CHAPTER 5
DICSUSSION AND CONCLUSIONS

The aim of this study was to provide a controlled and documented analysis of the performance of differently constructed gas extraction wells in a municipal landfill. This research also looked to provide an analysis and comparison of several different extraction methods, and a comparison of short-term and longer-term extraction testing.

The first significant, and not entirely unexpected finding from this study is that there appears to be a lack of correlation between the design and construction specifications of a landfill gas extraction well and its pneumatic efficiency as defined by both the specific capacity and the radius of influence. This finding suggests that, in general, smaller diameter, shallower (and cheaper) wells may be preferred when constructing landfill gas extraction wellfields, as there may be no performance benefits drilling bigger, deeper, and more expensive wells, provided that the overall depth of the wells is at least about half of the overall depth of the landfill. It is, however, possible that wells of varied construction will exhibit different long term performance in permanent extraction systems where their lifetime is years and not weeks or months.

A second potentially important finding (albeit one that must be qualified as being based only on the performance of a single well) is that the one well (GW05-06) not constructed with screening material around the pipe-screen was susceptible to the greatest amounts of oxygen ingress and had to be shut-in during every extraction test performed. It must be acknowledged that this well was relatively shallow (13 m), however, it must also be observed that GW08-07 (14 m depth), and GW06-07 (15 m depth), were not significantly deeper and each of these well did not exhibit significant oxygen ingress into the waste mass. Furthermore, the performance of these wells

(GW08-07 and GW06-07) was average to above-average in terms of the sustained flow of the wells (Fig 4.23) or in terms of specific capacity or ROI.

The third significant finding was not expected based on the published literature and supports the value of this sort of well-documented long term full scale study. It was determined that the specific capacity values calculated using only the data from the short-term tests were not substantially different from those calculated from the short- and longer-term test data combined. This is important because it suggests that short-term extraction testing may provide a reliable and sufficient evaluation of the longer-term extraction well pneumatic efficiency, thus reducing or even eliminating the need to conduct costly longer-term extraction tests for the purpose of well-field design (well spacing). However, it should be noted that this finding does not account for significant longer-term changes that might occur such as moisture changes in the waste mass in the vicinity of the well over the course of a longer time frame. It is expected that significant moisture changes as well as consolidation and degradation-induced settlement of the waste fill would affect the pneumatic characteristics over a long time period.

A last finding that was not expected, and the reason for which is not entirely understood, related to the method of control used in the header – wellhead systems to control the overall wellfield flow. The results of the constant pressure type extraction method in comparison to the constant flow type method indicate that the constant pressure method is superior due to its overall higher average flow rate and lower levels of oxygen ingress at the wells. One possibility for this observation is that the lower vacuum and the spatial consistency of this wellhead vacuum resulted in more consistent flow of gas to the wells, with lesser amounts of oxygen short-circuiting into the waste. Since oxygen ingress may be expected to be inhibitory to landfill gas generation within the waste mass, over time this would be associated with a reduced amount of gas flow. It must be emphasized that this hypothesis is quite speculative, however the finding that lower (and spatially uniform) wellhead vacuum provides superior wellfield yield is certainly deserving of further evaluation and study. The implication of this (admittedly tentative) finding is that large diameter header pipes and control valves may well be worth the increment of capital cost in extraction system construction.

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