An Abstract of the Thesis of Douglas J. Geller for the Master of Science Degree in Physical Sciences (Earth Science with Hydrogeology Emphasis) presented May 2011.

Title: An Evaluation of Three Methods for Assessing Long-Term Well Yield

Abstract approved: ____

Safe yield and sustainable yield are highly relevant topics in the fields of hydrogeology and water management. Most published information on safe yield has focused on aquifer systems, while relatively little attention has been paid to the safe yield of individual wells, termed here the long-term well capacity (LTWC). The little-studied long-term well capacity is typically viewed as a fixed value, although it might change over the life of any production well.

To test the hypothesis that methods to estimate LTWC may be more broadly applied, three LTWC estimation methods, all based on the theory of radial flow to wells, are tested in a comparative analysis. The methods are tested along with traditional analytical approaches for interpreting pumping tests to determine both hydraulic properties and LTWC. To gain insights into how individual well capacity may be related to the larger context of groundwater management, pumping test data from ten wells completed in a variety of hydrogeologic settings with yields ranging from 2 gpm to 3,500 gpm are assessed using the three LTWC methods, which allow the analyst to estimate either a 100-day (Q_{100d}) or a 20-year (Q_{20}) LTWC.

The subject wells, completed in confined, unconfined and fractured bedrock aquifers located in Kansas, Oregon and British Columbia Canada, are analyzed using pressure derivative analysis to determine radial flow conditions, interpreted using conventional pumping test analysis to estimate aquifer properties, and then further

evaluated using the three methods. From each set of results ratios of projected long-term specific capacity to actual measured short-term specific capacity are derived. A sensitivity analysis performed on the results involved systematically varying pumping time and a default safety factor applied in each LTWC equation. For two wells completed in the Ogallala aquifer in Kansas, the effects of aquifer depletion on LTWC are investigated, and the effects of well interference on two confined aquifer wells in Oregon are assessed.

The first of the three methods tested (Farvolden) was found to produce the least reliable results due to the assumption that drawdown during the first minute of pumping is negligible. This may lead to either an over- or under-estimation of LTWC. The Moell and CPCN methods were found to produce consistent results. Specific capacity ratios derived from each calculated data set helped validate results, and showed that four Farvolden calculations were questionable, projecting a long-term specific capacity that surpassed the measured or observed value during the test. The specific capacity ratios also facilitate qualitative assessment of sensitivity to changes in pumping time or safety factor. For most wells, the results showed similar sensitivity to order-of-magnitude changes in pumping time or 0.1 adjustment in safety factor, with either adjustment changing the resulting LTWC value by approximately 15%, although the LTWC values for the Moell method varied over a wider range when pumping time was varied by an order of magnitude, with the variation depending on whether the well had a low, moderate or high specific capacity ratio.

Effects of aquifer depletion in the High Plains / Ogallala aquifer significantly reduce the LTWC of production wells. This is due to reduced available drawdown (saturated thickness), and decreased aquifer transmissivity from progressive dewatering of permeable aquifer materials. Observed declines in two areas of Groundwater Management District 3 over the past 30 years resulted in an estimated 25 to 30% reduction in transmissivity, and a corresponding decrease in LTWC ranging from 40 to 75 % in the two wells studied. The assessment suggests that by 2030 one of the wells studied could have a LTWC value approaching zero.

It is relatively easy to estimate LTWC values for virtually any well subjected to a pumping test without altering the standard procedure for the pumping test. Such an approach coupled with a calculation of the applicable specific capacity ratio supplements the understanding that may be derived from traditional pumping test interpretation. Pumping test data from the time of original well construction are applicable to assessments of current or future LTWC using information on groundwater levels, well specific capacity, pump performance, and other pertinent data.

The evaluation of individual well long-term capacities is recommended when a water source is of particularly high value and there is a need to understand the long-term operational characteristics. Such assessment may be of value in supporting water balance studies in the groundwater systems and the “safe” or “sustainable” yield of aquifers. A Q_{20} analysis is probably better-suited to municipal wells or other sources used year-round on a perennial basis, while a Q_{100d} analysis may be better suited to wells used intermittently or seasonally for irrigation and other purposes.

AN EVALUATION OF THREE METHODS FOR ASSESSING LONG-TERM WELL YIELD

A Thesis

Presented to

The Departments of Physical Sciences

EMPORIA STATE UNIVERSITY

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

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May 2011

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ACKNOWLEDGEMENTS

I conceived of this project while running the trails at Helliwell Provincial Park on Hornby Island off the British Columbia coast in the summer of 2010. B.C. calls itself the “most beautiful place on Earth” and it is hard to argue with such a claim when experiencing a place like Helliwell. When I think back on this project, I know I will fondly recall the Garry Oaks, the Bald Eagles, and the crags, beaches and trails of Hornby Island.

Many individuals contributed to this project, first and foremost I want to acknowledge the support and guidance provided throughout by my advisor Dr. Marcia Schulmeister, Associate Professor of Hydrogeology at Emporia State University, and also thank my committee members Dr. James Aber, Earth Science Professor at ESU and Dr. Carl McElwee of Professor Emeritus at Kansas University for their valuable input during thesis preparation. Appreciation is also extended to my wife Mary Ann, and children, Ethan, Gabe, and Lucas for putting up with many evening sessions glued to the computer. This work was funded in part by the Kansas Water Office and Emporia State University and this support is appreciated. Jeff Binder of Burns and McDonnell engineers and Mike Dealy of KGS provided the Ogallala well data analyzed herein, and ESU Earth Science student Sarah Pick assisted with some of the spreadsheet data entry for the Ogallala wells.

Lastly, a word of thanks is extended to Dr. Garth van der Kamp of the National Water Research Institute of Environment Canada, who provided copies of the publications he co-authored that are cited herein, and whose work provided some of the impetus for pursuing this research study.

NOTES ON UNITS OF MEASUREMENT

The water well industry in North America continues to use imperial units of measurement, such as gallons per minute (gpm), feet (ft), and so on. The original data used in this study were also measured and recorded in these units. Therefore, imperial units of measurement are used throughout. Selected conversions from U.S. imperial to metric units of measurement appear in the table below.

Value	**U.S. imperial units**	**Metric equivalent**
Flow rate	Gallons per minute (gpm)	1 gpm = 3.78 liters per minute
Flow rate	Gallons per minute (gpm)	1 gpm = 5.4 m^3/day
Distance	Inches (in)	1 in = 2.54 cm
Distance or depth	Feet (ft)	1 ft = 30 cm
Distance or depth	Feet (ft)	1,000 ft = 305 m
Distance	Miles (mi)	1 mi = 1,610 m (1.6 km)
Aquifer transmissivity	Gallons-per-day per ft (gpd/ft)	1 gpd/ft = 1.2 E-02 m^2/day
Aquifer transmissivity	Square-feet per day (ft^2/day)	1 ft^2/day = 9.2 E-02 m^2/day
Hydraulic conductivity	Feet per day (ft/day)	1 ft/day = 30 cm/day = 3.6E-06 m/sec

Notes: cm = centimeters; m = meters; m^3 = cubic meters; km = kilometer; m = minute only when used in gpm

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CHAPTER 1

INTRODUCTION

Well yield is the measured volume of water produced per a unit of time (Driscoll 1986), usually expressed as gallons per minute (gpm). While the instantaneous discharge rate from a well can be readily measured, the determination of a reasonable or “safe” rate of production over the long-term is not so straightforward. Just as the discharge of a surface stream may vary over time, the same is true for groundwater well production, and yet water managers and the public at large tend to view well yield as a fixed value. Further complicating matters is the fact that there is no broadly applied or universally accepted approach within the field of hydrogeology to quantitatively estimate long-term well yield. Sophocleous (2000) noted that concepts of well yield, aquifer “safe yield” and “sustainable yield” have different meanings but are sometimes used interchangeably, and without sufficient context.

Just as there has historically been more published literature on aquifer hydraulics than papers focused on well hydraulics (Williams 1981), the literature on methods to quantitatively determine the yield of individual wells is sparse when compared to those assessing the safe or sustainable yield of an aquifer system, or a connected groundwater-surface water system.

The ultimate yield of an aquifer or aquifer system depends on several fixed and variable factors, including; the amount of water in storage, how readily water is transmitted through the aquifer pore spaces, the natural water input and output processes, the location, frequency, the location, duration and magnitude of groundwater pumping, and the effects that pumping has on the pre-development aquifer’s state of dynamic equilibrium (groundwater balance).

In turn, the long term yield of an individual well is governed by the hydraulic properties of the well, how it was constructed, the duration of pumping, as well as the hydraulic and hydrodynamic properties of the aquifer. Thus a seemingly simple question such as “how much water should I count on from this well”, while reasonable enough, is exceedingly difficult to answer, especially at the time of initial well installation when key regulatory and operational decisions about a well’s long-term use are typically made.

Maathuis and van der Kamp (2006) point out that the consequences of groundwater development are rarely predicted reliably, and only become apparent following a considerable period of time (usually years, or decades). And yet, there is a need to quantify an individual well’s yield for many reasons that are of immediate concern, such as choosing a well pump, planning for other wells, and assessing near-term impacts that may be caused by or inflicted upon a new groundwater source. Therefore, it follows that a sound approach to assessing an individual well yield forms an important step in the process of understanding how wells, and the aquifer in which they are completed, respond to long term groundwater withdrawals.

Concepts of aquifer “safe yield” and “sustainability” in groundwater resource management have been active discussion and research topics in the recent literature (e.g. Sophocleous [2000], Kendy [2003], Kalf and Wooley [2005]). Recognizing that the question of individual well yield has received less attention in the literature, and application of methodologies has been quite limited, this study intends to bridge gaps between the concepts of aquifer safe yield, sustainable groundwater development, and the long-term production capacity of individual wells (or yield). The goal of this thesis is to develop a framework for broader application of quantitative methods to estimate long-term well capacity (LTWC), and to provide recommendations for use of these methods in groundwater management. The two-part hypothesis to be tested in this study comprises the following:

1. That promising and yet under-utilized methods to assess LTWC could be applied more broadly and beyond the localities where they were first developed; and
2. By subjecting each method to a quantitative comparative analysis involving multiple data sets, the relative strengths, weaknesses and applicability of each method might be better understood.

To test the hypothesis that these methods could be applied more broadly than they are at present, the research compares three promising but understudied methods used to estimate the long-term capacity of individual pumping wells. LTWC predicted by the three methods were determined in multiple aquifer types based on eleven (11) sets of pumping test data from ten (10) wells. The results are evaluated in a discussion of the methods used for management of wells and aquifer systems for safe or sustainable yield. This first chapter introduces important concepts and definitions, outlines the research problem, and the study objectives.

1.1 Well and Aquifer Yield Concepts and Definitions

Within the practice of hydrogeology, the concept of safe yield has been in use since the early 1900s (Lee 1915) and in common use since about the mid-1900s (Baker 1955), while the key concepts began to be explored by Theis (1940) in what remains a vital contribution on the topic, titled "The source of water derived from wells." Other terms such as *Safe Well Yield, Safe Aquifer Yield, Sustainable Yield,* and *Long-Term Well Capacity* have also been introduced and used in the literature and in general practice. These terms attempt to describe and quantify values that are only be approximated or estimated with what is usually a considerable degree of uncertainty. As noted by Maathuis and van der Kamp (2006), because the long term response of aquifer systems to groundwater development is difficult to predict, the effects of withdrawal should be monitored, identified and dealt with as pumping proceeds. This statement is also true for individual wells within an aquifer system.

Despite the theoretical limitations in doing so, it remains a practical necessity to make predictions of well yield, and such assessments form a basis for water management decisions that have far-reaching implications. A U.S.G.S. report on a sustainable yield estimation tool for the state of Massachusetts (Archfield et al. 2009) noted that the "safe yield" term as it is most often used in water resource management typically implies that a single fixed value represents the water available for withdrawal given some singular limiting factor (or constraint), such as a predicted drought recurrence or (for surface water) a minimum instream flow threshold.

The following are a few definitions of the various safe yield terms, adapted from a number of sources including Driscoll (1986), Sophocleous (1998), Fetter (2001), Rivera (2006), Maathuis and van der Kamp (2006), and proposed for use in this study.

Well Yield (WY): Generally, well yield is defined as the flow rate that can be maintained over a given time period, such as gallons per minute (gpm). In practice, well yield may be estimated by a well driller or measured during a pumping test.

Safe Well Yield (SWY): While well yield is a measured flow rate, safe well yield is an estimated value and is the volume (or rate) of water that can reliably be produced by an individual well for a pre-determined length of time, usually based on one or more defined constraints. Typical safe well yield time factors range from 1 day to 20 years. SWY will be termed herein as the Long-Term Well Capacity (LTWC), so as to specifically avoid using the term "Safe." This convention thus makes a clear distinction between individual well capacity and aquifer system safe yield. The LTWC value may be calculated independently of any water-budget analysis or modeling; but should be a value that is less than the following two terms, if they are estimated. As noted by Rivera (2006), SWY is more of a local-scale concept determined primarily on the basis of a pumping test, with uncertainty addressed through the use of safety factors (see page 7) and other adjustments to the well yield.

Safe Aquifer Yield (SAY): This is the volume of water than can theoretically be removed from an aquifer based on the water budget. The water budget is the summation of all inputs to and outputs from the aquifer. The budget is usually derived from a combination of measured and estimated values, such as climate and runoff data, measured or estimated evapotranspiration, with the groundwater recharge calculated as a residual in the water balance equation. The water budget may also be expanded and refined by incorporating terms such as artificial recharge, groundwater pumping, irrigation return flow, inflow from adjacent aquifers and so on. Based on a water budget, SAY is commonly thought of as equal to groundwater recharge or discharge, although Sophocleous (2000) and others have noted that safe aquifer yield cannot be equal to the recharge (see further discussion below). As noted by Fetter (2001), over the years, the SAY definition has been modified by adding qualifiers such as:

- The amount of water that can be pumped regularly and permanently without dangerous depletion of the storage reserve (Lee 1915);
- The amount of water that can be pumped economically (Meinzer 1923); and
- The amount of water that can be pumped without causing undesirable water quantity or quality changes (Todd 1959).

A composite “modern” definition, from Alley et al. (1999) and Fetter (2001) is that SAY is the amount of naturally-occurring groundwater that can be withdrawn from an aquifer on a sustained basis, economically and legally, without impairing the native groundwater quality or creating an undesirable effect, such as land subsidence, or drying up of wetlands or other groundwater-dependent ecosystems. [It is worth noting that this SAY definition is what Sophocleous (2000) would probably consider to represent *Sustainable Yield*].

Regardless of the exact terminology used (safe or sustainable), there is relative consensus in recent literature that SAY is best represented conceptually as a percentage of the natural groundwater discharge (or a combination of discharge and induced recharge) that can be effectively captured (by wells) without causing undesirable effects. This percentage is not fixed in space or time, and should be governed by what and who are dependent on continued discharge from the aquifer system, and what economic, societal and environmental values are placed on continuation of such discharge. In parts of Australia, a default value of 30% of natural groundwater discharge may be captured and assumed to be safe (or sustainable), until proven otherwise in detailed studies (Kalf and Woolley, 2005).

Sustainable Groundwater Yield (SGY): The volume of water than can be removed from the aquifer based on the water budget, including water that must be reserved for ecological or other non-consumptive purposes.

Sustainable Development (SD): This is a regional-scale concept for a whole aquifer system, including interconnected stream-aquifer systems and groundwater-dependent ecosystems functioning in a watershed.

Safety Factor (Sf): Methods to determine LTWC may include a safety factor in the equation. The safety factor reduces the calculated LTWC value by an arbitrary amount, and is a means to account for natural variation in groundwater systems and/or uncertainties in the data analysis. The safety factor is explained further in Chapter 4.

The concepts of safe aquifer yield, and sustainable yield, in general, have been widely debated and discussed in the literature. An early cited reference to the concept of safe yield is the paper by Lee (1915). In a recent commentary, Keddy (2003) highlighted how the fundamental safe yield concepts, first introduced by Theis in 1940, have been actively reiterated and expanded upon by Bredehoeft et al. (1982), Bredehoeft (1997; 2002), Sophocleous (1997), and Alley et al. (1999), to name a few of the better-known papers. Many of these writers note how the simplification of safe yield concepts led to a practice, by some hydrogeologists, of determining safe yield on the basis of a water budget where the natural groundwater recharge rate is estimated, usually as a residual in a general water balance equation, and then this recharge rate is taken to be the upper safe limit of groundwater development. This approach fails because it ignores the fact that without inflow from recharge, natural or artificial groundwater discharge ultimately depletes the resource. Pumping up to 100% of the recharge reduces discharge to surface water, which has environmental consequences.

Lohman (1972) noted that the term “safe yield” has many definitions, as many have attempted to define it, and also noted that it is questionable as to who should determine safe yield (however it is defined) – hydrogeologists or those who manage a groundwater resource. Lohman settled on a definition that is easy for anyone to understand: “The amount of groundwater one can withdraw without getting into trouble” (p. 62).

The core of these literature "discussions" on what has been variously described as the "elusive" concept of safe yield (Sophocleous 1998) or the "paradox" of safe yield (Fetter 2001) is that prior to any groundwater development, there is a natural water balance such that recharge is equal to natural discharge (plus or minus any natural change in groundwater storage). Bredehoeft, Papadopolus and Cooper's "Water Budget Myth" paper (Bredehoeft et al. 1982) argued that the common practice of estimating the natural recharge rate and setting this as the limit of safe yield is not scientifically correct, going on to point out that the natural recharge rate is in fact irrelevant to the question of safe yield. Deconstructing the safe yield myth further, Alley et al. (1999) pointed out that the total pumping rate is also irrelevant, arguing that the net groundwater extraction (after correcting for return flows) must be differentiated in any detailed water balance analysis, as only the actual consumption should be included in the water balance equation.

Theis (1940) was the first to point out that any groundwater pumping must be balanced by one or more of the following:

- An increase in the recharge rate;
- A decrease in the natural discharge rate; and/or
- A reduction of water stored in the aquifer.

The above concepts were thoroughly reiterated later by Alley et al. (1999), Sophocleous (2000), and others. Theis (1940) also introduced the concept of "capture", which is the water derived from the combined decrease in natural (undeveloped) discharge and the increase in (undeveloped) recharge (Bredehoeft and Durbin 2009). Pumping that exceeds the system's capture capability destabilizes the system, and results in groundwater level declines.

The Okanagan Basin Water Board (OBWB 2009) in western Canada completed a basin-scale surface and groundwater balance study and model. This study incorporated the results of a detailed groundwater balance analysis that differentiated net consumptive groundwater use from return flows. This is but one of many examples of how these principles are now being applied. An annual water budget for a given land area of interest used in the OBWB (2009) study comprises the following terms:

P = SR + AET + GWR

where

P = average annual precipitation

SR = average annual surface runoff

AET = average annual actual evapotranspiration

GWR = average annual groundwater recharge

Long-term mining yield: Sophocleous (1998) also proposed a term for non-sustainable groundwater yield, termed the *mining yield*. This is the amount of water that can realistically be withdrawn from an aquifer that is in decline, such as is the case with parts of the High Plains Aquifer in western Kansas and other nearby states. This could take the form of planned or unplanned depletion. Projected groundwater level declines brought on by the progressive removal of groundwater in storage means that at some point in the future, if declines continue unmitigated, that aquifer or well yield approaches a null value. Decline in water levels impacts the yield of individual wells due to the loss of available drawdown and transmissivity. This has already been observed in irrigated agricultural regions reliant upon the High PlainsAquifer, including the portion of this aquifer system hosted in the Ogallala Formation in western Kansas, herein termed the *Ogallala aquifer*. Large groundwater level declines due to heavy pumping have reduced saturated thickness in some areas to the extent that farmers have abandoned their wells

(Groundwater Management District 3 2004). This study describes a predicted future well capacity based on forecasted decline rates as the *Long Term Mining Yield* (LTMY).

Other key concepts specific to aquifer and well pumping tests, including well test variables and abbreviations are introduced and defined in Chapter 2.

1.2 PROBLEM STATEMENT AND STUDY OBJECTIVES

As already noted, the topic of individual well safe yield (termed here long-term well capacity) has not been studied as much as the yield of aquifer systems through investigations of the "groundwater budget" and "safe yield." This study proposes that methods to estimate LTWC could be applied more broadly without altering the procedure for conducting a well pumping test and the ensuing data analysis. As a practical matter, most well pumping tests are of relatively short duration, and extract a smaller volume of water from the aquifer system being developed relative to the probable long-term withdrawal pattern. This requires pumping test data to be extrapolated, an exercise that is fraught with uncertainty (van der Kamp and Maathuis 2005). The problem of extrapolation is not unique to pumping test analysis, it is of fundamental concern to many groundwater studies, for example, in groundwater flow modeling (Anderson and Woessner 1992).

A thorough understanding of the assumptions, advantages and shortcomings of the various methods used to derive long-term well capacity estimates supports ongoing groundwater management and aquifer yield research. Furthermore, a more systematic approach to deriving well capacity from pumping test data contributes to more confident predictions of the groundwater extraction component of a water budget, and also allow for comparisons between predicted yield and actual groundwater usage. This is achieved by completing the following steps:

1. Compile and test a number of existing methods that are used to estimate long-term well capacity. Select quantitative methods for evaluation and testing.
2. Compare the methods by utilizing multiple data sets derived from controlled pumping tests on wells of varying depth and yield, and representing a variety of hydrogeologic settings.
3. Assess the temporal sensitivity of each method to different assumed pumping durations and whether results are sensitive to changes in other variables, for example safety factors.
4. For the test scenarios evaluated, draw out the relationships between individual well yield (capacity) and aquifer capacity and the implications for groundwater management. Investigate the implications of issues such as well interference, and groundwater level decline.
5. Determine if an adapted version of one or more of the long-term yield estimation methods evaluated would be valid for use in broader groundwater resource evaluation applications and how application of the methods ties in with groundwater resource management.
6. Provide the theoretical and empirical basis for the recommended methodology, and identify areas for further research.

Of the various methods known to be applied in North America to estimate the long-term capacity of individual wells, three were found to be promising and selected for detailed investigation involving a quantitative analysis using eleven pumping test data sets. These are the methods of Farvolden (1959), Moell (1975) and B.C. Ministry of Environment (CPCN; 1999) herein referred to as Methods A, B and C. These methods, while established, are under-utilized beyond the localities where they were developed, and in need of further study.

CHAPTER 2

AQUIFER AND PUMPING TEST OVERVIEW AND CONCEPTS

This chapter provides an overview of aquifer and well pumping tests starting with a discussion on the many purposes of pumping tests, and followed by a review of important analytical methods applied to pumping test data in order to determine aquifer and well properties. In any evaluation of well yield, it is necessary to have a solid understanding of aquifer properties and the conceptual hydrogeologic model. It is only with such understanding that the data derived from a pumping test may be used with confidence to predict future well performance and yield.

2.1 PURPOSES OF PUMPING TESTS

Numerous texts and papers, for example, Walton (1970), Stallman (1976), Freeze and Cherry (1979), Driscoll (1986), Fetter (2001), Weight and Sonderegger (2001), and Neville (2008) describe the many purposes of pumping tests, and speak to the importance of pumping tests to the practice of hydrogeology in general.

A recent technical commentary in the journal Ground Water by Butler (2009) reviewed the long-standing practice of conducting pumping tests in water supply and contaminated site investigations. While confirming the validity of pumping tests as a tool in water supply studies, Butler pointed out that hydrogeologists should be aware of the limitations of conventional pumping test approaches that yield bulk or averaged aquifer property values, especially in regard to contaminant site characterizations, where high-resolution information (both spatial and temporal) on aquifer properties and contaminant concentrations is often required. Such techniques have evolved in the past 10 years to include investigative approaches that may incorporate the use of direct-push technology (McCall et al. 2002; Schulmeister et al. 2003; Schulmeister et al. 2004). However, for evaluating water supply wells, the constant rate pumping test combined with the variable rate step test (with and without observation wells), remains the method of choice by most hydrogeologists, although high-resolution direct-push techniques hold considerable promise for use in solving site-specific groundwater supply problems, especially in highly stratified heterogeneous formations.

The hydraulic testing of wells forms an essential component of the hydrogeologic evaluation process (Weight and Sonderegger 2001), and enables assessment of groundwater supplies, wellhead protection areas, and groundwater remediation measures at contaminated sites. The purpose of a pumping test conducted on a water supply well may include one of more of the following:

- To provide insight into well performance such as specific capacity or well efficiency so that a properly-sized pump may be chosen;
- To enable aquifer hydraulic properties to be calculated;
- To provide a means to collect and analyze groundwater samples to assess general water quality, or geochemical changes in water quality due to pumping;
- To fulfill a regulatory requirement for completion of a well or reporting of well yield;
- To provide an indication of the potential yield of a well or a group of wells in an aquifer; to assess the effect of pumping on other wells and/or surface water;
- To assess the hydraulic response or connectivity of different hydrogeologic units, or relationships between groundwater and surface water; and
- To provide a calibration data set used in the development and testing of a groundwater flow model.

Depending on the situation, the specific objectives of a pumping test govern the design and implementation of the testing program. For example, a test with a primary purpose focused on "proving up" the short-term yield of a well so that an appropriate pump size can be supplied, is likely to be different from a test conducted in order to assess well-to-well interference, or to assess suspected aquifer boundaries located at considerable distances from the pumping well. We are concerned here primarily with "well tests"- i.e. those pumping tests carried out in order to assess an individual well's hydraulic capacity (its yield), although certain external factors affecting well capacity are addressed later (in Chapter 6). While the use of observation well arrays and multiple-well pumping tests provide further (and often critically important) insights into the question of well hydraulic capacity as well as aquifer hydraulic and geometric properties, the analytical approaches applied to observation well data are not discussed in detail, as the scope of this study focuses on single pumping well analytical approaches. The use of analytical and numerical modeling tools to adjust long-term well capacity estimates to account for well interference is discussed in Chapter 6.

2.2 ANALYTICAL METHODS TO DETERMINE HYDRAULIC PROPERTIES

The process of designing, carrying out and interpreting pumping tests (especially by hydrogeologists) should ideally be grounded in a conceptual understanding (i.e. a conceptual model) of how the well and the aquifer in which it is completed responds to pumping over the long term (Weight and Sonderegger 2001). Although by no means an exhaustive review of aquifer / pumping test analytical approaches, this section presents some of the important concepts and reviews the most common analytical approaches used to interpret pumping tests. In addition to the original scientific publications cited here, useful summaries may be found in Driscoll (1986), Kruseman and de Ridder (1990), Allen (1999), Neville (2008), and Maathuis and van der Kamp (2006), to name a few.

When there is no change in drawdown with respect to time after a sufficient amount of time has passed in a pumping test, this constitutes an equilibrium or steady-state condition. True equilibrium (steady-state) conditions are rarely encountered in pumping tests and consequently are not covered here in any detail. Although not reviewed here, useful summaries of equilibrium analytical methods including those of Theim (1906) and constant drawdown analysis (Jacob and Lohman 1952) may be found in Lohman (1972) and in Kruseman and de Ridder (1990).

Most pumping tests are of the non-steady state type, which means drawdown continues to increase (sometimes quite slowly) until the end of the test. Probably the two most widely-used methods to analyze non-steady, radial flow to a pumping well in a confined aquifer are those of Theis (1935) and Cooper and Jacob (1946). Through careful diagnosis of the pumping test response augmented by pressure derivative analysis, these methods may also be used for certain portions of pumping tests performed on wells completed in other types of aquifers, including fractured bedrock and unconfined systems.

Selected other analytical approaches for interpreting non-steady flow to wells are reviewed briefly, including models for linear and fracture flow, variable-rate (step) test analysis, and unconfined aquifer response.

2.2.1 Theis method of curve-matching

Theis' 1935 paper forms much of the basis for today's understanding of non-steady radial flow to wells. The hydrogeologic conceptual model on which this analytical approach is based makes the following major assumptions about the tested aquifer and the pumping test:

Aquifer assumptions:

- confined and of a large areal extent;
- isotropic and homogeneous, and of constant thickness;
- overlain by a low-permeability confining layer, which in turn is overlain by a water-table (unconfined) aquifer;
- the confining layer is impermeable and has a specific storage of zero; and
- all water removed from the aquifer is derived from storage.

Pumping test assumptions:

- The well has an infinitesimal diameter and fully penetrates the aquifer;
- Flow rate is constant;
- The only water level (head) changes measured are due to the subject pumping well;
- There are no inertial effects occurring in the wellbore; and
- Head in the aquifer remains above the stratigraphic top of the aquifer.

As noted by Neville (2008), the Theis solution and its underlying assumptions are highly idealized and rarely observed in the field. However, with proper interpretation, some parts of many well pumping test response data may be analyzed with this method. Because the Theis method is so widely used and well-known, it provides a useful "benchmark" (Neville, 2008, Ch. 2, p. 3) against which other conceptual and analytical models may be compared. The basic Theis formula for determining transmissivity is given as follows:

$$T = \frac{Q\,W(u)}{4\pi s}$$

The transmissivity (T) value derived from the above formula is in units of L^2/time (e.g. ft^2/day). The *W(u)* term is called the well function. The s term is the drawdown computed by using a series of type curves developed by Theis, and Q is flow rate during the pumping test. This drawdown value is that observed where the the 1/u and *W(u)* values both equal 1.0, known as the *match point*. The Theis method may easily be applied by entering well information, and the time-drawdown data into the data analysis wizard included in any of the commercially-available pumping test software packages. It may also be applied manually, by using hard-copies of the type curves overlain on the actual pumping test data plotted on logarithmic graph paper. Using a different equation, the aquifer storativity (S) may be derived if observation well time-drawdown data are available, and the radial distance between the pumping well and observation well is known. A typical logarithmic time versus drawdown Theis curve is shown in Figure 2.1.

2.2.2 Cooper-Jacob straight-line method

The Cooper-Jacob (1946) method provides a simpler approximation of the Theis non-steady pumping test analytical model, and it makes all the same assumptions as the Theis model, except that it is generally not valid for values of $u < 0.01$ or values of $1/u > 100$. This usually means the earlier time drawdown data cannot be used in determining T with the Cooper-Jacob method. As shown later, these early stage pumping test data only rarely give a true indication of near-well aquifer conditions, and so for this reason, the Cooper-Jacob method is probably the most widely used conventional pumping test analytical model.

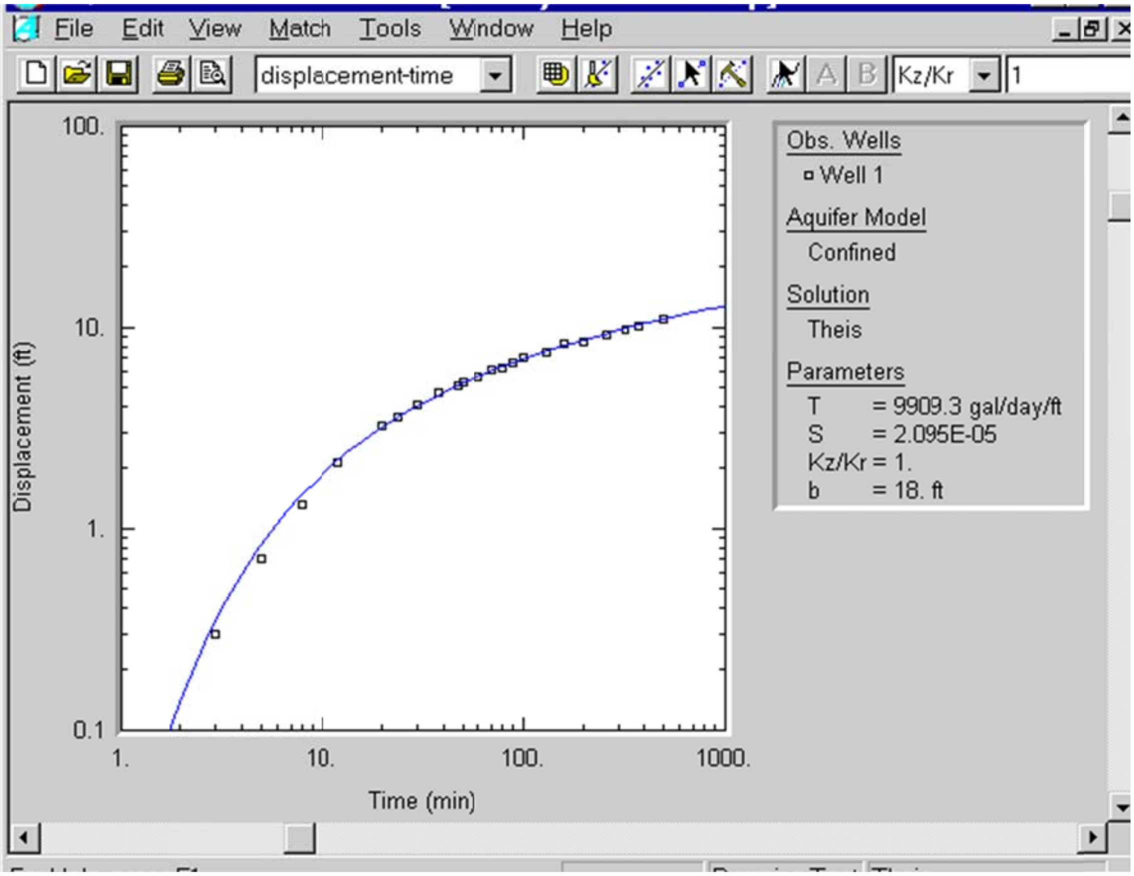


Figure 2.1 Characteristic Theis type time-drawdown response curve generated with the software program Aqtesolv™

To derive a value of T using the Cooper-Jacob method, the time-drawdown data are plotted on semi-logarithmic graph paper, with elapsed pumping time on the log scale. If radial horizontal (i.e. Theis-like) flow is occurring, the data should plot on a straight line. The slope of the straight line and the pumping rate determine the aquifer transmissivity. The Cooper-Jacob equation to estimate transmissivity is given as follows:

$$\mathbf{T = 2.30\ (Q / 4\pi\ \Delta S)}$$

Where ΔS = the slope of the semi-logarithmic time-drawdown plot

Figure 2.2 provides a typical Cooper-Jacob straight line plot of the log of time versus drawdown.

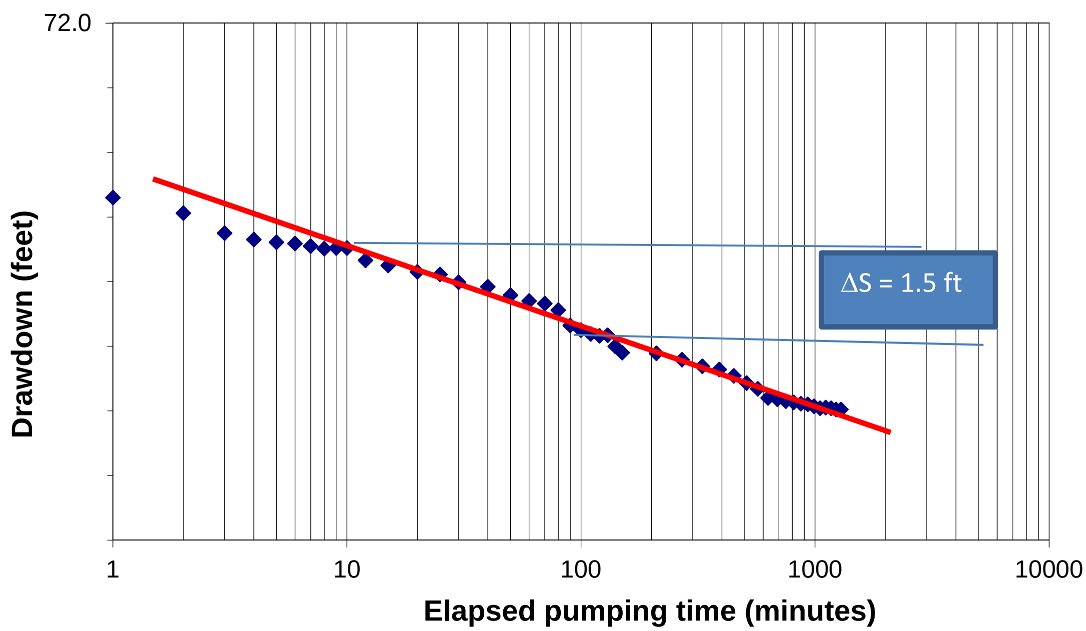


Figure 2.2 Typical semi-log straight line plot of drawdown versus log of time

2.2.3 Unconfined aquifers – delayed yield and surface water recharge effects

Neuman (1975) described methods to analyze pumping test data for wells completed in water table (unconfined) aquifers that exhibit dewatering effects as the water level is drawn down near the pumping well. This so-called "delayed yield" typically produces an apparent period of water level stabilization during a pumping test. This is caused by gravity-induced vertical drainage of pore water from the just-drained aquifer medium. The timing of the onset of the delayed yield effect depends on the properties of the aquifer and the pumping rate of the well. Neuman produced a series of algorithms and created a family of unconfined type curves that depart from the Theis curve in the middle part of the pumping test, but converge with the Theis curve late in the test (assuming the test is run long enough). This convergence with ideal confined-like behavior occurs when the bulk of the pore water drainage has been exhausted and the cone of depression continues to slowly expand under radial flow conditions.

One of the shortcomings of the Neuman method, and modifications of the Neuman method, summarized in Kruseman and de Ridder (1990) is that it does not account for the additional drawdown that occurs near the pumping well and the consequent reduction in near-well aquifer transmissivity due to dewatering. However, the Neuman method is useful for observation wells located a distance from the tested well that is at least greater than one unit of pre-pumping aquifer thickness (Allen 1999). Neuman’s method is less useful in predicting the drawdown behavior in the pumping well, which may be why some guidelines, including for example the CPCN Guidelines in British Columbia and texts such as Driscoll (1986), recommend a minimum 72 hour pumping test on wells in unconfined aquifers. After 2 or 3 days of pumping, the delayed yield effect has usually run its course, and radial flow conditions exist enabling conventional aquifer test analysis using, for example, the Cooper-Jacob method. The aquifer coefficient of storage (specific yield in unconfined systems) is notoriously difficult to estimate accurately with pumping test data, even when observation wells are used in unconfined systems, with software programs giving unrealistic values, that may be either too high (i.e. greater than 1) or too low (i.e. 1E-04). Many analysts simply assume a value on the order of 1E-01 based on a typical effective porosity value.

Sometimes delayed yield is difficult to differentiate from leaky aquifer response (Weight and Sonderegger 2001), and so an understanding of local geology and hydrology is required to make such interpretation possible. In addition, it is common for unconfined aquifers to be found and developed in close proximity to surface water sources. The author's experience in conducting pumping tests in shallow unconfined aquifers located in such settings has found that the delayed yield effect may be difficult to differentiate from surface water recharge boundary effects, because both delayed yield and induced surface water recharge effects may produce a period of apparent water level stabilization, and then as pumping continues, the cone of depression expands beyond the location of the surface water recharge source, and the aquifer continues to behave as an ideal, confined aquifer experiencing radial flow (i.e. a flat pressure derivative and a straight line on a semi-log plot). This phenomenon has been observed to occur in situations where a creek partially penetrates an unconfined aquifer and observation wells on the far side of the creek from the pumping well experience drawdown during a pumping test. When the source of surface water recharge is strong, then the well water level during a pumping test may be observed to stabilize quickly (sometimes within a minute or two), and then does not change unless the surface water level changes (Figure 2.3).

2.2.4 Linear and fracture flow models

Allen (1999) and Kruseman and de Ridder (1990) provide summaries of fracture flow and linear flow analytical models. The response of observation wells to pumping tests conducted in fractured bedrock aquifers with steeply-dipping (vertical) fractures is also explored in an earlier paper by Gingarten and Witherspoon (1972). The linear flow period is characterized as a straight-line on a log-log plot of time versus drawdown; and has a 0.5 slope (Allen 1999). If pumping continues long enough and if the vertical fracture behaves as a confined aquifer (i.e. is not significantly dewatered), then usually the later time drawdown data may be analyzed by the Cooper – Jacob (1946) method. According to Allen (1999), pumping tests in fractured bedrock wells exhibiting linear flow response must be continued long enough in order for radial-like flow conditions to occur in order to appropriately estimate the long-term well capacity or aquifer properties.

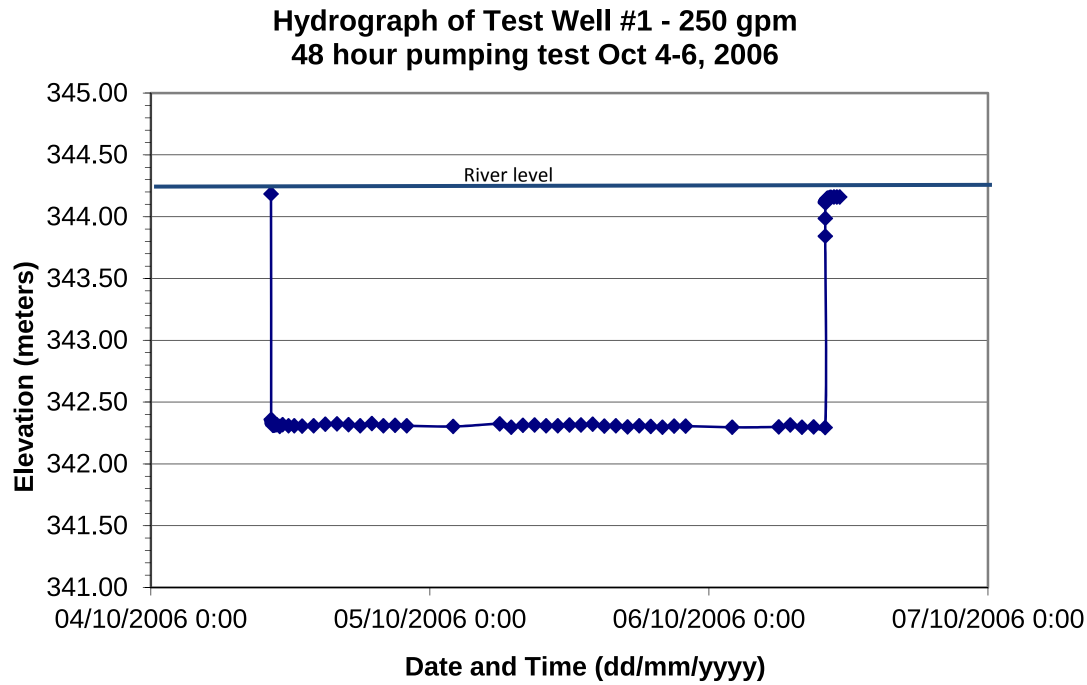


Figure 2.3 Hydrograph of a well exhibiting a strong surface water recharge effect

There are several other analytical models that attempt to approximate the highly variable nature of fracture flow response. These include the double-porosity models (Kruseman and de Ridder 1990) that may be applied to some aquifers. Figure 2.4 shows a semi-logarithmic time-drawdown plot for a bedrock well pumping test where the slope of the drawdown curve is shallow during the first 100 minutes and then shows an ever-steepening curve, which if plotted on a linear or full logarithmic hydrograph, would show a straight line. This response is indicative of linear fracture flow, and the pumping test would have to continue for a longer period in order for radial flow to be detected (if at all). In the case shown, the linear flow in the near-vertical fracture effectively dewatered the fracture, and so drawdown reached the deep pumping intake within one day. The next section discusses how pressure derivative analysis may be used to identify radial flow conditions during a pumping test.

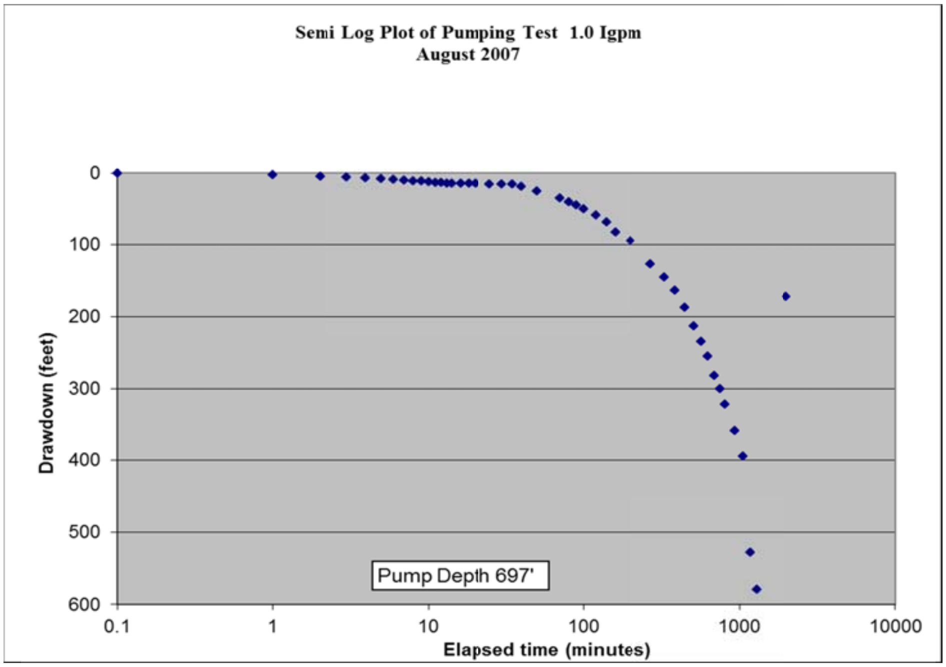


Figure 2.4 Hydrograph illustrating probable linear flow in a bedrock well pumping test

2.2.5 Pressure derivative analysis

The use of pressure derivative techniques evolved in the petroleum industry, where analysts devised diagnostic tools intended to evaluate reservoir geometry and formation pressure response to oilfield operations. The application of derivative analysis to groundwater resource studies was noted in early papers by Bourdet et al. (1989); expanded upon by Spane and Wurstner (1993), and further discussed in subsequent summaries by Allen (1999) and Neville (2008).

Pressure derivative analysis is best described as a diagnostic tool to assist the pumping test analyst in choosing which portion of a drawdown or recovery curve to use to derive aquifer hydraulic properties. As noted by Allen (1999), an infinitely acting radial flow regime (i.e. Theis-like flow) has no characteristic behavior on a type curve, but the logarithm of the derivative of drawdown (head) takes on a particular recognizable shape when plotted on a log-log plot against the log of elapsed pumping time. In essence, a pressure derivative plot is a log-log plot of a semi-logarithmic plot of time versus drawdown (Figure 2.2 is a semi-log plot). Derivative plots make it relatively easy to differentiate portions of a pumping test where linear or vertical flow may be occurring, and when key assumptions in a Theis or Cooper-Jacob analysis are not met due to casing storage, boundary effects, or other non-ideal conditions.

Typical characteristic features of derivative plots include a rising linear slope in early time (usually the first few minutes of a pumping test) indicating casing storage effects, a flat or mostly flat derivative indicative of radial (Theis-like) flow, a falling derivative indicative of a leaky aquifer or recharge boundary effect, or a rising derivative indicating a linear no flow boundary. Coupled with the conceptual model of the well site hydrogeology, other effects such as non-Darcy conditions caused by vertical flow (such as in a bedrock fracture or in an unconfined aquifer with large drawdowns) may be identified.

Figure 2.5 (Page 26) provides an example pressure derivative plot as generated by a spreadsheet tool developed and included in the Allen (1999) paper. This "DERIV" spreadsheet includes a fixed end-point algorithm that calculates the pressure derivative from basic elapsed time and drawdown data collected during a pumping test. This algorithm is less complex than the least-squares regression algorithm included with software programs (such as Aqtesolv™), but when the quality of data is good, the spreadsheet provides an effective diagnostic curve. The worksheet also displays semi-logarithmic and logarithmic time-drawdown plots. The DERIV fixed end-point algorithm calculates the first-order derivative of head (drawdown), with respect to the natural log of the change in time, using 3 data points (the point of interest and the ones immediately preceding and following that point). The mathematical expression used to calculate the pressure derivative is from Spane and Wurstner (1993) and is as follows:

$$(dp / dX)_1 = [(\Delta P_1 / \Delta X_1)\Delta X_2 + (\Delta P_2 / \Delta X_2) \Delta X_1] / (\Delta X_1 + \Delta X_2)$$

The 1 and 2 subscripts refer to the data points before and after the point of interest, P is pressure and X is time. Three columns of data are normally input into the DERIV sheet: time, water level and drawdown. Figure 2.6 shows a composite plot of a log-log (Theis) plot of time and drawdown and the corresponding pressure derivative, as generated by the commercial software package Aqtesolv^{TM}.

One additional point on derivative plots is that a late-time “end effect” is common (Spane and Wurstner 1993) and is characterized by increased noise in the data caused by a combination of factors including the relatively small rate of drawdown occurring in later time, and the amount of remaining drawdown data at the point of calculation. If necessary, this may sometimes be addressed by varying the L-spacing if the fixed end-point algorithm is used. Software programs providing derivative curves have automated smoothing routines to help deal with end-effect data scatter .

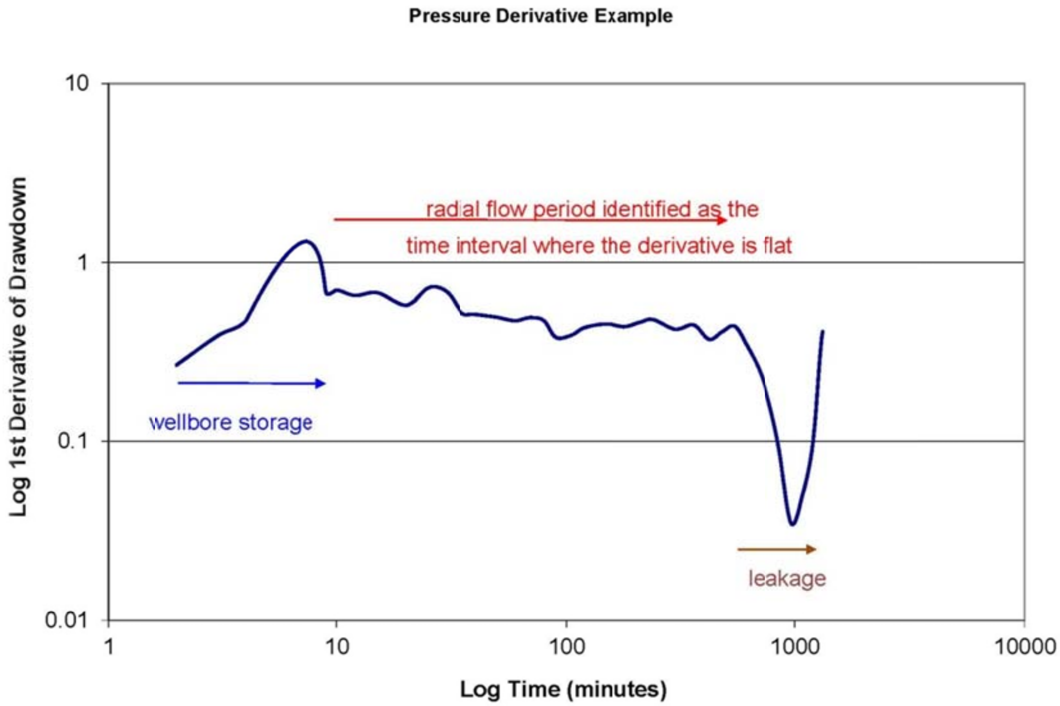


Figure 2.5 Pressure derivative characteristics (modified after Allen 1999)

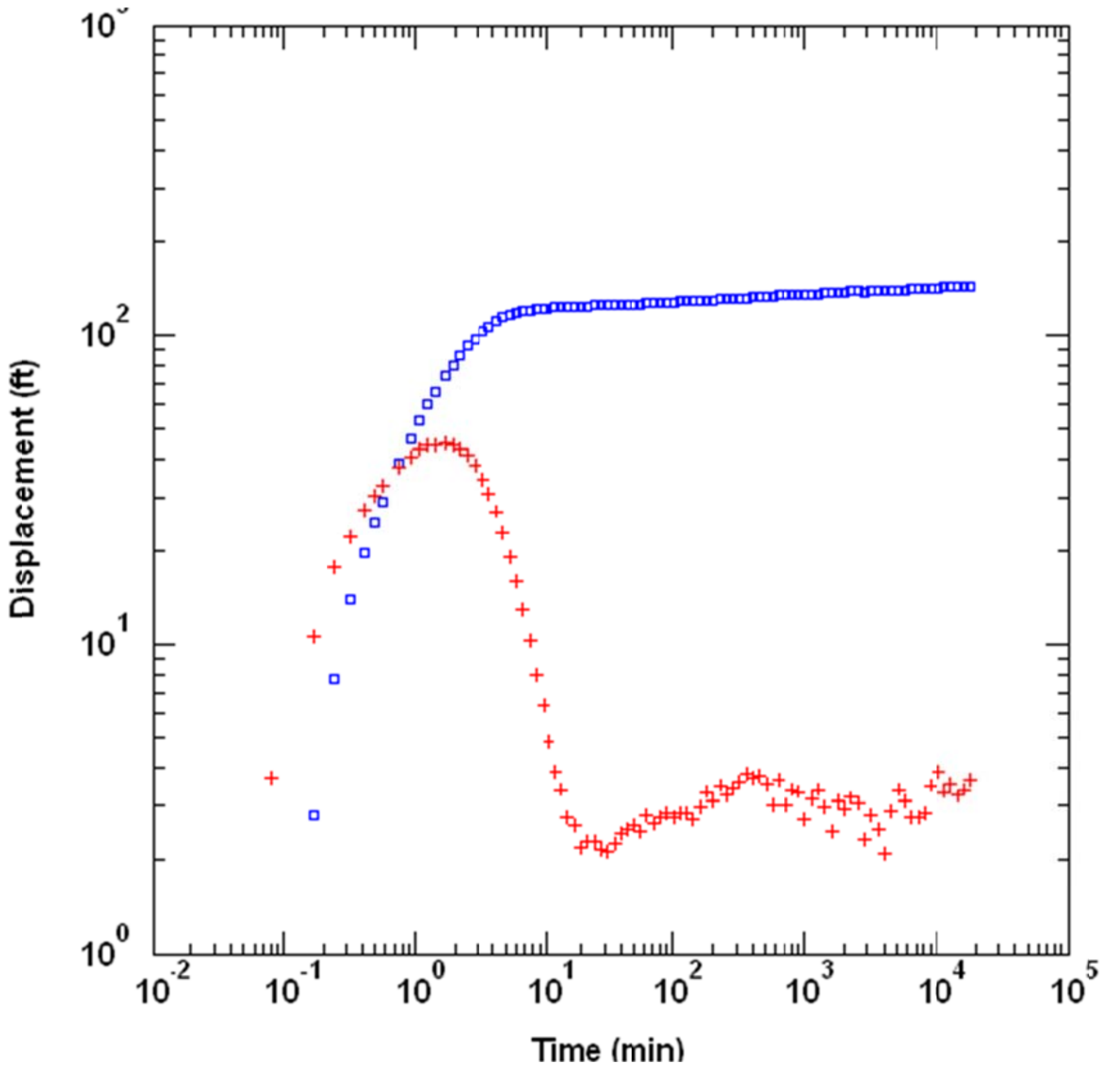


Figure 2.6 Composite plot of Theis curve (blue boxes) and pressure derivative (red crosses)

2.2.6 Step pumping tests

Before moving on to discuss well yield determination methods, a brief review of variable-rate or step pumping tests is in order. Such tests are commonly performed on water supply wells and involve operating the test pump at three or more different pumping rates that are held constant for anywhere from 30 minutes to 2 hours while measuring well drawdown (Weight and Sonderegger 2001). The relative specific capacity (flow rate divided by drawdown) of the well at the end of each pumping step is then determined. Besides giving a general indication of the well's performance, the step test provides potentially critical information having implications on the long term capacity of the well.

The concept of well efficiency is sometimes used to assess the results of step tests (Driscoll 1986). What this actually means is the proportion of drawdown in the well caused by laminar (Darcian) flow relative to the proportion of drawdown caused by non-laminar (turbulent) flow. When most of the drawdown (or well loss) is caused by laminar flow, then the drawdown in the well varies in proportion to flow rate and the well is considered hydraulically efficient. Significant drawdown caused by turbulent flow means that some of the drawdown varies in proportion to some exponent of the flow rate. The basic equation, developed by Jacob (1946) and given by Driscoll (1986) is as follows:

s (drawdown) = $BQ + CQ^2$ where

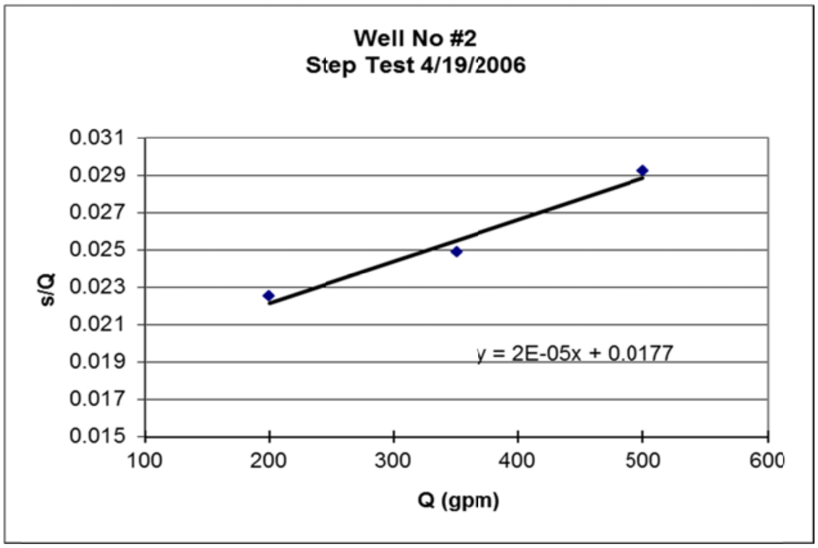
B = the laminar well loss coefficient
C = the turbulent well loss coefficient

When step test data are plotted on a linear graph with the ratio of drawdown to flow rate (s/Q, which is the inverse of specific capacity) plotted on the y axis and the flow rate (Q) on the horizontal axis, the slope of the line is C and the y intercept is B. The exponent applied to the CQ term is for convenience taken to be 2 (Driscoll 1986) but actually varies depending on the hydraulics of the well. The BQ term can be inferred as the drawdown occurring due to laminar flow in the aquifer near the well and the CQ^2 term is inferred to be the head loss due to turbulent flow as groundwater enters the well through the well screen openings or in bedrock wells, fracture openings. One expression of the empirical "well efficiency" is derived with the following equation (Driscoll 1986; Kruseman and de Ridder 1990):

$$L_p = (BQ/BQ+CQ^2) \times 100$$ (expressed as a percentage)

The L_p term is the percentage of well drawdown due to laminar flow loss and Figure 2.7 provides a s/Q versus Q plot and a sample calculation. For a reasonably efficient well that is not being over-pumped, the data should plot on a straight line as shown. If the higher flow rate s/Q values do not plot on the straight line, then this could indicate increased turbulent head loss (non-laminar flow) at higher pumping rates.

As shown later, some of the empirical equations for determining safe well yield (LTWC) may produce a theoretical value that far exceeds the test pumping rate. Because it is possible that a non-linear relationship between pumping rate and drawdown could exist at higher pumping rates, it is generally not a good idea to extrapolate a calculated well capacity beyond the rate at which a pumping test or step test has confirmed a laminar flow condition.



Well #2 Pumping Test Data and Analysis						
Step Test						
gpm	**feet**	**s/Q**	**Specific Capacity (gpm/ft)**		C (slope)=	0.00002
200	4.5	0.0225	44.4		B(intercept)=	0.01770
350	8.7	0.0248571	40.2			
500	14.6	0.0292	34.2			
B =	0.017702381		Well Loss Calculation for Q = 350 gpm			
C =	2.23333E-05		**Lp = (BQ/BQ +CQ^2)*100**		**69%**	

Figure 2.7 Example step test s/Q versus Q plot and laminar head loss calculation

CHAPTER 3

PREVIOUS WORK ON WELL YIELD DETERMINATION METHODS

As noted in the introduction concepts of Safe Aquifer Yield and Sustainable Groundwater Yield have been widely described, analyzed and debated in the literature, while by comparison, the Long Term Well Capacity (i.e. the safe yield of individual wells) has received relatively little attention. This is probably due to the fact that SAY and SGY involve theoretical approaches, whereas LTWC requires application of empirical methodologies, although these may be based on basic groundwater theory, such as radial flow to a well (e.g., Theis, 1935).

A search of literature sources including those available via internet search engines such as Google, as well as the publication search functions of the National Ground Water Association (NGWA); and International Association of Hydrogeologists (IAH); and numerous U.S. State and Canadian Provincial data bases and government websites revealed that there are a number of published methodologies or guidelines that are used to determine the long-term "safe" capacity or yield of a well. Some of these are categorized here as "quantitative" in that they use traditional analytical pumping test analysis (for example, determination of the slope of a drawdown curve on a semi-logarithmic plot) and use some type of numerical equation to determine well capacity as a function of pumping time and available drawdown in the well.

Other methods include those that consist of variations on volume-based determinations, which are relatively simplistic, and provide a means to estimate well capacity with little or no hydrogeologic expertise needed. Some guidelines appear to leave the question of determining the well yield to the judgement of a well driller or a hydrogeologist, without providing any suggested or required methodology. Examples of the various types of well capacity determination methodologies known to be in use in North America follow in the next two subsections. It is not known why numerous government jurisdictions having some form of regulatory control over groundwater use seem to have avoided the adoption of a standard methodology to estimate well capacity, or why most of the methods that do exist are from western Canada (Maathuis and van der Kamp 2006). This is true even for jurisdictions such as Ontario (2005a; 2005b) that have published fairly detailed (and sometimes prescriptive) well pumping test procedures, but have no quantitative methodology to determine long-term well capacity using pumping test data.

3.1 QUANTITATIVE METHODS BASED ON RADIAL FLOW THEORY

Several quantitative (equation-based) methods exist for the estimation of long-term well capacity or "safe well yield." Although empirical, these methods are founded in the fundamental scientific principles of radial flow to pumping wells, as originally described by Theis (1935). This section describes the three methods evaluated in detail in this study which are herein described as Methods A, B and C. Other empirical, volumetric or professional judgement-based methods are described in Chapter 3.2.

3.1.1 Theoretical background to the quantitative methods

There are several quantitative well yield estimation methods that are based on fundamental well and aquifer hydraulic principles, such as the Theis formula. The methods determine LTWC primarily as a function of the aquifer transmissivity and the pumping duration. Implicit in the use of these methods is the assumption (which should be confirmed with step tests) that drawdown in well varies linearly with the flow rate, and that the proportion of drawdown due to turbulent flow is relatively small.

The most widely used of the quantitative methods known in North America were all developed in western Canada. These include methods first used in the prairie provinces of Alberta and Saskatchewan (Farvolden and Moell); and more recent methods developed in British Columbia (B.C. Ministry of Environment). van der Kamp and Maathuis (2005) provided a review of the background on the first two methods, and also recommended adoption of a new method to replace the older methods, which in a subsequent publication (Maathuis and van der Kamp 2006) they termed the modified Moell method.

As described in detail by van der Kamp and Maathuis (2005) the so-called Q_{20} methods (Q_{20} standing for the safe or sustainable 20 year well yield) is for the case when the water level continues to decline during a pumping test, which indicates that the well is drawing water from storage. Presumably, 20 years is selected as the time horizon because this is sufficiently far in the future to allow for more study of the aquifer system and more planning for water supply infrastructure; it may also be tied to the groundwater licensing procedure in Alberta, where most groundwater use permits are typically up for renewal after 20 years. The rationale of the Q_{20} methods, then, is that if the well needs to last at least 20 years (which is about 10 million minutes), the drawdown curve when projected should not exceed the total available drawdown in the well (less a safety factor). In addition to the practical consideration of needing to allow for some minimum submergence of the well pump below the pumping water level, the use of a safety factor accounts for natural variability in groundwater and well systems, and also is a way to address uncertainty in the data analysis. Practitioners have somewhat arbitrarily selected a 70% (0.7) safety factor for use in calculating LTWC values.

When applied in the context of actual hydrogeologic conditions and groundwater use, the Q_{20} method could be conservative, because wells are generally not pumped continuously, and storage depletion is not the only source of water since aquifers may receive some amount of natural or induced recharge at some point each year. However, in cases where aquifer depletion is possible, such as highly confined aquifers, aquifers in dry climates, or situations of known groundwater decline (e.g. the High Plains Aquifer system in the U.S.), then the Q_{20} method might provide either a realistic or even an optimistic estimation of long-term well yield. Any method of determining LTWC could lead to overestimates when the combined effects of multiple well withdrawals lead to yearly declines in groundwater levels. In such cases, a Q_{20} determination would need to be adjusted (downward) to account for cumulative and progressive aquifer depletion. Relating well capacity to loss of available drawdown (or saturated thickness) has been explored in Kansas (Hecox et al. 2002) for the specific case of the Ogallala aquifer portion of the High Plains aquifer system.

The fundamental assumption in making long-term projections of well drawdown from pumping test data is that the drawdown trend is predictable, and importantly, conforms to the line predicted by the Theis (1935) and/or Cooper-Jacob (1946) methods for non-equilibrium pumping tests. This is conveniently taken to be in the form of a straight line when the time-versus-drawdown data are plotted on semi-logarithmic graph paper as shown in the example in Figure 3.1. van der Kamp and Maathuis (2005; 2006) noted that the idealized aquifer model of homogeneity and infinite extent is not always met, which might cause predictive uncertainty.

For a Q_{20} determination, there are eight log cycles of time between $1/10^{th}$ of a minute and 10 million minutes. So for a total available drawdown of H_A, $1/8^{th}$ of that amount is available during each log cycle of time. Assuming the Cooper-Jacob approximation is valid for the entire 20 year period, the "safe pumping rate" of the well may then be determined as described by the equations in the following sections. Figure 3.2 illustrates some of the terms used in the LTWC methods.

For a 100-day yield determination, the British Columbia method (Allen et al. 1999; see 3.1.4) projects the latest confirmed drawdown trend (even if it is a trend due to an aquifer boundary condition) to 100 days, calculates the well specific capacity at 100 days, and then applies a 0.7 safety factor. This approach is based on guidelines for obtaining a permit to operate a water utility, which is called a Certificate of Public Convenience and Necessity (CPCN) in B.C.

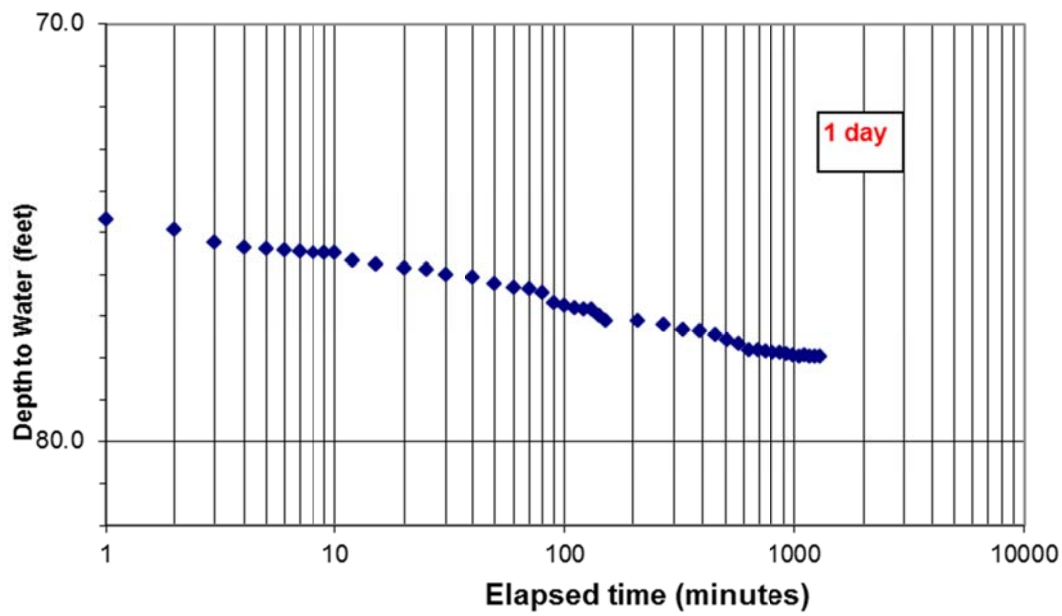


Figure 3.1 Semi-logarithmic plot of time on log scale and water level or drawdown on linear (y axis) scale

The CPCN method does not explicitly require the hydrogeologist to assume that Theis-like conditions (i.e. radial flow) persist for 100 days of pumping, since by definition a boundary condition is indicative of either a no-flow boundary, a recharge boundary, or a significant change in aquifer properties at some distance from the pumping well such that the key assumptions of the Theis and Cooper-Jacob methods are not being met (e.g., horizontal aquifer, homogenous properties, infinite in areal extent, and so on). However, the CPCN method does require that the later time data fall on a straight line and so the method cannot be applied if multiple boundary effects are noted in the test data, or if the data plot on a straight line on an arithmetic hydrograph or exhibit an ever-steepening trend on a semi-logarithmic time-drawdown plot (see Figure 2.4). Like the Q_{20} methods, the CPCN method is conservative in that it assumes no recharge and that the well is drawing water from storage (in cases where the data plot on a straight line with no boundary conditions).

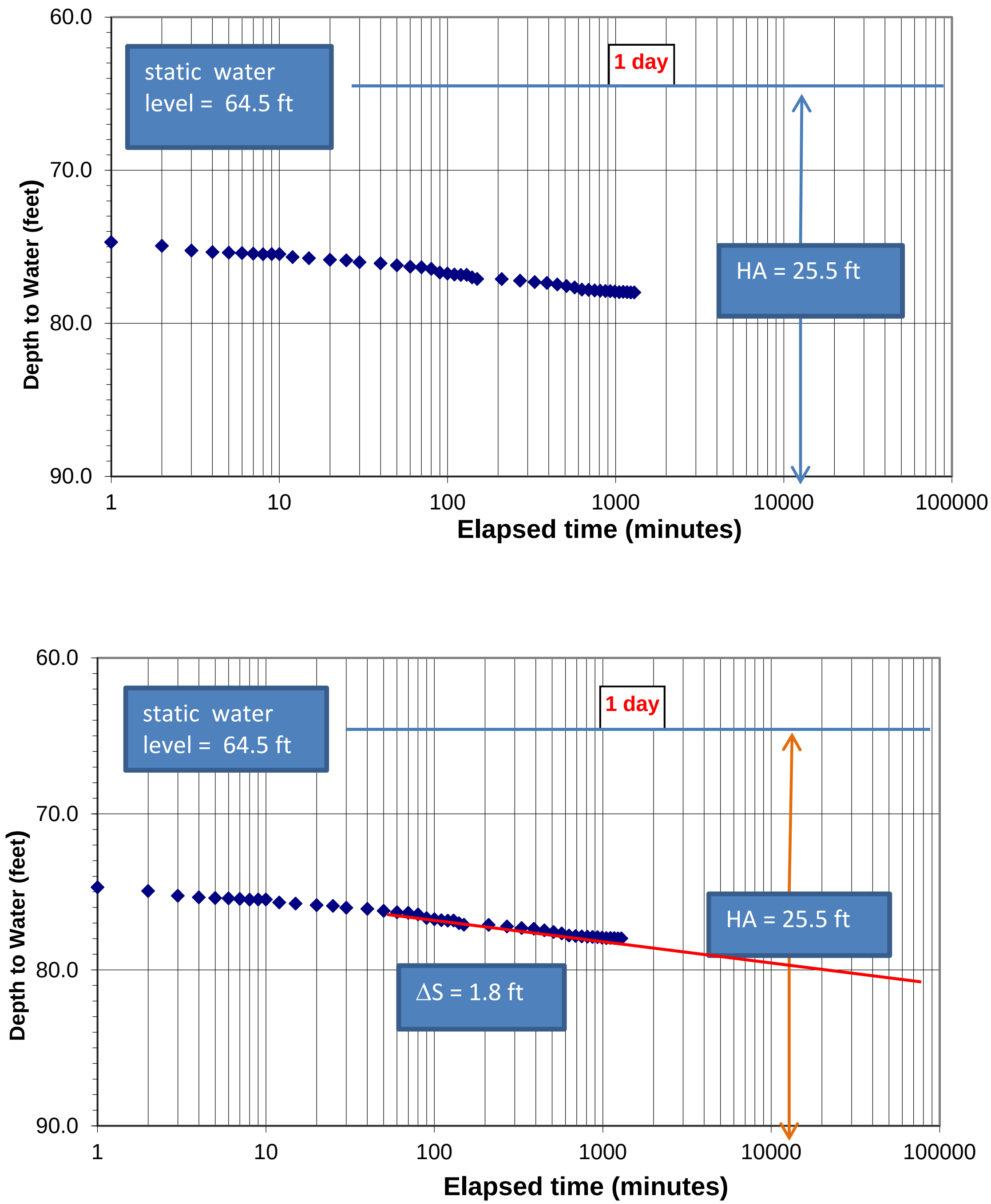


Figure 3.2 Semi-logarithmic plots showing ΔS and H_A values, and a straight-line drawdown projection

3.1.2 Method "A": Farvolden (1959)

The original Farvolden equation required the analyst to first derive an estimate of the aquifer transmissivity (T) on the basis of the pumping test. The Farvolden Equation, which is essentially a rearrangement of the Theis equation incorporating pre-defined constraints, is as follows:

$$\mathbf{Q_{20} = \frac{4\pi T\,(H_A/8) \times S\mathit{f}}{2.30}}$$

where

Q_{20} = estimated 20 year sustainable well yield m^3/day

T = aquifer transmissivity in m^2/day

H_A = available head (or available drawdown) in aquifer

S*f* = safety factor, normally taken to be 0.7

The safety factor is provided in the current guideline document (Alberta Environment 2003) with 0.7 as a default value, but this factor may be adjusted based on the professional judgement of the hydrogeologist. The available drawdown (head; H_A) is equal to the distance between the non-pumping water level in the well and the top of the aquifer, or top of well completion (i.e. screen) interval in confined aquifers, and is taken to be 2/3 of the difference between the non-pumping water level and top of well screen; or alternatively, 2/3 of the pre-test saturated thickness of the unconfined aquifer. The latter requires well-site specific information from fully-penetrating drilling logs. Simplified, the Farvolden equation may be rewritten (Alberta Environment 2003) as:

$\mathbf{Q_{20} = (0.68) \times (T) \times (H_A) \times (0.7)}$ to derive a Q_{20} value in metric units (m^3/day)

Note the Farvolden method required the analyst to determine the aquifer transmissivity. As van der Kamp and Maathuis (2005) noted, the Farvolden method assumes radial flow conditions, which means the long-term drawdown would follow the trend predicted by the Theis (1935) equation or the Cooper-Jacob (1946) approximation to the Theis equation for a confined aquifer. If this is the case, then the Farvolden equation may be rewritten as suggested by van der Kamp and Maathuis (2005) as:

$$\mathbf{Q_{20} = 0.7 \times H_A \times Qt/8\Delta S_p}$$

where:

Qt = test pumping rate

$8\Delta S_p$ = eight log cycles of drawdown (i.e. 0.1 to 10E+06 minutes, which equals 6,944 days or about 19 years and 9 days, which for convenience is apparently rounded to 20 years).

H_A and S_f as defined above

A key assumption of the Farvolden method is that the earliest drawdown, in particular the drawdown in the first 6 seconds and even the first minute (i.e. the first log cycle of time in most tests) is infinitesimally small compared to the total drawdown during the pumping test. When this is not the case, the Farvolden method might lead to an underestimation of the projected 20 year drawdown, and consequently, an overly-optimistic well capacity estimate. The effect of under-predicting the initial log cycle of drawdown is to displace the drawdown curve vertically upward such that all of the future drawdown values are underestimated. Published information on the Farvolden method does not provide a way to check the validity of the results when applied to a specific well test.

3.1.3 Method “B”: Moell (1975)

Recognizing that in some cases, large drawdowns may occur early in the pumping test, Moell (1975) derived an alternative formula that projects the drawdown trend as observed 100 minutes into the test out to 20 years. The Moell equation provided in Alberta Environment (2003) is as follows:

$$Q_{20} = S_f\,(0.7) \times H_A \times Qt \,/\, (S_{100min} + 5\Delta S)$$

This method does not require the analyst to derive an aquifer transmissivity value to estimate the theoretical long-term well yield (though elsewhere in Alberta Environment 2003, this is required for hydrogeological reports).

3.1.4 Method “C”: B.C. Ministry of Environment (1999)

Whereas the Q_{20} methods were developed in part to standardize safe well yield calculations for the purposes of groundwater licensing (water right permitting), British Columbia has to date not required a water right permit or license to extract groundwater. However, there is some regulation of groundwater use extraction through water utility legislation. This legislation and associated regulations and guidelines require private water utilities to license their water system by obtaining a CPCN permit.

Following enactment of the water utility regulation, the B.C. government in the 1990s developed guidelines for the regulated water utilities to follow. These guidelines included standards for groundwater well assessments, including design, analysis and reporting of aquifer pumping tests. Allen et al. (1999) prepared a report for the B.C. Ministry of Environment that became the basis for the CPCN groundwater evaluation guidelines. These guidelines include a specified method for determining a 100-day well capacity, termed the long term well capacity, for wells proposed to serve water utilities.

The scientific basis of the equation used is similar to the Q_{20} methods in that it requires a determination of the slope of the time-drawdown curve on a semi-logarithmic plot and directs the analyst to project the late-time drawdown trend to 100 days, from which the theoretical 100-day specific capacity is calculated. The CPCN method applies a 70 percent (i.e. 0.70) safety factor, and also requires minimum 24-hour pumping tests, and calls for 72-hour pumping tests in unconfined aquifers and in fractured bedrock formations. The CPCN well capacity formula for a 100-day LTWC (Q_{100d}) is provided below:

$$\mathbf{Q_{100d} = \mathit{S_f}\,(0.7) \times H_A \times (Qt/S_{100})}$$

The available drawdown term, which for consistency with the previous Q_{20} methods is abbreviated here by the term H_A, is defined in the CPCN guidelines. For fractured bedrock formations, this is taken to be the difference between the non-pumping (static) water level and the uppermost water-bearing fracture if one is noted on the well driller's log. In lower-yielding bedrock wells, where fractures are difficult to detect during drilling, normally a depth of 10 to 20 feet from the bottom of the hole is taken to be the fracture depth, based on the presumption that with low-yielding wells, the driller stopped soon after encountering a water-bearing fracture.

In other types of confined and unconfined aquifers, for example alluvial or glacial sedimentary systems, the available drawdown is the difference between the static water level and the top of the confined aquifer, or the top of the well screen, whichever is shallower. The 70% safety factor (0.7) is intended to allow for seasonal variations in water levels, well interference (unless this causes major additional drawdown), adequate submergence for the well pump, and possible declines in well performance.

Whereas the Q_{20} methods are based on the assumption that the groundwater resource becomes virtually exhausted after 20 years, the CPCN 100-day well capacity makes the assumption that the calculated long-term well capacity is sustainable over the long term, and that aquifer recharge occurs after 100 days. Thus, the method assumes that after a period of 100 days of high groundwater withdrawals, either groundwater recharge would occur and/or pumping demand would be reduced during the off-season (e.g. winter in coastal regions, spring in interior regions).

The guidelines for applying the CPCN method state that a well capacity should not be rated above the flow rate of the pumping test, unless supportive data and analysis are provided, for example a step test that confirms laminar flow at higher pumping rates, or well screen transmitting capacity data.

3.1.5 Modified Moell method of Maathuis and van der Kamp (2006)

Maathuis and van der Kamp prepared a report (2006) for government regulatory agencies in the Canadian provinces of Alberta and Saskatchewan. Their study reviewed the development of the so-called Q_{20} methods outlined above (Farvolden and Moell) and proposed an alternative method that explicitly accounts for the appropriate conceptual aquifer model describing the response of the aquifer to pumping. Van der Kamp and Maathuis argued that the straight-line extrapolation of drawdown (based on the slope of the semi-logarithmic time versus drawdown curve) could give rise to problems if the appropriate analytical model of aquifer response is not considered. This is not an issue if the long-term response pattern is detected during a pumping test (for example, a linear recharge boundary, delayed yield, or a linear barrier boundary). However, many pumping tests are only run for a few hours in Alberta and Saskatchewan and so accounting for boundary responses is of particular concern in these areas.

To update the Q_{20} methods, van der Kamp and Maathuis recommended first interpreting the pumping test data and well site hydrogeology in order to develop the conceptual model sufficiently such that the appropriate analytical model may be applied to generate the projected drawdown trend beyond the time frame of the pumping test. Although not noted in the paper, this is most readily done using one of the commercial aquifer test analysis software packages, which typically include an analytical simulation tool that solves for s (drawdown) after a specified pumping time.

This approach, in theory, would allow the analyst to utilize well-documented type curves for pumping tests exhibiting double-porosity effects, delayed yield (unconfined response), leaky aquifer response, and so on. The equation proposed by van der Kamp and Maathuis is a slight modification of the Moell (1975) equation, as follows:

Maathuis and van der Kamp modified Moell Equation:

$$\mathbf{Q_{20} = \mathit{S_f}\,(0.7) \times H_A \times Qt / (S_{100min} + [S_{20yr} - S_{100min}]_{theor})}$$

The difference between the modified equation and the Moell method as provided in Alberta Environment (2003) is that in the denominator of the former, the $[S_{20yr}\text{-}S_{100min}]$ is determined theoretically (as opposed to graphically) from the application of the appropriate analytical pumping test model used to derive a solution for transmissivity. Therefore, unlike the other equations described above, van der Kamp and Maathuis' method does not necessarily involve the straight-line extrapolation of the semi-logarithmic time-drawdown slope (ΔS). This method is similar enough to the Moell Method (Method C) that it is not investigated further in this study.

Maathuis and van der Kamp (2006) also introduced a concept they refer to as R_{20}, which is a pre-defined constraint on well pumping. The R_{20} is the radial distance of zero drawdown (or some other defined value of drawdown) that may be used to constrain the pumping rate or to identify a suitable radius from the tested well where other groundwater uses should be considered in a groundwater management framework. Application of the R_{20} concept may be used to make more conservative estimates of Q_{20} when, for example, it is desired to minimize drawdown at another well, or under a sensitive stream. Maathuis and van der Kamp suggest that wells with R_{20} values extending out considerable distances and encompassing many other wells or surface water features could require further analysis beyond a simple well test Q_{20} calculation.

3.2 OTHER METHODS

In the absence of guidelines or regulations governing how a well's long term capacity is determined, in some jurisdictions hydrogeologists may use professional judgement combined with analytical or numerical methods to assess well or aquifer capacity. Some examples of these various techniques follow, included here for completeness but not evaluated against Methods A, B and C.

3.2.1 Pumping test analytical simulation

This approach involves calculation of transmissivity and storativity from a pumping test, and then using these derived constants to model well drawdown trend at varying pumping rates, and extrapolating the drawdown trend out to a future point of time of interest (e.g. 120 days for a full irrigation or peak demand season). This is conceptually similar to the method advocated by Maathuis and van der Kamp (2006). If the projected drawdown at a given pumping rate remains above the pump intake or the top of the aquifer (with an appropriate safety factor applied), then the modeled pumping rate is deemed sustainable. This technique also lends itself to relatively straightforward application of the principle of superposition, from which the effects of multiple well interference or aquifer boundaries may be modeled. This may be done with a spreadsheet tool, or with some of the commercially-available pumping and aquifer test analysis software tools.

3.2.2 Flow modeling

Using a groundwater flow model to predict long-term well yield involves development and application of a calibrated groundwater flow model in combination with pumping test data that provides well loss information. With this method, a flow model can be used to predict drawdown at specific points of time in the future within a given cell of a finite-difference model, for example, but this value must then be adjusted to account for well losses occurring in the production well located within that model cell. In general, the use of a flow model without pumping test and well efficiency information provides a general indication of aquifer drawdown, but is not useful in predicting pumping well drawdown, unless there is good well efficiency data or if well losses can be reasonably estimated or accounted for with a safety factor.

In addition to allowing for well efficiencies, flow models must also account for changes in flow rate with the use of constant-speed pumps. Such pumps, still used in most water supply wells, typically experience reduced output as drawdown increases due to the increased lift requirement. The magnitude of the decreased output depends on the pump-capacity curve. Konikow (2010) describes how pump-capacity ratings may be incorporated into groundwater simulations, using the multi-node well package (MWN2) for MODFLOW (Harbaugh et al. 2000). Konikow also points out that variable-speed pumps are available that maintain a constant flow rate under changing head conditions. Single-well capacity estimates – particularly for wells with large drawdowns, should therefore consider whether or not a constant or variable speed pump motor will be used.

The above approaches allow for considerable flexibility in the technique applied by the analyst using professional judgement in the process of determining well yield. This means that potentially, significantly different findings are possible based on independent analysis of a given pumping test data set by two or more hydrogeologists. Some government regulatory agencies, particularly in western Canada, in an effort to achieve more consistency in the interpretation of well yield characteristics from pumping tests have developed approaches that comprise the focus of the comparative analysis portion of this research project.

3.2.3 Volumetric and other pumping test-based methods

Examples of other methods of determining well yield may be found in many government regulatory and guidance documents. These may consist of non-prescriptive directives, calling for a pumping test and a determination of well yield by a qualified individual, such as a hydrogeologist (Ontario Ministry of Environment, 2005a, 2005b) or a guidance document for private wells that provides only a cursory overview of well testing (State of Connecticut 2009). Other jurisdictions provide a prescriptive volumetric methodology for determining well yield.

For example, the Los Angeles County (California) Department of Public Health (2005) guidelines for determining well yield stipulate a pumping test followed by a recovery test, and state that the yield of the well is the recovery rate following pumping cessation if less than full recovery occurs after a period of time equal to the pumping duration. Thus, typically, a pro-rated portion of the pumping test withdrawal rate is taken to be the long-term well yield. This method does not require the analyst to determine whether or not radial flow conditions occurred, or whether or not aquifer boundary conditions, well interference, or other effects are apparent in the pumping test data. For these reasons, this type of volumetric method is probably too simplistic for broad application, especially in complex settings where there are numerous wells, where there is potential for well interference, large seasonal changes in water levels, and where longer term pumping may induce changes in the system.

The volume test used in L.A. County requires a 24-hour pumping test, with the flow rate and the total volume pumped recorded along with water levels before, during and after the pumping test. The permitted long term yield of the well is the total gallons pumped for 24 hours provided that full recovery occurs within 24 hours of pumping cessation. If full recovery does not occur, the allowable yield is equal to the flow rate for the 24 hour test, divided by the total number of minutes required to achieve full recovery. If full recovery does not occur within five days, then the well is considered non-sustainable. Full recovery is defined as 90 percent of the initial pre-test static water level. Application of hydrogeological principles is not required. An example application of this method for a well completed in a confined aquifer follows:

<u>Hypothetical well volume test</u>

A.	Total well depth:	200 ft.
B.	Depth to top of aquifer:	170 ft
C.	Initial static water level:	15.0 ft
D.	Test duration:	24 hours
E.	Maximum water level:	94.6 ft. (at time t equal to 24 hrs)
F.	Pumping rate (gpm)	100
G.	Final recovery reading of pumping test)	16.1 ft (at time t' equal to 48 hrs from start
H.	Maximum drawdown (E-C):	79.6 ft
I.	Amount of recovery: (G-B)	78.5 ft
J.	Percent recovery (I / H)	99 %

K. Volume pumped = 144,000 gallons / day (100 gpm) = allowable yield

The Township of Langley, British Columbia has a bylaw (Township of Langley 2010) regulating private domestic wells and prescribes a four-hour pumping test method to determine well yield. The well test must be performed at a minimum flow rate of 9 liters per minute (about 2.4 US gallons per minute) and uses the drawdown recorded after 10 minutes and 240 minutes of pumping to verify that the well can yield at least 1.74 liters per minute if pumped continuously for 30 days. The method plots the drawdown data on a semi-logarithmic hydrograph of drawdown versus the log of elapsed pumping time. A straight line projection is made by connecting the 10-minute and 240-minute drawdown and extending this line to 30 days (43,200 minutes).

The static depth to water, plus the 30-day projected drawdown, plus an assumed seasonal water level decline and a safety factor (usually 1 meter) must not exceed the depth to the well pump intake. The local hydrogeology in the Langley area is such that private domestic wells are completed in a stratified glacial-drift aquifer that is usually productive relative to the requirements of a private household well. This method may be useful locally, but is not considered to be adequate for higher capacity wells or wells that would be pumped continuously for long periods, such as municipal, industrial or irrigation wells.

A last example is found in the State of Vermont Water Supply Rules (2010), which provide a definition of safe yield for pumped groundwater sources serving community water systems. This flow rate can be no greater than the pumping test rate and must be able to be met by public water supply well sources for a period of 180 days at the projected water system average day demand, followed by a 3 or 7-day period of pumping at the projected system maximum day demand. The Vermont rules, however, do not provide a means to calculate the safe well yield other than the well source's total available drawdown must not be exceeded during the specified 183 or 187-day pumping period. In practice, this is typically demonstrated using conventional pumping test analysis. No safety factor or equation is provided for in the Vermont rules, but the rules do provide detailed procedures for conducting both step rate and constant rate pumping tests (72 to 120 hours in duration), and also detailed requirements for assessing potential well interference.

3.2.4 Equilibrium (stabilized drawdown)

Occasionally, it is possible to determine the long-term well capacity if true equilibrium conditions are encountered during a pumping test. This may occur if the flow rate of the well is small relative to the transmissivity of the aquifer, or more commonly, when the well is completed in an aquifer with a strong connection to a surface water recharge source (Figure 2.3). The key technical issues to consider in making the analysis of well capacity on the basis of equilibrium are: a) confirming that a stabilized drawdown level continued long enough (i.e. more than a few hours), b) that the pumping rate be held constant, and c) that the conceptual hydrogeological model supports the stabilized well response. Farvolden (1959) provided a simple formula to estimate safe well yield (Q_{20}) for stabilized pumping tests:

$Q_{20} = (Qt/s) * (H_A) * (S_f)$ (S_f usually = 0.7), where s is the stabilized value of drawdown.

The safety factor applied to the equilibrium well test data could be more conservative (e.g. 0.5 or 0.6) if the H_A value is small or if seasonal variation in water level (groundwater or surface water) is unknown or believed to be significant relative to available drawdown. The sensitivity of Q_{20} values to adjustments in the safety factor is assessed in Chapter 5.

CHAPTER 4

DATA SOURCES AND METHODOLOGY

This chapter provides a descriptive narrative of each pumping test data set and includes information on the production wells, the field testing conditions, test and monitoring equipment and methods, processing of field data, creation of hydrographs, and the methods applied to the data to interpret well and aquifer response and to determine LTWC.

4.1 DESCRIPTION OF PUMPING TEST DATA SETS AND TEST CONDITIONS

The following sections provide an overview of the wells used in this study, the rationale for their selection, and an overview of each pumping test data set.

4.1.1 Criteria for and process of selecting pumping test data sets

The data sets were selected on the basis of the following criteria:

1. Pumping test data must be readily available to the author in electronic format, and emphasize wells for which the author had direct knowledge of and/or involvement in data acquisition.
2. Wells should exhibit a range of flow rates, from small private domestic wells to large capacity municipal and irrigation wells.
3. Represent some of the major types of aquifers, with test data including wells completed in unconsolidated and consolidated aquifer systems, under both confined and unconfined conditions.
4. Data set must include one or more western Kansas Ogallala aquifer wells, in keeping with the goals of an earlier phase of the research, which intended to focus on pumping test methods to assess well sustainable yield in the western Kansas portion of the Ogallala aquifer.

The intent of the study design was to provide a reasonable selection of well and aquifer types sufficient to test the hypothesis, without conducting new field work and minimizing the need to acquire data from others. The Ogallala well data were specifically included to provide information on safe well yield in groundwater level decline conditions to the Kansas Water Office, who funded part of the research study.

The aquifer settings represented in the data set include some of the more commonly encountered types of confined and unconfined systems, though by no means do the data sets represent all possible hydrogeologic conditions. Extensive regional alluvial aquifers such as the Ogallala in Kansas and Portland (Oregon) basin are represented, as are unnamed local-scale aquifers formed in glacial deposits and crystalline bedrock formations located in British Columbia (Figure 4.1 depicts the general locations of the field sites).

Figure 4.1 General location of field sites in Oregon, British Columbia, and Kansas

A review of Fetter's (2001) discussion of groundwater regions in North America reveals that other important types of aquifers found outside the areas of the wells studied here are not represented, such as aquifers formed in limestone (Karst) in the non-glaciated central region, sandstone aquifers (also of the non-glaciated central region and also southeast coastal areas), plateau basalt, deep alluvial formations found in arid basins of the desert southwest, and unconsolidated and bedrock aquifers located on islands or in coastal settings.

The test data sets were selected to provide a range of wells and aquifer types that would enable quantitative examination of the well capacity estimation methodologies, and also enable detection of bias or weakness in the methods evaluated. Although the selected data sets used here are by necessity limited to a few examples of some but not all common aquifer types, the analysis presented using these data may be easily replicated by using any set of constant-rate pumping test data for which the analyst has knowledge of the test conditions and general data quality. The eleventh data set is from a second pumping test conducted on one of the selected wells. This test was run at a different flow rate and for a long duration (26 days) and thus enabled comparison of the methods applied with two separate data sets on the same well.

4.1.2 Description of test well data

The data set for this study consists of a series of eleven pumping test files, in Microsoft Excel format from pumping tests conducted on ten different wells between the years 1977 and 2010. There are two data sets taken from separate tests conducted on one of the wells. The two tests on this well were conducted a year apart, and at different pumping rates and durations. Based upon well completion method and aquifer setting, each well was categorized as falling into one of three types:

- Confined, sand and gravel aquifer wells
- Unconfined, sand and gravel aquifer wells

- Fractured bedrock aquifer wells (may behave as confined)

The data set includes

a) Three relatively low-yielding wells completed in fractured crystalline bedrock formations, ranging in depth from 180 to 720 feet;

b) Three confined to semi-confined aquifer wells, of moderate to high yield, ranging in depth from 91 to 623 feet; and

c) Four moderate to high yielding wells completed in unconfined or semi-confined aquifers, ranging in depth from 76 to 450 feet.

Confined wells are numbered CF1, CF2, CF3, while the unconfined wells are numbered UC1, UC2, UC3, UC4, and the three bedrock wells are numbered BR1, BR2 and BR3 in this study. Overall test pumping flow rates ranged from 1.75 to 3,520 gpm. Test durations ranged from less than one day to 26 days, and most of the tests ran between approximately 48 to 72 hours (2 to 3 days). Observation wells were monitored during many of the tests, but the data collected are not presented or analyzed here in any detail. Wells included in this study are located in Kansas (2), Oregon (2), and British Columbia, Canada (6).

Prior to use in this study, corrections were made to the pumping test data as needed to account for barometric pressure changes affecting the readings of unvented pressure transducers and/or confined aquifer water levels. The exceptions to this are the data sets for the two Ogallala wells, which were taken from the respective reports and deemed sufficiently accurate to use for the purposes of this study. In general, when relatively large drawdowns occur as seen during most pumping tests, the measurement or data correction error is relatively small compared to the head changes during the test.

With the exception of wells UC3 and UC4, which are completed in the (High Plains) Ogallala aquifer of western Kansas, the author visited each well site at least once during drilling and/or test pumping, and also personally designed and oversaw the pumping tests conducted on these wells. In connection with the early phases of preparing this research, the author visited the location of a number of irrigation and municipal wells in western Kansas Groundwater Management District 1 (GMD1), but did not visit the sites of UC3 and UC4, which are located in Southwest Kansas GMD3 in Ford and Finney Counties respectively.

The information on UC3 was provided to ESU by Mike Dealy, hydrologist with the Wichita office of the Kansas Geological Survey (KGS), and formerly a manager of Southwest Kansas Groundwater Management District 3. Information on UC4 was provided to ESU by Jeff Binder, a hydrogeologist with Burns and McDonnell, a Kansas engineering consulting firm.

4.1.3 Pumping test and data collection procedures

Table 4.1 provides a summary of each well selected for this study. Additional well construction details are provided in Appendix C. Further pumping test information is provided in Table 4.2. Figures 4.2 through 4.4 (Pages 58-60) depict photos of typical field test configurations. Figure 4.5 (Page 61) shows a typical Ogallala aquifer irrigation well in western Kansas, probably similar to well UC3. Figure 4.6 (Page 62) shows a submersible test pump being installed into a well.

In general, the pumping test procedures followed standard methods employed in the water well industry. Wells CF1 and CF2 were tested using a line-shaft vertical turbine test pump connected to a mechanical "right hand" drive powered by a diesel engine power plant.   Remaining wells except UC3 were tested with electric submersible test pumps, connected to a temporary power source and a temporary discharge line. Well UC3 is a Ford County, Kansas irrigation well and was likely tested with its lineshaft vertical turbine irrigation pump in place (see Figure 4.4 for a typical Ogallala / western Kansas irrigation well), with temporary equipment installed to enable flow and water level measurement. Well UC4 was installed in 1977 as a test-production well for a proposed coal-fired generating plant and was likely tested with a lineshaft vertical turbine test pump. Detailed presentation and analysis of the UC4 test data is provided in Burns and McDonnell (1977) but the report lacks details on pumping test equipment and data collection procedures.

In general, the discharge line for each tested well was equipped with at least one valve used to control the flow, a flow measuring device, such as a flow meter or an orifice tube (Figure 4.4), or an open discharge (in the case of the low yielding wells) that facilitated direct measurement of discharge into a calibrated container using a stopwatch. Water levels were measured using a temporary “sounding tube” placed inside the well casing with the test pump. The sounding tubes provided a safe housing into which electronic water level sensors were lowered. Some wells included two sounding tubes (Figure 4.6), one housing a pressure transducer connected to a data logger and the other for the electronic water level meter.

As is standard in the industry, water levels were measured in the wells prior to the tests in order to establish the non-pumping water level, and in some cases, multiple readings were made to ascertain any possible rising or falling water level trends. During the pumping phase of the tests, water level and flow were recorded at high frequency during the first 100 minutes of the test, and less frequently for the remainder of the tests. The data sheets in Appendix A provide detailed information. Each test ran at a steady or constant flow rate, generally not varying by more than 5% (often less). Several of the tests followed the recovery period of variable – rate (step) tests performed prior to the constant rate testing in order to assess well hydraulics and well specific capacity. Following the cessation of pumping, the recovery of water levels was typically recorded until full recovery occurred or until the rate of water level recovery as indicated on a graph, was following a clear trend. According to Dealy (pers. comm 2011), the flow rate of the 1979 test on UC3 was measured with a calibrated flow meter, and water levels were measured with an air line.

The pumping test on UC4 included down-hole velocity surveys (spinner surveys), used to identify specific production zones within a fairly long (160 ft) well screen assembly. This data set is considered high quality: there were 13 readings of drawdown in the first 60 minutes of the test, followed by hourly readings for the next 167 hours of pumping at a rate of 2,000 gpm. See Appendix C for copies of relevant well construction data.

Table 4.1. Well construction summary

Well	Hydrogeologic setting	Total depth (ft)	Casing diameter (in)	Depth to top of well screen or first fracture (ft)	Initial static water level (ft)
CF1	Regional alluvial aquifer system in Oregon; confined response	623	20	490	17.23
CF2	Regional alluvial aquifer system in Oregon; confined response	521	20	398	14.82
CF3.1	Alluvial fan aquifer in B.C., locally confined, recharged by creek losses	78	8	52	18.5
CF3.2	Alluvial fan aquifer in B.C., locally confined, recharged by creek losses	78	8	52	18.0
UC1	Alluvial/deltaic sand and gravel aquifer in B.C.; locally unconfined, recharged by creek losses	157	8	116	12.04
UC2	Small glacial drift aquifer in B.C., east slope of mountain range, no nearby surface water, unconfined	76	8	68	37.26
UC3	Ogallala aquifer, western KS, locally unconfined, in decline condition, no nearby surface water. Ford County, KS	84	12	64	43
UC4	Ogallala aquifer, western KS, locally semi-confined or unconfined, in decline condition, Finney County, KS	450	18	257	73.52
BR1	Fractured bedrock aquifer, B.C. completed in metamorphosed volcanic rocks, no nearby surface water	496	6	476	78.4
BR2	Fractured bedrock aquifer, completed in metamorphic schist formation, no nearby surface water	720	6	720	242.5
BR3	Fractured bedrock aquifer, completed in metasedimentary rock, overlain by saturated surficial sand/gravel aquifer, small creek within 300 ft of well	180	6	160	122.05

Photo by author

Figure 4.2 Typical test well configuration *showing well sounder, sounding tube (red arrow), sampling tap (A), control valve (B)*

Photo by author

Figure 4.3 Test pumping well head *with well sounder (A), flow meter (B) and control valve (C)*

Photo by author

Figure 4.4 Flow measurement using circular orifice plate and manometer

Photo by author

Figure 4.5 Typical High Plains / Ogallala aquifer irrigation well, Scott County, KS

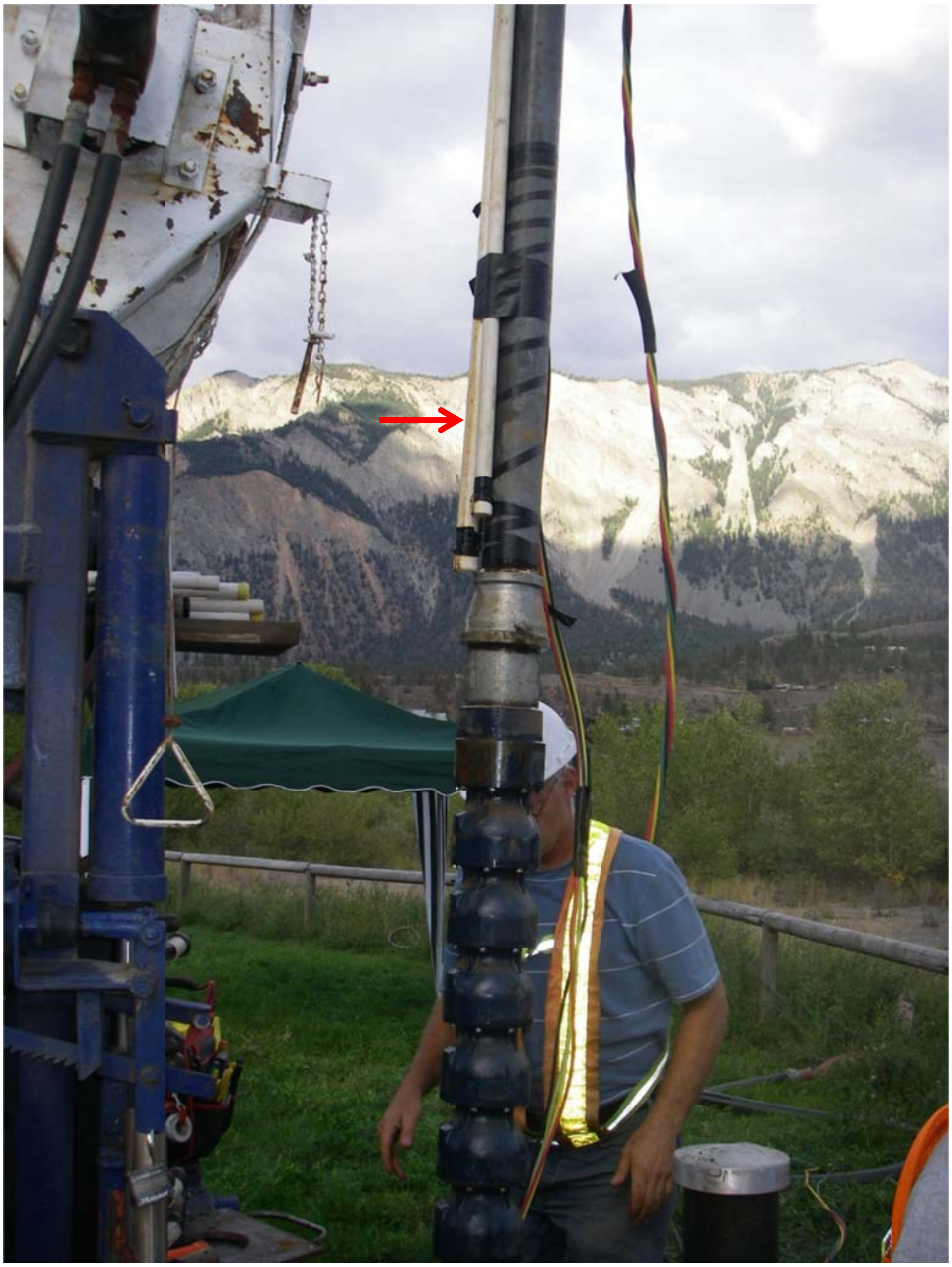


Photo by author

Figure 4.6 Preparing submersible test pump for installation. Note dual PVC sounding tubes (arrow)

4.1.4 Data set summaries

The following sections summarize the hydrogeologic setting and test conditions for each of the eleven well test data sets from the ten wells used in this study. Because many of the wells are public-water supply wells and the well owners may have concerns around disclosure of specific well location information in external documents, the specifics on the actual name or number of some wells and locations are purposefully omitted. This excluded information is not critical to the central purpose of this study. Copies of well logs and other pertinent information from the time of well construction are provided in Appendix C.

The two Kansas High Plains Aquifer (Ogallala) wells (UC3 and UC4) included in the study are identified as to location by conventional township, section and range coordinates. Analysis of the pumping tests completed on these wells more than 30 years ago coupled with current High Plains water level information enables examination of well yield estimation methodologies in situations where an aquifer is in a decline condition, thus providing an opportunity examine long-term mining yield utilizing pumping test information. Because of its fairly extensive data set, proportionally more detailed treatment is given to the UC4 data set, with further analysis on the implications of these data provided in Chapter 6.

<u>Wells CF1 and CF2</u>

Wells CF1 and CF2 are high-capacity 20-inch diameter municipal production wells completed within a confined to semi-confined alluvial aquifer. The wells are screened within the third and deepest of three aquifers developed in the vicinity of the production wellfield completed in a regionally extensive layered alluvial aquifer system. The two wells are part of a large production wellfield that serves a metropolitan area and has been extensively studied. A steady-state and transient-calibrated regional-scale multi-layer numerical groundwater flow model exists for the aquifer system, with a detailed model grid covering the vicinity of the production wells.

The CF1 and CF2 aquifer is hosted by an alluvial sand and gravel formation interpreted to be fluvial in origin and is composed largely of sand and gravel that is partially indurated, with calcium carbonate indicated to be the primary cementing agent. The most productive zones within the aquifer are typically the non-cemented layers, composed of clean medium-to coarse grained sand with minor gravel. Confining pressure is such that the non-pumping (static) water level rises some 250 feet or more above the top of the aquifer. The confining unit is composed of silt and clay, with inter-bedded thin zones of water-bearing sand. At the location of Well CF1, the confining unit behaves as an aquitard, and no leaky aquifer effects are notable in pumping tests performed on wells completed in this part of the aquifer system. The location of well CF2, about one mile to the east of CF1, is closer to the interpreted source of recharge to the aquifer system (the aquifer and overlying aquitard are interpreted to sub-crop against a saturated river channel deposit), and where the confining unit exhibits leaky aquitard effects.

The author’s knowledge of well tests conducted in the general area of CF2 suggest a boundary condition response indicative of either recharge or leaky aquifer effects. Because the top of the aquifer is shallower at CF2, however, there is less available drawdown and consequently, well yields are generally lower. A poorly understood negative boundary response was evident in the hydraulic response of observation wells monitored during the CF1 pumping test.

For both tests, non-pumping water levels at the time of testing were generally within 20 feet of ground surface and thus these wells had significant available drawdown (H_A). Both wells have long-string production assemblies consisting of approximately 100 feet of well screen, completed with an artificial sand pack in a sand-dominated formation. Each well was test pumped by first conducting a four hour step test, followed by a recovery period of approximately 24 hours, and then followed by a 1-2 day constant rate pumping test and then recovery measurements. Nearby wells were not operating during either of the pumping tests. During both tests, flow was measured with a calibrated totalizing flow meter and water levels were monitored with pressure transducers and manual water level meters using dual sounding tubes.

Well CF3

Well CF3 is an eight-inch diameter test-production well completed in a layered alluvial fan aquifer system located in the interior region of British Columbia, Canada. The aquifer at the well location is locally confined by a fine-grained silt and silty clay layer found between the ground surface and the top of the aquifer. A wellfield is being developed at the site to supply a planned fish hatchery operation. The well is located approximately 100 feet from a perennial creek. The conceptual model of the aquifer is that close to the apex of the alluvial fan (about 1 mile above the CF3 well site), the alluvial sediments are thinner and in direct hydraulic communication with the creek. It is in this upgradient location near the apex of the alluvial fan that the aquifer likely receives considerable recharge through infiltrative creek bed losses.

At the CF3 site, the aquifer is composed of coarse-grained sand, with interbedded fine gravel, and at the time of testing, the non-pumping static water level was within 20 feet of ground surface. CF3 was initially test pumped by conducting a step test, followed by a recovery period and then a 48 hour constant rate pumping test at 350 gpm (data set CF3.1). The following year, the well was test pumped again, this time at 145 gpm and for 26 days (data set CF3.2). During both tests flow was recorded with an orifice and manometer, and water levels were monitored with pressure transducers and manual water level meters. A barometer transducer was also employed in order to enable correction of the transducer data for atmospheric pressure variations.

Well UC1

Well UC1 is constructed similarly to CF3, but is completed in an unconfined alluvial fan / deltaic sand and gravel aquifer, also in the interior region of British Columbia, Canada. It is an 8-inch diameter well, constructed to supply a municipal water supply system, and completed in a productive aquifer that has seen minimal historic development (limited to two wells drilled for a park campground about 4,000 feet away). The aquifer is recharged principally by infiltrative losses from a creek that passes approximately 300 feet to the north of the well. A large valley-bottom lake is located 300 feet to the east of the well and is the natural discharge point for the alluvial aquifer. Well UC1 was subjected to 670 minute constant-rate discharge test at 500 gpm (the well was not tested longer due to the anticipated high capacity of the well relative to the yield requirement of the well owner). Flow rate was measured using an orifice plate and manometer (Figure 4.3). Water levels were measured with an electronic pressure transducer and data logger and supplemented with manual water level readings collected with electric well sounder using dual sounding tubes.

Well UC2

Well UC2 is a relatively shallow (76 ft) well screened in a small (less than 1 mi^2) stratified glacial drift aquifer system located in an upland area, composed of a large terrace that fronts the eastern rampart of the Purcell Mountain Range in the Rocky Mountains of British Columbia. The aquifer is of limited areal extent and was delineated through a process of exploratory test drilling as its surface expression is minimal and blends in with the surrounding landscape where only non-water-bearing glacial till and moraine dominate the surficial geology. Due to the small size of the aquifer and the relatively limited saturated thickness, Well UC2 was completed with just 8 feet of well screen. Despite the apparent limited nature of the resource, the well was successfully test-pumped for 72 hours at a constant rate of 159 gpm and exhibited strong recovery. During the test, flow rate was measured with a totalizing flow meter, and water levels were collected manually with an electric water level meter inserted into a single sounding tube. Care was taken to discharge the test water at a considerable distance from the well, to minimize short-circuiting of test water back into the aquifer during the test. No evidence of short-circuiting (i.e. recharge) was noted.

Well UC3

UC3 is located in the NW 1/4 , SE ¼, NE ¼ of Section 17, Township 28S, Range 21W in Ford County Kansas. The well was chosen because of the quality of well test documentation available: it was subjected to a 2.85-day (68-hr; 4,000 minute) constant rate pumping test under the supervision of KGS staff in 1979 (Dealy and Jenkins 1980). A plot of the pumping test data was used to generate time-drawdown data for use in this study. Well UC3 is an irrigation well that was drilled in 1974 for the Ford Land and Cattle Co. located near the community of Bucklin in Ford County, Kansas as few miles west of the Ford and Kiowa county line, which forms the boundary between GMD5 and GMD3. Groundwater resources in Ford County are presently managed by GMD3. The UC3 well is completed in the unconfined Ogallala aquifer, which unconformably overlies older bedrock units. Dealy and Jenkins (1980) noted that in Ford County, the undifferentiated Pleistocene deposits may be in direct contact with the Tertiary Ogallala Formation sediments, but where saturated, these units form a single aquifer. See Appendix C for further well information obtained from the Dealy and Jenkins report. The southeast Ford County area was noted by Dealy and Jenkins (1980) as having relatively low aquifer saturated thickness and as of 1979 was declining at a rate of about 0.6 ft/year. KGS maps indicate that the Ogallala aquifer saturated thickness in Haskell County (west of Ford County) reaches 200 ft in some locations and exceeds 300 ft in parts of Finney and Kearney counties further west (see UC4 description below for further discussion on saturated thickness). The UC3 static water level at the time of the 1979 test was 43 feet and at the well location, the Ogallala saturated thickness was a relatively thin 41 feet. The current saturated thickness at the well site is not known but from nearby WIMAS data, it is probably on the order of 27-29 feet, indicating a 12-14 ft decline since 1979. Annual water level measurements at selected water level monitoring wells (KGS 2010) in T28S R21W indicate a water level decline ranging between approximately 10 and 25 feet near UC3 over the past 30 years, or approximately 0.3 to 0.8 ft per year.

Well UC4

UC4 is an 18-inch diameter production well located at a coal-fired power generating plant located in Finney County a few miles west of Garden City near the community of Holcomb, and like UC3 is within Southwest Kansas GMD3. UC4 is located in the SW ¼ of Section 31, Township 24S, Range 33W and is completed within one of the thicker portions of the Ogallala aquifer in western Kansas, and significantly thicker than at UC3, which is located in an area where the predevelopment saturated thickness was relatively small. However, groundwater declines over the past three decades in Finney County near UC4 are considerably greater than in much of Ford County. For a full discussion of changes in depth to water and saturated thickness in GMD 3 refer to Macfarlane and Schneider (2007).

The well data set provided in the Burns and McDonnell (1977) report contains the following data pertinent to this study:

- Detailed well construction log for the test-production well;
- Detailed formation (geologic) logs for the test borehole adjacent to the completed well; and similar logs for several observation wells used during the pumping test;
- Step-rate pumping test data for pumping at rates between 500 and 2,500 gpm on UC4;
- Constant rate pumping test data for pumping at rate of 2,000 gpm for 7 days, followed by approximately 1 day of water level recovery measurement;
- Graphical plots of pumping test data for the pumping well and observation wells; and transmissivity estimates based on interpretation of the pumping test data;
- Downhole velocity (spinner) survey data, collected during the step rate and constant rate pumping tests; and
- An electrical resistivity log, presumably conducted on the test hole prior to well casing installation.

The saturated thickness (ST) of the Ogallala as defined by Macfarlane et al. (2005) is the total thickness of saturated sediments between the water table (as measured in the winter following an irrigation season) and the top of the bedrock surface. A concept developed by Macfarlane and others at KGS, the practical saturated thickness (PST) is a fraction of ST and represents only those layers identified as permeable and productive, and is based on KGS staff interpretation of driller’s log formation descriptions. At the time of its construction in 1977, the well exhibited a total Ogallala ST of approximately 360 ft., whereas Macfarlane and Schneider (2007) estimated the predevelopment (ca. 1950) practical (permeable) saturated thickness (PST) of the Ogallala in T24S, R33W in the range of 200 to 250 ft, and a 2006 PST of approximately 100 to 150 ft, with an overall PST/ST ratio of 50 to 75 percent.

The characteristic vertical stacking of contributing (water-bearing) and non-contributing zones within the Ogallala hydrostratigraphic section has been observed (Macfarlane and Schneider 2007) to produce a stair-step pattern of water level decline, with higher decline rates occurring when the phreatic surface falls through non-contributing zones and slower decline rates as the surface falls through permeable contributing zones. Macfarlane's method applies a defined set of "rules" that assign logged formation materials as either non-contributing, 30% contributing, 70% contributing, and 100% contributing, with complex mixtures assigned proportional PST values based on the major and minor lithologies.

Recognizing the limitations of applying PST estimates based only on well log information, Schulmeister and Geller (2009) developed an approach that uses downhole spinner surveys and geophysical logs (similar to the tests conducted on UC4 in 1977) to further refine the PST value at the scale of an individual well site. This technique could serve as an alternative method to assess PST and long-term well yield when a formation log is not available or is of poor quality, and could prove especially useful when groundwater decline threatens high-value water supplies, for example, municipal supplies or other individual water sources deemed important to the local economy.

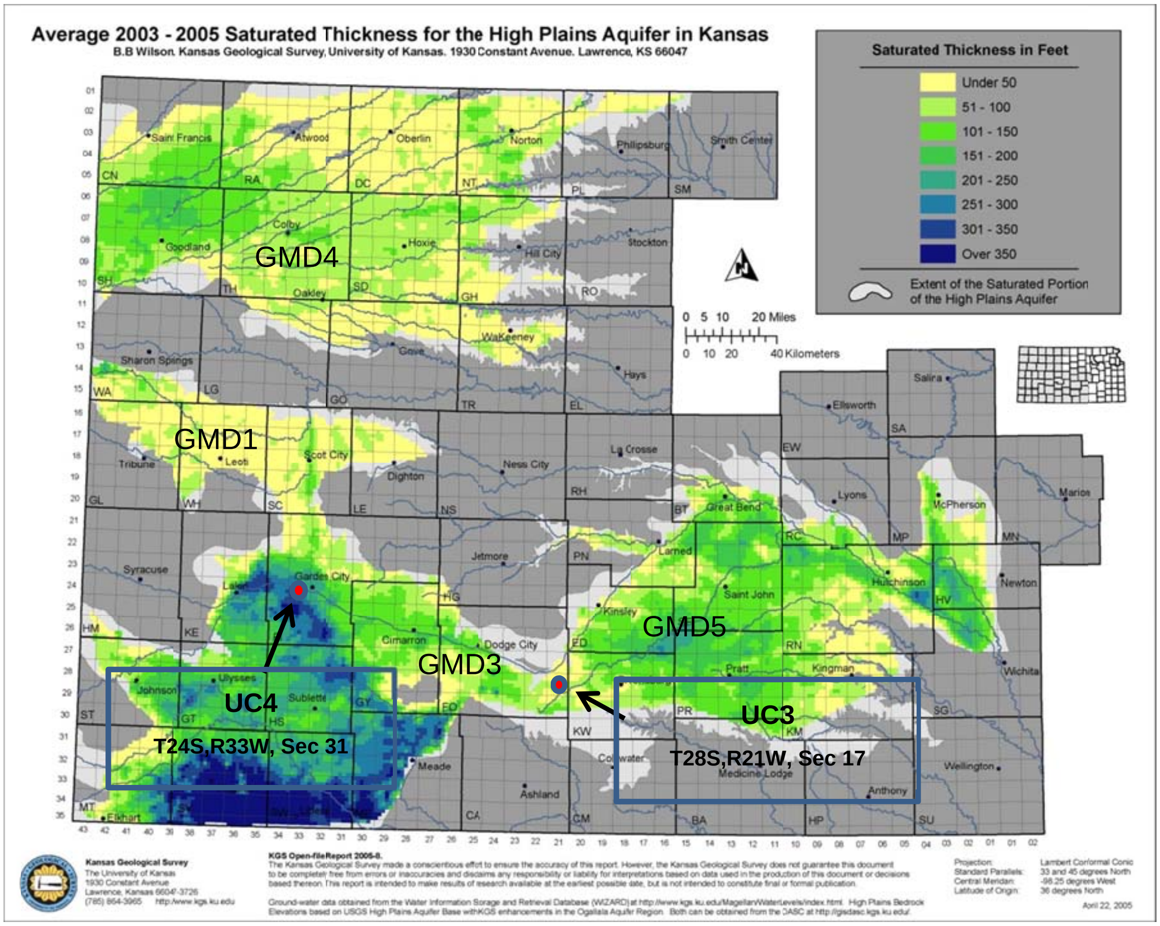
The value of spinner logs is that they provide a direct measurement of contributing and non-contributing zones, but can only be applied within the well screen interval, so the productivity of the saturated Ogallala present above or below the well screen cannot be assessed with this technique.

Combining spinner surveys with pumping tests increases the relative cost of pumping tests, although the small diameter of some tools makes it possible to use them without removing the well pump. In spite of the associated cost of well-specific testing involving spinner surveys and other tools, the time may come when these become necessary in order for well owners to make decisions about whether or not changes in the well design could be made to optimize the ability of the source to extract groundwater from a diminishing resource.

Appendix C contains the UC4 well log along with selected data from the original pumping tests, the spinner surveys, and the electrical resistivity log. The spinner survey and electric log data for UC4 suggest a PST value close to 50 percent of ST at this location. According to the well diagram provided in the Burns and McDonnell (1977) report, the UC4 screen assembly including blank sections spans approximately 180 feet between depths 257 and 437 ft. The UC4 spinner data indicate relatively little production was derived from the screen section below a depth of 370 ft. With the bottom of the well screen at 437 ft, this suggests approximately 65 ft of low-producing Ogallala. There was also relatively little contribution to the well from the upper 30 ft of screen between approximately 257 and 290 ft. The latter suggests that the well pump could be lowered by approximately 30 ft without compromising production from the intervals below. The majority of the well production appeared to have been derived from the screen interval between 295 and 370 ft, or about 45 percent of the 180 ft screen assembly interval. The electrical resistivity log showed good correlation (i.e. high resistivity) with the well log and zones of major inflow indicated on the spinner log, and also indicated a permeable fraction of the Ogallala within the screen zone of about 50 percent.

Well drillers logs for the production well and three observation wells located within 1,000 ft of UC4 interpreted using the technique of Macfarlane et al. (2005) also suggest current PST (assuming a year 2010 depth to non-pumping water level of approximately 175 ft) ranging from approximately 115 to 150 feet near UC4. If current ST is approximately 260 ft, then the PST/ST ratio in the vicinity of UC4 likely ranges from 45 to 58% with the most productive materials occurring in the approximate middle of the remaining saturated Ogallala section.

In summary, based on a review of the data, it appears that the PST/ST fraction at UC4 was approximately 50 percent when it was tested in 1977. A nearby annual water level observation well (T24S, R33W, 34CAC), indicates a decline of approximately 100 ft since 1977, which would put the static water level at 175 ft, which is approximately 75 to 80 feet above the top of the well screen and 110 ft above the top of the main producing zone. The 100 ft decline is likely affecting the long term capacity of UC4 and other similar wells in GMD3 where large declines are evident. Such effects are further assessed in Chapter 6.6. Figure 4.7 depicts the general well locations of the UC3 and UC4 as related to 2003-2005 KGS-mapped saturated thickness of the Ogallala aquifer.



Map source: KGS Open File Report 2005-025C

GMD = Groundwater Management District

Figure 4.7 General location of Ogallala wells UC3 and UC4

A significant number of other historic well pumping tests data sets for Ogallala wells reportedly exist in the files of KGS and/or the Kansas GMDs (see Table 3 of Hecox et al. [2002]). Therefore, the methodologies reviewed in this study may be of use to further evaluating long-term capacities of wells as a complement to the methods outlined by KGS (Hecox et al. 2002; Macfarlane and Schneider 2007) where pumping test data are not available or too costly to obtain. The UC3 and UC4 pumping test and GMD3 annual water level data will be used to examine the long-term well capacity in groundwater decline situations (see Chapter 6.6). This analysis explores the concept of *long-term mining yield* introduced in Chapter 2.

Well BR1

BR1 is a private domestic water well completed in a fractured bedrock aquifer located in the interior of British Columbia, Canada. The well is approximately 500 feet deep with an initial non-pumping static water level of 80 feet. As is typical of lower yielding bedrock wells, the well driller estimated the well flow rate by conducting a short airlift test using the drill rig. No water-bearing fracture information is provided on the well log. On the basis of the driller's estimated yield of 3 gpm, the well was test pumped for 48 hours at a rate of 1.75 gpm. The flow rate was regulated with a control valve on the discharge line and measured using the method of recording the time needed to fill a container of known volume (the "bucket and stopwatch" method). The flow measurements were made throughout the test at similar intervals to the water level measurements, which were recorded using a manual electric water level meter inserted into a single sounding tube.

Well BR2

BR2 is a proposed small community well source, completed in a deep fractured bedrock aquifer situated along the margins of a large valley. The valley is filled with relatively thick accumulations of glacial and alluvial sediment, while the adjoining hillsides are mantled with a relatively thin veneer of glacial till, and underlain by fractured bedrock. At a depth of 720 ft the deepest well used in this study, BR2 was test pumped for 72 hours at a rate of 15 gpm. In the early minutes of the test, the flow rate was initially 16.5 gpm and was then adjusted to 15 gpm. The flow rate was regulated with a control valve on the discharge line, and water levels were measured with an electric water level meter. Flow rate was measured with a magnetic flow meter; these measurements were supplemented with periodic "bucket and stopwatch" readings. No water-bearing fracture data are provided on the well log and so it is assumed that the production is derived from the lower part of the borehole.

Well BR3

This well, at 180 ft, the shallowest of the three bedrock wells selected for this analysis, is located in an upland setting, about halfway between the top of a broad mountainous plateau and the Okanagan Valley bottom in the interior of British Columbia. It is a proposed private domestic well and is situated within a proposed residential subdivision comprised of lots ranging in size from approximately 2 to 5 acres, all serviced by private wells. Although it has only about 35 feet of available drawdown, the fractured formation appeared capable of supplying enough water to sustain flow rates of 1 to 2 gpm (the driller estimated 4 gpm based on an airlift test). The fractures are thought to be steeply-dipping (i.e. vertical) and in hydraulic communication with an adjacent saturated surficial formation composed of sand, silt and gravel. There is also a small year-round creek passing through the area. BR3 was test pumped for 48 hours at a rate of 2.1 gpm. Flow rate was regulated with a control valve on the discharge line, and measured with a calibrated bucket and stopwatch. Water levels were measured with an electric water level meter inserted into a single well sounding tube.

Table 4.2 summarizes the pumping tests conducted on each of the ten wells selected for the comparative analysis.

Table 4.2 Pumping test summaries

Well	Test flow rate (gpm)	Test duration (minutes)	Available drawdown H_A (ft)	Drawdown at end of test (ft)	1 hour specific capacity (Q/s; gpm/ft)
CF1	3,520	2880	463	130.77	28.2
CF2	3,000	1680	375	103.79	29.2
CF3.1	350	2880	33	6.02	59.1
CF3.2	145	37000	33.5	3.6	63.0
UC1	500	670	67.3	9.65	50.0
UC2	159	4320	22.8	3.56	54.8
UC3	670	4050	27	10.0	67.0
UC4	2,000	10098	122.3	135	17.7
BR1	1.75	2880	407	193.51	.01
BR2	15	4320	467	186.0	.09
BR3	2.1	2880	48	21.09	.11

Note: H_A for unconfined wells = 2/3 of total available drawdown

4.2 DATA PROCESSING AND ANALYSIS METHODS

In order to provide a suitable comparative analysis, each of the eleven well test data sets was subjected to a consistent data processing and analytical procedure, which is summarized below. The described sequence was followed in order to enable an initial diagnostic step using the pressure derivative analysis, followed by calculation of aquifer transmissivity and assignment of values needed to apply the Method A, B, and C equations, calculation of LTWC, followed by assessment of sensitivity and other factors.

1. First, time, flow rate and water-level data were entered into two different spreadsheets. The first spreadsheet was used to create standard hydrographs of time versus drawdown and the drawdown versus the log of time (semi-log). This spreadsheet provided three basic columns of data (plus the pumping rate): time, depth to water, and drawdown, with depths in feet either to the nearest 0.01 or .1 feet depending on the data source. Then, these same data were copied and pasted

into the second 'DERIV' spreadsheet per the instructions for its use provided in Allen (1999).

2. Second, the pressure derivative graph was created and interpreted for evidence of radial flow (Theis-like) conditions. This test interval was then noted on the graph by the analyst.
3. Based on the radial flow period (if one was identified), an estimate of aquifer transmissivity was derived using mainly the Cooper-Jacob (1946) equation as outlined in Chapter 4.1.
4. Any wells exhibiting non-radial flow response were flagged for further analysis according to the appropriate analytical model, if one could be discerned in the data. If not, the "best fit" analytical solution assuming Theis or Cooper-Jacob was used, or a recovery analysis was done if sufficient recovery data were available.
5. For each well, input values for use in each of the three Long-Term Well Capacity estimation spreadsheets were then culled from the data set (e.g. ΔS, H_A, S_{100}, and so on). If the later time drawdown trend formed a straight line on a semi-log plot and could be explained by the general conceptual model, then this trend was used to assign the ΔS value.
6. Well capacity calculation spreadsheets were completed for each LTWC method, and are summarized in the next Chapter.
7. Three specific-capacity ratios were calculated, as further described in Chapter 4.2.1 below.
8. A sensitivity analysis was done on the well capacity calculation worksheets as summarized in Chapter 4.2.2 below.
9. Wells suspected or known to be influenced by external factors such as well interference or groundwater decline were flagged for further analysis as described in Chapter 6.

4.2.1 Specific capacity ratios

Three specific capacity ratios, an empirical technique developed by the author, are proposed to aid in comparison of the well capacity calculation results, and to give an indication of the temporal sensitivity of the calculated LTWC. These ratios are as follows:

- **Ratio 1**: is the Farvolden-method predicted 20 year specific capacity divided by the actual one-day specific capacity.
- **Ratio 2**: is the Moell-method predicted 20 year specific capacity divided by the actual 100 minute specific capacity.
- **Ratio 3**: is the CPCN-method predicted 100 day specific capacity divided by the actual one-day specific capacity.

There is no way to directly relate aquifer transmissivity to well capacity. Because there is a recognized empirical relationship between specific capacity and transmissivity (Driscoll 1986), the rationale for developing the specific capacity ratios is that the time-dependent drawdown behavior of wells (which is a function of both transmissivity and pumping rate) will be reflected by comparing a projected long-term specific capacity to a measured short-term specific capacity. Except in the case of true equilibrium conditions, all wells should have a specific capacity ratio less than 1.0. Wells with lower specific capacity ratios experience a greater amount of drawdown per log cycle of time, and so capacity calculations for such wells would tend to have greater temporal sensitivity.

Given the empirical relationship between pumping duration and drawdown in non-equilibrium situations, it follows that for a particular LTWC analysis to be valid, the specific capacity ratio should have a value less than 1.0 (i.e. the long-term drawdown is greater than the shorter term drawdown at the same pumping rate). When this condition (< 1.0 ratio) is not met, then this is a "flag" that the derived Q_{20} or Q_{100d} value(s) may not be valid, or indicative that further analysis is warranted.

4.2.2 Sensitivity analysis

In assessing groundwater problems where there are several variables, it is useful to perform a sensitivity analysis to assess how a particular mathematical solution changes when certain variables are systematically altered. For example, in groundwater flow modeling assessments, assigned aquifer properties such as hydraulic conductivity are typically varied in sensitivity analysis (Anderson and Woessner 1992). For pumping test evaluations, while there are examples of sensitivity analysis on results from the literature (Cobb, McElwee and Butt 1982), there are none for analyses of well capacity. However, given the known relationships between pumping rate, pumping duration, and drawdown, the pumping time (duration) for which a value of theoretical capacity is derived is considered a significant factor and so this was varied for each method by one order of magnitude of elapsed time. For example, the pumping time for the Method C (CPCN) was varied by running the analysis for a 10-day and a 1,000-day projected drawdown. As noted above, the specific capacity ratios were used as a starting point as indicators of the relative temporal sensitivity of each well test result. The sensitivity of the variables in each LTWC equation may also be demonstrated mathematically. The safety factor changes the resulting LTWC by an amount that is in exact proportion to the change in the safety factor; however, the magnitude of this change in terms of its effect on well capacity depends on the characteristics of the well and the aquifer. Temporal effects due to extending or reducing pumping time on calculated LTWC is more complex; the change in the calculated value resulting from varying pumping time does not vary in exact proportion to the change in pumping time.

For Method A (Farvolden), besides pumping time the only variable that could be altered was the safety factor since it is arbitrarily assigned and could reasonably be higher or lower. This was varied up and down by 0.1. For Method B (Moell) method, both the safety factor (+/- 0.1) and the 100 minute drawdown value were varied in addition to pumping time (increased and decreased by one order of magnitude). The 100 minute drawdown used in the Moell formula was varied by +/- 10% as this field-measured value could be subject to error caused by measurement inaccuracy or fluctuations in pumping rate early in the test. For Method C (CPCN), in addition to the time of pumping the safety factor was varied per the other methods.

CHAPTER 5

RESULTS

In this Chapter the principal findings of the investigation are presented including the pumping test data interpretations, the calculations of aquifer properties, and the resulting estimates of long term well capacity using the three principal methodologies. Finally, the results and implications of the specific capacity ratios and sensitivity analysis are presented.

5.1 PUMPING TEST INTERPRETATION

Pumping test data tables, hydrographs, derivative plots and aquifer parameter estimations are provided in Appendix A. Table 5.1 summarizes the interpreted results of the pumping test data, including the assessment of the pressure derivative, the drawdown response (either semi-logarithmic or logarithmic), and the estimated aquifer transmissivity (and method[s] employed).

Table 5.1 Aquifer Test Interpretation Summary

Well test data set	Pressure derivative: apparent time interval of radial flow (minutes)	Observed drawdown response	Estimated transmissivity T in gpd/ft and ft^2/day	Method(s) used to estimate T
CF1	10-1000	Flat derivative middle of test, late time negative boundary effect	42,200 / 5,600	Cooper-Jacob; Theis
CF2	5-800	Declining derivative; late time recharge effect	49,000 / 6,500	Cooper-Jacob
CF3.1	10-300	Mostly flat derivative; straight line on semi-log	84,000 / 11,200	Cooper-Jacob
CF3.2	10-2300	Barrier boundary evident after ~2600 minutes	95,000 / 12,800	Cooper-Jacob
UC1	10-80?	Apparent short period of radial flow	330,000 / 44,000	Cooper-Jacob
UC2	15-500	Apparent negative boundary at ~500 minutes	38,000 / 5,000	Cooper-Jacob
UC3[1]	10-4000	Mostly flat derivative	160,000 / 21,300	1979 T value per Dealy and Jenkins 1980 (used Cooper-Jacob)
UC4[2]	30-1300	Mostly flat derivative, with rising derivative in late time (possible variable pumping rate)	45,000 / 6,000	1977 T value per Burns and McDonnell report (used Cooper-Jacob)
BR1	100-800	Radial flow after early borehole storage effects	5.4 / 0.71	Cooper-Jacob
BR2	70-2000+	Radial flow after early borehole storage effects	115 / 15.3	Cooper-Jacob
BR3	100-2000+	Radial flow after early borehole storage effects	37.0 / 4.9	Cooper-Jacob

Notes:

1. Year 2010 effective transmissivity is less due to groundwater decline of approximately 14 feet; see Chapter 6.6.
2. Year 2010 effective transmissivity is less due to groundwater decline of approximately 100 ft; see Chapter 6.6.
3. + denotes radial flow may have continued beyond the value given, but this is uncertain due to end effects
4. ? denotes that radial flow may have lasted slightly less or more than the time interval indicated.

5.2 LONG TERM WELL CAPACITY RESULTS

Tables 5.2 through 5.4 provide the summary long term well capacity calculations for the three principal methods assessed in this study. Each table shows the basic input data and also provides predicted and actual specific capacity values and the respective specific capacity ratio (i.e. Ratio 1, 2 or 3). Table 5.5 provides a comparative view of the results for all three of the methods. Refer to Chapter 3 for explanation of the variables H_A, Q_t, 8ΔS and ΔS.

Table 5.2 Method A (Farvolden) well capacity estimation results

Well #	Test flow rate (gpm)	H_A (ft)	static water level (ft)	water level end of test (ft)	drawdown per log cycle of time ΔS (ft)	8 ΔS (ft)	Predicted 20 year specific capacity Q/s (gpm/ft)	Q20 (gpm)	Actual 1 day specific capacity Q/s (gpm/ft)	Ratio 1: 20 year to 1 day specific capacity
CF1	3,520	463	17.23	148	22	176	20.0	6,482	28.2	0.71
CF2	3,046	375	14.82	118.61	16.5	132	23.1	6,057	29.2	0.79
CF3.1	350	33	18.5	24.62	0.6	4.8	72.9	1,684	59.1	1.23
CF3.2	145	33.5	18	21.6	0.6	4.8	30.2	708	63	0.48
UC1	500	67.3	12.04	21.69	0.4	3.2	156.3	7,361	50	3.13
UC2	159	22.8	33.7	37.26	2.2	17.6	9.0	144	54.8	0.16
UC3	670	27	43	53	1.2	9.6	69.8	1319	67	1.04
UC4	2,000	122.3	73.52	208.6	11.7	93.6	21.37	1,829	15.6	1.37
BR1	1.75	407	78.4	271.91	85.5	684	2.56E-03	0.73	0.01	0.26
BR2	15	467	242.5	428.5	45	360	4.17E-02	13.62	0.09	0.46
BR3	2.1	48	122.05	143.14	15	120	1.75E-02	0.59	0.11	0.16

Boxed cells in red show specific capacity ratio value > 1.0 indicating invalid result

H_A = available drawdown (ft)

ΔS = change in drawdown in one log cycle of time (ft)

Table 5.3 Method B (Moell) well capacity estimation results

Well #	Test flow rate (gpm)	H_A (ft)	static water level (ft)	water level end of test (ft)	drawdown per log cycle ΔS (ft)	100 minute drawdown S100 min (ft)	5 ΔS (ft)	Q_{20} (gpm)	Actual 100 minute specific capacity (gpm/ft)	Predicted 20 year specific capacity (gpm/ft)	Ratio 2: 20 year to 100 minute specific capacity
CF1	3,520	463	17.23	148	22	100	110	5,433	35.2	16.8	0.48
CF2	3,046	375	14.82	118.61	16.5	92	82.5	4,582	33.11	17.5	0.53
CF3.1	350	33	18.5	24.62	0.6	4.9	3	1,023	71.43	44.30	0.62
CF3.2	145	33.5	18	21.6	0.6	1.64	3	733	88.41	31.25	0.35
UC1	500	67.3	12.04	21.69	0.4	9.9	2	1,979	50.51	42.02	0.83
UC2	159	22.8	33.7	37.26	2.2	2.2	11	192	72.27	12.05	0.17
UC3	670	27	43	53	1.2	8	6	905	83.75	47.86	0.57
UC4	2,000	122.3	73.52	208.6	11.7	115.67	58.5	983	17.29	11.48	0.66
BR1	1.75	407	78.4	271.91	85.5	71.6	427.5	1.00	0.02	0.00	0.14
BR2	15	467	242.5	428.5	45	120	225	14.21	0.13	0.04	0.35
BR3	2.1	48	122.05	143.14	15	11	75	0.82	0.19	0.02	0.13

Table 5.4 Method C (CPCN) well capacity estimation results

Well #	Test flow rate (gpm)	available drawdown H_A (ft)	static water level (ft)	water level end of test (ft)	projected drawdown per log cycle of time ΔS (ft)	projected 100 day drawdown (ft)	Predicted 100-day specific capacity Q/s (gpm/ft)	Q_{100} (gpm)	Actual 1 day specific capacity Q/s (gpm/ft)	Ratio 3: 100 day to 1 day specific capacity
CF1	3,520	463	17.23	148	22	180	20.1	6,338	28.2	0.71
CF2	3,046	375	14.82	118.61	16.5	141.5	21.5	5,651	29.2	0.74
CF3.1	350	33	18.5	24.62	0.6	7	50.0	1,155	59.1	0.85
CF3.2	145	33.5	18	21.6	0.6	2.74	52.9	1,241	63.0	0.84
UC1	500	67.3	12.04	21.69	0.4	10.3	48.5	2,287	50	0.97
UC2	159	22.8	33.7	37.26	2.2	6.4	24.8	397	54.8	0.45
UC3	670	27	43	53	1.2	12	55.8	1,055	69.8	0.80
UC4	2,000	122.3	73.52	208.6	11.7	147.5	13.6	1,161	15.56	0.87
BR1	1.75	407	78.4	271.91	85.5	361.6	0.0	1.4	0.01	0.48
BR2	15	467	242.5	428.5	45	250	0.1	20	0.09	0.67
BR3	2.1	48	122.05	143.14	15	35	0.1	2.0	0.11	0.55

Table 5.5 Comparison of all methodologies results

Well #	Test flow rate (gpm)	Method A Q20 (Farvolden)	Method B Q20 (Moell)	Method C Q100 (CPCN)	Ratio 1	Ratio 2	Ratio 3	Remarks
CF1	3,520	6,482	5,433	6,338	0.71	0.48	0.71	
CF2	3,046	6,057	4,582	5,651	0.8	0.5	0.74	
CF3.1	350	1,684	1,023	1,155	**1.23**	0.62	0.85	Farvolden over-predicts
CF3.2	145	708	733	1,241	0.48	0.35	0.84	
UC1	500	7,361	1,979	2,287	**3.13**	0.83	0.97	Farvolden over-predicts
UC2	159	144	192	397	0.16	0.17	0.45	100 day capacity>> 20 yr
UC3	670	1,319	905	1,055	**1.04**	0.57	0.80	Farvolden over-predicts
UC4	2,000	1,829	983	1,161	**1.37**	0.66	0.87	Farvolden over-predicts
BR1	1.75	0.73	1.00	1.4	0.26	0.14	0.48	Method A Farvolden appears to be conservative in low-yielding bedrock wells. Also note that 100 day capacity is greater than the Q20
BR2	15	13.62	14.21	19.6	0.46	0.35	0.67	
BR3	2.1	0.59	0.82	2.0	0.16	0.13	0.55	

Boxed cells with red values indicate Ratio 1 being greater than 1.0, which means Q20 values are likely over-predicted by Method A.

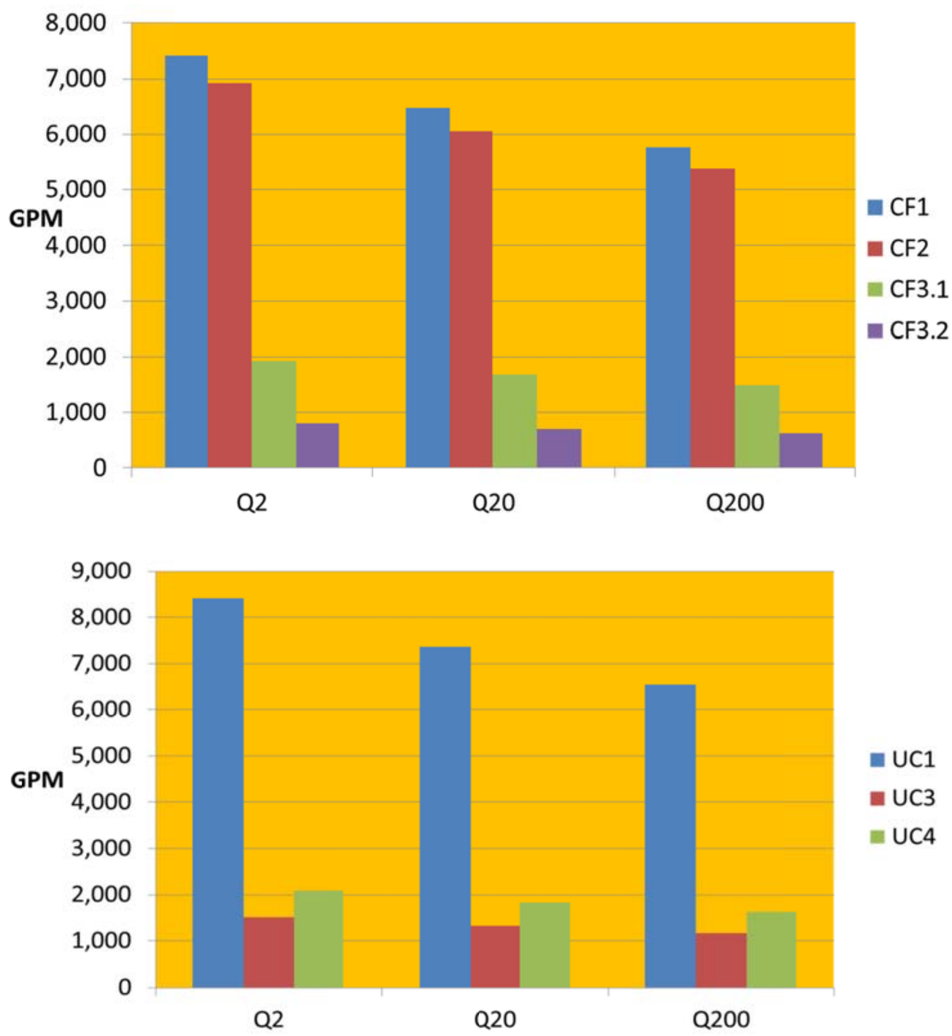
As indicated in Tables 5.1 to 5.4, the wells selected for this study exhibit a range of transmissivities, LTWC values, and specific capacity ratios. Regarding the ratios, there are three groupings of wells: those with lower specific capacity ratios (i.e. less than 0.50), wells with generally higher specific capacity ratios (> 0.50) and one well (UC1) with high Ratio 2 and 3 values that approach unity. The Farvolden method ratios (Ratio 1, shown in boxed cells with red numbers in Table 5.5) help explain the high LTWC values for these four wells, which are considered significant over-predictions. The higher the Ratio 1 values indicate a strong under-prediction of early time drawdown and an over-prediction of Q_{20}.

5.3 SENSITIVITY ANALYSIS RESULTS

The sensitivity analysis performed below for each of the well capacity calculation methods confirmed some of the more important relationships in deriving well capacity estimates. These include wells with low specific capacity ratios proving more sensitive to pumping time than wells with high ratios (except for the Farvolden method); and that LTWC estimates for wells with high ratios are more sensitive to the safety factor than wells with low ratios. In general, LTWC values of wells with higher specific capacity ratios are less sensitive to changes in pumping time, and relatively more sensitive to changes in the safety factor. LTWC values of wells with moderate specific capacity ratios may be expected to be somewhat sensitive to changes in pumping time or the safety factor. LTWC values of wells with low specific capacity ratios may be expected to be relatively more sensitive to changes in pumping time, but less sensitive to changes in the safety factor.

5.3.1 Method A Farvolden sensitivity

Figures 5.1 and 5.2 provide example bar graphs illustrating the pumping time and safety factor sensitivity analysis for wells analyzed with Method A (Farvolden). Four of the well test data sets exhibited a specific capacity ratio (Ratio 1) of greater than 1.0: well test CF3.1, UC1, UC3, and UC4. The Ratio 1 value for these test data sets indicates the method over-predicts Q_{20} due to the under-prediction of the actual early-time drawdown. Well UC1, completed in a highly productive aquifer and pumping at a relatively low rate relative to the transmissivity of the aquifer exhibited an unrealistically high Method A Q_{20} of more than 7,000 gpm. Comparing the calculated Q_2, Q_{20}, and Q_{200} values, the results showed that the higher-yielding wells with moderate to high Ratio 1 values have more sensitivity to changes in the pumping time, while the lower-yielding bedrock well Q_{20} values were much less sensitive to decreases or increases in pumping time – principally because the Farvolden method does not tend to under-predict early-time drawdown in low-yielding bedrock wells. This may be due to the relatively low rate of drawdown from casing storage effects during the earlier part of the pumping test. The same general pattern is seen in the sensitivity analysis run with safety factors of 0.6 and 0.8 as compared to the default 0.7 value. As indicated by the arrows in Figure 5.2, for most wells, varying the Q_{20} safety factor by 0.1 changed the LTWC value by about the same amount (about 15%) as when pumping time was varied by one order of magnitude.



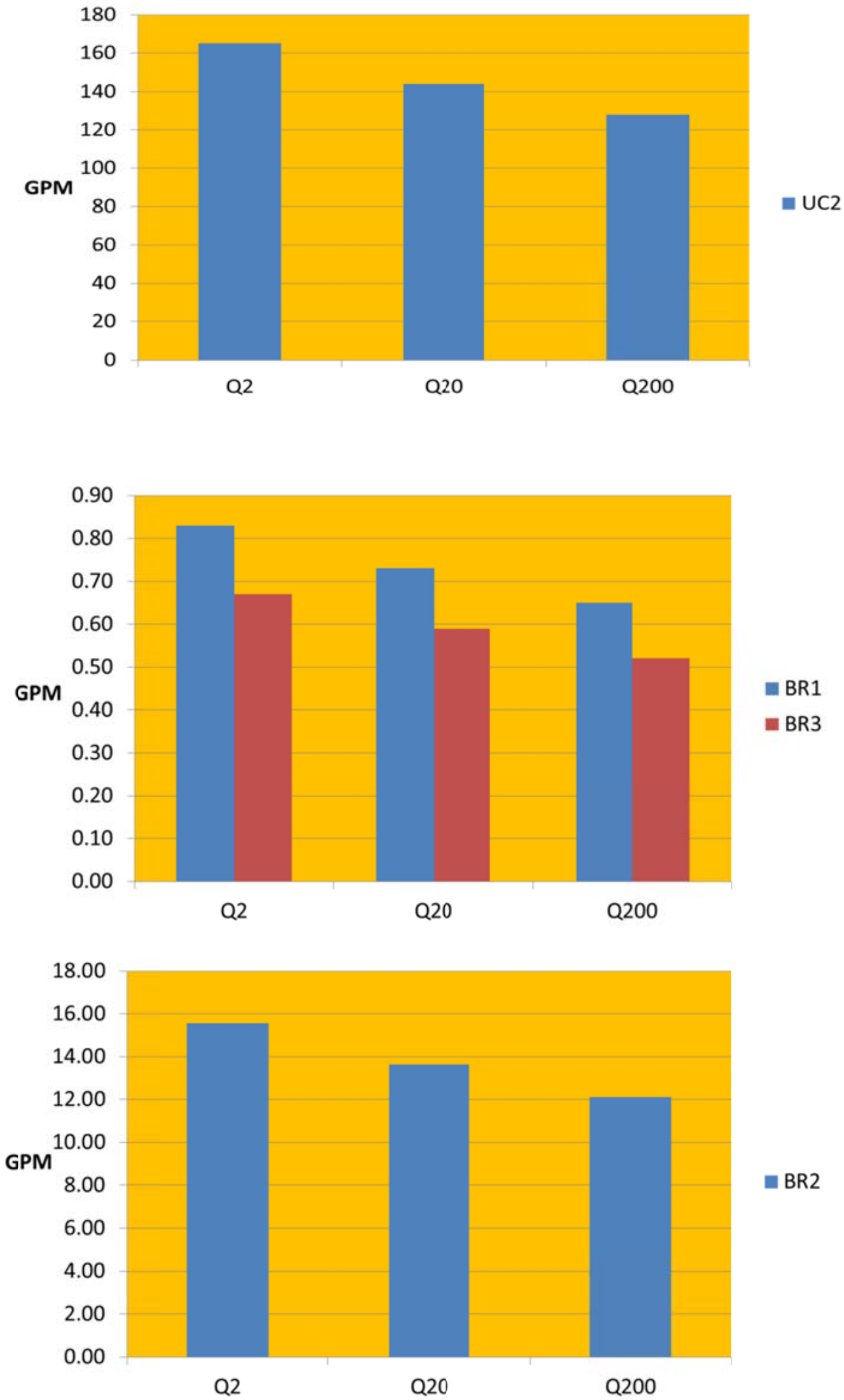


Figure 5.1 Method A time-of-pumping sensitivity graphs

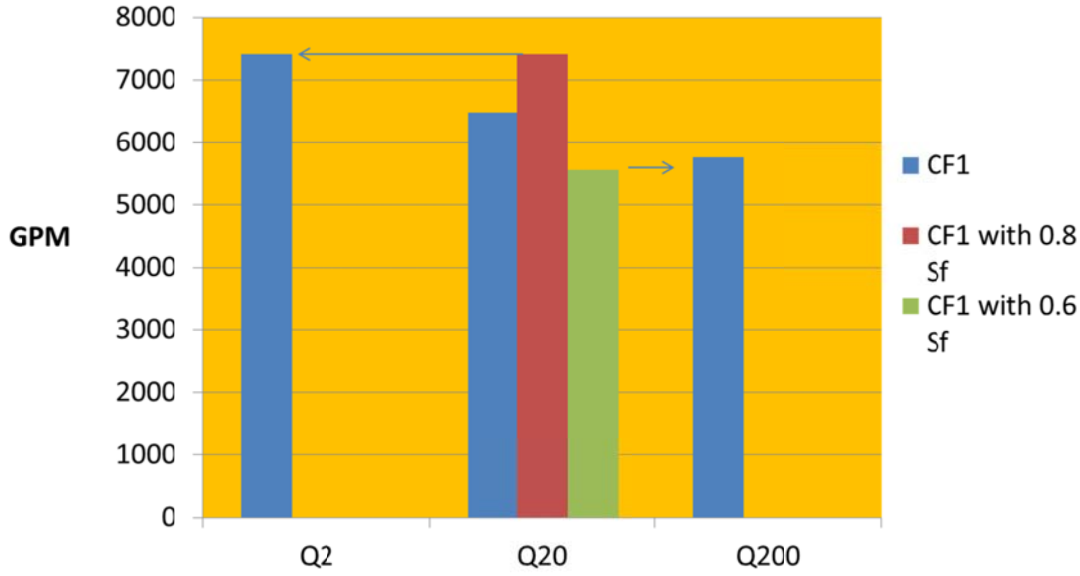
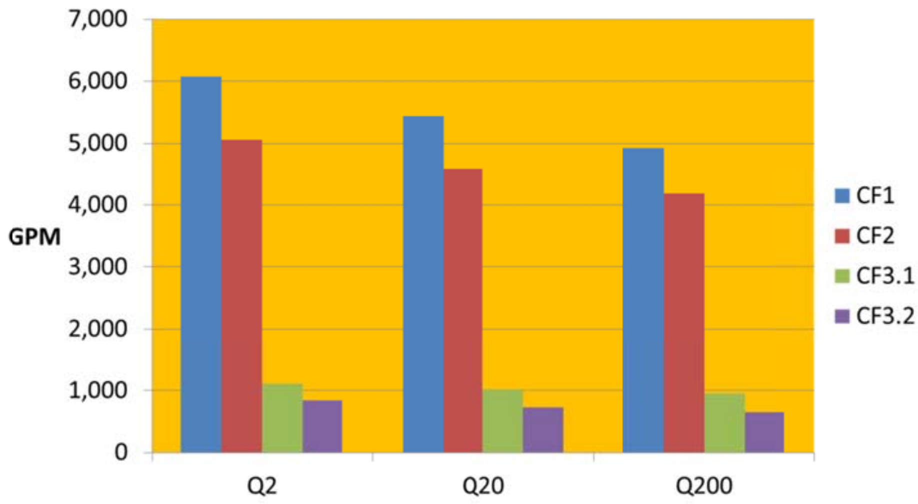
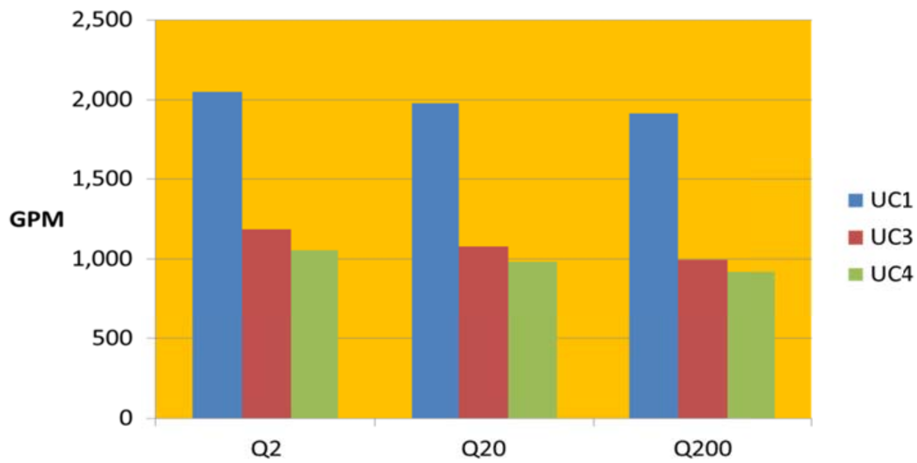


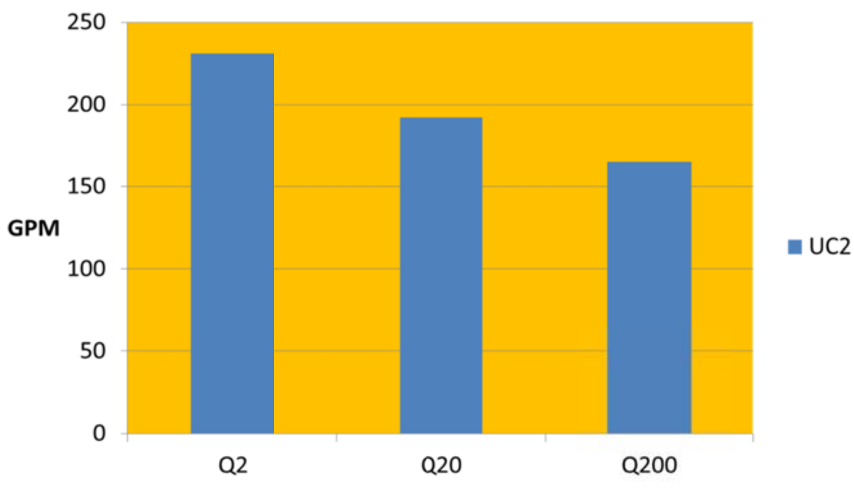
Figure 5.2 Method A Q_{20} safety factor sensitivity graph for CF1

5.3.2 Method B Moell method sensitivity results

The Moell method results proved to be relatively insensitive to changes (error) in the measured 100-minute drawdown value, which was varied by +/- 10% in the sensitivity analysis. The capacity results showed comparable variation to changes in pumping time and safety factor as the Farvolden and CPCN methods. Figures 5.3 and 5.4 provide example bar graphs.


7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
GPM
Q2
Q20
Q200
CF1
CF2
CF3.1
CF3.2


2,500
2,000
1,500
1,000
500
0
GPM
Q2
Q20
Q200
UC1
UC3
UC4


250
200
150
100
50
0
GPM
Q2
Q20
Q200
UC2

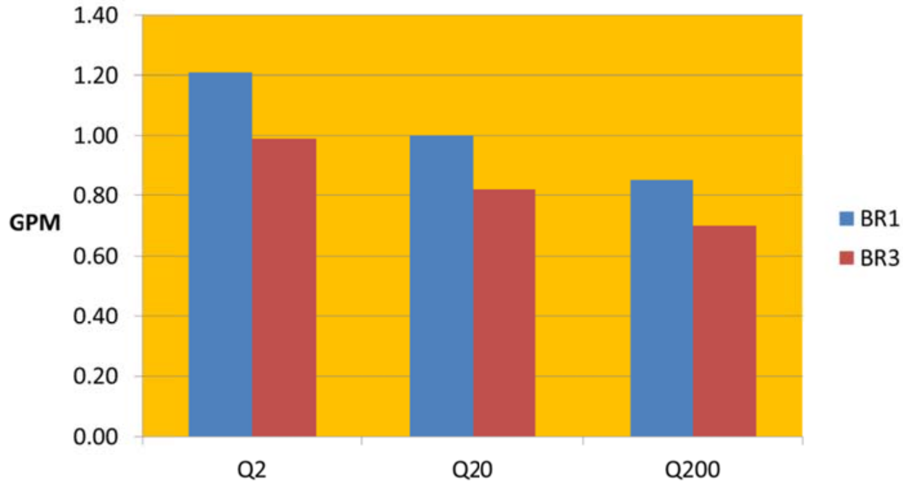
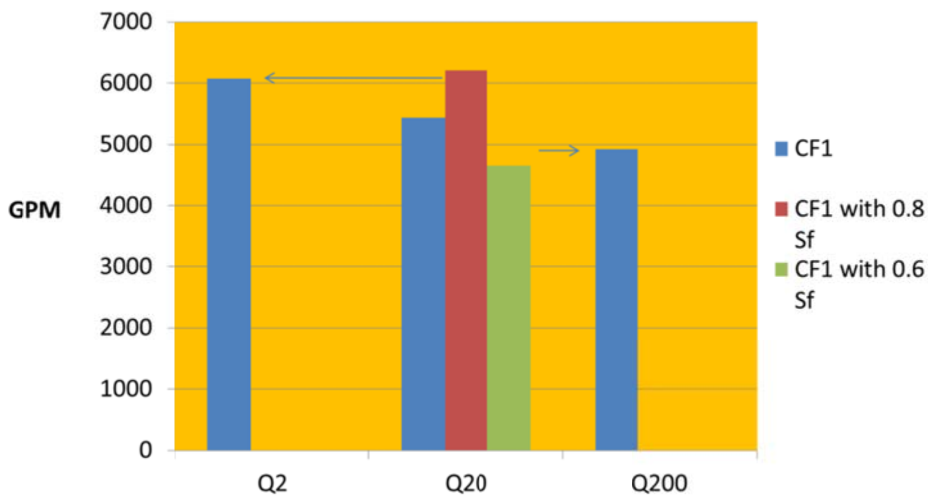


Figure 5.3 Method B time of pumping sensitivity graphs



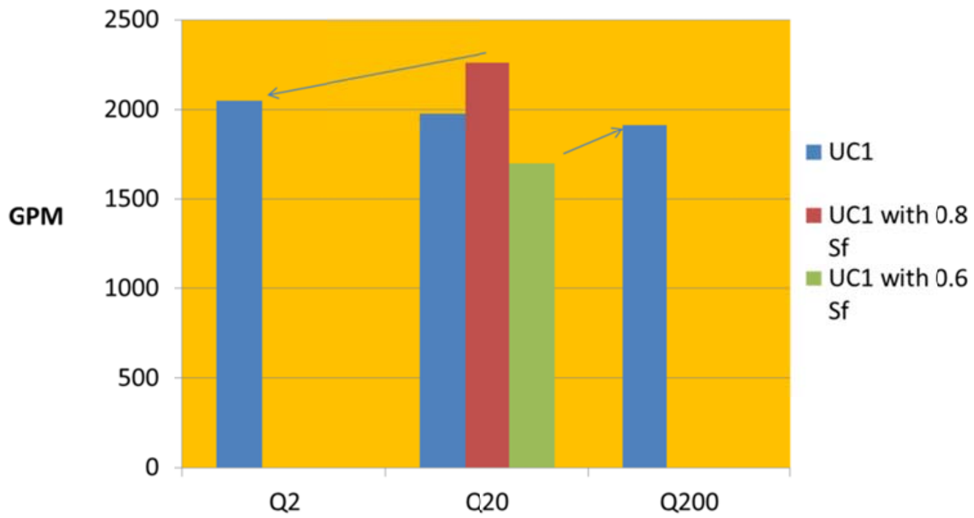


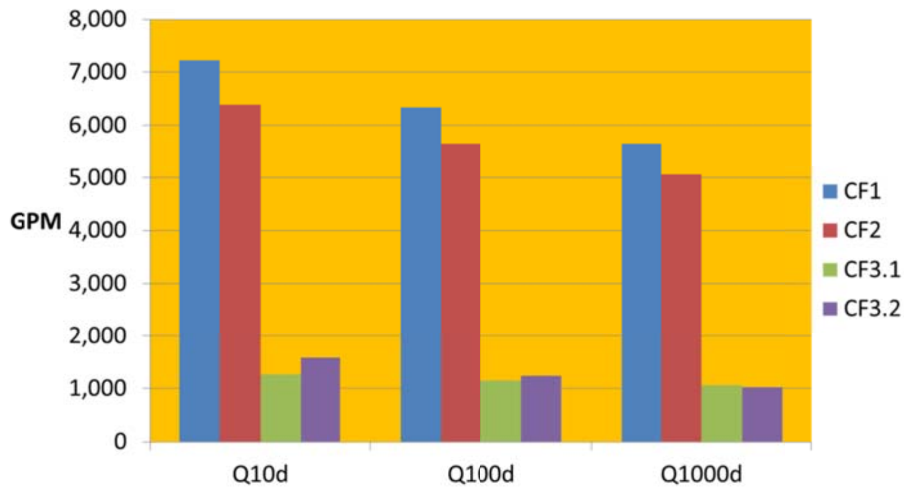
Figure 5.4 Method B Q_{20} safety factor sensitivity graph for CF1 and UC1

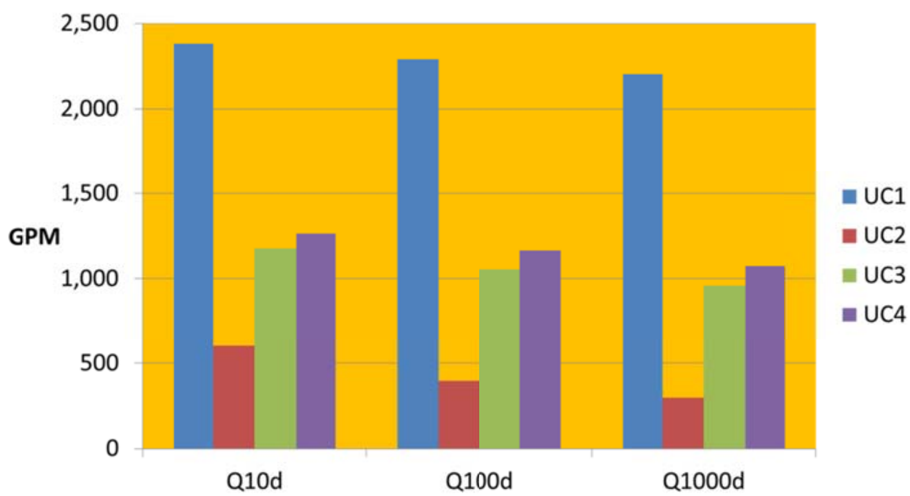
Well CF1 had a moderate Ratio 2 value of 0.48 and a one order of magnitude change in the pumping time provides estimated yield values that are quite similar to values obtained by adjusting the safety factor in the Q_{20} formula by 0.1.

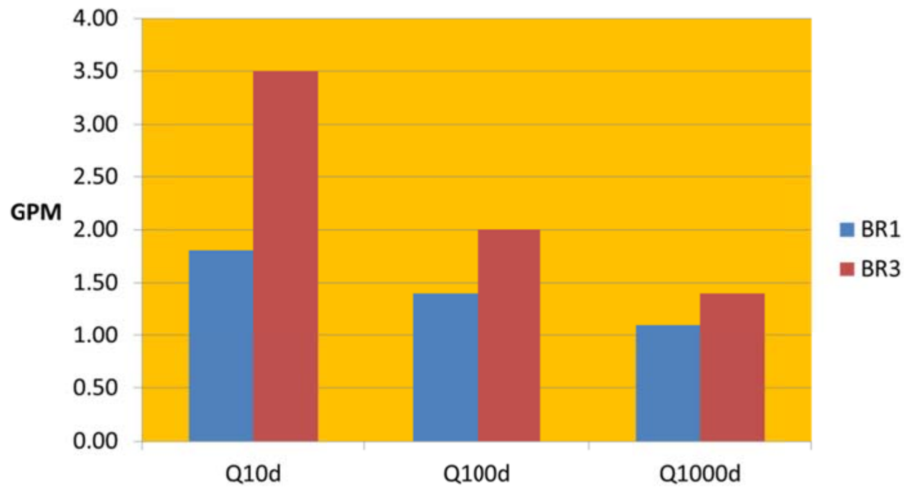
Well UC1 had a high Ratio 2 value (0.83) and consequently, the adjustment of the safety factor has a more pronounced effect on the Q_{20} value compared to increasing or decreasing pumping time. This analysis shows that in general, the higher the specific capacity ratio, the more sensitive the Q_{20} result would be to the safety factor applied in the formula. Interestingly, a 10% error in the 100 minute drawdown as varied for the Moell method sensitivity analysis does not appear to significantly affect the results in most cases.

5.3.3 Method C CPCN sensitivity results

The same general relationships between specific capacity ratios, safety factor adjustment, and Q_{20} sensitivity observed for Method B was evident in the results for Method C. As expected, there were relatively significant differences in the well capacities determined for the 10-day and 1,000-day sensitivity runs. For example, the 1,000-day capacity of Well CF1 was 20% less than the 10-day value. Overall, the time of pumping and safety factor sensitivity results followed the same pattern of variation as seen for the Method B Moell analyses (see 5.3.4 below for a summary). Figure 5.5 provides example bar graphs for the time of pumping sensitivity.







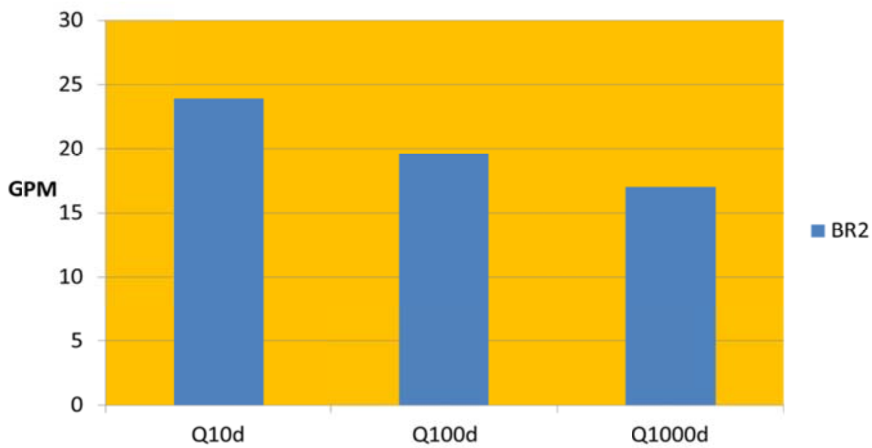


Figure 5.5 Method C time of pumping sensitivity graphs

5.4 SUMMARY

The sensitivity analysis demonstrated how evaluating the effect of increasing or decreasing the pumping time and adjusting the safety factor could affect the resulting LTWC calculation. In general, adjusting the safety factor by 0.1 affected the resulting Q_{20} or Q_{100d} value by approximately 15% due to the linear relationship between the safety factor and LTWC. The order of magnitude variation in pumping time affected LTWC values typically in the range of 5 to 15% because of the more complex mathematical relationship between pumping time and well capacity: when ΔS is small, then the ΔQ_{20} or ΔQ_{100d} will also be small when pumping time is varied.

In cases where there is uncertainty about long-term recharge to the aquifer, or possible future well interference, it could be advisable to adjust the safety factor to 0.6 or even 0.5 in a Q_{20} analysis. For Method C, which calculates a single peak season well yield for 100 days of pumping, the pumping time may be extended one order of magnitude to provide a three-year well capacity (1000 days), which would be one way to plan for a drought scenario.

Pumping test data sets combined with the application of the long-term well capacity analyses provides an easy way to calculate the well's specific capacity ratio. The ratios assigned for the 10 well test data sets showed how the Farvolden method could lead to over or under-predicted Q_{20} values, whereas the Moell and CPCN methods were generally deemed reliable and each data set exhibited a consistent pattern in changes to LTWC estimates in the sensitivity analysis, indicating that these methods may be used reliably. Maathuis and van der Kamp (2006) recommended that use of the Farvolden method be discontinued, which seems reasonable given that the Moell method is just as easy to apply. In a Q_{20} LTWC calculation using Method B (Moell), if the 100 minute drawdown data point is not available, or cannot be reasonably interpolated from test data, then a safety factor of 0.5 or 0.6 should be considered for wells analyzed with the Farvolden method.

For all three methods, LTWC estimates sometimes surpassed the test pumping rate and/or the practical limit of production due to the well diameter, and for UC1, CF1, CF2 and CF3 the exceedance was by a considerable amount. In the case of the three confined aquifer wells, well interference factors into the actual LTWC and is discussed further in Chapter 6. The CPCN method states that the calculated Q_{100d} not exceed the test pumping rate unless sufficient justification is provided by the hydrogeologist. Similarly, the State of Vermont (2010) water supply rules only allow for a 10% upward adjustment in the safe well yield (provided justification is given in the hydrogeologic report). Such limitations are well-advised, because the LTWC analysis already extrapolates relatively short-term pumping tests to long term pumping scenarios. Assigning a higher pumping rate based on this extrapolation could lead to unforeseen problems. The determination of a high theoretical Q_{100d} or Q_{20} is useful in that the result may indicate that a larger well, or a higher rate pumping test, or both, may be feasible to assess the resource further.

CHAPTER 6

DISCUSSION ON SELECTED TECHNICAL ISSUES

The foregoing analysis of LTWC focused on evaluating yield from an individual well over a specified time period, giving consideration to well and aquifer hydraulics, but with minimal consideration of outside factors. There are a number of these potentially complicating factors that may need to be considered during the process of assigning a value of “well yield”, which could serve to further constrain the derived value, and provide a means to predict how well yield may change with the dynamics of the well-aquifer system. Some of these issues may be accounted for by using professional judgement and applying a more conservative safety factor as noted above. Other situations would likely require further assessment. The following sections highlight some of the more important considerations and provide further assessment using some of the well test data sets to help illustrate the potential significance of these issues.

6.1 WELL CONSTRUCTION FACTORS INFLUENCING LONG TERM CAPACITY

Conventional aquifer test analysis usually assumes that wells are “fully penetrating”, that is, they are open to the entire saturated thickness of the aquifer. In practice, this is rarely the case in unconfined aquifers, and even in confined aquifers with high piezometric heads, it is usually not necessary to screen the entire aquifer thickness in order to develop a successful production well. In fact, placing the well screen or open interval as deep as possible is usually good practice, as it allows for additional available drawdown.

Driscoll (1986) noted that well casing diameter is more important than screen diameter when it comes to constraints on well yield, because casing diameter limits the size and capacity of well pumps.

For wells completed with screens in unconsolidated formations, well development is critical to long-term well yield. If development is not completed, then well performance is likely to decline. The resulting loss of specific capacity has a direct impact on the long-term well capacity.

Well screen transmitting capacity is sometimes stated as a limiting factor to well yield by hydrogeologists, engineers and water well drillers. When radially flowing groundwater approaches a well, its velocity (actually the specific discharge) increases (Williams 1981). If velocity exceeds a critical value, head losses could occur as the water passes through the screen and/or if turbulent flow occurs. The concepts of entrance and approach velocity and head losses as they relate to well design are discussed in Rorabaugh (1953) Williams (1981), and Driscoll (1986), among other papers. The basic theory is that as water is drawn into a well screen from the formation, the increased head difference between the formation and the pumping water level in the well causes the velocity of the flow to increase. This velocity further increases as water passes through the well screen openings. When the flow reaches a critical velocity, it may become turbulent, which leads to further well losses (greater drawdown) and over the long term may contribute to deteriorating well performance. Rorabaugh (1953) found that turbulent flow due to over-pumping effects may have a dramatic effect on increasing well drawdown.

As Williams (1981) noted, a high approach or entrance velocity may mobilize fine formation sediment toward the well screen, contributing to plugging of the screen and adjacent formation. For wells completed with well screens it is advisable to review the screen transmitting capacity and consider this theoretical value in assigning an appropriate long-term well capacity.

6.2 Seasonal or Annual Water Level fluctuation

Seasonal and annual patterns of groundwater level variation should be understood, either through direct observation well data or through analysis of available regional data, when assessing long-term well yield. If a given well is test-pumped during the normal period of high water levels, and it is intended to be operated primarily at times of low water levels, this information must be factored into the final assessment of long-term well capacity by adjusting the available drawdown (H_A) term. When possible, wells should be tested and evaluated against low water conditions in order to derive a conservative estimate of long-term well capacity. Then, a higher operating capacity can be assigned for certain pumping periods that coincide with normally higher groundwater levels.

6.3 Factoring in Changes in Well Performance (Specific Capacity)

The CPCN Guidelines (Allen et al. 1999) list changes in well performance as one of the issues that could be addressed through the application of the recommended 0.7 safety factor. However, in cases where there is good evidence that production well performance declines are common, a site-specific well performance factor should be considered in assessing long-term well yield. This requires professional judgement, and a subjective "de-rating" of the calculated well capacity that is intended to reduce the operational pumping rate, and possibly delay the onset of well performance problems.

6.4 Pump Performance Considerations

In assessing long-term well capacity, the hydrogeologist may need to consider pump design and performance issues, and make appropriate recommendations that take these issues into consideration. These issues are normally beyond the scope or control of a hydrogeological assessment, and involve engineering and economic factors. The recent paper by Konikow (2010) discusses some of the more important concepts, such as the fact that most well pump motors operate at a single speed, which means the flow rate changes as drawdown in the well increases. With most wells being assigned a single, fixed "safe" yield, well owners need to be able to properly plan for the effects of long-term pumping on well production rates. Variable speed pumps combined with flow control valves are an attainable way to engineer a steady flow rate from wells. The main issues to consider are whether or not the well has a low specific-capacity ratio and if so, then if the well pump to be used is a constant-speed, then the long-term flow rate of the well decreases as drawdown increases. Variable speed pumps can maintain a steady flow rate under a much broader range of water level conditions, and in some cases may be needed to enable a predictable flow rate.

As noted above, well casing diameter generally limits the size pump that can be installed in wells. Driscoll (1986) provides some guidelines on the typical practical maximum yield of wells based on diameter. As a further example, Well CF1, although it has a theoretical yield of more than 4,000 gpm, is limited to approximately 3,500 gpm because it is a 20-inch diameter well. A similarly-constructed 24-inch diameter well at the location of CF1 could potentially yield more than 4,000 gpm.

6.5 INVESTIGATION OF WELL INTERFERENCE EFFECTS

Well interference must be accounted for when measurable drawdown occurs during the simultaneous operation of wells. In terms of the effect on calculating well capacity, well interference reduces the available drawdown (H_A value). If well interference represents only a small percentage of H_A, then the default 0.7 safety factor may be sufficient to account for the effect of interference. If well interference is larger, then either the H_A value or the safety factor requires adjustment, and the resulting estimate of well capacity should be less than the theoretical value derived on the basis of the pumping test. Application of the R_{20} concept as proposed by Maathuis and van der Kamp (2006) is one way to address well interference, and this may be done with or without observation well time-drawdown data.

This section presents the results of applying a well interference factor to the well capacity estimation method for two of the wells: CF1 and CF2. Operation of other wells completed in the same aquifer causes approximately 100 ft of drawdown in each of these wells. For this analysis, an additional 100 ft of drawdown attributed to well interference is factored into the well capacity estimation spreadsheets. This is easily accounted for in the calculation spreadsheets by reducing the H_A value by 100 ft. Table 6.1 summarizes the resulting Q_{20} and Q_{100d} values calculated for these two wells. It is evident that factoring interference could have a significant effect on the resulting well capacity calculation and the magnitude of the effect is similar for each of the three methods, with the greatest reduction in capacity seen in the Farvolden method.

Table 6.1 Analysis of Wells CF1 and CF2 well interference effects

Scenario	Well CF1 LTWC (gpm)	Well CF2 LTWC (gpm)
Method A no interference	6,482	6,057
Method A with 100 ft of well interference	5,082	4,442
Difference	1,400	1,615
Method B no interference	5,433	4,582
Method B with 100 ft of interference	4,259	3,360
Difference	1,174	1,222
Method C no interference	6,338	5,651
Method C with 100 ft of interference	4,969	4,144
Difference	1,369	1,507

6.6 INVESTIGATION OF LONG TERM MINING YIELD

This section assesses how the loss of saturated thickness, i.e. groundwater decline affects the theoretical long-term capacity of wells completed in the Ogallala aquifer in Kansas, using the two example wells evaluated in this study located in GMD3. First, a simple analysis based only on water level changes will be presented. Then, the effect of reduced aquifer transmissivity will be investigated in order to illustrate the potential decline in well yields between when they were originally tested and the present-day, and the implications for expected reduction in well capacity that could occur over the next 20 years. These results are then compared to the findings of Hecox et al. (2002), which presented KGS' area-wide assessment of the relationship between well yield and saturated thickness in the Ogallala aquifer.

6.6.1 LTMY of UC3 and UC4 using current H_A

Focusing on the two Q_{20} methods, this exercise started with the 1977 and 1979 pumping test data, then factored in current (2010) water level observation data (KGS 2010) to calculate an estimated current H_A value, and then assumed a continued trend of decline for the next 20 years to derive theoretical current and future LTWC values. Based on a 15 ft decline at UC3 since 1979 (approx. 0.5 ft/yr) and a 100 ft of decline at UC4 since 1977 (approx. 3 ft/yr), the year 2010 LTWC values and projected year 2030 values are summarized below in Table 6.2

Table 6.2 Estimated long-term mining yield of High Plains / Ogallala wells UC3 and UC4

Well	Farvolden Q_{20} when tested	Farvolden Q_{20} in 2010	Farvolden Q_{20} in 2030	Moell Q_{20} when tested	Moell Q_{20} in 2010	Moell Q_{20} in 2030
UC3	1,319	865	70	905	606	392
UC4	1,911	364	0	983	398	74

Note that the year 2030 Q_{20} value for Well UC4 is calculated as effectively zero. This is attributed to the H_A value being taken to equal 2/3 of the saturated thickness in unconfined wells. However, given a 1977 total available drawdown of approximately 183 ft, a 3 ft/yr decline between 1977 and 2030 (159 ft) would nearly exhaust the resource at the location of that well, even if H_A was set equal to the total available drawdown without the 2/3 factor.

It is acknowledged that the assumed 3 ft/year rate of decline at UC4 could be overly conservative in that ongoing water conservation efforts in the GMDs appear to be slowing the decline rate in some areas (Macfarlane and Schneider 2007). The hydrograph of the annual water level observation well in T24S, R33W, 34CAC (Figure 6.1 below, about 3 miles from UC4) shows a rapid decline occurred between approximately 1975 and 1985, a slower decline until 2000, and then an accelerating decline between 2000 and 2010, with the 192.9 ft January 2010 water level more than 90 ft below the February 1977 level. Other wells reviewed in the KGS Wizard system that are located closer to UC4 in parts of T24S, R33 and R34W and T25S and R33 and R34W do not have a period of record extending from the 1970s to 2010, but during the 1980s and 1990s exhibited annual rates of decline in the range of 3 to 5 ft/yr.

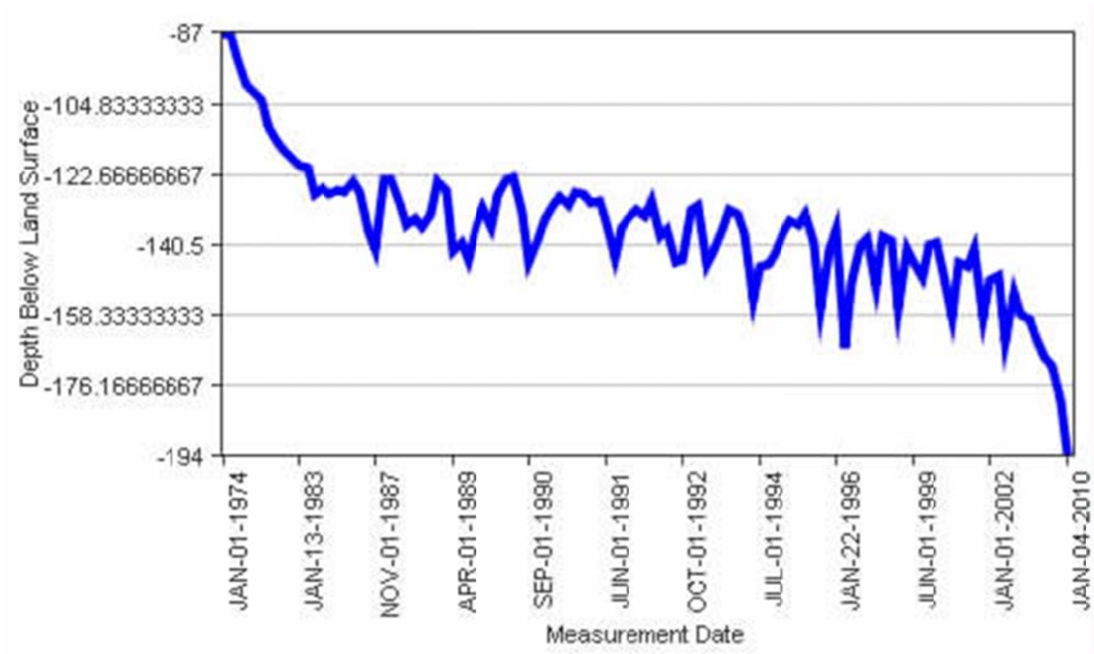


Figure 6.1 Hydrograph of Annual Water Level Well T24S, R33W, 34CAC

Figure 6.2 Hydrograph of Annual Water Level Well T28S, R21W, 23DBC

Data source: KGS online WIZARD application

The hydrograph of water level observation well T28S, R21W, 23DBC (Figure 6.2, located approximately 3 miles from UC3) shows approximately 13 feet of decline since 1979.

As noted in Chapter 4.1.3, the upper 30 ft of the UC4 well screen contributed little to the well flow during the test pumping program. If so, deepening of the well pump (if screen diameter permits) combined with a slower decline rate could extend the usable life of the resource.

6.6.2 Effect of reduced aquifer transmissivity on long-term well capacity

Transmissivity (T) is the product of hydraulic conductivity (K) and thickness (b), and so loss of saturated thickness reduces the transmissivity of the aquifer. When highly conductive materials are dewatered, the relative reduction in T may be greater than the percentage of saturated thickness lost to decline. This section considers the future production potential of wells completed in the Ogallala by factoring in the effects of changed drawdown behavior as a consequence of reduced transmissivity.

In the Hecox et al. (2002) paper, KGS estimated the minimum saturated thickness required to sustain 90 days of flow to production wells, choosing 50 gpm, 400 gpm and 1,000 as the example production rates. The analysis modeled both single wells and well arrays on quarter-section centers (minimum well spacing approximately 2,600 ft) and was based on available estimates of Ogallala hydraulic conductivity (K) and thickness. For higher K (200 ft/day) portions of the aquifer, Hecox et al. (2002) estimated that at least 60 ft of saturated thickness was required to sustain multiple wells at 1,000 gpm and 40 ft needed for 400 gpm. For lower K (25 ft/day) portions of the aquifer, KGS estimated 150 ft of ST is required to sustain 1,000 gpm and 90 ft is required for 400 gpm.

The reported UC3 transmissivity value in 1979 (Dealy and Jenkins 1980) was 160,000 gpd/ft and based on the reported aquifer thickness of 43 ft, this indicates a hydraulic conductivity of 520 ft/day, which is considered a high K value. The reported UC4 T value in 1977 (Burns and McDonnell 1977), as indicated by the response of both the pumping well and nearby observation wells, was approximately 45,000 gpd/ft. If we take the aquifer thickness in 1977 to be the difference between the base of the producing zone determined in the spinner survey and the static water level, then the Ogallala saturated thickness was about 300 ft, indicating a low to moderate K value of 20 ft/day at that well location. Based on Hecox et al. (2002), at least 150 ft of ST would be required to sustain 1,000 gpm for 90 days at UC4, and at UC3, the ST requirement could be as low as 30 ft (KGS did not assess K values higher than 200 ft/day).

Subtracting the approximate relative declines at both wells sites of 15 ft for UC3 and 100 ft for UC4, and assuming an equivalent bulk K value for the remaining saturated aquifer at both locations, the year 2010 effective transmissivity is estimated to be 109,000 gpd/ft at UC3 and 30,000 gpd/ft at UC4. Thus at both sites, approximately 30% of the late 1970s transmissivity has been lost due to the effects of depletion. To depict this change, a predictive drawdown spreadsheet developed by the Halford and Kuniansky (2002) was used to check the validity of these estimates by simulating a 24 hour drawdown test as shown in Figures 6.3 through 6.6. This spreadsheet is referred to as the confined prediction worksheet, and is based upon the Theis equation. Although the Ogallala is geologically an unconfined (water-table) system throughout much of western Kansas, the pumping test response observed in wells UC3 and UC4 indicated the aquifer behaves like a confined system especially for longer pumping durations.

For each well, the first confined prediction plot shows the "base case" defined as the year the original pumping tests occurred in the late 1970s. The second plot shows the predicted drawdown curve in 2010 based upon the reduced aquifer thickness and transmissivity. The K values used in the base case prediction were adjusted slightly from the values depicted above in order to obtain a good match between the base-case predicted and actual drawdown. These calibrated values were 520 ft/day for UC3 and 18 ft/day for UC4. The 1977 transmissive thickness was also adjusted at UC4 from 300 to 250 ft. Only the base case and year 2010 conditions are illustrated, but given any projected groundwater decline rate, future years could be modeled using this technique.

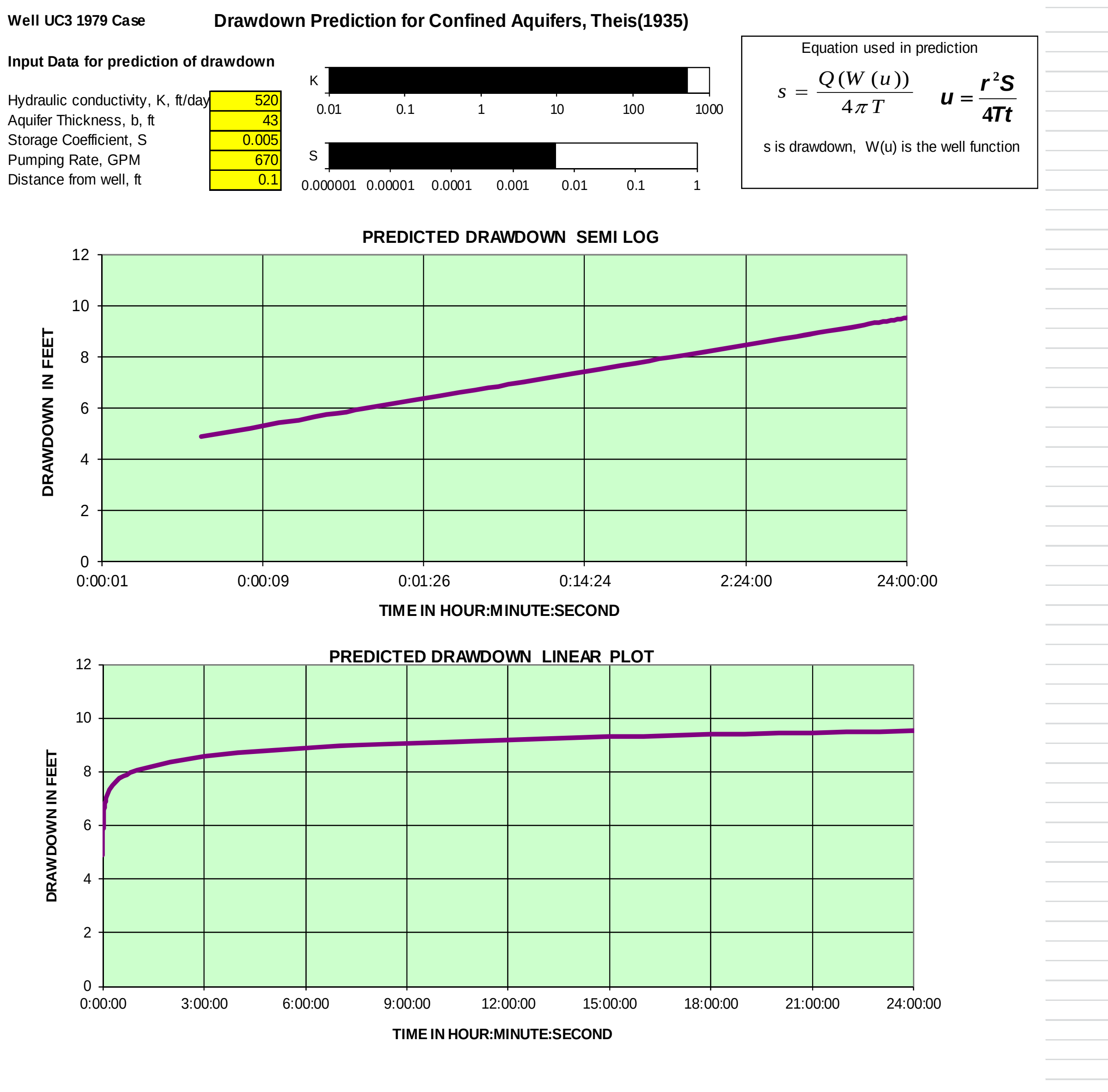


Figure 6.3 Base case (1979) predicted drawdown curve for UC3

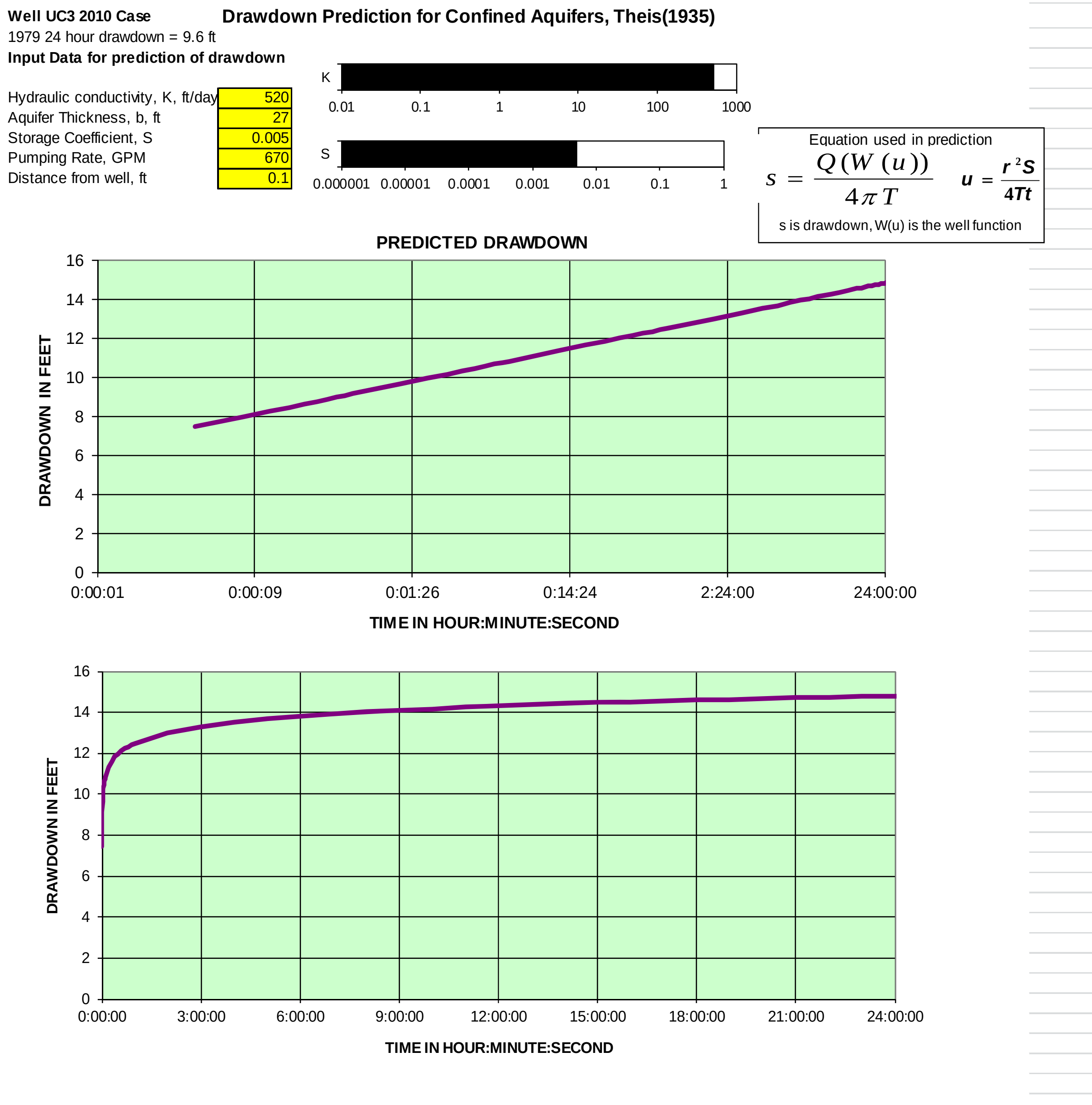


Figure 6.4 Year 2010 predicted drawdown response for UC3

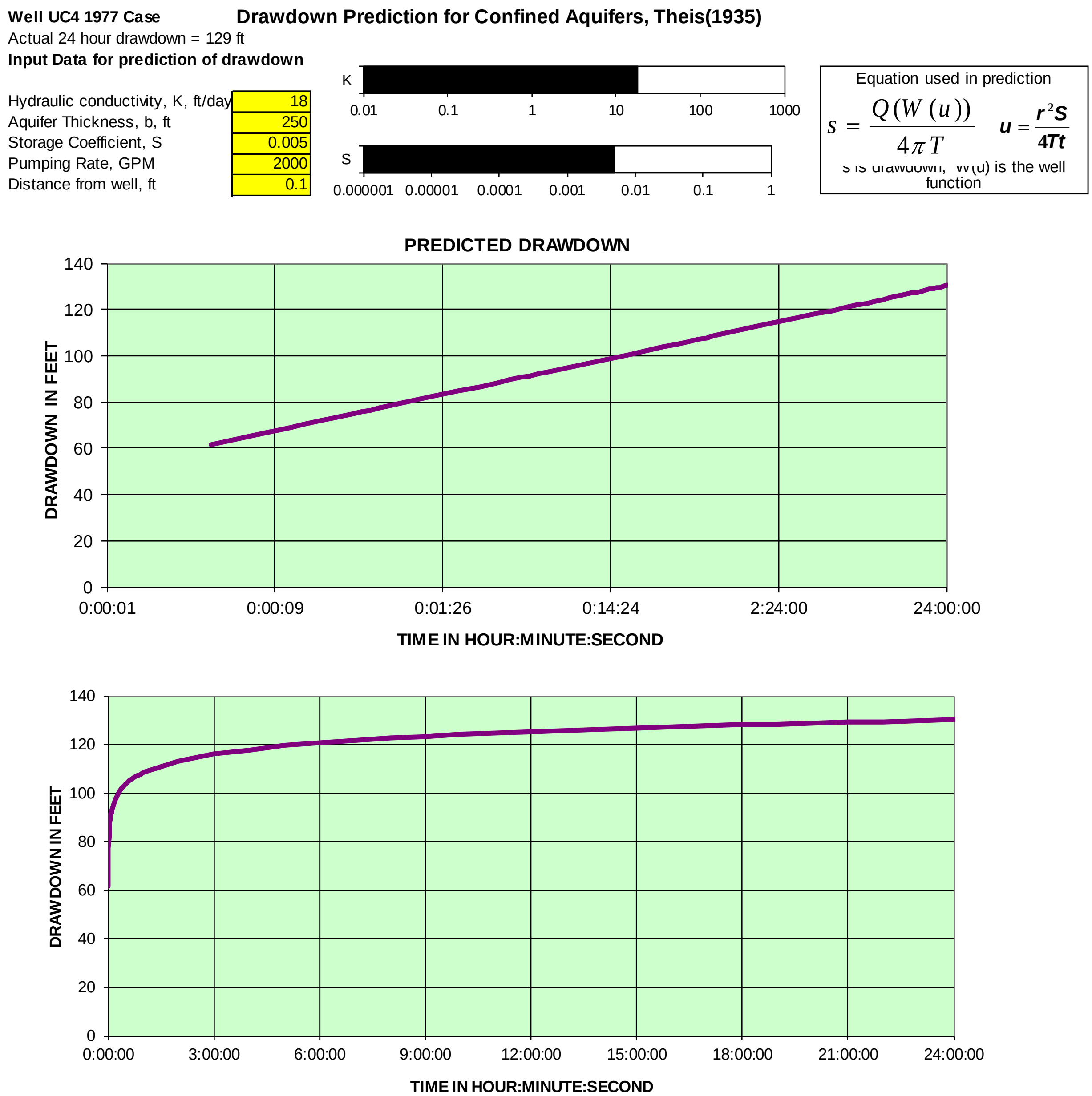


Figure 6.5 Base-case (1977) predicted drawdown curve for UC4

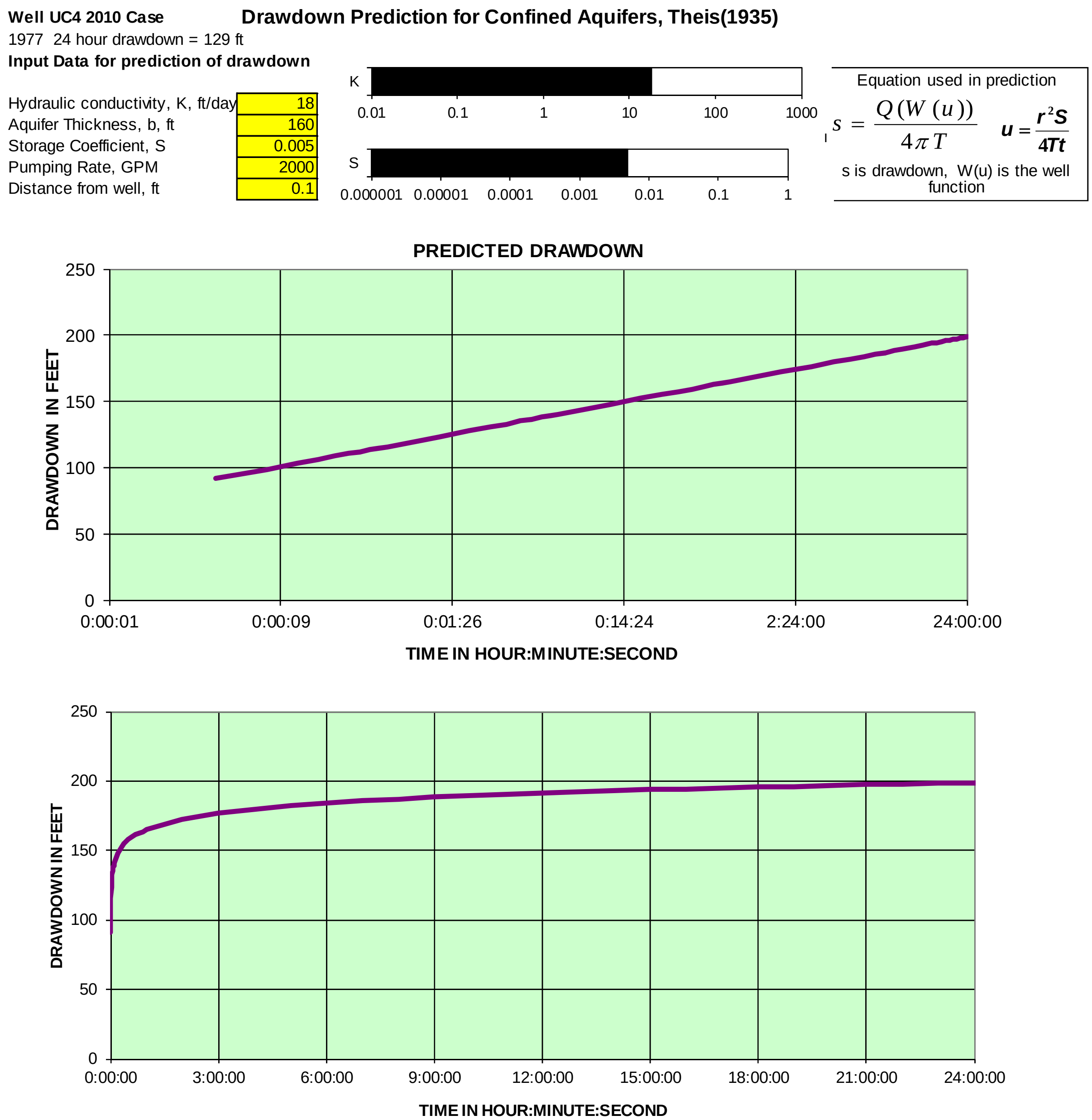


Figure 6.6 Year 2010 predicted drawdown curve for UC4

The implication of reduced transmissivity is that if for example UC4 was test pumped in 2010 at a constant rate of 2,000 gpm, the ΔS value (change in drawdown per log cycle of time) would be greater than the adjusted base case 1977 value of 18 ft, due to a lower transmissivity, which in turn would reduce the calculated Q_{100d} or Q_{20} value.

Examining either Figure 6.4 or 6.6, or re-arranging either the Theis (1935) or the Cooper-Jacob (1946) equations makes it possible to estimate the change in drawdown behavior.

For UC4, using Cooper-Jacob, the estimated 2010 ΔS at 2,000 gpm would be approximately 25 ft per log cycle of time. This is significantly higher than the observed 1977 value of 11.7 ft or the confined prediction modeled value of 18 ft. If this 25 ft ΔS value is used in the Method B Moell Q_{20} calculation spreadsheet (without changing the 100 minute drawdown value), then the estimated Q_{20} value would be approximately 288 gpm, compared to the 983 gpm value calculated for 1977 test conditions, a 70% decrease, and 398 gpm calculated in Chapter 6.6.1 solely on the basis of reduced available drawdown. Due to lower T, the actual 100 minute drawdown would be higher in 2010, and so the 288 gpm value might be optimistic. If the 25 ft ΔS value is used in the Method C Q_{100d} calculation spreadsheet, then the 2010 Q_{100d} value would be 277 gpm compared to 1,165 gpm under 1977 test conditions (a 75% decrease).

Again using Cooper-Jacob, the estimated ΔS for UC3 at 670 gpm would be 1.6 feet, as compared to the observed 1979 value of 1.2 ft. Using the 1.6 ft value in the Moell worksheet results in a Q_{20} of 550 gpm compared to the 905 gpm value calculated for 1979 test conditions, a 40% decrease.

If we assume approximately 80 ft of ST remained at UC4 in 2010, then the Hecox et al. (2002) estimate of 400 gpm (for K value of 25 ft/day) compares favorably with the above estimates of 288 to 398 gpm. It is more difficult to draw comparisons for UC3, because of the apparent high hydraulic conductivity of the Ogallala at the well location. The 550 gpm Q20 value, and the high K suggest that even with a ST as low as 25 ft, moderate well production in the range of 400 to 600 gpm might be feasible, but would require a pumping test to confirm.

In summary, even though UC3 and UC4 are located considerable distance apart and the thickness and hydraulic properties of the Ogallala aquifer are quite different at each location, the groundwater decline that has occurred since the late 1970s has effectively reduced aquifer transmissivity by about 25 to 30% at both well sites. This change results in a corresponding decrease in theoretical long-term well capacity ranging from 40% (UC3) to as much as 75% (UC4). The effect has been more pronounced in Finney County (UC4) due to the fact that large declines have occurred, and the aquifer exhibits a relatively low hydraulic conductivity.

Even if the Ogallala decline rate moderates near UC3 and UC4 and other similar localities over the next 20 years, by 2030 a further decrease in the theoretical and actual well capacity is likely. From this, it is clear that the magnitude of the declines seen in parts of western Kansas, should they continue even at a slower rate through a planned depletion policy (Sophocleous 2009), could be expected to significantly limit the ability of individual wells to operate at their historically used flow rates.

6.7 USE OF ANALYTICAL AND NUMERICAL MODELS

Analytical models may be used to simulate groundwater pumping from one or more wells, based on the Theis equation or other pumping test analytical methods; other analytical tools can simulate groundwater flow in two-dimensions and thus can generate drawdown contours. Numerous spreadsheet tools exist to generate a prediction of drawdown at varying distances from a pumping well, including the USGS “Confined Prediction” spreadsheet discussed in Chapter 6.6 (Halford and Kuniansky 2002), which uses the following formula (based on the Theis equation) to generate values for drawdown (s):

Equation used in prediction

$$s = \frac{Q(W(u))}{4\pi T} \qquad u = \frac{r^2 S}{4Tt}$$

s is drawdown, W(u) is the well function

Commercial software tools used in aquifer test analysis apply similar mathematical expressions to generate simulated drawdowns in one or multiple wells, based on pumping scenarios specified by the use; these simulations are not limited to a Theis analysis but could incorporate several analytical aquifer test models. Numerical models, both finite-element type and finite-difference type are more sophisticated tools that have three-dimensional transient capabilities. When relatively large pumping rates occur, and significant exchanges between surface water and groundwater are expected, with possible ecological or water user conflicts, then a flow model is a tool of choice to examine scenarios that cannot be addressed through conventional pumping test analysis and conceptual hydrogeologic modeling. Detailed assessment of well capacities based upon pumping tests, combined with detailed information on hydrostratigraphy and aquifer hydraulic properties is required in order to construct numerical models. Numerical models now have the capability to incorporate well hydraulics (e.g. well efficiency) in order to generate both aquifer and pumping well drawdown values.

CHAPTER 7

CONCLUSIONS

Of the various methods known to be applied in North America to estimate the long-term capacity of individual wells, three were investigated in detail and applied in quantitative analysis using eleven pumping test data sets. These are the methods of Farvolden (1959), Moell (1975) and B.C. Ministry of Environment (CPCN; 1999) herein referred to as Methods A, B and C.

This Chapter reviews the principal findings of the investigation and identifies opportunities for further research. In summary, the objective of compiling pumping test data sets from wells completed in a variety of hydrogeologic settings was successfully applied to test three methods used to estimate long-term well capacity. The results were interpreted along with conventional pumping test data analysis and other factors of relevance to groundwater resource management. Research findings including confirmation of the hypothesis, and the broader implications of the investigation are presented below.

7.1 FINDINGS ON THE Q_{20} METHODS A AND B OF FARVOLDEN AND MOELL

This study confirms the finding of Maathuis and van der Kamp (2006) that the Farvolden method may not be a reliable indicator of LTWC. Depending on the well test conditions, Farvolden may in fact significantly over-estimate or under-estimate well capacity. This is due to the fact that the early time drawdown value (in the first minute of pumping) is not taken into account in the equation. This study devised an easy way to test of the validity of the result by calculating specific capacity Ratio 1, a value which should always be less than 1.0.

Interestingly, the Farvolden method did not tend to over-predict Q_{20} in lower-yielding wells with large available drawdowns, represented in this study by the three fractured bedrock aquifer wells. It is believed that this is because in such wells, the early time drawdown is dominated by casing storage effects and as pumping continues, the rate of drawdown usually increases.

The Moell method or the modified Moell method as proposed by Maathuis and van der Kamp (2006) appears to produce reasonable Q_{20} values with specific capacity ratios that support the validity of the results.

Both the Farvolden and the Moell methods are fairly sensitive to adjustments in the default safety factor of 0.7. The sensitivity analysis showed that it is not likely necessary to alter this factor by any more than 0.1 in specific situations. For pumping tests that are long enough to determine the appropriate analytical conceptual model but not long enough to ascertain the long-term drawdown pattern, detailed analysis as suggested by Maathuis and van der Kamp (2006) may be warranted.

The temporal sensitivity to a LTWC value, as calculated by the Q_{20} methods to other assumed pumping durations, such as 2 years or 200 years, is directly related to the aquifer transmissivity and the drawdown behaviour as represented by the specific capacity ratio. Since it is easy to calculate a Q_2 and a Q_{200} value and a Ratio 1 or 2 from any Q_{20} pumping test analysis, this is likely to prove insightful in many cases.

The sensitivity analysis also showed that the effect of increasing or decreasing pumping time by an order of magnitude, in most cases, had a similar effect on the resulting Q_{20} value as changing the safety factor by 0.1 (usually about 15%), except for wells with a high Ratio 1 or 2 value, which tend to have Q_{20} values that are more sensitive to changes in the safety factor.

7.2 FINDINGS ON THE Q_{100d} METHOD C (CPCN)

The CPCN method appears to be a reliable tool in examining long-term well capacity. Other than the pumping time, the main difference between this method and the Q_{20} methods is the assumption that recharge occurs annually, and that the late-time drawdown trend (if it plots on a straight line on a semi-log graph) should be used to predict the 100-day drawdown value. The Q_{20} methods do not specify which portion of a pumping test drawdown curve should be used. When the conceptual hydrogeologic model is consistent with the observed drawdown behaviour, for example, well UC2 which exhibited the effects of a probable linear no-flow boundary during the pumping test, then it is appropriate to use the late time drawdown trend. In the case of UC2, this resulted in a more conservative Q_{100d} and Q_{20} estimate.

The Q_{100d} is a more practical method to assess long-term well capacity for wells that are not likely to be pumped on a near continuous basis for more than a few months, such as irrigation wells, or other water supply wells used seasonally.

Like the Q_{20} methods, the CPCN method shows fairly consistent sensitivity to order of magnitude changes in pumping time or a 0.1 adjustment in safety factor and as with the Q_{20} methods, the CPCN method appears to show roughly the same sensitivity to a one order of magnitude change in pumping time as a 0.1 change in the safety factor.

7.3 IMPLICATIONS FOR GROUNDWATER MANAGEMENT

The hypothesis that the three promising but under-utilized methods for estimating LTWC are viable for broader application was confirmed by the results of the study. The comparative analysis showed the relative strengths and weaknesses of the three methods, and the sensitivity of the methods to changes in variables, thus supporting the second part of the hypothesis. The following sections summarize the key relationships between individual well capacity and implications for aquifer capacity studies and groundwater management.

7.3.1 Municipal and other semi-continuously used wells

For municipal wells, which typically operate year-round if they are primary water sources for a water system, it is advisable to consider the future-projected Q_{20} value determined with Method B or a modified Method B, for the water supply must be available year-round (even if water demand is higher in summer). If 20 years is too long of a time horizon for planning, the pumping time may be easily adjusted either by an order of magnitude to 2 years or some intermediate value that may be determined mathematically or by plotting Q_2, Q_{20} and Q_{200} on a graph and interpolating. For well fields and situations where groundwater use is intensive there may be issues of well interference and/or streamflow capture to consider. Further assessment beyond the capability of a long-term well capacity analysis is indicated for such cases, which may involve increased monitoring of groundwater and surface water, pumping tests, detailed water budget analysis, and groundwater flow modeling.

7.3.2 Irrigation and other seasonally used wells

The irrigation season varies according to climate and weather patterns and the crops being irrigated, but is typically part of a year. For irrigation wells or any seasonally used groundwater source, a Q_{100d} value may be more applicable for determining the annual long-term well capacity; but this value must be updated and corrected if the situation changes, such as increased well development or groundwater level decline.

Well interference may be accounted for in most situations by reducing the H_A value by the amount of interference expected. If well interference represents a significant percentage of saturated thickness in an unconfined aquifer, further analysis on the effect of reduced transmissivity may be warranted. Any further uncertainties may be addressed by either reducing the safety factor by 0.1 or extending the pumping time by one order of magnitude.

7.3.3 Wells in groundwater decline situations based on the Ogallala case

The current and future yield of Kansas High Plains (Ogallala) aquifer wells (or any well located in an area with documented groundwater decline) may be reasonably well-predicted using either the Q_{100d} or Q_{20} methods, provided that sufficient data exist to constrain the bulk K value of the aquifer, which would ideally be from a previous or recent pumping test, and a record of groundwater levels is available for the area of interest. The drawdown behavior under current and future conditions can be predicted using relatively simple techniques such as the USGS confined prediction spreadsheet tool illustrated in Chapter 6.6.

The irrigation season in western Kansas typically ranges from 90 to 110 days for crops such as sunflower, corn, grain sorghum and soybeans (Lamm et al. 2006). Therefore, for Ogallala irrigation wells, a Q_{100d} value is considered applicable for determining the annual long-term well capacity; but this value must be updated and corrected frequently if there is a continuing decline or if the pattern of decline changes. Recall that a key assumption in the Method C (CPCN) is that recharge occurs after 100 days, which is not the case with the over-subscribed Ogallala system.

Municipal wells that have never been subjected to a controlled pumping test should be tested if information on the long-term water supply is needed for planning purposes. If done, this testing should be combined with a downhole flowmeter (spinner) survey so that the actual production through the well screen or open interval may be measured and compared to lithologic logs, thus enabling an integration of the PST method of Macfarlane et al. (2005) with site-specific well data.

As the Ogallala system continues to lose saturated thickness, sustaining or increasing municipal pumping rates could require ever larger areas of the aquifer to be reserved for municipal production and other high priority groundwater uses, because the net output per well might decrease as saturated thickness and transmissivity values fall. The implication here is that in future more municipal wells may be needed not only to sustain population growth in urban or town centers, but also because the average yield per well will likely be lower than historic pumping rates.

7.4 OPPORTUNITIES FOR FURTHER RESEARCH

As Allen (1999) noted, coming up with an appropriate standard for the length of a pumping test is challenging. On the one hand, pumping tests are relatively costly and time-consuming procedures, and so there is a tendency in water management to rely on modeling using averaged or assumed aquifer hydraulic properties. On the other hand, as Butler (2009) noted, pumping tests are practically indispensable when the task is to assess well and aquifer hydraulic properties and assess groundwater supplies. Some of the well test data sets used in this analysis exhibited boundary effects during the test that had they gone undetected, could have led to either an over-estimation or an underestimation in LTWC. The two Ogallala aquifer wells assessed in this research underscore the highly variable nature of this aquifer system and how differently the effects of depletion might impact well production.

The author is aware of well tests that have encountered significant boundary conditions occurring ten days or more into a constant rate aquifer test. Much has been written on pumping test procedures, such as how to control and measure the flow rate, how often to record water levels, the use of observation wells, and so on, but relatively little consensus has emerged from the literature on pumping test duration, especially as it relates to the task of determining well capacity as opposed to estimating aquifer properties. Further research into the applicability and utility of longer-term pumping tests could provide insight into the relative value on the information provided by the data, versus what could be derived from extrapolation, assumptions, and modeling.

Another area for further research would be to expand the analysis presented here to include a broader spectrum of well and aquifer types, and development of a tool that could be used to rapidly estimate long-term well capacity and specific capacity ratios as a routine exercise in the analysis of any pumping test. Just as the calculation of transmissivity, storativity and specific capacity are part of the routine analysis of water well pumping tests, the same could be done to examine LTWC under both test conditions and assumed future conditions that may incorporate well interference, water level decline, or a decrease in well performance (specific capacity). Broader application of the LTWC methodologies has the potential to better inform water management decisions and is therefore recommended as a supplement and not as a replacement for existing methodologies such as modeling or water budget analysis. Within Kansas, the opportunity exists to re-assess historical pumping test data reportedly on file for numerous Ogallala wells as described in Table 3 of Hecox et al. (2002).

It is relatively easy to estimate LTWC values for virtually any well subjected to a pumping test. It is not known why quantitative methods to estimate “safe well yield” (LTWC) are not more widely applied. Such an approach should only improve the understanding that may be derived from traditional pumping test interpretation. Pumping test data from the time of original well construction are potentially relevant to present-day assessments of LTWC, provided that information on groundwater levels, well specific capacity, pump performance, and other pertinent data are available.

The evaluation of individual well long-term capacities is recommended when a water source is of particularly high value and there is a need to understand the long-term operational characteristics whether or not there is detailed water balance information on the aquifer system and its “safe” or “sustainable” yield. A Q_{20} analysis is probably best-suited to municipal wells or other sources used year-round on a perennial basis, while a Q_{100d} analysis may be better suited to irrigation wells or other wells used only seasonally (for example, wells used at resorts).

Further spreadsheet or software tools could be developed to enable prediction of Q_{20} or Q_{100d} using any analytical model, as recommended by Maathuis and van der Kamp (2006). Some of these models involve matching the observed data to one of a family of related drawdown curves. In the case of predicting long-term well capacity, the proper match must include a good-fit for the later time drawdown trend as this trend would likely need to be used in the Q_{20} or Q_{100d} calculation.

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