Aquifer test guidelines for the Greater Wellington region

Prepared for
Greater Wellington Regional Council

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Executive Summary

These guidelines have been prepared to provide guidance on how to design, perform and analyse pumping tests to provide a sufficiently high standard of information to support consent applications to take groundwater within the Wellington region.

Aquifer tests include single well tests, which are generally used to determine well performance, and tests with observation wells, which provide more information on the aquifer response to pumping than a single well test.

A well-performed constant discharge test using both a pumping well and observation wells can provide useful drawdown data from which information on hydrogeological parameters, such as transmissivity and storativity, and aquifer boundaries can be obtained. This information can then be used to assess environmental effects as part of a consent application to take groundwater, including interference on neighbouring wells, salt water intrusion and depletion effects on surface water ways.

These guidelines are intended to be used by groundwater consultants involved in designing, undertaking and analysing test data and by staff at Greater Wellington Regional Council (Greater Wellington) who are auditing applications accompanied by aquifer test information.

Key points for a successful test outcome are listed below together with the relevant sections of this report that provide further detail on these points:

- Timing the testing, where possible, to avoid effects from influences such as rainfall events and interference from neighbouring bores (section 5.1).
- Considering the aquifer type and potential boundaries in advance to ensure the test design will adequately capture the aquifer response (section 5.3).
- Estimating drawdown in advance, and carrying out trial pumping where possible, to determine ideal observation well locations and test duration (sections 5.2, 5.4 and 5.5).
- Measuring the pumping rate, water level in the observation wells, barometric pressure and any other required measurements with a sufficient accuracy and for a sufficient period pre- and post-test to adequately assess background fluctuations and to ensure that the recovery data can be used to constrain the analysis (section 6.0).
- Correcting the data for background fluctuations such as antecedent water level trends, barometric efficiency and tidal effects in order to isolate a drawdown response (section 7.0).
- Choosing an appropriate method for the analysis that is justifiable for the hydrogeological setting and aquifer response (section 8.0).
- Providing a comprehensive report on the aquifer test and analysis and on any longer term extrapolations based on the data, including full details of and justification for calculations and all assumptions (section 9.0).

Glossary

The response of a groundwater system to recharge and discharge is governed by two key controls: the storage capacity of the system and the rate at which the strata allow water to move. These key parameters related to these two controls are the *storage coefficient* and *hydraulic conductivity*.

This glossary sets-out the terms related to storage and hydraulic conductivity used in these guidelines. Units are provided in terms of length (L) and time (T).

Hydraulic head terms

The **Hydraulic head (symbol h; L**) is the total energy of the water per unit weight of the water. This is also referred to as the piezometric head. For groundwater, it is the height of water in a well relative to a certain datum.
The **Hydraulic gradient (symbol i; L/L)** is a measure of the change in hydraulic head (**h**) within saturated strata over a given distance (**L**). As the change in hydraulic gradient increases within a groundwater system, so do the groundwater velocities.

Hydraulic conductivity terms

The **Hydraulic conductivity (symbol K; L/T)** of a medium is a constant of proportionality between the specific discharge of a fluid through the saturated medium and the hydraulic gradient. It describes the rate at which the strata allow water to move. **Darcy's equation** (Darcy, 1986) is an empirical relationship that describes how the velocity (**v**) of groundwater through a saturated medium is proportional to the hydraulic gradient (driving force) and the hydraulic conductivity of the strata.
The term **Transmissivity (symbol T; L^2/T)** is defined as the product of the horizontal hydraulic conductivity of an aquifer (**K**) and its saturated thickness (**B**). Transmissivity is one of the parameters typically interpreted through the analysis of pumping tests.
The term **Aquitard conductance (symbol K'/B'; T^{-1})** is defined as the ratio of an aquitard's vertical hydraulic conductivity (symbol **K'**) to the saturated thickness of the aquitard (symbol **B'**). This term indicates how rapidly groundwater can flow vertically through an aquitard, under a unit vertical hydraulic gradient across the aquitard.
The term **Effective aquitard conductance (symbol $(K'/B')_{effective}$; T^{-1})** is a widely applicable term. In most geologic systems, there is more than a single geologic unit with a contrasting permeability to the pumped aquifer between the pumped aquifer and the water table. The effective aquitard conductance incorporates the effects of a number of geologic units. For most aquifer tests where vertical flow is observed, the parameter obtained through the analysis is actually the effective aquitard conductance rather than the aquitard conductance, as usually there are a number of different strata between the pumped aquifer and the water table

The term **Streambed conductance (symbol λ,; L/T)** is defined as the ratio of streambed hydraulic conductivity (symbol **K''**) to the streambed thickness (symbol **B''**), multiplied by the streambed width **(b)**. This term indicates how rapidly groundwater can move through a streambed.

Storage parameters

The total volume of groundwater contained within a groundwater system is the amount of water contained within all the pore spaces of all the saturated strata. The following terms describe how much water is released from storage when there is a reduction in actual water level or groundwater pressure.

The **Specific yield (symbol S_y, dimensionless)** is the proportion of drainable pore space of a material. In a geologic formation that contains a water table, such as an unconfined aquifer or aquitard, water is released from storage as a result of physical drainage of the pore spaces at the water table. The volume of water that is released from storage per unit surface area under a unit decline in head in an unconfined aquifer is equivalent to the specific yield. The specific yield is typically less than the total porosity of a material, because when piezometric heads decline, not all of the water stored within the pore spaces at the water table will be released.

The **Specific storage (symbol S_s; m^{-1})** of confined and semi-confined aquifers is the volume of water that is released from elastic storage per unit volume of the geologic formation under a unit decline in head. In a semi-confined aquifer, if the head in the aquifer is always above the base of the overlying aquitard there can be no physical drainage of the aquifer pore spaces. Therefore, the volume of water released from the pumped aquifer itself is only that which is released via the expansion of the water and compression of the aquifer strata as heads fall (elastic storage).

The associated **Elastic storage coefficient (symbol S, dimensionless),** or storativity, is the volume of water that is released from storage per unit surface area under a unit decline in head due to compression of the strata and expansion of the water (with no physical drainage of the pore space). For a particular confined or semi-confined aquifer, this is equivalent to the specific storage multiplied by the thickness of the formation.

Lough and Williams (2009) provide details of the equations used to obtain these terms.

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1.0 Introduction

1.1 Scope

These guidelines have been prepared to provide guidance on how to design, perform and analyse pumping tests to provide a sufficiently high standard of information to support consent applications to take groundwater within the Wellington Region.

They are intended to be used by groundwater consultants involved in designing, undertaking and analysing test data and by Greater Wellington Regional Council staff auditing applications that are accompanied by aquifer test information.

1.2 Purpose of aquifer testing

Aquifer tests can provide valuable information on a groundwater resource. In addition to determining well performance, they enable more precise modelling of the potential environmental effects of a groundwater abstraction, such as well interference and stream depletion effects.

It is important to target the design of the test to the desired outcome. For example, if the testing is carried out solely to determine well performance, a step-test will suffice, whereas if the testing is performed to determine stream depletion effects, a long-duration constant discharge test with observation wells might be required.

1.3 Aquifer test type

Aquifer tests include single well tests, which are generally used to determine well performance, and tests with observation wells, which provide more information on the aquifer response to pumping than a single well test.

A single well test (Section 8.2), such as a step-drawdown test, is short, relatively simple and relatively inexpensive to conduct. However, a single well test is not as useful as a test with observation wells because storage coefficients cannot be determined and it is difficult to precisely isolate the drawdown due to aquifer losses from that caused by frictional and turbulent well losses.

A well-performed constant discharge test using both a pumping well and observation wells (Section 8.1) can provide useful drawdown data from which information on hydrogeological parameters such as transmissivity and storativity and aquifer boundaries can be obtained. This information can then be used to predict effects such as interference on neighbouring wells, salt water intrusion and depletion effects on surface water ways.

The advice in this report is focused on constant discharge tests.

1.4 Structure

The report is structured as follows:

- An overview of the of the geology and groundwater of the Wellington region is provided;
- Greater Wellington Planning Documents relevant to aquifer testing are outlined;
- Groundwater hydraulics and terminology relevant to this report are detailed;
- Guidance on the design of aquifer tests is provided;
- Important measurements during aquifer testing are detailed;
- Advice on the analysis of aquifer testing is provided;
- Reporting requirements are outlined.

2.0 Overview of the geology and groundwater of the Wellington region

There are three main groundwater resources in the Wellington region. These are located in the Lower Hutt Valley, the Kapiti Coast and the Wairarapa Valley. Smaller groundwater resources occur in Upper Hutt, the Mangaroa Valley, the Wainuiomata Valley and sections of the eastern Wairarapa coastline. Aquifers in all of these areas exist within unconsolidated alluvial, aeolian, and beach sediments of varying grain size (Jones and Baker, 2005). Smaller aquifers are also found in limestone and fractured greywacke in some areas of the Region. The three main groundwater resources are described in the following sections of this report.

Groundwater management zones have been defined for most groundwater resources in Greater Wellington's Regional Freshwater Plan (WRC 1999, Figure 1).

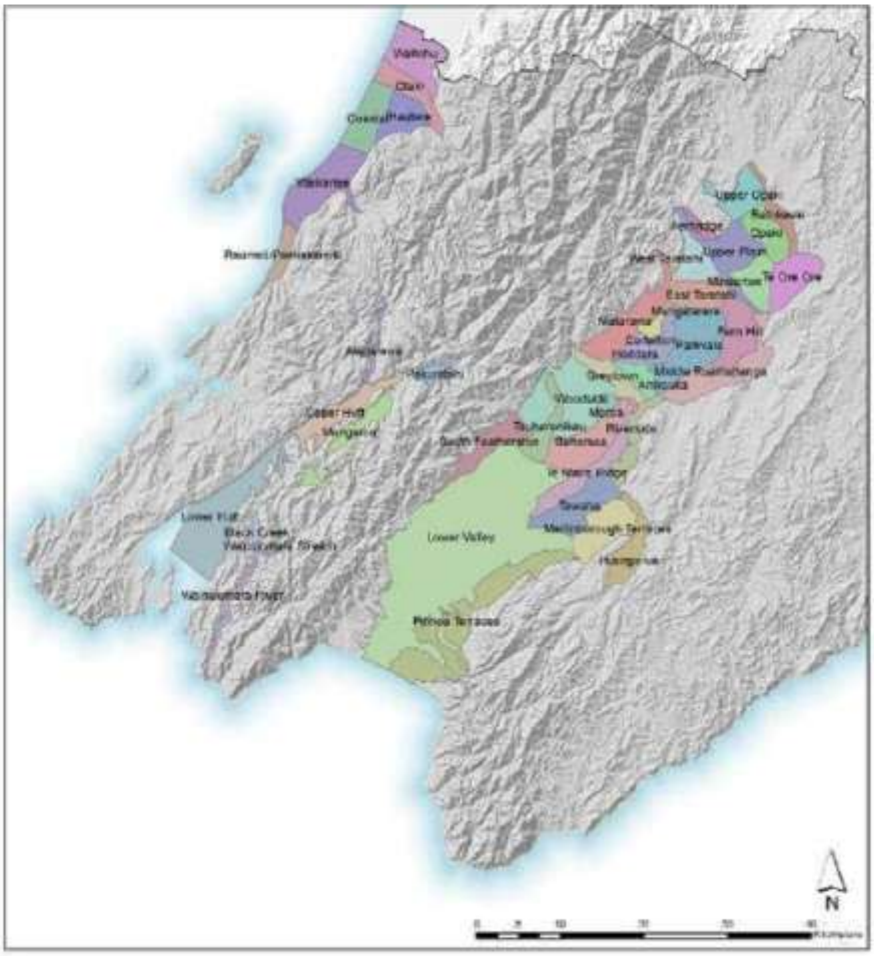

Figure 1: Groundwater management zones in the Wellington Region (WRC, 1999). NB: The boundaries and labels for some zones have been updated.

2.1 Lower Hutt Valley groundwater

As described in Jones and Baker (2005), the Lower Hutt basin is bounded by the Wellington fault to the west and basement rock to the east. The basin has formed as a result of movement on the fault, and folding to the east of the fault, over the last million years. The basin has been in-filled with sediment over the course of its evolution. The thickness of sediment varies from a few metres at Taita Gorge, to over 600m at Kaiwharawhara.

The basin sediments are predominantly gravel, sand and silt sourced from the southern Tararua Range and deposited by the Hutt River. This alluvial material is separated by less permeable fine-grained marine sediments. The marine sediments have been deposited during interglacial periods over the last 350,000 years, when sea levels were higher and extend inland as far as Avalon.

Aquifers exist within the alluvially deposited gravels and are distinctly separated by aquitards formed by beds of the fine-grained marine sediments. The shallowest aquifer is confined by a surface layer of fine-grained marine sediments at the coast, but becomes unconfined north of Avalon. The shallow aquifer is recharged predominantly by losses through the bed of the Hutt River. Rainfall recharge is only a minor component of the water balance.

The shallowest aquifer, known as the Upper Waiwhetu Aquifer, is the main aquifer targeted for abstractions, and is highly productive with high transmissivity values. It is well connected to the Hutt River. Deeper units referred to as the Lower Waiwhetu Aquifer and the Moera Gravel aquifer are less productive with lower transmissivity values.

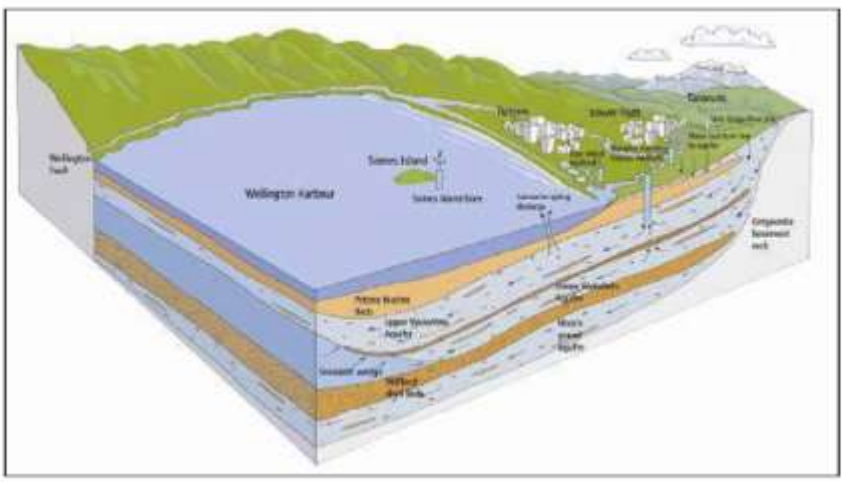

Figure 2: Conceptual model of the Lower Hutt groundwater system

2.2 Kapiti Coast groundwater

The Kapiti Coast is a narrow coastal plain on the western side of the Tararua Range that is located at the south-eastern margin of the South Wanganui Basin (the groundwater resources in the majority of this basin are controlled by Horizons District Council).

As in Lower Hutt, the present day landforms and subsurface depositional sequence are a function of relative sea level change caused by tectonic movement and sea level changes during the Quaternary Period. Tectonic movement has caused uplift of the Tararua Range and subsidence of the South Wanganui Basin. Global climate change has resulted in cycles of sea level change of many tens of metres.

Erosion in the Tararua Range and the subsequent deposition of thick layers of alluvial gravel, sand and silt occurred during cooler climatic periods. During warmer inter-glacial periods, sea level rose and deposited beach and marine sediments over earlier alluvial material over large parts of the coastal plain. Aquifers along the Kapiti Coast occur within the glacial and inter-glacial deposits, the post-glacial beach and dune sand deposits and in the recent river gravels.

The thick sequence of glacial and inter-glacial deposits forms the deeper aquifer system along the length of the coast. Stratification within this system and the overlying strata provide semi-confinement to the aquifers that exist within it.

The overlying post-glacial sand deposits form a wedge shaped aquifer system which thins inland and terminates at an inland sea-cliff marking the maximum extent of the last sea level rise. This aquifer system within these sand deposits is unconfined although it may produce a semi-confined response due to pumping at depth towards the coast due to stratification. Rainfall is the dominant recharge mechanism.

The recent river gravels are gravels that have been reworked by waterways including the Waikanae River, Otaki River and the Waitohu Stream. These gravels form high yielding unconfined aquifers that are in direct hydraulic connection with surface water.

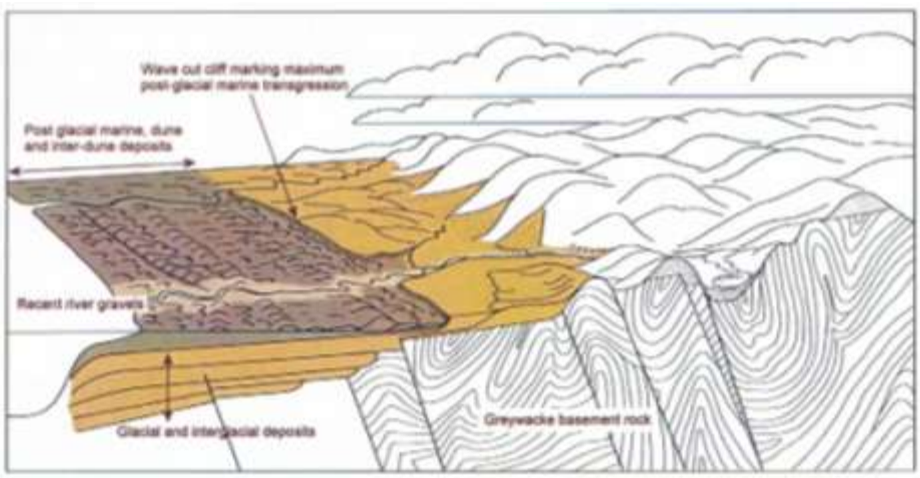

Figure 3: Schematic of Kapiti Coast system (from Jones and Gyopari, 2005)

2.3 Wairarapa groundwater

The Wairarapa Valley is a fore-arc basin bound to the west by Mesozoic greywacke basement along the Wairarapa Fault and to the east by Tertiary/early Pleistocene mostly mudstone marine deposits that form the eastern hill country.

The rivers draining the Tararua Range have filled the valley with coalescing fans of gravel, sand and silt over the last 800,000 years (Jones and Baker, 2005). Folding and faulting during that time has shifted these fluvial deposits and uplifted basement in parts of the valley. The fluvial deposits are variable in thickness, up to 150 m thick in the Lake Wairarapa basin but typically less than 50 m thick across the remainder of the valley. In the lower part of the basin, lacustrine and estuarine sediments have been deposited between the alluvial deposits. These layers of fine-grained sediments form aquitards that separate the aquifers contained within the alluvial gravels.

Aquifers in the Wairarapa exist within alluvial fan and sub-basin deposits, recent river gravels and the stratified lower valley deposits.

The alluvial fans deposited by the major rivers consist of poorly sorted gravel with a significant sand and silt content that form moderate to low permeability stratified aquifer systems across much of the western side of the Wairarapa Valley. The sub-basins contain moderately permeable water bearing gravel units interspersed with lower permeability sand and silt deposits forming a sequence of semi-confined aquifers (Hughes and Gyopari, 2011).

The recent river gravels occur alongside the large rivers within the valley and form highly productive unconfined aquifers. These aquifers are in direct connection with surface water.

The stratified lower valley deposits comprise sand and gravel layers that form productive confined aquifers and are separated by fine grained marine sediments.

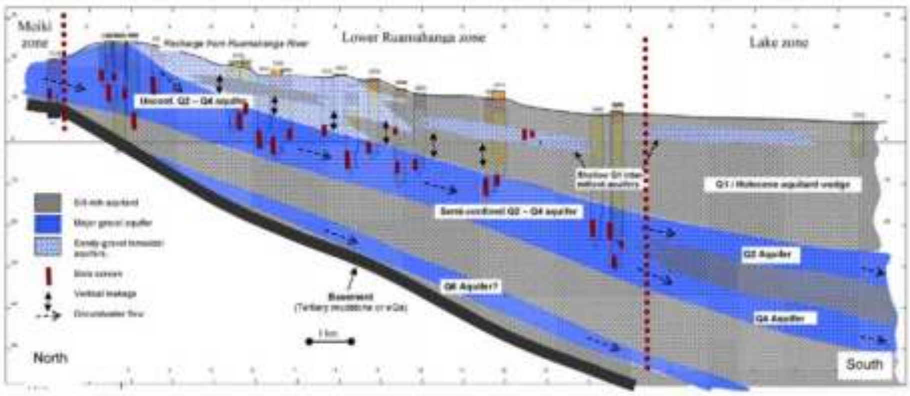

Figure 4: Lower Wairarapa Valley schematic section along axis of Ruamahanga Valley (Hughes and Gyopari, 2011)

3.0 Relevant Greater Wellington planning objectives, rules and polices

3.1 Regional Policy Statement and Proposed Regional Policy Statement

The Operative Regional Policy Statement (RPS) outlines the resource management issues of significance to the region and provides a framework for managing the natural and physical resources of the region in a sustainable manner. It identifies objectives, policies and methods which are designed to achieve integrated management of the natural and physical resources of the whole region.

The RPS will ultimately be superseded by Greater Wellington's Proposed RPS. At the time of writing these guidelines, the proposed RPS was at the stage where appeals on the various sections of the Proposed RPS had been received and will be worked through before it can be made operative.

While there are a number of objectives and policies in the Operative and Proposed Regional Policy Statements related to groundwater, such as groundwater allocation, there are no specific policies on aquifer testing. However, the information obtained from aquifer testing will assist in achieving these objectives.

3.2 Regional Freshwater Plan

The Regional Freshwater Plan (RFP) contains objectives, policies and rules seeking to avoid, remedy or mitigate the potential adverse effects of the use and development of water bodies.

Policy 6.2.3 is to manage the aquifers in each groundwater zone using the safe yield determined for each zone and to maintain discretion over the allocation of aquifers not identified in the RFP. In the explanation for this policy it is stated that different parts of an aquifer often have variable yield capabilities. For this reason all wells will need to be pump tested to provide detailed "at site" information on the sustainable abstraction rate and to ensure that adverse effects on existing users or on surface waters are identified.

Policy 6.2.8 sets out that permits to take groundwater must consider excessive reductions in the yields of nearby wells and avoid significant adverse effects on surface water bodies. In the explanation for this policy it is stated that *"In most cases the consent authority will require pump tests to be undertaken and may put conditions on any subsequent water permit as a result of these tests."*

Groundwater takes are included in Rule 16, which relates to the taking, use, damming or diversion of water, or the transfer to another site of any water permit to take or use water. Section 6.4.2 of the plan sets out the information that must be submitted with a consent application to take water under this rule and this includes, for groundwater abstractions, a description and the results of any pump or other tests which have been undertaken.

3.3 Proposed framework for conjunctive water management

Hughes and Gyopari (2011) prepared a Greater Wellington report recommending a method of groundwater allocation for the Wairarapa Valley that is based on conjunctive groundwater-surface water management. Greater Wellington is planning to adopt the recommended method. Work is currently underway to apply the same methodology and thresholds to the management of groundwater resources in other parts of the Wellington Region including the Kapiti Coast and the Hutt Valley.

There are two key components to the method:

1. Management of groundwater abstractions that have a direct or immediate effect on the surface water environment through application of pumping controls based on minimum flows established for hydraulically connected surface waters.

2. Establishment of fixed allocation volumes for individual groundwater management units that recognise that groundwater abstraction may cumulatively cause a reduction in river or stream baseflow. These allocation limits will apply where groundwater abstraction does not result in an immediate or direct streamflow depletion effect.

The method proposed involves classifying groundwater abstractions into one of three categories, depending on how rapidly the abstraction results in surface water depletion. These are detailed in the following sections.

3.3.1 Category A: Direct hydraulic connectivity

Category A covers abstractions in areas where stream depletion effects develop rapidly with pumping to a level close to the pumping rate and decrease rapidly once pumping ceases. Because of the similarity of these abstractions to direct surface water abstractions, it is recommended that they be managed in an equivalent manner.

As proposed, Category A includes all abstractions requiring resource consents within the recent river gravels, which are shallow and typically very permeable, along the riparian margins of the main river systems.

It is recommended that the weekly average abstraction rate rather than peak pumping rate be included in the surface water allocation block, which recognises that there is a time lag between the abstraction and the stream depletion effect.

Given the Category A classification, no stream depletion assessment is required, but technical assessments may be required for well interference, in which case an aquifer test may need to be carried out to obtain the relevant parameters.

3.3.2 Category B: High hydraulic connectivity

Category B covers abstractions in areas where induced surface depletion effects develop more slowly than for Category A, so pumping restrictions based on flows in the affected waterway may not be the best management option.

As proposed, Category B abstractions are to be managed either in terms of surface water or groundwater allocation depending on local factors such as hydrogeological parameters, abstraction rates, abstraction depth and distance to surface waterways.

It is recommended that Category B include all abstractions located along the margins of Category A areas and in those areas of the alluvial fan systems where hydraulically connected surface water bodies such as spring-fed streams, seeps and wetlands are present.

The Category B classification allows the stream depletion effects to be assessed for each specific site as part of the resource consent process. The report states that this will require development of a conceptual model of the hydrogeological setting based on results of aquifer testing on the proposed well. Therefore, it is expected that aquifer testing be carried out for all Category B groundwater abstractions.

As Category B abstractions will have a depletion effect that develops more slowly than Category A abstractions, it is proposed that abstractions with a weekly average abstraction rate less than a proposed minimum rate of 5 L/s be managed solely as groundwater takes. Abstractions above this threshold are to be assessed in terms of their hydraulic connection and volumetric assessment criteria.

The hydraulic connection and volumetric assessment criteria for these Category B abstractions is that they shall be subject to pumping restrictions based on minimum flows and water levels in the associated surface waterway where the stream depletion effect is either more than 60% of the average pumping rate over 150 days or more than 10 L/s. For the takes above the threshold, the stream depletion effect is to be included in the surface water allocation block.

Section 8.1.6 of these guidelines provides guidance on aquifer testing to enable stream depletion assessments for Category B abstractions.

3.3.3 Category C: Moderate to low hydraulic connectivity

Category C covers abstractions in areas where groundwater abstraction may contribute to an overall depletion in surface flow, possibly across a number of waterways, but the effects develop over a long time scale such that pumping restrictions based on flows in the affected waterway(s) are not an effective mitigation measure. It is recommended that these takes be managed at a catchment or sub-catchment scale through the establishment of volumetric abstraction limits.

4.0 Groundwater hydraulics and terminology relevant to this report

This section presents and explains the terminology relevant to these guidelines. Please refer to the glossary on page ii of these guidelines for further details of these terms.

The changes in head that occur within a groundwater system in response to recharge and discharge, including groundwater pumping, are governed by two key controls: the storage capacity of the groundwater system and the rate at which the strata allow water to move.

The *storativity* of the medium describes how much water can be stored within it. Groundwater is stored within the pores of a saturated medium, for example, in the voids between the individual particles of gravel within an aquifer. Depending on the aquifer type, changes in the volume of stored water occur by changes in the saturation of the pore spaces and, to a very much lesser degree, compression or expansion of the water and aquifer medium.

The *hydraulic conductivity* of the medium controls the velocity at which groundwater moves under a specific hydraulic gradient. Under the same hydraulic gradient, water will move through sands and gravels much more rapidly than it could move through materials such as silt or clay, as the sands and gravels have larger connected pores i.e. a higher hydraulic conductivity.

Geologic units that are permeable enough to yield useful quantities of water are usually referred to as *aquifers*. Intervening units of lower permeability that restrict the movement of water to aquifers are often referred to as *aquitards*. An *aquiclude* is a geologic unit which may contain quantities of water, but does not transmit water. Kruseman and de Ridder (1991) provide examples of dense un-fractured igneous or metamorphic rocks as typical aquicludes but point out, that in nature, truly impermeable geological units seldom occur; all of them can transmit water to some extent. The definitions are relative to the surrounding material. In aquifer tests, the definitions are useful for building a conceptual model of a system but it is the physical properties of the strata which are relevant for aquifer test analysis.

Confining material is saturated material bounding an aquifer that has a lower permeability than the aquifer. This material restricts the rate of flow into and out of the aquifer. The confining material may be an aquitard or a series of aquitards. Where an aquifer is not overlain by any confining material, it is classed as an *unconfined aquifer*. Where confining strata overlie an aquifer, the rate of vertical flow into and out of the aquifer through the less permeable material is controlled by the hydraulic conductivity of this confining material. This type of aquifer is referred to as a *semi-confined aquifer* or, alternatively a leaky aquifer or leaky confined aquifer. Groundwater abstraction from a *semi-confined aquifer* produces a different piezometric response than in an unconfined aquifer, due to the restriction on vertical flow. Aquifers are sometimes referred to as a *confined aquifer*, which is the opposite end of the spectrum from an unconfined aquifer. In reality, there are very few aquifers that can be considered completely confined as vertical flow through the overlying deposits will change with prolonged pumping. However, an aquifer may appear to behave as fully confined over the short duration of a constant discharge test. Lough and Williams (2009) provide more detail on these definitions.

Figure 5 shows schematic examples of these three aquifer types and the sources of water to a pumping well. Figure 6 illustrates different types of semi-confined aquifers.

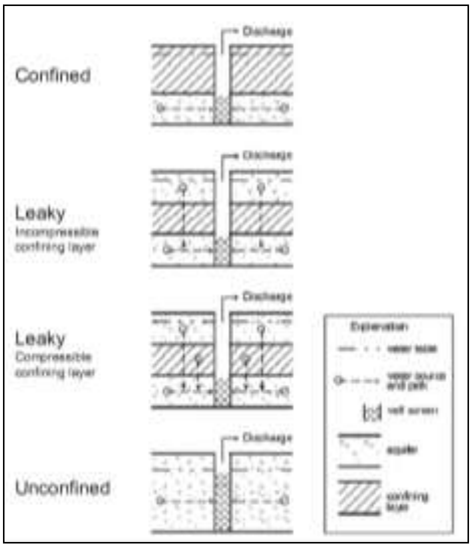

Figure 5: Aquifer types and sources of water (from Brooks (1998))

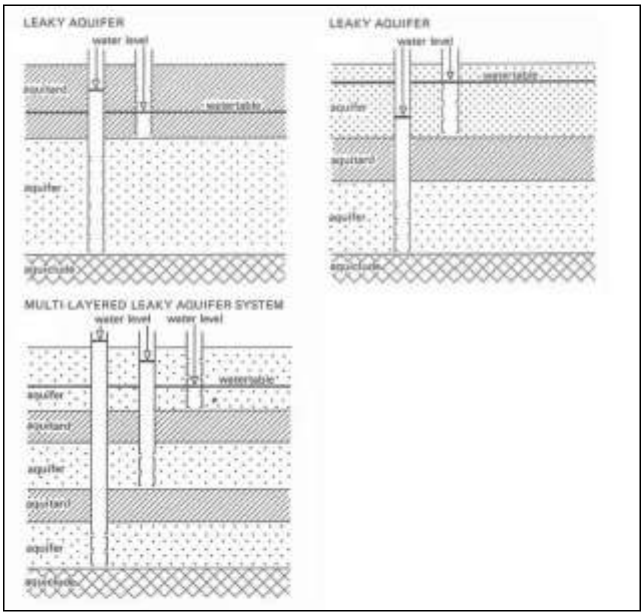

Figure 6: Semi-confined (leaky) aquifers (from Kruseman and de Ridder (1991))

Where all physical properties are the same throughout a geologic unit it is described as *homogeneous*. Conversely, if the physical properties vary at different locations within a geologic unit it is described as *heterogeneous*.

Where the hydraulic conductivity of an aquifer is the same in all directions at a single point, the aquifer is described as *isotropic.* Conversely, where the hydraulic conductivity changes with direction, it is *anisotropic*. Alluvial depositional processes tend to result in material that has a much higher hydraulic conductivity in the horizontal direction than vertical, so are classified as *vertically anisotropic*.

Homogeneity and isotropy are both scale-dependent. The homogeneity of a material is judged by comparing the length scale of the feature of interest. A poorly sorted gravel aquifer that has a range of particle sizes may be considered as being heterogeneous over a small scale but homogenous over a large scale. Where there are a number of sedimentary layers, each possessing a different hydraulic conductivity, on a sufficiently large scale, the number of layers could be grouped together and classed as a single anisotropic unit. Further details of the relationship between layer conductivities, layer thicknesses and the overall anisotropy of hydraulic conductivity are described by equations 2.31 and 2.32 in Freeze and Cherry (1979).

5.0 Designing aquifer tests

The design of an aquifer test should be carefully prepared prior to the testing and must be targeted to the purpose of the test and the hydrogeological conditions present at the test site. These two factors dictate test details such as well location, number of wells, well depth, pumping rate and test duration.

This section of the report provides recommendations on the test design. It might not be practical to implement all these recommendations at every test site or it might not be necessary for the particular objectives of the test.

The test design should identify the equipment and preparation required. The likely range in aquifer responses that may be observed should be considered to ensure the test details are appropriate. Checklists for an aquifer test design plan are included in Appendix A. Specific details to consider in the test design are summarised in Table 1 and elaborated on in the following sections of this report.

If the testing is being carried out to provide information for a consent application, it is recommended that a plan of the test design be submitted to Greater Wellington for review by a groundwater scientist to maximise the chance of the data obtained from the test meeting Council requirements. It should be noted that any prior advice the Council provides will not constitute acceptance of test results. The test design should primarily address the purpose of the test, the rationale for the test design, well screen depths and well location and the estimated drawdown in the observation wells.

Table 1: Specific details to consider in aquifer test design

Details to consider	Explanation
Timing of testing	In rural areas, aquifer tests are best undertaken outside the irrigation season when large scale pumping interference from neighbouring wells is less likely. Where practical, steps should be taken to prevent neighbouring wells from being pumped during a test. If this is not possible, the pumping rate and time of pumping of these wells should be accurately recorded so it can be accounted for in the analysis.
Hydrogeological conditions	The aquifer type and potential boundaries should be considered to ensure the test design will adequately capture the aquifer response.
Location and depth of observation wells	The optimum location and depth for observation wells can be estimated by considering the likely drawdown response. Consideration of the method to be used for analysis should also be made, for example, to ensure the well depth and location will meet assumptions on horizontal flow contained in analytical methods.
Test duration	A test must be sufficiently long to capture the desired hydrogeological information. For semi-confined or anisotropic aquifers, the test should continue until the full characteristic drawdown response is observed, where this duration is practical. However, longer duration tests may experience larger background fluctuations due to atmospheric influences, neighbouring wells pumping and other external influences, which can complicate the analysis.
Discharge method	The pumped water must be discharged at a sufficient distance and manner such that recharge to the aquifer will not occur, unless this can be accurately accounted for in the analysis. The environmental effects of the discharge, such as flooding and erosion, must be considered.
Data measurement method and duration	The methods of measuring pumping rate, water level in the observation wells and barometric pressure must ensure the collected data have a sufficient accuracy. Additional measurement of other influences such as tidal effects and stream flow may be required in some cases. It is very important that a sufficient period of pre- and post-test monitoring is carried out to ensure the aquifer recovery can be used to constrain the analysis and to adequately infer background trends.

5.1 Timing of testing

An aquifer test should ideally be conducted when there is minimal background interference in the water level data being collected. Water levels can be affected by sources including pumping from other wells, atmospheric changes and rainfall events. Where possible, testing should be planned for stable atmospheric conditions, preferably outside of the irrigation season. In some circumstances background pumping cannot be avoided, but will need to be accounted for in the analysis and can result in additional potential error.

If neighbouring well owners cannot interrupt their pumping schedules, one option is to request they start pumping several hours before the test pumping is started and continue pumping until after the test pumping is stopped. This is not practical for multi-day tests so an alternative is to measure and record the flow rates and pumping times for neighbouring wells. These can then be corrected for or included in the final aquifer test analysis.

5.2 Aquifer test trial

For pumping tests with observation wells, an aquifer test trial is highly recommended to establish whether a drawdown response is observable in the observation wells and to resolve any recording difficulties. This trial can be as simple as a step-drawdown test to determine an appropriate pumping rate for the subsequent constant discharge test.

The trial can be of short duration (several hours only). Observations of drawdown in the pumping and observation wells should be made. The absence of any drawdown may lead to a re-evaluation of the suitability of the aquifer test design and layout of observation wells to meet the aims of the test. It is recommended that the aquifer test proper should not commence until the observation wells and pumped well have recovered to at least 95% of the initial depth to water, and preferably longer. If full recovery has not occurred, then superposition of the well pumping may be required in the analysis.

5.3 Hydrogeological conditions

5.3.1 Aquifer type

The aquifer type and potential boundaries should be considered to ensure the test design will adequately capture the aquifer response.

As outlined in section 4.0, aquifers are generally classed into one of three categories types: unconfined, semi-confined and confined, although there are very few aquifers that can be considered completely confined. This is because vertical flow through the overlying deposits will change with prolonged pumping. However, an aquifer may appear to behave as fully confined over the short duration of a constant discharge test.

Figure 7 shows the characteristic time-drawdown response on a semi-log scale for an unconfined aquifer. Figure 8 shows the characteristic time-drawdown response on a semi-log scale for a semi-confined aquifer. An unconfined aquifer may produce a semi-confined response where the vertical hydraulic conductivity is lower than the horizontal hydraulic conductivity (it is vertically anisotropic) or if the well screen is located some depth below the water table. It is also worth noting that a semi-confined aquifer overlain by multiple layers can be considered to be a vertically anisotropic unconfined aquifer on a large scale. Essentially, in a groundwater system where there is greater resistance to vertical flow than horizontal, or the well screen is a sufficient depth below the water table, the drawdown response will have the characteristic shape of the semi-confined curve in Figure 8. Further information on the response of semi-confined aquifers is described in Lough and Williams (2009).

For constant discharge tests carried out in aquifers confined by low permeability deposits, the required duration to observe the characteristic flattening of the curve due to vertical leakage may be impractically long. In this case, the aquifer will appear to be fully confined. Despite this, it is possible to define through analysis maximum values for the parameters which control the leakage rate - aquitard conductance or vertical hydraulic conductivity. It is also possible to define a minimum value for the specific yield, which controls the point of departure from the pseudo steady-state section of the curve.

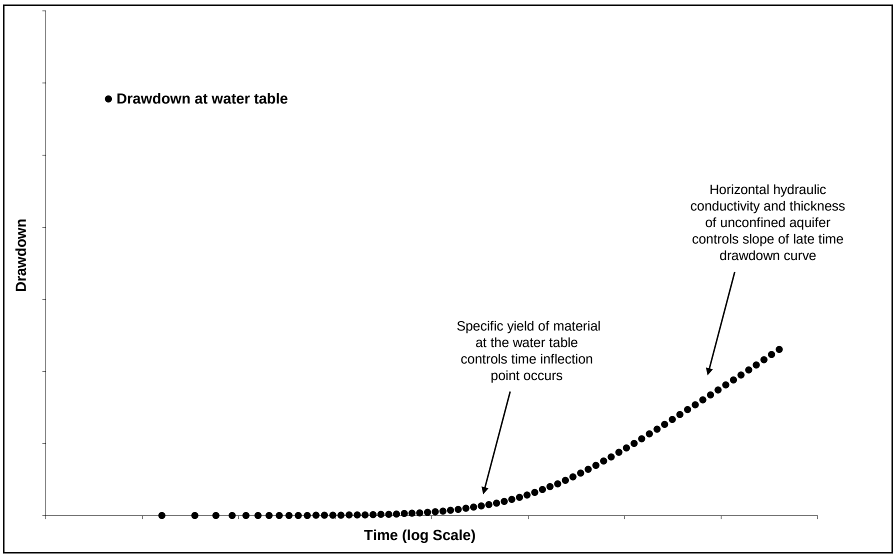

Figure 7: Drawdown sensitivity to hydrogeological parameters in a pumped unconfined aquifer

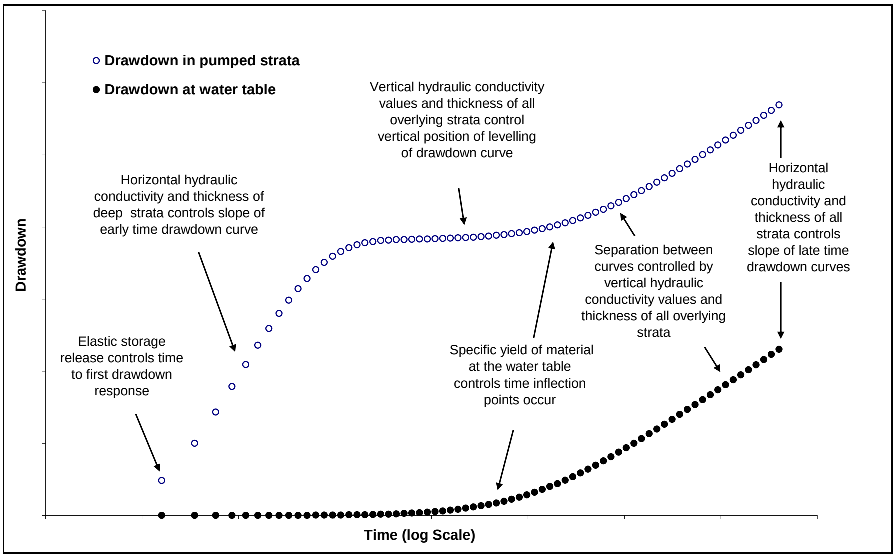

Figure 8: Drawdown sensitivity to hydrogeological parameters of a layered system with pumping from a semi-confined aquifer (from Lough and Williams (2009))

5.3.2 Hydrological boundaries

The presence of any hydrological boundaries must also be considered in test design and analysis. These include flow boundaries that exist due to geological constraints such as a laterally bounded alluvial aquifer in a valley floor or changes in hydraulic conductivity and strata type, due to geological faulting for example. These also include recharge and constant head boundaries such as streams, lakes and wetlands.

The presence of a no-flow boundary usually presents as a steepening of the slope of the time-drawdown curve on a semi-log scale, while the presence of a recharge boundary usually presents as a flattening of the slope of the drawdown curve.

It is important that, where such boundaries need to be defined for future predictions of the pumping effects, the aquifer test is carried out for long enough to capture these effects, where practicable.

Drawdown data from an aquifer test where no-flow boundaries have been encountered can be analysed using the principle of an image well, located equidistantly from the boundary as the pumped bore, but on the opposite side of the boundary.

Drawdown data from an aquifer test where flow boundaries have been encountered can be analysed with an appropriate analytical equation. Drawdown data where interaction between groundwater and a stream has altered as a result of the pumping can be analysed to determine these various hydrogeological characteristics:

- The transmissivity (T) and storage coefficient (S) of the aquifer.
- The aquitard conductance (K'/B') or effective aquitard conductance for pumping from a semi-confined aquifer and specific yield at the water table (S_y).
- The streambed conductance (λ) of the affected stream or river.

Figure 9 shows the characteristic time-drawdown response on a semi-log scale for a semi-confined aquifer that is hydraulically connected to a stream. The actual stream depletion rates over the course of the test will follow the same pattern as the drawdown curve in the pumped strata. For pumping from an unconfined aquifer connected to a stream, the drawdown response will follow the same pattern as shown in Figure 9 for drawdown at the water table. Further information on the drawdown response when an aquifer test has induced stream depletion is provided in Lough (2004).

It is important that, where an aquifer test can not be run for a sufficient duration to observe the full characteristic time-drawdown response in Figure 9, that an alternate reliable method is used to determine a value for the streambed conductance. This should supplement the aquifer test data. Alternate methods for obtaining this parameter, such as combined gauging and piezometric surveys, infiltration tests and seepage surveys are outlined in *Guidelines for the assessment of groundwater abstraction effects on stream flow* (PDP, 2000) and in the supplementary document to this (Smith, 2009).

Those stream depletion guideline documents outline which methods are more reliable than others. In general, methods that involve measurements of large areas of streambed such as aquifer tests and combined gauging and piezometric surveys provide much more reliable estimates of streambed conductance than measurements that sample small sections of streambed, such as infiltration tests and seepage surveys.

It is very important for cases where the streambed conductance cannot be defined, or the method of measurement provides a value with a significant degree of uncertainty, that a sensitivity analysis of the predicted stream depletion rates to the possible range in this parameter is carried out.

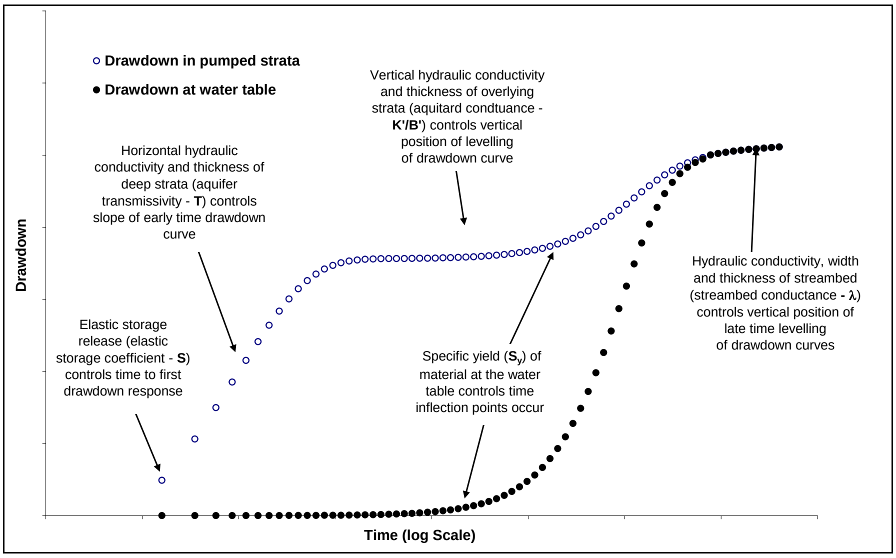

Figure 9: Drawdown sensitivity to hydrogeological parameters where a semi-confined aquifer is in hydraulic connection to a stream (modified from Lough (2004))

In some parts of the Greater Wellington Region, groundwater pumping near to the coast may affect the interaction between groundwater and the sea (which is a constant head boundary). To predict the effects of longer term pumping in these settings, the assessment techniques outlined in the *New Zealand Guidelines for the Monitoring and Management of Sea Water Intrusion Risks* (PDP, 2011) may need to be used.

5.4 Observation wells

An ideal aquifer test site would comprise purpose-drilled pumping and observation wells installed at appropriate spacing and depths. In reality, due to the expense of well drilling, aquifer tests usually make use of existing wells. This section outlines optimal details for observation wells, but it is recognised this may not be practical for all sites.

At least one well, more where practical, should be screened in the pumped aquifer and monitored prior to, during and after the course of the test. It is important to ensure that a sufficient drawdown will be measured if an existing well is used as an observation well. While the well needs to be close enough to provide a reasonable drawdown signal, it also must be far enough from the pumped well not to violate the assumption in many of the analytical models that the pumped well is screened over the entire aquifer thickness such that flow is entirely horizontal.

For semi-confined aquifers, at least one observation well screened in the shallow strata containing the water table should be monitored to determine the absence or presence of drawdown effects at the water table over the pumping duration. This should be as close to the pumped well as possible to maximise the chance of observing drawdown that is discernible from background fluctuations. The reason for this is that water table drawdown can be very small in response to pumping from a deep aquifer. Even if no drawdown is discernible in a shallow well, this provides useful information on the system and is important in calibrating the analysis of drawdown data from other wells.

If additional wells located in different strata are used for observation purposes, these may not be able to be analysed to obtain the desired parameters (most analytical techniques model drawdown only at the pumped well depth and at the water table). However, they can still be useful in understanding how the groundwater system behaves in response to the pumping. Wells with multiple screens in different aquifers should not be used for drawdown analysis, as the measured drawdown does not accurately reflect the drawdown response in any of the screened aquifers. It is also important that the pumped well is not multi-screened.

It can also be useful to monitor a well at a large distance from the pumped well that is likely to experience either a very small or no drawdown signal to better assess background trends. This can be difficult because, if the well is too close, it may experience drawdown as a result of the pumping; conversely, if it is too far away the background changes may not be representative of the background changes in the wells used for drawdown analysis.

One of the most useful steps to determine the optimum location of observation wells within the pumped and adjacent geological units is to estimate the likely drawdown in advance of the pumping.

5.5 Duration of pumping

The optimum duration of an aquifer test depends on the hydrogeological setting and the purpose of the test.

A test must be sufficiently long to capture the desired hydrogeological information. For semi-confined or anisotropic aquifers, the test should continue until the full characteristic drawdown response (shown in Figure 8) is observed, where this duration is practical. For aquifers hydraulically connected to surface waterways, tests should ideally be carried until observable changes in groundwater-surface water interaction occur. Longer term pumping periods may also be required to observe the influences of other boundaries such as no flow boundaries. However, it is often not practical to carry out a test for long enough to observe the full aquifer or surface waterway response. In some settings, the required duration may be weeks.

Other than the expense of long duration tests, another issue is that the magnitude and variability of background fluctuations due to other causes may make it difficult to isolate the drawdown response precisely. It may also be difficult to maintain a constant pumping rate over such a period, and therefore the data would need to be corrected for this prior to analysis. The benefit of obtaining a full data set needs to be weighed up against practicalities such as the cost of pumping and potentially adverse environmental effects arising from the pumping test itself.

A trial test is useful in estimating the ideal duration for the aquifer test. Where this is not possible, background water levels in the observation well(s) can be monitored and the magnitude of the background fluctuations compared to the expected drawdown response. Where the fluctuations are large in comparison to the estimated or measured drawdown response during the trial pumping, and it is not possible to increase the well pumping rate for the test or to use a closer observation well, a long duration test may be impractical.

Reviewing the collected drawdown data during the test can be very useful in determining whether sufficient information has been obtained, whether unexplainable/uncertain fluctuations are an issue and how much longer the test should continue.

In summary, the duration of a test is specific to that test so there is no recommended duration for all tests in Wellington. 2 to 3 days of pumping may provide adequate observation data for many sites and purposes, but not all. The duration must simply be long enough to allow assessment of the aquifer parameters required at a precision sufficient to enable them to be used justifiably in assessments.

5.6 Discharge of water

It is important that the pumped water is discharged at a sufficient distance and in a manner such that recharge to the aquifer will not occur, particularly where monitoring of the water table is being carried out. In circumstances where this is not possible, it should be carefully planned and monitored so that it can be accounted for in the analysis, although this is not ideal. The environmental effects of the discharge, such as flooding and erosion of the land at the site or neighbouring properties, must be considered. Water race operators and district councils may need to be contacted if any problems are envisaged.

6.0 Conducting aquifer tests

There are three key variables that require measurement during an aquifer test. These are the pumping rate, the water level in the observation wells and barometric pressure. Additional measurement of other influences such as tidal effects and stream flow may be required in some cases. Measurements can be made manually or electronically and accurate records must be made to allow for the analysis and interpretation of test data.

It is very important that the time at which measurements are made is recorded accurately and that it is standardised across measuring devices. For example, if data loggers are being used, the time on these devices should be synchronised before the monitoring commences.

It is also very important that a sufficient period of pre- and post-test monitoring is carried out to ensure the aquifer recovery can be used to constrain the analysis and to adequately infer background trends.

As explained in section 5.5, it is helpful to review and graph observation data as the test progresses to determine if the duration of the test should be altered.

Examples of standard data collection forms are presented in Appendix B.

6.1 Pumping rate

There are a number of methods for measuring the pumping rate. The most appropriate method depends on the flow rate and test requirements. Measurement frequency must be sufficient to allow any changes in pumping rate to be observed and corrected for in the analysis. Table 2 presents some of the pumping rate measurement methods available and comments on their suitability.

Table 2: Methods of measuring pumping rate

Method of measurement	Comment
Stopwatch and container	Excellent for low pumping rates, impractical for larger rates. Labour intensive if frequent measurement is required.
Orifice meter	Good measurement accuracy if installed correctly. Disposal method needs to be considered as the orifice cannot always be installed into irrigation works.
Sharp-crested weir	Good measurement accuracy if installed and designed correctly. Similar limitations to the orifice meter.
In-line flow meter	Accuracy will vary according to installation and meter specifications but many are capable of high measurement accuracy. Simple to use, especially if already installed. Older meters may not be compatible with a data logger, in which case manual readings will be required.
Acoustic flow meter	Portable versions can measure to a high accuracy, but pipe material and dimensions must be correctly defined.

6.2 Depth to water measurement

Depth to water measurements must be recorded for the pumped well and all observation wells before pumping starts to determine the static depth to water. Monitoring of water levels in the wells and barometric pressure changes should be carried out for a sufficient period before the test (between 1 and 3 days is generally sufficient), to establish background trends and the effect of external influences. Monitoring of recovery should be for at least as long as the duration of pumping and ideally for an additional one to two days beyond this.

Water levels can be measured manually with an electrical dipper for example, or electronically via pressure transducers with built in data loggers. The readings from the pressure transducers should always be verified with a number of manual depth to water measurements. Transducers are advantageous as they allow tests to be conducted with minimal personnel and also allow frequent measurement.

Frequent measurements are required at the start of the test and at the start of recovery, as this is when the water levels change the most rapidly. The frequency of measurement can reduce as the test continues. Kruseman and de Ridder (1994) suggest a measurement frequency for observation wells that decreases to daily measurements beyond 48 hours. Their suggested frequency is considered appropriate for manual measurement only where there are no other external influences. However, external influences are common for most aquifer tests. Ideally, to enable precise isolation of the drawdown signal from other influences, water level data should be measured electronically at the intervals shown in Table 3. Data loggers usually have sufficient capacity to store data from a number of days of pumping at frequent measurement intervals.

Table 3: Suggested interval of water level measurements in wells

Time since start of pumping/start of recovery	Time interval
0 to 2 minutes	Approx 10 seconds
2 to 5 minutes	30 seconds
5 to 15 minutes	1 minute
50 to 100 minutes	Maximum 5 minutes
100 minutes to shutdown of the pump/end of recovery monitoring	Maximum 15 minute interval

6.3 Time measurement

Time measurements should be recorded as precisely as possible. Times across all measuring devices used such as stop watches, personal watches, and data loggers used for flow or depth to water measurement should be synchronised before monitoring commences and checked for consistency when monitoring ceases. The reference time scale should be recorded, i.e. whether it is local time (New Zealand Standard Time (NZST) or Daylight Savings Time (NZDT)), Coordinated Universal Time (UTC) or Global Positioning System (GPS) time.

6.4 Other measurements

6.4.1 Rainfall

Ideally, aquifer tests should be conducted during dry weather, so the weather forecast should be consulted before commencing the test. Any rainfall event that does occur during an aquifer test should be recorded. If rainfall is not measured on site, information from the nearest climate station should be obtained. Rainfall can complicate the analysis of aquifer tests as it is often difficult to establish with any certainty the effect of the rainfall on groundwater levels.

6.4.2 Barometric pressure

Barometric pressure should be measured prior, during and after testing to enable correction for the effects of barometric pressure changes on groundwater levels (as explained in section 7.2). If sealed (non-vented) pressure transducers are used, barometric data will be required to isolate the water pressure from the devices combined measurements of barometric pressure and water pressure. It is usually best to use a pressure transducer to measure barometric pressure on site, and have this programmed to take measurements at the same frequency as the transducers in the observation wells to simplify data processing.

If only manual measurements of water level are taken, the barometric pressure recorded should be obtained from the nearest climate station to correct the collected data for barometric efficiency effects.

6.4.3 Flow and level in surface features

Where the test is expected to influence flow in a nearby flowing surface waterway, it is useful to measure the flow provided the flow is sufficiently small such that the expected changes will be less than the flow gauging error. This is usually only possible in small streams.

Stream flow is most accurately measured with weirs or flumes, but can also be measured via current meters. Ideally, the gauging locations should be placed at an upstream or downstream location outside of the zone of influence of pumping in order to measure the full stream depletion effect. This can be difficult especially if there are tributaries to the stream. It is also useful to measure the stream flow at the closest point in the stream, as in text book settings, the measured depletion effect at this point will be half the total effect.

Calculating stream depletion via stream flow measurements is complicated by measurement error and antecedent trends in stream flows. In addition, the maximum stream depletion rate will not occur over the short duration of most aquifer tests. However, stream flow measurement can be useful in determining the presence of a stream depletion effect. Where the flow can be measured precisely, it can be analysed with an appropriate equation, such as the Hunt (2003) equation (refer section 8.1.6), to determine aquifer and streambed properties.

Further advice on stream flow measurement is provided in the *Guidelines for the assessment of groundwater abstraction effects on stream flow* (PDP, 2000) and in the supplementary document to this (Smith, 2009).

Large changes in flow in nearby streams and river flow may have a significant influence on groundwater levels over the course of the testing if there is a significant change in the stage height or wetted perimeter of the surface waterway. For example, a large flood in a nearby river draining a mountain range is likely to create a noticeable rise in groundwater levels in the riparian margins of the river. It is useful to make observations of flow in nearby surface water features over the course of the testing, and obtain flow records where possible if a significant flow change has occurred and the groundwater level data appear to be affected.

Where the abstraction has the potential to affect surface water levels in a wetland, it is useful to monitor water levels over the course of the aquifer test. For larger wetlands and lakes, a discernible change is unlikely. However, the effect of the pumping on these features can sometimes be determined from the drawdown data in observation wells.

7.0 Aquifer test data processing and corrections

Appropriate corrections to remove groundwater influences other than the pumping effects from the water level record are vital to the successful analysis of drawdown data. Methods for corrections are outlined in the following sections. The methods are presented in the logical order for which they should be made. For example, barometric pressure influences should be removed before attempts are made to correct for other background water level trends, due to rainfall recharge for example, as the apparent trend in the raw data may be due to an increase or decrease in barometric pressure. For some test data, an iterative approach to data corrections may be appropriate.

In addition to correction for external influences, some corrections may need to be made due to problems that occurred during the testing for example, if recharge of the discharged water created noticeable groundwater mounding, if the level of a transducer changed or if significant fluctuations in the pumping rate occurred.

Full details of any data corrections applied, along with copies of the original and corrected data, should accompany any aquifer test report supplied to Greater Wellington.

7.1 Conversion of transducer data to water level

At present, the most commonly used pressure transducers are non-vented, which means they are not vented to the atmosphere. When they are out of the water they measure barometric pressure. When they are submerged under water, such as in an observation well, they are recording the sum of water pressure and barometric pressure.

To convert the readings to water pressure, the barometric pressure must be subtracted. These water pressures can then be converted to a depth to water measurement by referencing them to a manually measured water level.

It is possible that the resulting water levels may display an inverse relationship to barometric pressure (i.e. the water level appears to decrease as the barometric pressure increases). If this is the case, the corrections for barometric efficiency described in the following section will need to be applied.

7.2 Barometric corrections

A barometric correction is required for changes in heads caused by atmospheric pressure changes. If the barometric change was transmitted to the water in the monitoring well with 100% efficiency, a 1hPa change in atmospheric pressure, which is equivalent to a change in water head of 0.0102 m, would cause a change in groundwater level of 0.0102 m. In a confined or semi-confined aquifer, the transmission of atmospheric pressure changes to the groundwater in the aquifer is less than 100% efficient because some of the change is transmitted to the solid aquifer media and some to the water that fills the pore space. It is only the change transmitted to the water for which the monitoring data need to be corrected. The ratio of the observed water level fluctuation to the change that would occur under 100% efficiency is referred to as the barometric efficiency (BE).

There are a variety of approaches that can be taken to assess the barometric efficiency of an aquifer. A useful graphical method for determining the barometric efficiency is to convert the barometric pressure to an equivalent water pressure (1hPa change = water head change of 0.0102 m) and plot this versus time on the same graph as the water level data, using the same scale. An initial estimate of the BE value can be made by comparing the magnitude of water level change to a particular barometric change over the same period. A new series of "corrected" water levels can be added to the graph (with the BE effect subtracted) and compared to the barometric record to ensure that barometric effects have been sufficiently removed. If the water levels are still displaying a dependence on barometric pressure, the BE value can be adjusted until this effect is removed.

7.3 Tidal fluctuations

Where the monitoring record shows a tidal effect, the test data will need to be corrected prior to analysis. This type of correction needs to account for the change in frequency and magnitude of each tidal cycle. If testing is carried out within several kilometres of a tidal body this effect should be checked for in the pre-test monitoring data. Tidal effects can propagate inland through a confined aquifer for surprisingly large distances.

Ideally monitoring of water levels in the tidal surface water body should be carried out to allow correction of background fluctuations. If this is not possible, tidal data can be obtained from the Sea Level Data Downloads page on the Land Information New Zealand (LINZ) website. There is a site in Wellington Harbour.

http://www.linz.govt.nz/hydro/tidal-info/gauges/sea-level-data-downloads

It is also useful to monitor levels in a shallow well close to the coast that is not impacted by the pumping during the aquifer test to help remove the tidal effect from drawdown data.

In theory, tidal effects can be corrected for by applying a tidal efficiency (i.e. groundwater levels change by a set percentage of the actual tide change) and a time-lag (there is a delay in the response). This method usually works well where the distance to the sea does not change significantly. However, in some settings, such as aquifer tests near estuaries, the distance can change significantly. If this is the case, the period of pre-test monitoring can be used to infer the background pattern and it can in most cases be assumed that this same pattern will occur during the period of pumping.

7.4 Other causes of water level fluctuations

Where water level data still exhibit fluctuations following correction for barometric pressure changes and tidal effects, further correction may be required to remove other effects where possible, such as pumping interference of nearby wells.

Natural background trends that require correction include steadily increasing heads prior to, and following a pumping test caused by a rainfall event prior to the testing or a natural recession following cessation of a natural recharge event. Corrections for these types of background influences commonly assume a linear trend over the course of the test, but it should be recognised that a linear correction is not always appropriate.

Large rainfall events or floods in rivers may not be possible to remove with any accuracy and could mask the drawdown effect.

Data corrections are probably the largest source of uncertainty in an aquifer test analysis and they must be made with care as they can have a significant bearing on the ability to determine aquifer parameters with any accuracy.

7.5 Ratio of magnitude of corrections

Ideally, the magnitude of corrections compared to the observed drawdown signal should be small to minimise the uncertainty in the interpreted drawdown response. However, provided that corrections for barometric pressure effects, tidal effects and other background influences are made accurately, it is still possible to reliably identify a drawdown response even where the magnitude of the corrections are larger than the drawdown signal.

In practice, corrections for water level fluctuations caused by stresses other than the pumping are often difficult to assess with certainty. The unexplainable/uncertain fluctuations prior to, during and after the pumping test need to be as small as possible relative to the drawdown signal, ideally, less than 10% of the drawdown signal.

Where the unexplainable/uncertain fluctuations are much larger than this, there will be significant uncertainty in the inferred hydrogeological parameters. If this is uncertainty is unacceptable for the purposes of the test, the test may need to be repeated.

7.6 Saturated thickness

For most solutions used for aquifer test analysis, the aquifer is assumed to be of constant saturated thickness. In an unconfined aquifer, this condition is not met if the drawdown is large compared to the aquifer's original saturated thickness. The Jacob (1944) adjustment described in Kruseman and de Ridder (1991) can be applied to data where this occurs using this equation:

$$s_{corrected} = s - \frac{s^2}{2D}$$

Where $s_{corrected}$ is the corrected drawdown, s is the observed drawdown and D is the original saturated aquifer thickness.

This adjustment is different to the corrections described in the previous sections as it is an adjustment to the actual drawdown data to make it amenable to analysis. It is important that the inferred transmissivity from this method is interpreted as the initial transmissivity of the aquifer, rather that the reduced transmissivity that has occurred due to the pumping.

7.7 Partially penetrating wells

For some tests, a correction may be required to account for a partially penetrating pumping well. Flow in the vicinity of a pumped well that is partially screened over an aquifer will be higher than a well that is screened over the full aquifer thickness. This larger flow can result in additional head loss, which is not accounted for in the simplifying assumptions of many solutions used for analysis. This effect decreases with increasing distance from the pumping well, and no corrections are required at distances greater than 1.5 to 2 times the saturated thickness of the aquifer, depending on the amount of penetration. Methods of adjustment to make data amenable to the analysis method chosen are outlined in more detail in Chapter 10 of Kruseman and de Ridder (1994). An arguably better alternative is to analyse the data with a method that accounts for partial well penetration (e.g. the Zhan and Zlotnik (2002) solution described in Section 8.1.5).

8.0 Methods of analysis

Once the data have been corrected to isolate the drawdown response to the pumping from other sources of water level changes, the data are ready for analysis with an appropriate solution.

8.1 Constant discharge test analysis – multiple wells

There are a variety of analytical equations and numerical modelling packages that can be used to analyse the drawdown response observed in observation wells during a constant discharge test. These need to be selected based on the known details of the hydrogeological setting and the type of response observed.

Numerical modelling packages can be used where this will enable the drawdown response to be more accurately analysed than with an analytical equation, for example where there are multiple locations of groundwater-surface water interaction. Guidance on the construction of a numerical model is outside the scope of these guidelines, but particular care should be taken not to introduce unnecessary and unjustified complexity into the model. It is best to construct a simple model to begin with, similar to the conceptual models for analytical equations, and add complexity if required and only if there is sufficient information to do so. Guidelines to assess the validity and uncertainty of predictions using numerical modelling are outlined in Pattle Delamore Partners Ltd (2002).

A variety of analytical methods appropriate for different hydrogeological settings are presented in the following sections. These methods are those that are likely to be most appropriate for the majority of aquifer test analysis within the Wellington Region. The methods presented describe unsteady flow to the pumped well.

The drawdown and recovery data from all observation wells should be analysed simultaneously using the method of superposition to combine the effects of both the pumping and recovery periods. As outlined in Lough (2004) the principle of superposition and time translation used by Jenkins (1968) enables analysis of recovery data. This is based on the principle that the recovery period can be modelled as continuous abstraction from the pumped well, with a recharge well superimposed in the same location which commences at the instant of pump shutdown and recharges continuously at the abstraction rate.

The reason that the analysis of drawdown and recovery data should be carried out simultaneously is that the recovery data provide useful information on how the system would have responded with continued pumping (and therefore potentially allows an interpretation of parameters not determinable from the response during pumping such as the specific yield and transmissivity of other strata).

A curve-fitting approach for the analysis, which involves manually changing the parameters to achieve the best match, allows the analyst to obtain insight into the parameter sensitivity. Alternatively, automated processes and alternative methods to estimate hydrogeological parameters from drawdown data are available in some software.

If a good fit between the corrected data and modelled drawdowns cannot be achieved with parameter optimisation, then corrections may need to be applied or the potential for an alternate model to better describe the system investigated.

It is important that, where significant uncertainty remains in the values of aquifer parameters, ranges in possible sets of hydrogeological parameters should be developed, leading to corresponding ranges in any longer term predictions.

If no drawdown response has occurred in some observation wells, this is useful information as it guides the choice of parameters used to fit the drawdowns observed in the other wells. The hydrogeological parameters inferred from an observed drawdown response in one well should be used in the appropriate model to confirm they match the lack of response in the other wells.

8.1.1 Method assumptions

Assumptions common to the techniques discussed in the following sections, unless otherwise stated, are outlined here, with brief comments about the appropriateness of these assumptions.

1. *The aquifers and aquitards are isotropic, homogeneous and uniform in thickness*

This assumption is likely to be violated as most strata in natural groundwater systems are anisotropic, heterogeneous and of variable thickness. However, the scale of the heterogeneity can be small relative to the volume affected by the test. In addition, the parameters derived are average parameters for the volume of aquifer affected, and, using these average parameters for longer term assessments will, where there is reliable drawdown data and analysis, provide a reasonable approximation of head and flow changes. Therefore this simplifying assumption will, in general, not significantly affect the quality of the analysis and predictions.

2. *The aquifers and aquitards are of infinite lateral extent*

Aquifers and aquitards cannot be of infinite lateral extent. Aquifers in the Wellington region are in places bound by low permeability basement rocks, often representing mountain ranges. In other areas, the aquifers are laterally bound by surface water features such as the sea or rivers. If the area of influence of an aquifer test is likely to encounter boundaries, this assumption will not be valid and a method of analysis that accounts for these boundaries should be used.

3. *The base of the pumped aquifer is impervious (an aquiclude)*

This assumption will be violated in many cases, especially for pumping from shallow aquifers. The assumption ignores the release of elastic storage from pervious underlying layers into the pumped aquifer. This may mean the inferred elastic aquifer storage coefficients and transmissivity values represent a larger volume of the groundwater system than the pumped aquifer alone. However, the values obtained are still useful for predicting longer terms effects as they represent the actual response of the system. It should be noted that the contribution of water stored elastically in underlying layers is very short-lived.

4. *All layers, other than the pumped aquifer, are incompressible (zero elastic storage)*

This assumption is similar to the previous assumption, and may mean the inferred elastic storage coefficient includes the effects of some storage release from other layers. For all realistic values of the elastic storage coefficients of the other layers, the effect of this is usually small and does not prevent useful drawdown analyses or predictions.

5. *Storage is released instantaneously with a decline in head*

Boulton (1955) showed that the release of stored water at the water table is not always instantaneous and the time delay between a decline in the water table level and the release of stored water via drainage from the material can be significant. This means that the specific yield derived from aquifer test data from unconfined aquifers may be lower than the actual value. Where the reduction in the level of the water table occurs very slowly, in response to pumping from a semi-confined aquifer for example, this assumption is valid.

6. *The diameter of the well is infinitesimally small such that storage of water within the well casing can be neglected*

The appropriateness of this assumption can be checked by calculating the change in the volume of water within the well casing during pumping and comparing this with the amount of water abstracted from groundwater before there is a response in the nearest observation well. Provided the change in the volume of water in the well is comparatively small, this is a reasonable assumption. For a single well test, well storage is an important consideration.

7. *The well is screened over the entire thickness of the pumped aquifer*

This assumption is appropriate provided the nearest observation well is located where flow within the pumped aquifer is predominantly horizontal. As outlined in section 7.7, monitoring wells should be located outside this zone of convergent flow if the method used for the drawdown analysis contains this assumption.

8. *A large conductivity contrast exists between the pumped aquifer and aquitard, which implies that flows in the pumped aquifer and aquitard are horizontal and vertical, respectively (this assumption is relevant to analysis methods for semi-confined aquifers)*

This assumption is appropriate is areas where aquifers and aquitards are discrete entities and have a high hydraulic conductivity contrast, or where the net vertical hydraulic conductivity of the groundwater system is much smaller than the net horizontal hydraulic conductivity. If the hydraulic conductivity contrast is small, it may be more appropriate to model the system as an anisotropic aquifer (section 8.1.5).

9. *Prior to pumping, the piezometric surface in the pumped aquifer and at the water table are horizontal*

In most groundwater systems in the Wellington region, including the Wairarapa Valley, Lower Hutt and Kapiti Coast, the water table slope will likely be small enough to satisfy this assumption.

8.1.2 Confined aquifers

As described above, fully confined aquifers are considered rare, although for aquifers where the overlying strata are of low permeability, the effect of vertical leakage through these layers may not be observable in drawdown data. In this case, the data could be analysed with an analytical solution that described confined conditions, although any aquifer test reporting should acknowledge that longer term pumping may induce vertical leakage. Alternatively, the data could be analysed with a semi-confined solution (e.g. Hunt and Scott (2007)) so that a maximum possible value for the aquitard conductance can be determined. This could assist in constraining the predictions of longer term effects.

The Theis (1935) solution describes unsteady flow to a well in a homogeneous aquifer of infinite horizontal extent that receives vertical recharge or leakage. Top and bottom aquifer boundaries are assumed to be impermeable. The conceptual model of a pumped aquifer bounded on top by aquicludes is shown in Figure 10.

Aquifer test drawdown and recovery data for a confined aquifer, or a semi-confined aquifer that does not show any effect of vertical recharge or leakage, can be analysed with the Theis (1935) solution to obtain estimates of the aquifer transmissivity and storativity.

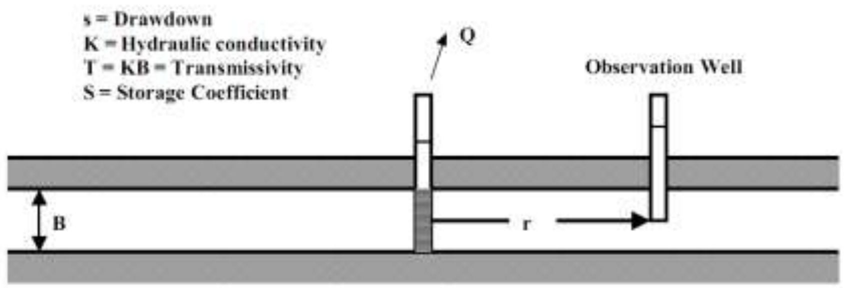

Figure 10: Conceptual model for the Theis (1935) solution (from Hunt (2008a))

8.1.3 Semi-confined aquifers

There have been a number of analytical equations developed over the years that describe unsteady flow in response to pumping from a semi-confined aquifer. An overview of these is provided below and a more detailed description of these can be found in Lough and Williams (2009).

Hantush and Jacob (1955) developed the first analytical unsteady flow equation that accounted for leakage from an aquitard overlying a pumped semi-confined aquifer. Their equation described the drawdown response that would occur if the aquitard was overlain by an unconfined aquifer with infinite storage. This assumption may be appropriate over the course of an aquifer test, but with prolonged pumping the volume of water in the pore spaces of the overlying unconfined aquifer reduces due to drainage. Neuman and Witherspoon (1968) proposed a similar solution to the Hantush and Jacob solution, but also accounted for elastic storage in the aquitard. This solution has the same problematic assumption of infinite storage at the water table. The Hantush and Jacob (1955) and Neuman and Witherspoon (1968) solutions may be appropriate for the analysis of aquifer test data where the assumption of infinite storage is satisfactory over the course of the test. However, they are not appropriate for longer term predictions.

A new equation developed by Boulton (1973) was an improvement on the Hantush solution in that it allowed for drawdown at the water table. This solution was originally obtained for unconfined flow to a well (Boulton 1955, 1963) but it was shown by Boulton (1973) and Cooley and Case (1973) that it can be used to model flow to a well in an aquifer overlain by an aquitard containing the water table. The conceptual model for this solution is shown in Figure 11.

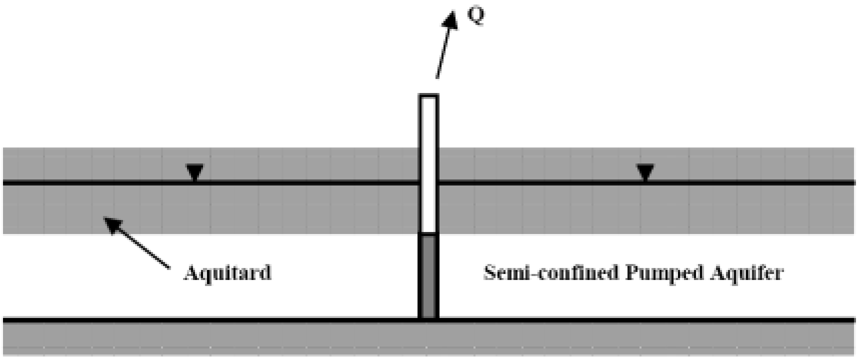

Figure 11: Conceptual model for the Boulton (1973) solution (from Hunt (2008a))

Hunt and Scott (2005) demonstrated that the Boulton solution also applies when the pumped aquifer is overlain by any number of aquitards provided that none of the layers has a transmissivity that exceeds about 5% of the pumped aquifer transmissivity. This is the main limitation of the Boulton solution, as the case where a semi-confined aquifer is overlain by other permeable aquifers is quite common.

In 2007, Hunt and Scott documented their new solution that allows for this horizontal flow to occur in other overlying aquifers. The basic conceptual model that their solution describes is a semi-confined aquifer overlain by an unconfined aquifer (Figure 12), which is equivalent to that described by Hantush and Jacob (1955) solution. The solution differs in that it allows for both drawdown and horizontal flow within the unconfined aquifer. The solution reduces to the Boulton (1973) solution where the horizontal flow in the overlying aquifer is negligible.

If the full characteristic drawdown curve shown in Figure 8 is observed in aquifer test data, the data can be analysed to determine the following terms which appear in the Hunt and Scott (2007) solution. These terms are also illustrated in Figure 12, in which the drawdown in the pumped aquifer is denoted by ‘s’ and the drawdown of the water table in the overlying unconfined aquifer is denoted by ‘η’. The control these parameters have on the shape of the drawdown curve is illustrated in Figure 13.

T = transmissivity of pumped aquifer

S = elastic storage coefficient

K’/B’ = aquitard conductance (ratio of hydraulic conductivity of overlying aquitard to thickness of the aquitard)

S_y = specific yield of the unconfined aquifer

T_0 = transmissivity of overlying aquifer

The volume of water sourced from the pumped aquifer and the corresponding volume of water depleted from storage at the water table can also be calculated via the equations described in Hunt and Scott (2007), as presented by Scott and Hunt (2007). The controls on the way in which water is released from storage are illustrated in Figure 14.

While the Hunt and Scott (2007) solution is considered to be the most widely applicable analytical solution for the analysis of drawdown data and predictions of long-term effects for pumping from semi-confined aquifers in the Wellington Region, it is important that values for the above parameters are only reported where there are sufficient data to see the complete drawdown curve shown in Figure 13. Although it is possible to establish parameter thresholds even for an incomplete drawdown curve, e.g. a minimum value for the specific yield.

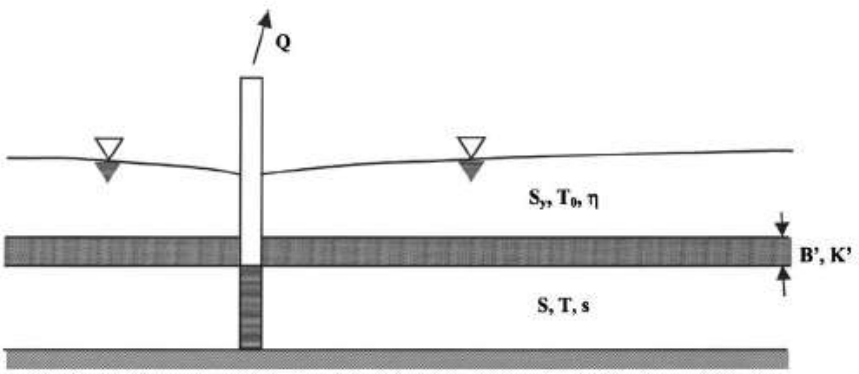

Figure 12: Terms used in the Hunt and Scott (2007) solution (from Hunt and Scott (2007))

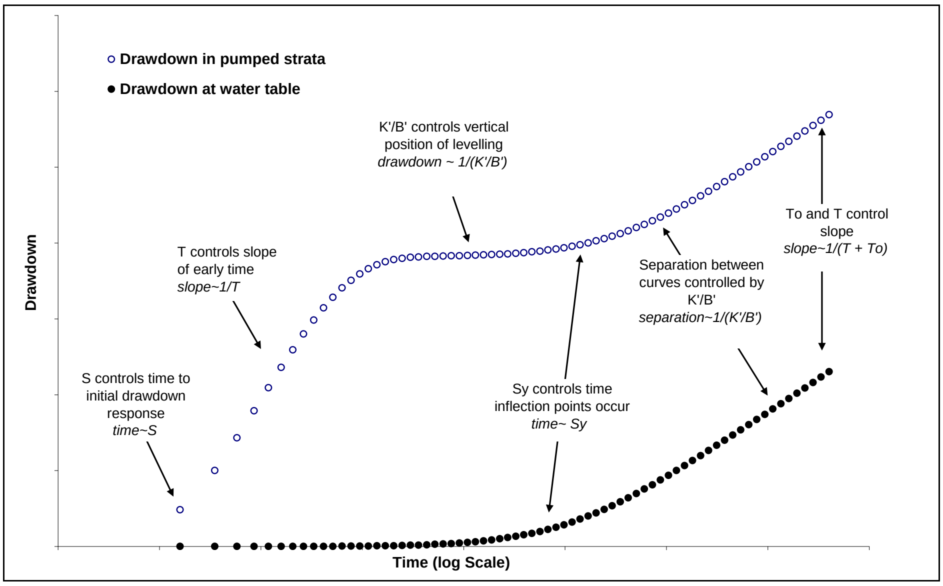

Figure 13: Drawdown sensitivity to parameters of a system with two aquifers separated by an aquitard (as described by Hunt and Scott (2007) solution)

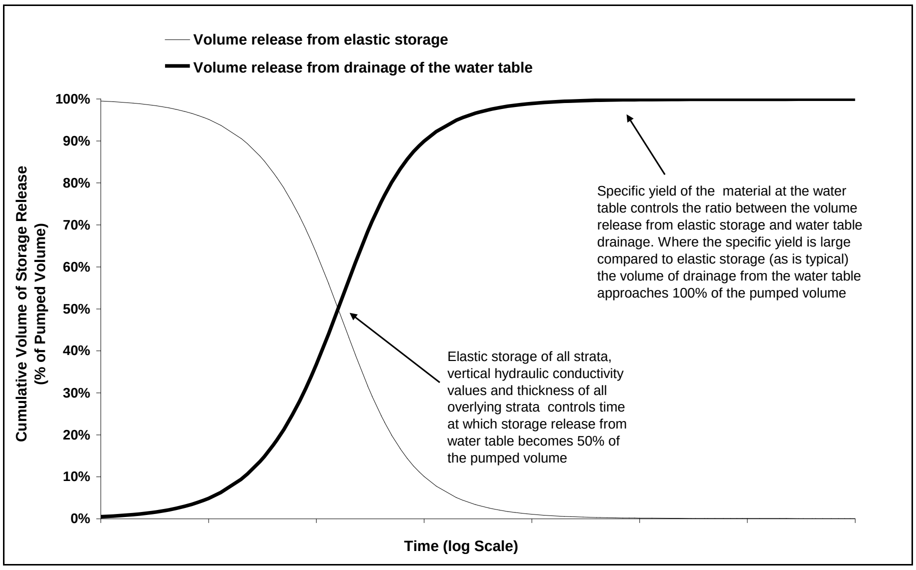

Figure 14: Storage release sensitivity to hydrogeological parameters of a layered system

8.1.4 Unconfined aquifers

In an unconfined aquifer, the dominant storage release is via physical drainage of the pore spaces as the water table lowers. The release of water via elastic storage in an unconfined aquifer is negligible in comparison to this.

For settings where a pumped well is screened across the full aquifer thickness of a homogenous isotropic unconfined aquifer, the response in an observation well will not typically show an elastic storage response. In this case, the drawdown data can be analysed with the Theis (1935) solution. Although the solution was developed for a confined aquifer with an impermeable top boundary, the top boundary can be a free surface if maximum free surface drawdowns are not a significant portion of the saturated aquifer thickness. If they are significant, then the saturated thickness adjustments described in Section 7.6 can be applied.

If an elastic storage response and vertical flow are evident, then the Zhan and Zlotnik (2002) solution described in the following section can be used to analyse drawdown data from an unconfined aquifer. In an unconfined aquifer, this response may occur if the pumped well is screened some distance below the water table or if vertical anisotropy exists due to fine layering or a preferred horizontal orientation of solid particles in the aquifer matrix.

8.1.5 Anisotropic aquifers

The characteristic drawdown response shown in Figure 8 can also occur when pumping occurs from a well screened at depth within an unconfined anisotropic aquifer. It is possible to use the Hunt and Scott (2007) solution in this setting, but there are alternate models for which the equations more closely match a conceptual model of an unconfined, anisotropic aquifer.

The equations described here can also be applied to pumping from deeper semi-confined aquifers if the system can be modelled as an anisotropic aquifer over the scale of the effect of the aquifer test.

Neuman (1974) developed a solution to a set of equations describing flow in an unconfined, homogeneous anisotropic aquifer. For this reason, an unconfined, homogeneous anisotropic aquifer is often referred to as a Neuman-type unconfined aquifer.

Zhan and Zlotnik (2002) obtained a solution to describe drawdowns in an unconfined, homogeneous anisotropic aquifer resulting from pumping a well with a screen of a defined length and orientation. Because of this allowance for the screen, these equations are very useful for settings where partial penetration of wells has an impact on drawdown data. The Zhan and Zlotnik (2002) is essentially an extension of Neuman's (1974) equations.

It is recommended that the Zhan and Zlotnik (2002) solution, which is coded into Bruce Hunt's Function.xls (Hunt, 2008a), or the Neuman (1974) solution, which is coded into other aquifer test analysis software, be used for anisotropic aquifers.

Some particular settings may be better modelled by an alternate analytical solution that describes flow to a sink within a semi-confined anisotropic aquifer (an anisotropic aquifer overlain by an aquitard). This solution is described on page 49 of Hunt (2008a).

8.1.6 Aquifers with hydraulic connection to surface water

The previous methods presented do not account for groundwater-surface water interaction. This section outlines appropriate methods to use where changes in groundwater interaction with a surface waterway occur over aquifer test or the assessment period.

The Hunt (2003) solution allows for the depletion that results from a stream when water is abstracted from a well in a semi-confined aquifer. This is essentially equivalent to the Boulton (1973) solution, but includes the effects of stream depletion. Stream depletion is either a reduction in groundwater flow to a stream or an increase in flow from a stream to groundwater. The solution can be simply modified, through the choice of parameter values, to an earlier solution described by Hunt (1999) for stream depletion in confined or unconfined aquifers. It can also be reduced to the solution described by Theis (1941) (which is more commonly referred to as the Jenkins (1968) solution) to model depletion from pumping a confined or unconfined aquifer that is perfectly connected to a surface waterway.

The conceptual model that the Hunt (2003) solution is based on is shown in Figure 15. The parameters are the same as described for the Hunt and Scott (2007) solution (section 8.1.3), except there is no overlying aquifer and one additional parameter, the streambed conductance, λ. The definition for this is shown in Figure 15, although where the hydraulic conductivity of the material between the stream and the pumped aquifer is higher than the aquitard hydraulic conductivity, the value of hydraulic conductivity (K') in that expression should be increased accordingly.

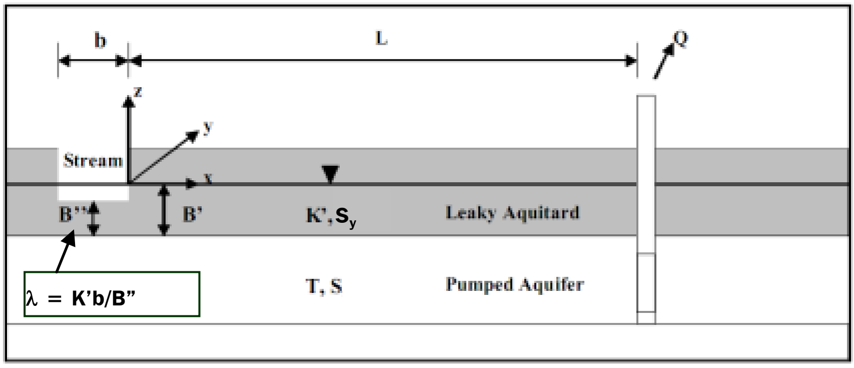

Figure 15: The Hunt (2003) solution conceptual model

Lough and Hunt (2006) demonstrated that the Hunt (2003) solution is applicable to a setting where the pumped aquifer is overlain by multiple aquitards, rather than a single aquitard, although this solution does not incorporate horizontal flow in overlying layers.

The Hunt (2003) solution is likely to be a widely applicable solution for aquifer tests in the Wellington region. However, it does have the potential to underestimate stream depletion where the stream is in interaction with an unconfined aquifer or where the semi-confining layers that the stream or river is connected to permit horizontal flow. For that setting, a simple numerical model or the solution described in Dudley Ward and Lough (2011) can be used. It is worth comparing the predicted stream depletion using the Hunt (2003) solution with the Dudley Ward and Lough (2011) solution to check which solution is likely to provide the more accurate estimate.

Hunt (2008b) provides a solution for stream depletion arising from pumping a semi-confined aquifer of finite width. This solution is appropriate for aquifer test analysis in narrow alluvial valleys.

Where an aquifer is hydraulically connected to a spring, both drawdowns at the water table and flow to the spring will be reduced by pumping. This reduction in spring flow is known as spring depletion. The improved Hunt (2004) spring depletion solution described in Hunt and Smith (2008) can be used to model spring depletion.

As described in section 3.3, aquifer tests are required to determine whether a groundwater abstraction requires a restriction based on surface water flows if it is classed as a Category B abstraction. These tests should be carried out in accordance with the recommendations provided in these guidelines, including the guidance on flow measurements in section 6.4.3.

For most settings, the analytical equations described above can be used for Category B stream depletion assessments but complex settings may require a numerical model. Where there is uncertainty in the parameters, this should be accounted for in the stream depletion assessment. For example, if the test duration has been insufficient to determine a value for streambed conductance, the possible range in stream depletion rates should be presented for the feasible range of streambed conductance values.

It is strongly recommended that aquifer test plans carried out for Category B stream depletion assessments are submitted to Greater Wellington for review prior to commencing the test. Greater Wellington will need sufficient evidence that the stream depletion effect is either less than 60% of the average pumping rate over 150 days or less than 10 L/s to grant a consent application without imposing low flow restrictions or including the stream depletion effect in the surface water allocation block.

8.2 Single well tests

Single well tests are more popular than aquifer tests using monitoring wells due to the practical advantage that only one well is needed. However, only the transmissivity or hydraulic conductivity can be estimated from a single well test.

Water levels in a pumping well decrease both with pumping duration (unless a recharge boundary is encountered) and pumping rate. The water level decrease (drawdown) is made up of two components: aquifer loss and well loss.

Aquifer loss is the head loss caused by the resistance to flow created by the strata on the water flowing towards the well screen. The equations typically used for step drawdown test analysis assume the flow in the aquifer is laminar, and the head loss is proportional to the resistance provided by the material forming the aquifer.

Well loss includes linear and non-linear head losses. The non-linear head losses in the well include frictional losses inside the well screen and suction pipe where flow is turbulent and in a portion of material outside the well screen where flow is turbulent. Linear well losses include losses due to damage to the aquifer, such as compaction, during the well drilling.

It is often difficult to isolate the aquifer losses from the well losses, therefore the transmissivity estimate obtained from a single well test is often quite uncertain. In addition, partial penetration will result in greater drawdowns than theoretically occur, which will decrease the transmissivity estimate obtained from many of the equations.

In addition to partial penetration, single well test analyses typically make no allowance for leakage, or other recharge/no-flow boundaries. This means that if the transmissivity is estimated from the section of the time-drawdown curve where leakage or a recharge boundary is affecting drawdowns, the transmissivity will likely be over-estimated. If a no-flow boundary is affecting drawdowns, the transmissivity will likely be under-estimated as the drawdown curve steepens when a no flow boundary is encountered.

Another disadvantage of a single well test is that the storativity cannot be reliably determined. In addition, well storage effects need to be corrected for before transmissivity estimates can be made.

8.2.1 Step drawdown tests

A step drawdown test provides information on well performance and can be used to estimate a well's efficiency and determine an optimal pumping rate for the well, as well as provide an estimate of maximum yield under various water level conditions.

In a step drawdown test, the abstraction rate from the well is increased in a number of even steps up to a rate ideally equal to or greater than the proposed design flow. A general guideline for these types of tests is to start pumping at half the peak pumping rate and increase the pumping rate in even incremental steps up to the peak rate. The steps should be of sufficient duration for the drawdown to begin to stabilise, usually around 30 minutes to 2 hours per step. A step test should have at least three steps.

Step drawdown test data can be analysed with the Eden-Hazel (1973) method, which is based on the Jacob straight line method, to give an estimate of transmissivity. This is described in Kruseman and de Ridder (1991).

8.2.2 Specific capacity tests

It is common for drillers to report the specific capacity of the well from the several hours of test pumping that is frequently carried out on completion of the drilling. The specific capacity is the ratio of the test pumping rate to the measured drawdown. Note that in most cases, the calculated specific capacity reduces with increasing pumping rate and extended duration due to increasing aquifer losses with time and non-linear pumping losses.

There are some empirical formulas that describe the relationship between transmissivity and specific capacity. These can be useful for obtaining a general idea of how permeable an aquifer is, but the calculated values are not particularly accurate due to well losses and the variation in calculated specific capacity with time. If a constant discharge test is carried out on a pumped well with no observation wells, it is useful to take a number of measurements of drawdown over time so that transmissivity can be estimated from the slope of the drawdown graph over time (e.g. Jacob's straight-line method described in Kruseman and de Ridder (1991)) rather than from a single measurement of specific capacity. It is important, however, that the transmissivity is estimated from a section where well-storage effects have ceased or are corrected for and where no leakage or aquifer boundaries are affecting the drawdown data.

8.2.3 Slug tests

A slug test involves adding or removing, very rapidly, a known volume of water or solid to a well and measuring the water level response. The hydraulic conductivity of the strata around the well screen can be estimated from these measurements. Slug tests are simple to perform and can provide an indication of the hydraulic conductivity of the strata over a larger area when several wells in an aquifer or area are tested. It is advisable to repeat the slug test several times for each well to improve the reliability of the calculated hydraulic conductivity.

Slug tests have the same disadvantages as other single well tests in that the results are affected by the well construction and represent only a localised area of strata around the well screen.

Manual measurements can be made in areas where the hydraulic conductivity is sufficiently low, but automatic recorders will be required for higher hydraulic conductivity strata because the water levels recover so quickly. Kruseman and de Ridder suggest automatic measurement for transmissivity values of more than 250 m^2/day.

Kruseman and de Ridder (1991) describe methods for analysing slug tests in confined and unconfined aquifers to obtain hydraulic conductivity estimates.

8.2.4 Recovery tests

Measurement of water level recovery in a pumped well following a constant discharge test is usually carried out for all constant discharge tests.

Drawdown measured during recovery is often more stable than at the commencement of a pumping tests because it is not affected by fluctuations in the pumping rate.

The Theis recovery method, as described in Kruseman and de Ridder (1991), can be used to obtain a transmissivity estimate from the slope of the water level recovery data over time for confined, semi-confined or unconfined aquifers.

The transmissivity estimate can be compared to that derived from the analysis of drawdown in any observation wells and the pumped well during the test, to check for consistency.

During the initial phase of recovery, water level measurements should be made frequently but this can decrease with time, which is the same measurement pattern suggested during the pumping period of a constant discharge test.

9.0 Aquifer test reporting

An aquifer test report should contain a comprehensive record of the aquifer test and subsequent analysis. It should be complete, clear, and accurate.

It should state at the outset the objectives of the testing (e.g. obtaining aquifer parameters for a stream depletion assessment) and whether these were met. It should also state all factors that affected, or potentially affected, the accuracy of the test results.

Any test report submitted to Greater Wellington should include the items summarised in the Checklist for Aquifer-Test Reports in Appendix B. Key requirements for the report are:

- Details of the specific design of the test including modifications from the planned original configuration and the reasons for any modifications.
- Map of test location, GPS locations, depths of wells and screens and other relevant spatial features.
- Hydrogeological conditions including a description of the conceptual hydrogeological model of the system based on current understanding and well logs.
- Test dates, times and test duration.
- Measurements of the static water level in all wells before testing began and during recovery.
- Test conditions, including whether the pumping rate was maintained.
- Details about the discharge of the pumped water.
- Summary of response, including type of drawdown response (unconfined, semi-confined, confined).
- Data corrections.
- Details and justification of the analysis methods used and any other calculations used to determine aquifer characteristics.
- Plots of measured and calculated drawdown versus time.
- Test results, including all interpreted aquifer parameters.
- Discussion of data and analysis reliability.
- References for all cited information.

- Data records, including original and corrected water levels, measurement time, pumping rate, and antecedent recordings for any wells or other monitored variables (such as surface water flow measurements).
- Well construction details (well logs, etc.) for all wells.

If the aquifer test results are used to extrapolate longer term effects of the pumping, full details of these calculations should be provided together with details of all assumptions used for the assessments and justification for these assumptions.

10.0 Summary

These guidelines have been prepared to provide guidance on how to design, perform and analyse pumping tests to provide a sufficiently high standard of information to support consent applications to take groundwater within the Wellington Region.

The key aspect of aquifer testing is that it is performed and analysed in a manner that optimises the opportunity of achieving the desired outcome of the test. In some cases, the testing may simply be carried out to determine well performance, while in other cases it may be carried out to gain aquifer parameters to use in a stream depletion assessment.

A well-performed constant discharge test using both a pumping well and observation wells is usually the best way of obtaining hydrogeological parameters to use to assess environmental effects as part of a resource consent application to take groundwater, including interference on neighbouring wells, salt water intrusion and depletion effects on surface water ways.

11.0 Acknowledgements

The production of this report has been a collaborative effort between Pattle Delamore Partners Ltd and Greater Wellington. Particular acknowledgement needs to be given to Environment Canterbury who has given permission for use of sections of their Aquifer Test Guidelines (Aitchison-Earl and Smith, 2008).

References

Aitchison-Earl, P. and Smith M. 2008. Aquifer test guidelines (2nd edition) Environment Canterbury Technical Report R08/25, 57 p.

Boulton, N. 1955. Unsteady radial flow to a pumped well allowing for delayed yield from storage. Proceedings General Assembly Rome: International Association Sci. Hydrologists Publication 37, p 472-477.

Boulton, N.S. 1963. Analysis of data from non-equilibrium pumping tests allowing for delayed yield from storage. Proc. Inst. Civil Eng., 26, Paper No. 6693:469-482.

Boulton, N.S. 1973. The influence of delayed drainage on data from pumping tests in unconfined aquifers. Journal of Hydrology, 19, p 157-169.

Brooks, T., 1998. Aquifer Test Guidelines. Environment Canterbury Technical Report U98/10.

Cooley, R. L. and Case, C. M. 1973. Effect of a water table aquitard on drawdown in an underlying pumped aquifer. Water Resources Research, 9(2), p 434–447.

Darcy, H., 1856. Les Fontaines Publiques de la Ville de Dijon, Victor Dalmont, Paris. 647 p.

Dudley Ward, N. and Lough, H. 2011. Stream Depletion from Pumping a Semiconfined Aquifer in a Two-Layer Leaky Aquifer System. Journal of Hydrologic Engineering, 16(11). p 955-959.

Freeze, R. A. and Cherry, J. A., 1979. Groundwater, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 604 p.

Hantush, M.S. and C.E. Jacob. 1955. Non-steady radial flow in an infinite leaky aquifer. Transactions American Geophysical Union, 36, 95-100.

Hughes, B. and Gyopari, M. 2011. Wairarapa Valley groundwater resource investigation. Proposed framework for conjunctive water management. Greater Wellington Regional Council Report. May 2011.

Hunt, B. 1999. Unsteady stream depletion from ground water pumping. Ground Water, 37(1), p 98-102.

Hunt, B. 2003. Unsteady stream depletion when pumping from semi-confined aquifer. ASCE Journal of Hydrologic Engineering, 8, p 12-19.

Hunt, B. 2004. A spring-depletion solution. ASCE Journal of Hydrologic Engineering, 9, p 144-149.

Hunt, B., and Scott, D. 2005. Extension of the Hantush and Boulton solutions. Journal of Hydrologic Engineering, 10, p 223–236.

Hunt, B., Scott, D. 2007. Flow to a well in a two-aquifer system. Journal of Hydraulic Engineering. 12, No. 2, p 146–155.

Hunt, B., Smith, M. 2008. Improved spring depletion solution and analysis. Journal of Hydraulic Engineering. 13, No. 7, p 577–584.

Hunt, B., 2008a. Groundwater analysis using *Function.xls*. Manual to accompany Hunt's Excel spreadsheet software Function.xls. Version updated 15th August 2008. Downloadable from the website http://www.civil.canterbury.ac.nz/staff/bhunt.shtml

Hunt, B. 2008b. Stream depletion for streams and aquifers with finite widths. Journal of Hydraulic Engineering. 13, No. 2, p 80–89.

Jacob, C.E., 1944. Notes on determining permeability by pumping tests under watertable conditions. US Geological Survey Open File Report.

Jenkins, C. T. 1968. Techniques for computing rate and volume of stream depletion by wells. Ground Water, 6(2), 37-46.

Jones, A. and Gyopari, M., 2005. Investigating the sustainable use of shallow groundwater on the Kapiti Coast. Greater Wellington Regional Council Technical Publication, February 2005.

Jones, A. and Baker. T. 2005. Groundwater monitoring technical report. Greater Wellington Regional Council Report. June 2005.

Kruseman, G.P. and de Ridder, N.A. 1991. Analysis and evaluation of pumping test data, International Institute for Land Reclamation and Improvement. Wageningen, The Netherlands, 377 p.

Lough, H. 2004. The evaluation of hydrogeological parameters for stream depletion assessments. Thesis submitted in partial fulfilment of the requirements for the Degree of Master of Engineering at the University of Canterbury, Christchurch, New Zealand. 301 p.

Lough. H.K. and Hunt, B. 2006. Pumping test evaluation of stream depletion parameters. Ground Water, 44 (4), 540-546.

Lough, H. and Williams, H. 2009. Vertical flow in Canterbury groundwater systems and its significance for groundwater management. Environment Canterbury Technical Report U09/45, 69 p.

Neuman, S. P. and Witherspoon, P. A. 1968. Theory of flow in aquicludes adjacent to slightly leaky aquifers. Water Resources Research, 4, 103-112.

Neuman, S. P. 1972. Theory of flow in unconfined aquifers considering delayed response of water table, Water Resour. Res., 8(4), 1031–1044, 1972.

Neuman, S.P. 1974. Effect of partial penetration on flow in unconfined aquifers considering delayed gravity response. Water Resources Research, 10, no. 2: 303312.

Pattle Delamore Partners Ltd. 2002. Groundwater Model Audit Guidelines. Prepared for Ministry for the Environment, New Zealand. 72 p + appendices.

Pattle Delamore Partners Ltd. 2011. New Zealand Guidelines for the Monitoring and Management of Sea Water Intrusion Risks on Groundwater. Envirolink Project 420-NRLC50. 108 p.

Pattle Delamore Partners Ltd and Environment Canterbury. 2000. Guidelines for the Assessment of Groundwater Abstraction Effects on Stream Flow. Environment Canterbury Technical Report. U00/11, 114 p.

Scott, D.M. and B. Hunt, 2007. A water budget perspective of leaky aquifer response to pumping. Rotorua New Zealand Hydrological Society annual conference abstract.

Smith, M. 2009. Techniques for evaluating stream depletion effects: A supplement to the guidelines for the assessment of groundwater abstraction effects on stream flow (2000). Environment Canterbury Report No. R09/53.

Theis, C. 1935. The relation between the lowering of the piezometric surface and the rate of duration of discharge of a well using ground-water storage. Trans. American Geophysical Union 2, 519-524

Theis, C. V. 1941. "The effect of a well on the flow in a nearby stream." American Geophysical Union -- Transactions, 22(3), 734-738.

Zhan H., and Zlotnik., V. A. 2002. Groundwater flow to a horizontal or slanted well in an unconfined aquifer, Water Resources Research, 38 (7), 1108.

Appendix A: Aquifer Test Design

Equipment Considerations for Pumping Tests

Pumping Test Design Plan Checklist

Equipment Considerations for Pumping Tests

At pumping well

- ☐ Pump with a non-return valve. It is important when the recovery starts that no water from the irrigation system or connected pipes flows back into the pumped well when water level measurements are taken at the pumped well.
- ☐ A flow meter close to the pumped well so the person adjusting the pump valve can immediately see the effect of adjustment on the flow rate.

At the discharge point

- ☐ Water chemistry sampling bottles and supplies (if required).
- ☐ Anti-scour materials to prevent erosion while discharging test water.

At each observation well

- ☐ Water-level probe (each well to have its own) or other water-level measuring device.
  Transducers are excellent for recording but ideally will be checked with regular manual measurements. Data loggers should all be synchronised
- ☐ Record keeping materials, if measurements are taken manually at each site.
- ☐ Label the measuring point on every measured well.

Other

- ☐ Location sketch of the test layout including wells, discharge point and any other important surface features (e.g. streams).
- ☐ Camera
- ☐ GPS
- ☐ Field communications: 2-way radios for communicating between sites and agreed hand signals, if required
- ☐ Laptops for logger download.
- ☐ Copy of relevant health and safety guidelines.

Pumping Test Design Plan Checklist

A pumping test design plan should cover the following:

- ☐ **Test Purpose**
- ☐ **Expected hydrogeological environment**
  - Potential boundary conditions (streams/geological boundaries).
  - Existing pump/step test information
- ☐ **Map of test site** including pumping well, observation wells, discharge point, and surface water bodies.
- ☐ **Well Details** (pumping observation and background)
  - GPS location
  - Depth, screen placement, bore-log
  - Static water level range
  - Distance to pumping well
- ☐ **Proposed test duration**
- ☐ **Proposed Pumping rate(s)**
- ☐ **Estimated drawdown at monitoring wells** based on proposed pumping rate(s) and estimated parameters and model.
- ☐ **Methods of measurement**
  - **Pump rate measurement**
    - Proposed frequency and Method (e.g. orifice meter).
  - **Depth to water level measurement**
    - Proposed frequency and Method
- ☐ **Other measurements**
  - Barometric pressure, Location, frequency and method
  - Rainfall, Location, frequency and method
  - Stream Flow, Location, frequency and method
- ☐ **Discharge of water**
  - If discharge is to a stock/irrigation water race or stream, is water body capable of receiving the water? (i.e., will flooding be an issue).
  - Does local District Council need to be informed of discharge?
  - Is discharge of water likely to cause aquifer recharge that will affect testing results (i.e. if test is in same aquifer or a highly connected aquifer)?
- ☐ **Legal requirements**
  - Does pumping test meet relevant Regional Council requirements? (i.e. duration, pumping rate).

Does test design meet requirements of any relevant consent conditions?

Appendix B: Example Aquifer Test Forms

Constant Discharge Aquifer Test Data

Step Drawdown Aquifer Test Data

Constant Discharge Aquifer Test Summary

Step Drawdown Aquifer Test Summary

Checklist for Aquifer Test Reports

Constant Discharge Aquifer Test Data

Observation well number ....
Pumping well number ....
Persons measuring ....
....

Distance from pumping well ....m
Pumping rate (average)..L/s
Initial depth to water..m
Measuring point description ....

Page ____ of _____ pages

Date	Clock time (24-hour)	Time into test (min) Pumping	Recovery	Depth to water (m)	Uncorrected drawdown (m)	Drawdown correction (m)	Corrected drawdown (m)	Pumping rate (L/s)	Person measuring (initials)	Comments

INSTRUCTIONS
Data pages for *Constant Discharge* Aquifer Test

General Instructions

1. Each well (pumping or observation) has its own unique sequence of data pages.

Specific Instructions:

I. Unit definitions: L, litre; m, metre; min, minute; s, second

II. Observation well number Well number for the data recorded on the page
   - A. A record for the pumped well will record the same well number in this space as in the next line for Pumping well number.
   - B. A data record for a non-pumping well will record its own well number here.

III. Pumping well number: The well number for the well that is being pumped.

IV. Persons measuring: Record last name and first 2 initials of those recording data at this observation well.

V. Measuring point description: Brief description, such as "top of casing" or "white paint on casing." *Here and elsewhere, depths below datum are without sign or are negative (-), above datum are positive (+).*

VI. Page ____ of ____ pages Record sequential page numbers as pages are completed; then add the total pages at test completion.

VII. Date It is sufficient to record the date at the start of the test and with the start of each new day's date.

VIII. Clock time Record the real time, as you see on your watch during the test at each measurement time.

IX. Time into test
   - A. Record as minutes. If you record the first several measurements as seconds, clearly label the values in seconds (label with "s") in the upper half of the box and later convert to minutes in the lower half of the box.
   - B. Examples
     1. "-10" indicates a measurement at 10 minutes before the pump is scheduled to be turned on, this may be used when establishing the Initial depth to water.
     2. "0" is the moment the pump is turned on.
     3. "10" is ten minutes after the pump was turned on.
   - C. Pumping Times recorded while the pump is pumping
   - D. Recovery Times recorded after the pump was turned off; "0" minutes at the moment the pump is turned off.

X. Uncorrected drawdown Determined from the following calculation: Depth to water - Initial depth to water.

XI. Drawdown correction Any and all corrections to raw test drawdown data, such as corrections for antecedent trends during test duration in which water levels have risen or dropped, regardless of the test occurring.

XII. Corrected drawdown Drawdown to be plotted for analysis, after corrections for antecedent trends, barometric efficiency, etc. Corrected drawdown = Uncorrected drawdown – Drawdown correction.

XIII. Pumping rate Complete this column only for the pumping well data form.

XIV. Person measuring Initials of person(s) making each measurement; record for every measurement or use ditto marks to indicate successive measurements by the same person(s).

XV. Comments Record any information that may later explain an anomalous measurement, such as "pump stopped," "odd, will re-measure," or "train passed."

Step Drawdown Aquifer Test Data

Pumping well number .... Observation well number ....
Pumping rates: 1)....... . 2) .... 3)......... 4).......... 5)..........L/s Distance to pumping well ....
Initial depth to water ... .m Persons measuring ....
Measuring point description ....

Page ____ of _____ pages

Date	Clock time (24-hour)	Time into test (min) Pumping	Recovery	Depth to water (m)	Uncorrected drawdown (m)	Drawdown correction (m)	Corrected drawdown (m)	Pumping rate (L/s)	Person measuring (initials)	Comments

INSTRUCTIONS
Data pages for *Step Drawdown* Aquifer Test

General Instructions
1. Each well (pumping or observation) has its own unique sequence of data pages.

Specific Instruction

I. Unit definitions: L, litre; m, metre; min, minute; s, second.

II. Measuring point description Brief description, such as "top of casing" or "white paint on casing." *Here and elsewhere, depths below datum are without sign or are negative (-), above datum are positive (+).*

III. Persons measuring Record last name and first 2 initials of those recording data at this well.

IV. Page ____ of ____ pages Record sequential page numbers as pages are completed; then add the total pages at test completion.

V. Date It is sufficient to record the date at the start of the test and with the start of each new day's date.

VI. Clock time Record the real time, as you see on your watch during the test at each measurement time.

VII. Time into test
   - A. Record as minutes unless you label as seconds, such as within the first few minutes of the test where measurements may be in seconds. Where you record seconds, write the values in seconds (label with "s") in the upper half of the box and later convert to minutes in the lower half of the box.
   - B. Examples
     1. "-10" indicates a measurement at 10 minutes before the pump is scheduled to be turned on, may be used to establish Initial depth to water.
     2. "0" is the moment the pump is turned on.
     3. "10" is ten minutes after the pump was turned on.
   - C. Pumping Times recorded while the pump is pumping.
   - D. Recovery Times recorded after the pump was turned off; "0" minutes at the moment the pump is turned off.

VIII. Uncorrected drawdown Determined from the following calculation: Depth to water - Initial depth to water.

IX. Drawdown correction Any and all corrections to raw test drawdown data, such as corrections for antecedent trends during test duration in which water levels have risen or dropped, regardless of the test occurring.

X. Corrected drawdown Drawdown to be plotted for analysis, after corrections for antecedent trends, barometric efficiency, etc. Corrected drawdown = Uncorrected drawdown – Drawdown correction.

XI. Pumping rate Complete this column only for the pumping well data form.

XII. Person measuring Initials of person(s) making each measurement; record for every measurement or use ditto marks to indicate successive measurements by the same person(s).

XIII. Comments Record any information that may later explain an anomalous measurement, such as "pump stopped," "odd, will re-measure," or "train passed."

CONSTANT DISCHARGE AQUIFER TEST SUMMARY

Report number:		**Well numbers**					
Town:							
District:							
Grid reference:		Pumping	Observation				
Test date:							
Test results							
	Reported	Individual					
Aquifer							
Transmissivity (m^2/d)							
Storativity							
Specific yield							
Hydraulic conductivity (m/d)							
Vertical hydraulic conductivity (m/d)							
Specific capacity ((L/s)/m)							
Confining Layer							
Aquitard Conductance (m/d)							
Supplemental information							
Distance from pumping well (m)							
Aquifer saturated thickness (m)							
Confining layer thickness (m)							
Average pumping/discharge rate (l/s)							
Final depth-to-water (m)							
Initial depth-to-water (m)							
Maximum drawdown (m)							
Analysis methods (Tick applicable methods)							
Confined	Theis						
	Other						
Semi-confined	Hunt and Scott						
	Other						
Unconfined	Theis						
	Other						
Other: …………………………………………………							
Data corrections (Tick applicable corrections)							
Tidal							
Antecedent trend							
Barometric efficiency							
Jacob correction for unconfined							
Boundaries							
Well interference							
Other: …………………………………………………							

Duration: pumping ……………..min; recovery……………..min

Water chemistry collected: • field values • lab analysis

Test commissioned by …………………………………………………

Test undertaken by ……………………………………………………

Test analysed by ………………………………………………………

Comments

……………………………………………………………………………

……………………………………………………………………………

……………………………………………………………………………

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……………………………………………………………………………

Reliability:…… Rated by/date:………………………………

Plan view of test site (wells, discharge, landforms, etc.)

STEP DRAWDOWN AQUIFER TEST SUMMARY

Pumping well number ....
Report number ....
Test date ..../......./....................

Town ....
District ....
Grid reference ....

Test results

Transmissivity ....m^2/d
Hydraulic conductivity ....m/d
With observation wells:

Well number	Distance from pumping well (m)	Storativity	Confining layer vertical hydraulic conductivity (m/d)

Step-discharge test coefficients
Linear aquifer/well loss coefficient $B(r_{ew},t)$ ....d/m^2
aquifer loss $B_{1(rw,t)}$ ....d/m^2
well loss B_2 ....d/m^2
Non-linear well-loss C ....d^2/m^5

Well efficiency ....%
Maximum long term pumping discharge ....l/s

Supplemental information

Aquifer saturated thickness ....m
Confining layer thickness ....m
Free flowing (artesian) discharge........................L/s
Water chemistry collection and analysis
- Field values
- Laboratory analysis

Test commissioned by ....
Test undertaken by ....
Test analysed by:...

Analysis method

Confined
- Eden-Hazel
- Other

....

General
- Hantush-Bierschenk
- Rorabaugh
- Sheahan
- Other

....

- Other

....

Data corrections

- Tidal
- Antecedent trend (natural water-level fluctuation)
- Barometric efficiency (confined analysis)
- Jacob modification of confined for unconfined
- Boundaries
- Well interference
- Other ....

Step number	Dis-charge (L/s)	Step duration (min)	Draw-down (m)	Drawdown increment (m)	Specific drawdown (d/m^2)	Specific capacity ((L/s)/m)	Plan view of test site (wells, landforms, etc.) Please attach as larger copy.

Comments

....

....

Reliability rating: .... By: .... Date: ....

CHECKLIST FOR AQUIFER-TEST REPORTS

An aquifer test report is to re-create the aquifer test conditions and events for a person who did not participate, including all items that affect the test results. More specifically, a test report should include the items in the following outline.

Title page to include

- ☐ Report title including locality and pumping well number.
- ☐ Author(s) and report date.

Executive summary to include:

- ☐ Test location, including the nearest town and district.
- ☐ Date and duration of the testing.
- ☐ Purpose of testing (Aquifer parameters, actual well interference etc.).
- ☐ Aquifer parameters value that represent the aquifer test results and the range of values.

Report to include:

- ☐ Hydrogeological summary.
- ☐ Map of test site including; pumping well, observation wells, discharge point, any recharge/no-flow boundaries, and surface water bodies.
- ☐ Dates and duration of pumping and recovery periods.
- ☐ Wells pumped and observed, with static water levels.
- ☐ Any data corrections applied (such as antecedent trends, barometric, etc.).
- ☐ Analysis method(s) applied to determine aquifer characteristics, along with solution assumptions.

Discussion and analysis.

- ☐ Data used to correct observed data.
- ☐ Plotted test data.
- ☐ Include all calculations that lead to the determination of aquifer characteristics.
- ☐ Discussion of reliability of data and analysis; aquifer test assumptions.
- ☐ Note any unmet or partly met assumptions.
- ☐ Note any other general factors that affected test or analysis results.

Submit the final report to Greater Wellington as:

- ☐ Paper copy.
- ☐ Electronic copy.
- ☐ Please include a copy of all data electronically.