Groundwater/Surface Water Integrated Management

MAUNU-MAUNGATAPERE-WHATITIRI BASALT AQUIFERS

- Final
- February 2012

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Executive Summary

The Northland Regional Council (NRC) requires technical assessments to determine the interconnection between groundwater and surface water, particularly the degree of connectivity and the temporal and spatial impacts of groundwater pumping in basalt aquifers (i.e. Maunu-Maungatapere-Whatitiri and Kaikohe (Monument Hill) basalt aquifers). This information is needed to inform policy relating to water allocation for the Regional Plans and to provide a clear direction on how such policy could be framed.

A review of Regional Plans was undertaken for all Regional and Unitary Councils throughout New Zealand, with particular emphasis placed on recent Plan Changes in order to assess the latest policies and rules adopted regarding surface water and groundwater interactions. Overall, the review indicated that many Regional and Unitary Councils throughout New Zealand are taking a pragmatic approach to the management of the interconnection between surface water and groundwater (i.e. development of specified guidelines, acknowledgement of potential lag effects in the surface water-groundwater connection). However, the current policy that addresses the nature of surface water and groundwater interaction has not been specifically developed for basalt aquifers and hence can not be used to inform NRC on policy for basalt aquifers.

Given this finding, stream depletion analytical methods, which use mathematical solutions to calculate the effects of stream depletion as a result of groundwater abstraction and typically constitute the basis for the management methods used by regulatory authorities, were reviewed in order to assess their applicability to basalt aquifers and hence their usefulness to NRC for the assessment of surface water/groundwater interactions. Overall, this review determined that there are several methods available that could be applicable to basalt aquifers, in particular methods that incorporated boundaries. The incorporation of aquifer boundaries are consistent with the geological setting of Northland's basalt complexes.

Following these reviews, work was undertaken in order to assess whether an analytical method for assessing groundwater-surface water interaction specific to Northland basalts could be developed. The work undertaken involved three stages:

- ***Aquifer Conceptualisation*** –identification of four typical geological settings found within Northland basalt, from analysis of the typical geological settings within the Maunu, Maungatapere, Whatitiri and Monument Hill basalt complexes;
- ***Numerical Modelling*** - Development and simulation of conceptual numerical models to represent the four conceptual aquifer settings;
- ***Analytical Methods*** – Development of an analytical method and calibration to the numerical models for assessment of stream depletion effects.

The results of this work indicated that:

- Preliminary testing of the three fractured basalt settings all produced very similar results for stream depletion in numerical simulations and as such can all be represented using the fractured basalt setting;
- Scoria settings likely to occur in the Northland basalt aquifers are likely to have the water body (either a spring or stream) situated at the edge of the boundary between the scoria and the less permeable units at its boundary, making the scoria setting similar to the fractured basalt setting with the hydraulic properties of basalt replaced with those of scoria; and
- Use of a bounded aquifer tool such as the Hunt (2007) method would be appropriate for determination of stream depletion effects in localised basalt flows or compartmentalised basalt catchments.

With this understanding, the Hunt (2007) method was further developed with the purpose of producing a prototype Stream Depletion User Interface Tool for NRC to evaluate it usefulness in assisting applicants or Council staff in water allocation applications or decisions.

The tool predicts a stream depletion rate from input parameters in a consent or consent application, such as proposed peak and average abstraction rates, the distance of the bore from the stream, aquifer setting type, and the thickness of the aquifer.

This tool implements an adaptation of the Hunt (2007) method. Several methods were assessed against numerical simulations, however this method was chosen because:

- It allows for the extent of the aquifer to be limited. This is necessary because the catchment and geological boundaries of the aquifer focus depletion into the stream.
- It is available in excel format and can be easily modified.
- It can be distributed on the condition that the original source (Bruce Hunt) is acknowledged.
- It produced good results on the slightly conservative side when it was compared against numerical simulation results for the same settings.

Following the development of this tool, recommendations for changes to the current Regional Plan with regards to groundwater-surface water interaction in basalt aquifers are as follows:

- The first step of the process is to define the minimum flow requirements for the stream of interest. In order to keep this assessment conservative, the minimum flow recommendations in the Proposed National Environmental Standard on Environmental Flows and Water Levels (Ministry for the Environment, 2008) could be used.
- It is recommended that the Stream Depletion User Interface Tool, if considered appropriate, be incorporated into the Regional Plan via a Schedule. This Schedule could be developed in a

similar format as Schedule 5A of the Proposed Plan Change 1 C for the Otago Regional Council (see **Section 2.13**). As such, this Schedule would overview the tool and provide advice on matters such as:

- situations where stream depletion effect in basalt aquifers is unlikely;
- use of analytical equations other than Hunt (2007); and
- use of numerical flow models to determine streamflow depletion effects.

1. Introduction

The Northland Regional Council (NRC) requires technical assessments to determine the interconnection between groundwater and surface water, particularly the degree of connectivity and the temporal and spatial impacts of groundwater pumping in basalt aquifers (i.e. Kaikohe and Maunu-Maungatapere-Whatitiri basalt aquifers).

This information is needed to inform policy relating to water allocation for the Regional Plans and to provide a clear direction on how such policy could be framed. Many Regional Councils in New Zealand have policies relating to the interconnection between surface water and groundwater, however few of these policies relate specifically to basalt aquifers.

For the purpose of this study, the technical assessments will concentrate on specific features or conceptual aquifer settings that are prevalent in the Maunu-Maungatapere-Whatitiri and Kaikohe basalt aquifers, both of which have previously been studied separately for groundwater yield and surface water yield.

The specific objective of this project is to:

- provide appropriate methodologies to determine groundwater and surface water interaction in basalt aquifers in Northland. These methodologies need to consider the limitations of the data available for some of Northland basalt aquifers; and

- recommend appropriate surface and groundwater interaction policy, and provide a draft of how these policies may be framed and transferred to basalt aquifers in Northland.

This project will be undertaken in the following stages, comprising:

1) ***Review of Background Information*** – high level review of technical assessments and policy development undertaken both in New Zealand and Australia relating to surface water and groundwater interconnection, particularly in regards to applicability to basalt aquifer catchments.
2) ***Analytical Method Development*** – this stage aimed to assess whether an analytical method for assessing groundwater-surface water interaction specific to Northland basalts could be developed. The work undertaken involved three steps described as follows:
   - ***Aquifer Conceptualisation*** –identification of four typical geological settings found within Northland basalt, from analysis of the typical geological settings within the Maungatapere, Whatitiri, Maunu and Monument Hill (Kaikohe) basalt complexes;
   - ***Numerical Modelling*** **-** Development and simulation of conceptual numerical models to represent the four conceptual aquifer settings;

- ***Analytical Methods*** – Development of an analytical method and calibration to the numerical models for assessment of stream depletion effects.

2. Review of New Zealand Policy and Rules

2.1. Introduction

The movement of water between surface water and groundwater, and hence interconnection between water bodies occurs in all settings, e.g. in streams, lakes, and wetlands with aquifers. Given the interconnection between water bodies, abstraction from groundwater bores can reduce the flow and/or volume of water in neighbouring surface water bodies. This effect is commonly called stream depletion.

Understanding the magnitude and timing of stream depletion effects has become increasingly important in the management of surface water bodies, particularly in catchments where surface water allocation is reaching sustainable limits.

Regional Councils throughout New Zealand have been developing policies and rules that deal specifically with the management of water allocation in hydraulically connected water sources. In general, these policies and rules have taken into consideration the characteristics of the surface waterway that could be depleted as wells as the type of aquifer (and hence the level of connection) from which the groundwater abstraction is occurring, e.g. a riparian aquifer located along a surface waterway will have a high connection, while a confined aquifer will have a low connection with surrounding surface waterways.

A review of Regional Plans was undertaken for all Regional and Unitary Councils throughout New Zealand, with particular emphasis placed on recent Plan Changes in order to assess the latest policies and rules adopted regarding surface water and groundwater interactions. Gisborne District Council and Marlborough District Council have not been included in the review below as the Regional Plans for both Councils do not include any specific information regarding surface water and groundwater interactions.

2.2. Auckland Council

The Auckland Regional Plan: Air, Land and Water (ALWP) provides for the management of air, land and water resources in the Auckland Region. The ALWP was made operative in part on the 21st October 2010, with Chapter 6, relating to Water Allocation, being currently operative.

The potential for stream depletion effects from groundwater abstraction is outlined in Section 6.1.3.6 of the ALWP. High use aquifers that are particularly vulnerable to these effects are identified and include the Onehunga, Mt Wellington and Franklin volcanic aquifers. In addition, Section 6.1.4 outlines the management approach adopted by Auckland Council in order to meet the objectives of the ALWP, which includes “integrated management where surface and groundwater availability are closely related”.

The integrated management of surface water and groundwater resources is outlined in Policy 6.4.13 that states:

6.4.13: Where a resource consent is granted to take, use and/or dam water, the consent shall include a condition setting the duration and review date of the consent such that:

(c) Where surface and groundwater availabilities are closely related, all consents to take surface water and groundwater within the combined catchment/aquifer system shall be reviewed concurrently and shall expire at a date that coincides with a future review date so that water quantity and quality issues within that catchment/aquifer system can be considered on an integrated and comprehensive basis;

unless it is appropriate to set a different expiry or review date for any individual consent in order to avoid, remedy or mitigate the adverse effects of that activity.

In addition, Policy 6.4.28 outlines the factors that should be used to determine the sustainable volume of water from an aquifer. These factors include:

(a) Aquifer recharge;
(b) The spatial distribution of bores; and
(c) Outflow requirements of the aquifer, including
(i) flow at the coast, to prevent saltwater intrusion;
(ii) requirements of streams and springs;
(iii) recharge of adjacent or underlying aquifers.

The management of groundwater resources and the potential effects of groundwater abstraction on surface water bodies is undertaken using the calculated water availability within aquifers (i.e. sustainable yields) as outlined in Policies 6.4.29 and 6.4.32, which state:

6.4.29 Water allocated to users in an aquifer shall not exceed the water availability for that aquifer as specified in Schedule 2 of this plan.

6.4.32 In aquifers where monitoring shows that outflow requirements are not being met (as indicated by, for example, the occurrence of saltwater intrusion, reduction of stream and spring base flow to levels where an adverse effect is occurring or where adequate recharge to adjacent or underlying aquifers is not occurring), adverse effects on the environment shall be avoided, remedied or mitigated by:

(a) Ceasing any further allocation of groundwater;

(b) Temporarily restricting the taking of water by the issuing of a water shortage direction under Section 329 of the RMA;

(c) Reviewing the conditions of existing consents in accordance with General Policy 6.4.14.

Lastly, Policy 6.4.35 states that any application to take and use groundwater shall demonstrate that:

(a) Water availability for the aquifer will not be exceeded;
(b) The taking of groundwater will not reduce groundwater levels to below a minimum level at a location in an aquifer set by this plan;

(c) The taking of groundwater will avoid, remedy or mitigate adverse effects on surface water flows, including:

(i) base flow of streams and springs; and
(ii) any stream flow requirements;

The ALWP does not have any specific rules related to stream depletion effects, other than identifying that any applications for groundwater abstraction from a high use aquifer is a discretionary activity.

Overall, this review has identified that Auckland Council has adopted a sustainable yield approach for managing stream depletion effects from groundwater abstraction, and relies on applicants to demonstrate that the level of groundwater abstraction will not result in any adverse effects within the surface water body. In addition, although there are volcanic aquifers throughout the Auckland Region identified as being High Use Aquifers, there are no specific stream depletion policies or rules for these aquifers.

2.3. Waikato Regional Council

The Waikato Regional Plan contains policy and methods to manage the natural and physical resources of the Waikato Region. The Plan became operative in part on 28 September 2007. The non-operative sections of the Plan are those that remain subject to variations. Proposed Variation No 6 (Variation 6) – Water Allocation was proposed to manage the allocation and use of fresh water over the Waikato Region.

Variation 6 was notified for submissions in late 2006, with submissions heard by a Hearing Committee between December 2007 and March 2008. Waikato Regional Council adopted the recommendations of the Hearing Committee in October 2008 as its decision.

Thirty seven notices appealing the decision were lodged with the Environment Court on all aspects of the decisions. The Environment Court sat between February and August 2011 and the committee have indicated that the decision will be released by the end of 2011. The most up-to-date version of Variation 6 is understood to be "End of Environment Clean Hearing Version – 8 August 2011", which has been used in the following review.

The interconnection between surface water and groundwater has been included extensively within the policies of Variation 6 as Waikato Regional Council have identified the importance of accounting for stream depletion effects in water management, particularly in surface water catchments that are considered as being over-allocated.

The following policies of Variation 6 outline surface water and groundwater interactions and how they are to be managed in the Waikato Region:

Policy 5: How Groundwater Takes will be Classified

The Waikato Regional Council shall manage that taking of groundwater resources in a manner that meets the criteria for establishing Sustainable Yields from groundwater resources listed in Policy 2 by:

h) Notwithstanding Policies a) to g), assessing the nature of hydraulic connection (if any) between groundwater takes and surface water bodies and, if there is such a connection as defined by Policy 9 sa), having regard to relevant parts of Policy 8 and Policy 9 when making decisions on groundwater takes.

Policy 9: Consent Application Assessment – Criteria – Groundwater

When assessing resource consent applications for groundwater takes and/or any associated water use, the effects of these activities shall be assessed individually and cumulatively with all other existing (or currently applied for) water take and use activities. In doing so the Council shall have particular regard to the following matters:

sa) The nature of hydraulic connection (if any) between the groundwater resource from which water is proposed to be taken and surface water bodies will generally be assessed on a case by case basis by evaluating:

i) groundwater depletion of surface water bodies (i.e. replacement of abstracted groundwater by flows from surface water bodies); and

ii) where no Table 3-6 Sustainable Yield has been identified for the groundwater resource, groundwater interception (i.e. the reduction of groundwater flows to surface water bodies)

Where the case by case assessment demonstrates that there is a hydraulic connection and the assessed maximum surface water body depletion and interception loss (in cubic metres per day) calculated for the term of the consent exceeds 15 cubic metres per day then the Waikato Regional Council will assess the nature of the effect of the groundwater take on surface water bodies having particular regard to the relevant parts of Policy 8.

The nature of hydraulic connection does not need to be assessed and the groundwater take need not be assessed against Policy 8 or Policy 9 s) where:

iii) the physical separation between the surface water body(s) and the underlying groundwater table is large enough to ensure that if there was a lowering of the groundwater table from pumping this would not impact the surface water body (as calculated for streams using the Advisory Note at the end of this Policy); or

v) the take is allowed by s14(3)9b) of the RMA, or is less than 15 cubic metres per day (the maximum allowed by Permitted Activity Rule 3.3.4.9); or

vi) the take is temporary and is allowed by Permitted Activity Rule 3.3.4.11; or

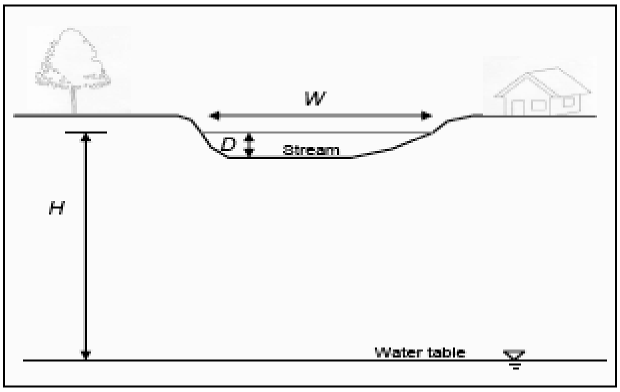
vii) the take is for well or aquifer testing and is allowed by Permitted Activity Rule 3.3.4.12; or *ix) the take is a renewal of a groundwater take consent within the Waikato River catchment upstream of the HPS mixing zone* and the take was authorised at 15 October 2008*

Except in the circumstances described under (v) to (ix) above, the nature of hydraulic connection shall always be assessed for groundwater takes within the Waikato River catchment upstream of the Karapiro Dam unless a Table 3-6 Sustainable Yield has been set for the groundwater resource from which the groundwater take is to occur.

s) Restricting groundwater takes in circumstances where there is a hydraulic connection between the groundwater resource from which the applicant proposes to take groundwater and a surface water body and the take will reduce the amount of water that would otherwise be available for renewable electricity generation or be used for cooling of the Huntly Power Station, including in particular any groundwater takes from the Waikato River catchment upstream of the HPS mixing zone whose surface flow depletion effects, when assessed in combination with all other authorised water takes, would exceed 100% of the primary allocable flows in Table 3-5.

Advisory Notes for Policy 9(sa)

- *The physical separation described in Policy 9 sa) iii) for streams exists when:*
  - *i. The depth to the water table (H) below a stream that occurs within the area affected by the groundwater abstraction is greater than five times the maximum depth of water in the stream (D), i.e. $H \geq 5D$, and*
  - *ii. The depth to the water table below any potential affected stream surface (H) is greater than twice the stream width (W), i.e. $H \geq 2W$.*
- *For avoidance of doubt, the water table (H) is the level below the land surface at which the subsurface material is fully saturated with water.*



Implementation Method 3.3.4.6B Groundwater Depletion of Surface Water (Method to implement Section 3.3.3 Policy 5(h))

Waikato Regional Council will manage the surface water depletion effects identified by Policy 5 h) and Policy 9 sa) using either one or both of the following methods.

a) *A groundwater take will have surface water restrictions imposed where there is a hydraulic connection between the two systems, and a restriction of the groundwater take will result in an increase in surface water flows during times of restrictions.*

b) *Where a groundwater take is assessed under Policy 5 h) as impacting on surface water resources and this cannot be solely managed with restrictions on the groundwater take, the reduction in surface water flow occasioned by the groundwater take will be quantified and included in the surface water allocation regime used for assessing the cumulative allocation for the surface water takes in Chapter 3.3. The remainder of the groundwater take (the actual rate of take less the amount quantified as being a reduction in surface water flow) will be allocated against the sustainable yield in Table 3-6.*

Overall, the Variation 6 policies outlined above ensure that an assessment of potential impacts on the connection between surface water and groundwater is considered by the applicant when a groundwater take application is undertaken and the appropriate implementation method can be applied to the resource consent.

However, the applicability of these policies to all aquifer types and catchments can become problematic. In particular, applying the Advisory Note in Policy 9 sa) to confined or semi-confined (leaky) aquifers.

A confined aquifer is hydraulically isolated from overlying aquifers or surface water bodies by a confining layer (aquiclude) or layers (aquitards), and hence in these aquifers, groundwater pressure measured in a well or standpipe may be significantly different to groundwater levels in the overlying unconfined or water table aquifer. Semi-confined aquifers, while not totally isolated from overlying aquifers, exhibit a significant degree of disconnection from the overlying aquifers or surface water bodies, hence may also have differing groundwater levels. Where the aquifer is confined, vertical separation distance between the surface water body and the water table is not relevant because there is no hydraulic connection. The applicability of the method outlined in Policy 9sa) to basalt aquifers is outlined in **Section 4.2**.

2.4. Bay of Plenty Regional Council

The Bay of Plenty Regional Water and Land Plan aims to promote the sustainable and integrated management of land and water resources within the Bay of Plenty Region. The Plan was made operative on 1 December 2008, with Plan Change 8 (Groundwater Bores and Flooding Conditions) incorporated in 2 March 2010.

Chapter 5 of the Regional Water and Land Plan outlines the regions objectives, policies and methods for Water Quantity and Allocation. The following are the sections of the Regional Plan that specifically relate to the interconnection between surface water and groundwater.

Objective 43
Abstraction of groundwater at a volume and rate that does not:
(a) Permanently or unsustainably lower water levels or decrease groundwater quality in aquifer systems.
(b) Permanently or unsustainably lower water levels in streams or rivers where groundwater and surface water bodies are linked.

Policy 74
To investigate the linkage between groundwater and surface water bodies to determine if groundwater takes are adversely affecting water flows in streams, rivers and springs.

Policy 75
To take appropriate action within the framework of this regional plan (including future plan changes) to address the adverse effects of groundwater takes on associated surface water bodies where investigations prove this is a significant issue in the areas noted in Method 184.

Method 165
Consider using any of the following methods to address the adverse effects of groundwater takes on associated surface water bodies:

- *(a) Initiate a Plan change to address the outcomes of the investigations in respect to the linkage between groundwater and surface water bodies. This may include, but not be limited to, provisions to control the proximity of groundwater bores to surface water bodies, and the volume of groundwater abstractions.*
- *(b) Work with existing groundwater abstractors, including water user groups where appropriate*

Method 184
Investigate the linkages between groundwater and surface water in the Bay of Plenty, as necessary, in the Galatea plains, Opotiki plains, and areas where there are large abstractions of groundwater in the recharge areas of springs used for municipal water supply.

Overall, the information within the Bay of Plenty Regional Water and Land Plan on the interconnection between surface water and groundwater is currently high level, with provision to update the Plan based on the findings from any investigations undertaken into these connections. Hence, these policies and methods do not aid in the identification of policies for use in basalt aquifers.

2.5. Hawkes Bay Regional Council

The Hawkes Bay Regional Resource Management Plan (RRMP) sets out a policy framework for managing resource use activities in an integrated manner across the whole of the Hawkes Bay Region. The RRMP became operative in August 2006.

The interconnection between surface water and groundwater was identified within the RRMP as an important consideration, particularly with regards to the Heretaunga Plains aquifer (an unconfined gravel aquifer). This is due to the fact that the main recharge to Heretaunga Plains aquifer is from the Ngauroro and Tutaekuri Rivers, and direct infiltration of rainfall on the unconfined aquifer.

Policy 77 outlines the environmental guidelines within the RRMP with regards to groundwater quantity as outlined below.

POL 77 ENVIRONMENTAL GUIDELINES - GROUNDWATER QUANTITY
(a) To manage takes of groundwater to ensure abstraction does not exceed the rate of recharge.
(b) To manage the available groundwater resource to ensure supplies of good quality groundwater.
(c) To manage the groundwater resource in such a manner that existing efficient groundwater takes [21(1)] are not disadvantaged by new takes.
(d) To manage takes of groundwater to ensure abstraction does not have an adverse effect on rivers, lakes, springs, or wetlands.

The guidelines to achieve this policy are set out in Table 11.

Table 11. Environmental Guidelines – Groundwater Quantity
Guidelines that apply across the entire Hawke's Bay region

Item	**Guideline**
1. Demand	*The safe yield identified for an aquifer should not be exceeded*
2. Effects of takes on water quality	*Takes should not contribute to the intrusion of salt water into fresh water aquifers*
3. Effects of takes on levels of river, lakes, springs and wetlands	*Takes should not cause a reduction in the flow of rivers, levels of springs or lakes or ecologically significant wetlands*
4. Effects of new takes on existing authorised users	*The take should not adversely impact on existing efficient groundwater or surface water takes unless written approval from affected persons is obtained.*

Although the interconnection between surface water and groundwater has been identified within the RRMP, in particular under Item 3 in the Environmental Guidelines that states that no reduction in river flows etc is allowed, there is no direction in the policies or rules outlining the method to determine the level of effect on surface water bodies. As such, the Council are reliant on applicants to provide information in resource consent applications regarding the level of connection, and hence the assessment of effects.

[1] **21** For the purposes of this Plan **"efficient taking"** of groundwater means abstraction by a bore which penetrates the aquifer from which water is being drawn at a depth sufficient to enable water to be drawn all year (i.e. the bore depth is below the range of seasonal fluctuations in groundwater level), with the bore being adequately maintained, of sufficient diameter and screened to minimise drawdown, with a pump capable of drawing water from the base of the bore to the land surface.

2.6. Horizons Regional Council

Horizons Regional Council notified the proposed One Plan on 31 May 2007. Hearings on the One Plan started in July 2008, with Horizons Regional Council releasing its decision in August 2010. The One Plan has been appealed and is currently awaiting an Environment Court hearing. As such the plan is not currently operative.

Part 1 of the proposed One Plan comprises the Regional Policy Statement for the Manawatu-Wanganui Region and is outlined in Chapters 1 to 10A. This statement describes the significant resource management issues facing the region and sets out objectives, policies and methods for addressing these issues.

Part II of the proposed One Plan is the Regional Plan for Manawatu-Wanganui Region and is outlined in Chapter 11 to 18. The main focus of Part II is on the regional rules outlining how activities are regulated and also contains policies designed to guide decision-making on resource consent applications.

The objectives and policies in Part 1 and Part II of the One Plan relevant to surface water and groundwater interconnection are outlined below.

Objective 6-3: Water quantity and allocation
Water quantity is managed to enable people, industry and agriculture to take and use water to meet their reasonable needs while ensuring that:

- b) *For groundwater:*
  - i) *takes do not cause a significant adverse effect on the long-term groundwater yield*
  - ii) *groundwater takes that are hydrologically connected to rivers are managed within the minimum flow and allocation regimes established for those rivers*
  - iia) *groundwater takes that are hydraulically connected to lakes or wetlands are managed to protect the life-supporting capacity of the lakes or wetlands*
  - iii) *the significant adverse effects of a groundwater take on other groundwater and surface water takes are avoided*

Policy 6-21: Overall approach for bore management and groundwater allocation

- a) *new bores must be constructed and managed in accordance with Policy 15-2A*[2]
- aa) *Groundwater Management Zones are mapped in Schedule C*
- b) *Total groundwater allocations must comply with the annual allocable volumes for groundwater managements zones set out in Policy 6-23*[3]
- c) *The measured or modelled effects of a proposed groundwater take on other groundwater users, surface waterbodies and saltwater intrusion must be managed in accordance with Policies 15-1*[4]*, 15-2B*[5]*, 15-2C and 15-2D*[6]

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[2] Bore Construction and Management (not relevant to this study)
[3] Groundwater Management Zones (not relevant to this study)

Policy 15-2C: Effects of groundwater takes on surface water bodies

The effects of groundwater takes on surface water bodies including wetlands must be managed in the following manner:

(a) An appropriate scientific method must be used to calculate the likely degree of connection between the groundwater and surface water at the location of the groundwater take e.g., using Targets for the Assessment of Groundwater Abstraction Effects on Stream Flow prepared by Environment Canterbury (Environment Canterbury Report R00/11, ISBN 1-86937-387-1, First Edition, June 2000).

(b) Subject to (a), the potential adverse effects of groundwater takes on surface water depletion must be managed in accordance with Table 15-1.

***Table 15-1** - Surface water depletion*
Classification of Surface Water

Classification of Surface Water Depletion Effect	***Magnitude of Surface Water Depletion Effect***	***Management Approach***
Riparian	*Any groundwater take screened within the geologically recent bed strata of a surface water body*	*The groundwater take is subject to the same restrictions as a surface water take, unless there is clear hydrogeological evidence that demonstrates that the effect of pumping will not impact on the surface water body*
High	*The surface water depletion effect is calculated as 90% or greater of the groundwater pumping rate after seven days of pumping, or 50% or greater of the average groundwater pumping rate after 100 days of pumping.*	*The groundwater take is subject to the same restrictions as a surface water abstraction.*
Medium	*The surface water depletion effect is calculated as 20% or greater and less than 50% of the groundwater pumping rate after 100 days of pumping.*	*The calculated loss of surface water is included in the surface water allocation regime, but no specific minimum flow restrictions are imposed on the groundwater take.*

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[4] Consent decision-making for takes and uses of surface water and groundwater (not relevant to this study)
[5] Effects on groundwater takes on other groundwater takes (not relevant to this study)
[6] Saltwater intrusion (not relevant to this study)

Low	*The surface water depletion effect is calculated as less than 20% of the groundwater pumping rate after 100 days of pumping.*	*The calculated loss of surface water is not included in the surface water allocation regime and no specific minimum flow restrictions are imposed on the groundwater take*

Overall, the policies within the Proposed One Plan provide prescriptive advice to applicants regarding how to calculate the stream depletion effects (i.e. reference to Environment Canterbury report *(Environment Canterbury Report R00/11, ISBN 1-86937-387-1, First Edition, June 2000)* in Policy 15-2C a). These guidelines have been developed to help the recognition of situations where significant stream depletion effects may occur and to provide tools that quantify the effects of groundwater abstraction on surface waterways. These tools include initial screening of sites where stream depletion is likely to occur, based on specific hydrogeological conditions, as wells as analytical methods developed to calculate the stream depletion effects. The applicability of these methods to basalt aquifers are outlined in detail in **Section 4.**

2.7. Taranaki Regional Council

The Regional Fresh Water Plan promotes the sustainable management of the Taranaki Regions freshwater resources and became operative in 2001. Policies and rules within the Regional Fresh Water Plan that relate to the interconnection between surface water and groundwater are outlined below.

POL 6.4.1
The taking of water from shallow groundwater within close proximity of a surface water body may affect water levels and flows in the surface water body and accordingly any consideration of such an abstraction will take into account:
- *(a the contribution of groundwater to surface flows;*
- *(b) the effects of any abstraction on the surface water body at the location in question.*

POL 6.4.3
When assessing resource consents for the taking and use of groundwater, the Taranaki Regional Council will take into account:
- *(a) the need to ensure groundwater is available for reasonable domestic needs, stock watering requirements and fire fighting purposes;*
- *(b) the need for the volumes of water sought;*
- *(c) the need to use water efficiently and with a minimum of waste;*
- *(d) the degree to which use of groundwater will avoid, remedy or mitigate adverse effects on surface water resources;*
- *(e) the need to install systems to accurately measure the volumes of water abstracted.*

Under the explanation section regarding Policy 6.4.1, the Plan states that "*where the taking of shallow groundwater in close proximity to a surface water body affects, or is likely to affect, water levels and flows in the surface water body, the Taranaki Regional Council will apply the same* *policies as would apply to a take directly from the adjacent surface water body*". These policies include having regard to:

- *the allocation limit of the water body;*
- *the natural, ecological and amenity values of the water body;*
- *the relationship of Tangata Whenua with the water body;*
- *the hydrological characteristics of the catchment including flow variability, flow recession characteristics and the relationship to groundwater recharge;*
- *the significance of flows and groundwater recharge for the maintenance or enhancement of downstream flows;*
- *Requiring quantities, levels and flows of water in rivers and streams that retain at least 2/3 habitat at mean annual low flow.*

Although this explanation outlines the process to be undertaken where a shallow groundwater take would, or is likely to, affect a surface water body, there is no direction in the policies or rules outlining the method to determine the level of affect, in particular with regards to different aquifer type, e.g. whether lag times in semi-confined (leaky) aquifers are taken into consideration. The only direction regarding groundwater takes with respect to surface water is stated in Permitted Activity Rule 48 below:

Permitted Activity Rule 48:

Activity	***Standard/Terms/Conditions***
Taking and use of water from a well or bore	• *The daily volume of abstraction shall not exceed 50 m^3* • *The rate of abstraction shall not exceed 1.5 L/s* • *The bore shall be located not less than 500 m from the sea of adjacent bores* • *The well shall be located not less than 25 m from the sea or adjacent wells or surface water bodies* • *The well or bore shall be located not less than 50 m from any effluent treatment pond, septic tank, silage stock or pit.*

The applicability of using a set back distance of groundwater takes from surface water bodies in a basalt aquifer setting will be investigated with the conceptual numerical modelling exercise, outlined in **Section 5**.

2.8. Greater Wellington Regional Council

The Regional Freshwater Plan for Wellington identifies issues to be addressed so that freshwater resources can be sustainably managed. The Plan became operative on 17 December 1999, with three Plan Changes implemented between 2007 and 2009.

Within the Regional Freshwater Plan, groundwater in the Greater Wellington Region is managed as groundwater zones. A safe yield[7] is specified for each groundwater zone that determines the volume available for allocation. These safe yields have been developed to ensure that environmental issues are minimised.

The interconnection between surface water and groundwater is outlined in Policy 6.2.8 below:

Policy 6.2.8 To ensure that water permits to take groundwater:

- *• consider excessive reductions in the yields of nearby bores (including excessive interference drawdowns); and*
- *• avoid significant adverse effects on surface water bodies.*

***Explanation**.*
In the context of this policy, avoiding "significant adverse effects" in relation to surface water bodies, includes having regard to Policies 6.2.1 and 6.2.2.[These Policies relate to minimum flows and water allocation for the regions rivers].

Overall, this review has identified, that like the Auckland Council, the Greater Wellington Regional Council has adopted a sustainable yield approach for managing stream depletion effects from groundwater abstraction, and relies on applicants to demonstrate the level of effects on surface water bodies.

2.9. Tasman District Council

The Tasman Resource Management Plan (TRMP) contains the District Plan, the Regional Coastal Plan and other Regional Plan provisions. The sections of the TRMP have variable operative dates, with Part V (Water) operative in part from 26 February 2011.

The importance of surface water and groundwater interconnection in the Tasman Region is outlined in Section 30.0.2.2 of the TRMP, while Section 30.0.3 states how interconnected water bodies are managed by Council, as outlined below:

Section 30.0.2.2 Groundwater Uses and Water - Some groundwater resources also sustain important uses and values of surface water resources, such as special aquatic ecosystems and fisheries. The Te Waikoropupu Springs, alluvial coastal springs such as Neiman and Pearl Creeks, and the Riwaka River are particularly significant examples.

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[7] **Safe yield** is defined as the maximum amount of water which can be safely abstracted from a given aquifer without affecting its sustainable yield (as defined in Chapter 3 of the Regional Freshwater Plan for Wellington). Sustainable yield (as defined on page 82 of the Regional Freshwater Plan for Wellington), is calculated from the annual water balance information for specific aquifers.

Section 30.0.3 Sustainable Water Management - Council manages the allocation of water from interconnected water bodies by establishing water management zones. The zones may include both surface and groundwater bodies which have common policies and rules.

The Policies within the TRMP that relate to surface water and groundwater interconnection are outlined below:

Policy 30.1.3.4 *To establish the sustainable yield of aquifers taking into account:*

- *a) depletion of aquifer yields;*
- *b) reduction of connected surface water flows, including coastal springs and wetlands;*
- *c) potential for compression of the aquifer;*
- *d) potential contamination of the aquifer by seawater intrusion;*
- *e) potential for excessive drawdown of groundwater levels;*
- *f) presence and significance of living organisms naturally occurring in the aquifer;*
- *g) effect of land use activities on recharge of the aquifer;*

to avoid:

- *i) long term aquifer depletion;*
- *ii) drying up of surface waters;*
- *iii) compression of the aquifer;*
- *iv) irreversible seawater contamination of the aquifer;*
- *v) over-allocation of water from the aquifer.*

Policy 30.1.3.11 *To ensure that the connections between groundwater and river flows are fully accounted for when setting and reviewing water allocation limits and minimum flow regimes and when deciding on applications to take or divert water in relation to both rivers and their connected groundwater systems.*

Section 30.1.30 outlines the Principal Reasons and Explanations for the objectives and policies within Part V (Water). The information regarding groundwater, currently not operative as of 26 February 2011, states:

The Council will take into account the degree of interconnection between groundwater bodies and adjacent surface water bodies in setting allocation limits. It recognises that the storage capacity or nature of some aquifers means that takes from groundwater have no or less immediate effect on surface water flows and levels. It will encourage takes from groundwater in preference to surface water takes, particularly in relation to the surface water resources of the Motueka catchment.

Schedule 30A (not operative as at 26 February 2011) identifies specific uses and values of water bodies including named aquifers. Use and values of aquifers include the maintenance of specific water bodies (i.e. Delta Zone Aquifer) and flow in coastal springs (Motueka Plains Aquifer).

Overall, once again the approach taken by the Tasman District Council relates to the defined sustainable yield of the aquifer, which has been developed taking into consideration the reduction of surface water bodies. However, the information provided in the TRMP does indicate that Tasman District Council are taking a pragmatic approach to the interconnection between surface water and groundwater, for example in Section 30.1.10 they recognise factors such as the storage capacity or nature of some aquifers will reduce the interconnection between surface water bodies and groundwater.

2.10. Nelson City Council

The Nelson Resource Management Plan (NRMP) is a combined District (land use) and Regional (coastal, land disturbance and freshwater) plan, which became operative in part on 1 September 2004. Chapter 5 of the NRMP outlines the policies specific to surface water and groundwater interaction, as outlined below.

Policy DO18.2.1 managing underground abstractions
The effects of underground abstractions on aquifer levels and on surface flows and levels will be considered on a case-by-case basis, having regard to the precautionary principle.
Explanation and Reasons

DO18.2.1.i The potential effects of groundwater abstractions need to be carefully assessed due to the lack of information on groundwater resources. The link between groundwater and surface flow, including wetlands, should be given particular consideration. Where the outcome of a proposed groundwater take is unknown or there is insufficient information to enable a reasonable assessment, abstraction should be avoided.

DO18.2.1.ii Unless there is information to the contrary, groundwater takes adjacent to rivers listed in Appendix 28.4 will be taken as having a one to one effect on river flows, for the purposes of water allocation and implementing water restrictions.

There are no specific rules related to these policies, nor is there any definition of the word “adjacent”, i.e. what is the distance criterion for classifying a bore beside a river as “adjacent”. In addition, it is unknown whether hydrogeological factors such as the depth of bore or confining layers can be taken into consideration when making the assessment. Hence, these policies and methods do not aid in the identification of policies for use in basalt aquifers.

2.11. West Coast Regional Council

The Proposed Regional Land and Water Plan was notified on 17 September 2010, with Council currently reviewing submissions. The Plan combines three of the West Coast Regional Council’s resource management plans, namely:

- Proposed Regional Land and Riverbed Management Plan
- Proposed Regional Water Management Plan
- Regional Plan for Discharge to Land

The interconnection between surface water and groundwater is identified in the Introduction to Chapter 10 – Groundwater as outlined below:

There is often a hydrological connection between surface water and groundwater. Where the connection is significant, there needs to be recognition of the fact that the use of surface water can affect groundwater, and vice versa. Takes of groundwater can adversely affect other existing groundwater takes through bore interference, and impact on hydraulically linked surface water. Bore interference relates to groundwater takes that lower water levels in a neighbouring bore so that they may be unable to take the water they require, or their pumping costs may increase. Shallow bores that are adjacent to surface water bodies may share water through freely draining gravels. This connection means that lower groundwater levels prevents surface water users from taking their authorised amount of water, or damages the ecological values of the water body. The potential for interference between bores, or between a bore and a surface water body is related to the proximity of the bore to neighbouring bores or a surface water body, the transmissivity within the aquifer and the rate at which water is taken.

There are three objectives within the Regional Land and Water Plan that relate to the interconnection between water bodies.

10.2.1 To sustain existing uses of the West Coast's groundwater, by protecting water quantity and quality and avoiding depleting surface water flows.

10.2.3 To avoid, remedy or mitigate adverse effects on surface water bodies associated with groundwater takes.

10.3.2 In managing the taking of water from any groundwater aquifer, priority will be given to the avoidance of:

(a) The total take from all bores exceeding the annual renewable yield of the aquifer; and
(b) Depletion of any surface water resource.

However, although the interconnection between surface water and groundwater has been identified within the Regional Land and Water Plan, there are no specific policies or rules regarding the management of the resources. As such, the Council are reliant on applicants to provide information in resource consent applications regarding the level of connection, and hence the assessment of effects.

2.12. Environment Canterbury

In June 2011 Environment Canterbury made the water and land chapters (Chapter 4 to 8) of its Natural Resources Regional Plan (NRRP) operative. However, as this information had been developed over a period of significant change (e.g. resource demands, governance requirements and community expectations), it is proposed to review this information. As such, Environment Canterbury is currently in the process of developing a new Land and Water Regional Plan, with a consultation process currently underway. As the Land and Water Regional Plan is in the initial stages of development, this review will consider the information currently available in the NRRP.

The importance of the interconnection between surface water and groundwater in the Canterbury Region is outlined in Sections 5.2.4.2 and 5.2.4.3, as outlined below:

Section 5.2.4.2 Life-supporting capacity of groundwater and associated river ecosystems
When groundwater is abstracted from an aquifer, there will be a lowering in water levels over the aquifer, with the greatest decline occurring close to the abstraction well(s). In time, the decline may extend to at least one of the aquifer boundaries where groundwater naturally discharges, generally to the sea, streams or springs. The amount of decline in natural discharge will equal the amount of groundwater permanently removed by abstraction.

In this way, the flows in many of the smaller rivers and streams on the lower plains are sustained by groundwater discharging as springs and seeps, which is also the case in inter-montane basins where most of the groundwater in the basin will discharge to lower catchment springs that feed the lakes and rivers there. As discussed in Section 5.2.1.2, abstractions from these rivers or streams, and linked aquifers, will increase the frequency and duration of periods of low flow, as well as the period such rivers and streams may cease to flow, and extend the length of dry riverbed. In this way, groundwater does have an effect on the life-supporting capacity of rivers and streams and the habitat of the adjacent riparian zones.

5.2.4.3 Modification of groundwater levels and pressures
Groundwater flows from west to east in the unconfined aquifer and when it meets the confined aquifers a large proportion emerges as spring flow. The headwaters of many groundwater-fed rivers and streams, for example, the Cam, Styx, Avon/Otakaro, Heathcote, Halswell and Irwell rivers, emerge as springs and seepages near the western edge of the coastal confined aquifer system. During periods of low rainfall, almost all of the base flow in these rivers comes from groundwater. Higher groundwater levels/pressures lead to higher river flows, and conversely lower groundwater

Given the importance of understanding of surface water and groundwater interconnection, the following objectives and policies are outlined in the NRRP:

Objective WQN3 Groundwater management
Enable present and future generations to gain access to the region's groundwater resources for social, economic, cultural and other benefits while ensuring that:
- *(a) abstractions from groundwater that is hydraulically connected to surface water do not cause adverse effects on flow, level and allocation regimes, including effects such as:*
  - *(i) not maintaining instream values;*
  - *(ii) significantly increasing the length and frequency of naturally occurring dry river or stream beds; and*
  - *(iii) drying of wetlands;*

Policy WQN7 Stream depletion effects
- *(1) Unless an alternative approach has been set out in either Schedule WQN1*[8] *or Schedule WQN3*[9] *for a particular aquifer, Environment Canterbury will manage the impact of groundwater takes on surface water bodies as set out below and in Canterbury Natural Resources Regional Plan Schedule WQN7.*

  For the purposes of this plan:
  (a) the degree of hydraulic connection shall be classified as follows:

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[8] Water Management Regimes for Rivers in the Canterbury Region (not relevant to this study)
[9] Groundwater Management in Specified Zones in the Canterbury Region (not specifically relevant to this study)

(i) a direct degree of hydraulic connection is where the effect of seven days of continuous steady groundwater abstraction on the surface water body is equal to or greater than 90% of that abstraction rate;

(ii) a high degree of hydraulic connection is where the effect of seven days of continuous steady groundwater abstraction on the surface water body is less than 90% of that abstraction rate but the effect of 150 days of continuous steady groundwater abstraction is greater than or equal to 60% of that abstraction rate;

(iii) a moderate degree of hydraulic connection is where:

1. the effect of 150 days of continuous steady groundwater abstraction on the surface water body is less than 60% but greater than or equal to 40% of that abstraction rate; or

2. the effect of 150 days of continuous steady groundwater abstraction on the surface water body is less than 40% of that abstraction rate but pumping the proposed annual volume over 150 days at a continuous steady rate exceeds five litres per second; and

(iv) a low degree of hydraulic connection is where the effect of 150 days of continuous steady groundwater abstraction on the surface water body is less than 40% of that abstraction rate and the effect of pumping the proposed annual volume over 150 days at a continuous steady rate is less than five litres per second;

(b) any take(s) from a bore or borefield classified as having:

(i) a direct degree of hydraulic connection will be managed the same as a surface water take for flow and allocation purposes as per Policies WQN13,WQN17 and WQN18[10]*;*

(ii) a high degree of hydraulic connection will have the stream depletion effect determined as the greater of:

1. the effect after 150 days of pumping at the continuous rate required to deliver the seasonal volume; or

2. the maximum effect of pumping at the proposed rate;

This stream depletion effect shall be counted as part of any applicable surface water body allocation block (refer Policy WQN13). Where the stream depletion effect exceeds either the stream depletion cut-off limit set in Schedule WQN1, or where none has been set in Schedule WQN1, five litres per second, the take shall be subject to any flow or level regime, and to restrictions in accordance with Policy WQN18;

(iii) a moderate degree of hydraulic connection will have the stream depletion effect determined as the effect after 150 days of pumping at the continuous rate required to deliver the seasonal volume. Where the stream depletion effect exceeds either the stream depletion cut-off limit set in Schedule WQN1, or where none has been set in Schedule WQN1, five litres per second, this stream depletion effect shall be counted as part of any applicable surface water body allocation block as per Policy WQN13; and

(iv) a low degree of hydraulic connection shall not be included in any surface Canterbury Natural Resources Regional Plan water allocation block or subject to any flow regime for the surface water body, but all of the effective allocation will be included in the appropriate groundwater allocation block as per Policy WQN13.

(2) Environment Canterbury will review water permits to take groundwater adjoining a surface water body which it assesses as being classified as having a direct or high degree of hydraulic connection with the surface water body when the surface water body has been added to Schedules WQN1 or WQN3 to bring them into accord with Policy WQN7(1).

The hydraulic connection categories, outlined under Policy WQN7 are shown in Figure WQN5 in terms of the stream depletion effect as a percentage of the overall pumping rate.

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[10] WQN13 – Allocation Regimes for Surface Water and Groundwater (not specifically relevant to this study)
WQN17 – Transfer of Water Permits to Take or Use Water (not relevant to this study)
WQN18 – Restriction of Water Use During Times of Low Water Availability (not relevant to this study)

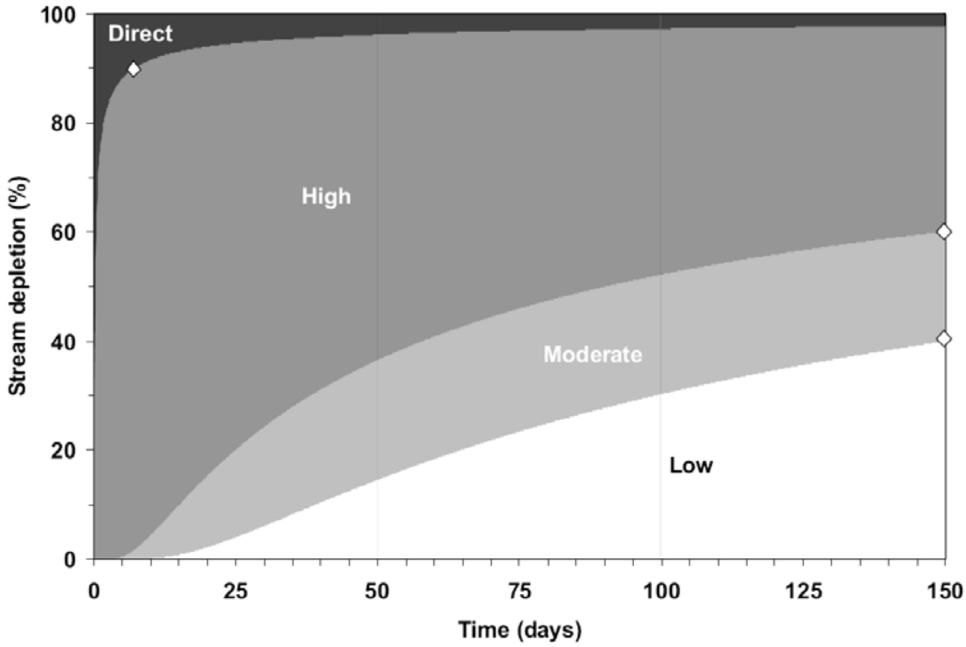

Figure WQN5: Hydraulic connection categories for the management of stream depletion effects

This approach, as with that adopted by Horizons Regional Council, provides prescriptive advice to applicants regarding how to calculate the stream depletion effects based on the Environment Canterbury guidelines.

2.13. Otago Regional Council

The Regional Plan: Water for Otago (Water Plan) became operative on 1 January 2004. Numerous variations to the Water Plan have been made since it became operative. Two of these Variations are relevant to this review, namely Proposed Plan Change 1C (Water Allocation and Use) and Proposed Plan Change 4A (Groundwater and North Otago Volcanic Aquifer). For the purpose of this review the following documents were consulted:

- Proposed Plan Change 1C (Water Allocation and Use) to the Regional Plan: Water for Otago, Appendix 1: Regional Plan: Water for Otago Incorporating Council Decisions on Proposed Plan Change 1C (Water Allocation and Use), 10 April 2010.
- Proposed Plan Change 4A (Groundwater and North Otago Volcanic Aquifer), Regional Plan: Water for Otago, 18 September 2010

Otago Regional Council takes an integrated water management approach to management of surface and groundwater bodies to enable effective management of aquifers which have a hydraulic connection to surface water bodies. Groundwater allocation in Otago is thus managed in accordance with the degree of connection with surface water bodies.

Policy 6.4.1A A groundwater take is allocated as:

- *(a) Surface water, subject to a minimum flow, if the take is from any aquifer in Schedule 2C; or*
- *(b) Surface water, subject to a minimum flow, if the take is within 100 metres of any connected perennial surface water body; or*
- *(c) Groundwater and part surface water if the take is 100 metres or more from any connected perennial surface water body, and depletes that water body most affected by at least 5 litres per second as determined by Schedule 5A; or*
- *(d) Groundwater if (a), (b) and (c) do not apply.*

Schedule 2C referred to in Policy 6.4.1A identifies aquifers where groundwater takes are to be considered as primary allocation and subject to minimum flows of specified catchments. All of the aquifers identified in this Schedule are alluvium aquifers.

Schedule 5A of the Proposed Plan Change 1C provides the requirements to determine stream depletion on surface water, with particular reference to analytical methods and numerical modelling. This Schedule is reproduced below:

Requirement to determine stream depletion on surface water
The Bekesi and Hodges equations are used to determine whether a proposed groundwater take may have an effect on nearby surface water that is greater than 5 litres per second. The Bekesi and Hodges equations are preferred to other equations reported in the literature as they are less demanding of hydrogeological data, and allow a reasonable relationship to be calculated empirically, which can be transposed to determine the threshold distance between the point of groundwater take and the surface water body. These equations consider pumping occurs over 30 days, and assumes a 90 percentile confidence. Which equation is used depends on the proposed maximum rate of take (Q in litres per second):

Where $5\ l/s \leq Q \leq 25\ l/s$ $r = 65 \times Q$

Where $Q > 25\ l/s$ $r = 1138 \times \log Q$

r = distance between abstraction structure and surface water body (metres)

If r is greater than the actual distance from the point of groundwater take to the surface water body, then the stream depletion effect is considered to be greater than 5 litres per second. However, there may be exceptions to the empirical relationship (see below).

Calculation of stream depletion effect and allocation to surface water
The Jenkins equations are used to calculate the stream depletion effects (or Qs) which will be considered against the available allocation of the relevant surface water body.

Qs = Qwerfc(U)

U = -(r2S/4Tt)

Where:
Qs is the rate of stream depletion (cubic length per time)

Qw is the pumping rate of the well (cubic length per time)

r is the perpendicular distance from the point of groundwater take to the surface water body (length)

S is the storativity (or specific yield) of the aquifer (dimensionless)

T is the transmissivity of the aquifer (square length per time)

t is time

'erfc(U)' refers to the Complementary Error Function of U

Where subsurface intake structures have a bore head in a different location from the position of the intake screen, the closest part of the intake screen or gallery should be used for the purpose of measuring the distance to the surface water body in terms of Policy 6.4.1A(c) and the equations set out above.

Situations where stream depletion effect is unlikely

There are a number of situations where the stream depletion effect of groundwater is not likely to be valid; these include hydrological factors related to the depth of the bore screen. In addition, the Bekesi and Hodges, or Jenkins equations have situations where they are less valid or have violated their basic assumptions. The situations referred to above are summarised as follows:

Where the adjacent surface water body;

- *(a) Has an impermeable bed; or*
- *(b) Is ephemeral, or dry for extended periods, containing or conveying water only in episodes of high runoff; or*
- *(c) Is separated from the underlying water table by an unsaturated zone, decoupling the interaction into a one-way loss of surface water from the surface water body.*

Where the groundwater system;

- *(a) Has very low permeability (e.g. schist fractured rock aquifers. Although the low permeability will calculate a very low stream depletion effect in the Jenkins equation, this is not considered in the empirical Bekesi and Hodges equations); or*
- *(b) Has very steep gradients or perched water tables adjacent to surface water body boundaries; or*
- *(c) Does not influence surface water due to the depth of the bore or well screen. These situations are often not immediately discernable and may require a higher level of assessment to distinguish the nature of connection between groundwater and surface water. Where an applicant seeks that Policy 6.4.1A should not apply, and that the take should be considered as a full groundwater take under the provisions of 12.2, then the applicant may apply to take groundwater as a discretionary activity under Rule 12.2.4.1.*

Use of analytical equations other than the Jenkins Equation:

The use of analytical equations will be accepted over the equations given above, when an applicant can clearly demonstrate:

1. *That the analytical equation is derived from, or is otherwise comparable to, the Jenkins Equation; and*
2. *That this equation is in common use for the purpose, and shares a degree of acceptance in such use amongst groundwater professionals.*

Use of numerical groundwater flow models:

The use of numerical groundwater flow models will be accepted over the equations given above, when an applicant can clearly demonstrate:

1. *That the numerical method is validated or potentially validated at a generic level against either the Theis Equation or the Jenkins Equation; and*
2. *That the model is in common use for the purpose, and shares a degree of acceptance in such use among groundwater professionals.*

Otago Regional Council is the only Council to provide specific analytical methods within a Regional Plan and in addition providing specific information on hydrogeological settings where stream depletion is unlikely to occur. The Bekesi and Hodges equations have been developed specifically for Otago groundwater dependent ecosystems and are based on the Jenkins (1968) method (see **Section 4**), using a range of conservative transmissivities that are relevant to Otago aquifers (i.e. 100 to 3,500 m^2/day).

It is considered that implementation of this method (like all methods based on the Theis equation, which assumes homogenous aquifer properties and infinite aquifer extents) requires caution, and particular attention to i) whether the method is actually suitable for the site specific nature of the basalt aquifer and ii) parameter uncertainty (i.e. the range in parameters that are physically feasible), given the variable nature of basalt aquifers hydraulic properties (e.g. fractured, unfractured, vesicularity, presence of scoria).

With regards to Proposed Plan Change 4A, this builds on the groundwater management system of taking water within a maximum allocation volume, with a specific focus on the North Otago Volcanic Aquifer. This aquifer is composed of tuff and basaltic volcanic deposits (Waiareka Tuffs and Deborah Volcanics) within limestone, diatomite (intrusive volcanic rocks) and siltstone sedimentary rocks (Totara and McDonald Limestones). Groundwater is contained within pores, fractures, joints, fissures and other voids. Overall, the bulk permeability is low to moderate. Groundwater modelling was undertaken on the aquifer by Rekker et al, (2008) in order to assist assessments of current and future groundwater management. Overall, this modelling helped inform Proposed Plan Change 4A, in which a maximum allocation limit and aquifer water level restriction levels have been defined for the North Otago Volcanic Aquifer. Hence, the approach adopted for the North Otago Volcanic Aquifer is similar to that adopted by Auckland Council and Tasman District Council.

2.14. Environment Southland

The Regional Water Plan for Southland was publically notified on 30 September 2000, with the majority of the Plan approved and made operative on 18 January 2010.

Surface-groundwater interaction in the Regional Water Plan for Southland is outlined under Policy 29 –Stream depletion effects.

Policy 29 – Stream depletion effects

(a) Manage the stream depletion effect of any groundwater abstraction with a rate of take exceeding 2 litres per second as follows:

(i) where there is a direct hydraulic connection between the groundwater source and an adjacent surface water body, the stream depletion effect will be determined as the maximum instantaneous

rate of take and will be managed in the same manner as a surface water abstraction for flow and allocation purposes. The abstraction will therefore be subject to any relevant minimum flow regime;

(ii) where there is a high degree of hydraulic connection between the groundwater source and an adjacent surface water body, the stream depletion effect will be determined as the greater of:

1. *the effect of 150 days pumping at the continuous pump rate required to deliver the seasonal volume;*

2. *the effect of continuous pumping at the maximum permitted pump rate over the period required to deliver the seasonal volume.*

   The calculated rate of stream depletion will be managed in the same manner as a surface water abstraction for allocation purposes with the remainder of the abstraction included in the allocation volume for the relevant groundwater zone. Where the calculated rate of stream depletion exceeds 2 litres per second, the abstraction will be subject to any relevant minimum flow regime;

iii) where there is a moderate degree of hydraulic connection between the groundwater source and an adjacent surface water body, the stream depletion effect will be determined as the effect of 150 days of pumping at the continuous pump rate required to deliver the seasonal volume. The calculated rate of stream depletion will be managed in the same manner as a surface water abstraction for allocation purposes with the remainder of the abstraction included in the allocation volume for the relevant groundwater zone;

(iv) where there is a low degree of hydraulic connection between the groundwater source and an adjacent surface water body, the stream flow effect is considered to be minor and the individual abstraction will not be taken into account in determining surface water allocation but will be included in the allocation volume for the relevant groundwater zone.

For the purposes of this policy, the degree of hydraulic connection is classified as follows:

Direct*: Where the stream depletion effect of seven days continuous abstraction at the maximum permitted rate on an adjacent surface water body is greater than or equal to 80 percent of the maximum pump rate.*

High: *Where the stream depletion effect of seven days continuous abstraction at the maximum permitted rate on an adjacent surface water body is less than 80 percent of the maximum pump rate and the stream depletion effect of 150 days of pumping at the average continuous rate required to deliver the seasonal volume is greater than or equal to 60 percent of the average continuous pump rate.*

Moderate: *Where the stream depletion effect of seven days continuous abstraction at the maximum permitted rate on an adjacent surface water body is less than 80 percent of the maximum pump rate and the stream depletion effect of 150 days of pumping at the average continuous rate required to deliver the seasonal volume is either:*

(a) less than 60 percent but greater than or equal to 30 percent of the average continuous pump rate; or

(b) has an overall magnitude greater than 5 litres per second.

Low: *Where the abstraction is not classified as having a direct, high or moderate degree of hydraulic connection.*

(b) Minimise the cumulative stream depletion effect of groundwater abstraction by:

(i) imposing minimum flows on resource consents for groundwater abstraction where there is a direct or high degree of hydraulic connection and the stream depletion effect exceeds two litres per second in accordance with any relevant surface water minimum flow regime (including those established under any Water Conservation Order);

(ii) managing the total stream depletion effect of groundwater abstractions greater than two litres per second with a direct, high or moderate degree of hydraulic connection in accordance with any relevant surface water allocation regime (including those established under any Water Conservation Order);

(iii) ensuring the total stream depletion effect of groundwater abstractions greater than two litres per second with a direct, high or moderate degree of hydraulic connection does not result in surface water flows less than prescribed minimum flows or surface water allocation regimes being exceeded.

This approach is the same as used in both Horizons Regional Council and Environment Canterbury Regional Plans and is currently used to determine stream depletion effects for all types of aquifers. In addition to this policy regarding stream depletion, Policy 30 outlines Environment Southland's recognition of different types of aquifers as outlined below. Staged allocation volumes are prescribed for each aquifer type as outlined in Rule 23, also outlined below.

Policy 30 – Groundwater abstraction

(a) Use a staged management approach to allocate groundwater for abstraction in Southland to allow the knowledge gained by the progressive development of the region's groundwater resources to be built into its future management.

(b) Recognise the different characteristics of the following aquifer types when managing groundwater abstraction:

(i) riparian aquifers;
(ii) terrace aquifers;
(iii) lowland aquifers;
(iv) confined aquifers;
(iv)fractured rock aquifers.

Rule 23 - Abstraction and use of groundwater[11]

(a) In addition to the takes authorised by Section 14(3) of the Act and the abstraction and use of groundwater permitted under Rule 23(b), the abstraction and use of up to 20,000 litres of groundwater per landholding per day is a permitted activity provided the following conditions are met:

(i) the rate of abstraction does not exceed 2 litres per second, except where the abstraction is for the purpose of carrying out an aquifer test or hydrological study; and

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[11] **Advice note**: To determine the aquifer type and allocation volume for a proposed groundwater abstraction, Plan users should firstly refer to Groundwater Map 1 of Appendix D to establish the relevant groundwater zone. Once the relevant groundwater zone has been established, Appendix H can be used to determine the aquifer type.

(ii) the abstraction does not result in adverse effects on existing water users, surface water ecosystems or groundwater quality.

(b) In addition to the takes authorised by Section 14(3) of the Act and the abstraction and use permitted under Rule 23(a), the abstraction and use of groundwater for milk-cooling water or washing down of dairy sheds and piggeries is a permitted activity provided the following conditions are met:

(i) the abstraction and use was lawfully established as a permitted activity up to and including as at 31 July 2004; and

(ii) the volume or rate of abstraction, or the number of stock using the dairy shed or piggery, does not increase beyond the levels established up to and including as at 31 July 2004; and

(iii) the groundwater after use is discharged pursuant to a discharge permit granted prior to 31 July 2004. For the avoidance of doubt, the discharge permit referred to in this clause does not include any discharge permit granted in substitution or by way of renewal of that discharge permit; and

(iv) the abstraction does not result in adverse effects on existing water users, surface water ecosystems or groundwater quality.

(c) Except as provided for in Rules 23(a) and 23(b) and the takes authorised by Section 14(3) of the Act, the abstraction and use of groundwater from any of the following sources is a restricted discretionary activity, provided the rate of take is less than or equal to 2 litres per second:

(i) a riparian or terrace aquifer where the total volume of water allocated from the relevant groundwater zone is less than 25 percent of mean annual land surface recharge; or

(ii) a confined aquifer where pumping of an individual bore results in a maximum reduction of less than 25 percent in the potentiometric head at a distance of 250 metres from the pumped bore[12]

The Council will restrict its discretion to the following matters:

(i) any effects on aquifer storage volumes, existing bore or well yields, river and stream flows and wetland and lake water levels (stream depletion effects), and groundwater quality;

(ii) the efficiency of water use;

(iii) the need for the installation of a water measuring device;

(iv) the need for pump tests;

(v) monitoring requirements.

(d) Except as provided for in Rules 23(a) and 23(b) and the takes authorised by Section 14(3) of the Act, the abstraction and use of groundwater from any of the following sources is a discretionary activity:

(i) a riparian or terrace aquifer where the total volume of water allocated from the relevant groundwater zone is between 25 and 50 percent of mean annual land surface recharge;

(ii) a lowland aquifer where the total volume of water allocated from the relevant groundwater zone is less than or equal to 15 percent of mean annual land surface recharge;

(iii) a confined aquifer where pumping of an individual bore results in a maximum reduction of between 25 and 50 percent in the potentiometric head at a distance of 250 metres from the pumped bore;

(iv) a riparian, terrace or confined aquifer where the rate of take is greater than 2 litres per second, except as provided for in Rule 23(e);

(v) a fractured rock aquifer; or

(vi) a source outside of the groundwater zones identified on Groundwater Map 1 of Appendix D.

(e) Except as provided for in Rules 23(a) and (b) and the takes authorised by Section 14(3) of the Act, the abstraction and use of groundwater from any of the following sources is a noncomplying activity:

(i) a riparian or terrace aquifer where the total volume of water allocated from the relevant groundwater zone is greater than 50 percent of mean annual land surface recharge;

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[12] To be measured with reference to static state potentiometric surface (no pumping effects) and referenced with respect to the top of the confined aquifer at the pumped bore.

(ii) a lowland aquifer where the total volume of water allocated from the relevant groundwater zone is greater than 15 percent of mean annual land surface recharge; or

(iii) a confined aquifer where pumping of an individual bore results in a maximum reduction of more than 50 percent in the potentiometric head at a distance of 250 metres from the pumped bore.

(f) The status of the activity under Rules 23(c) to (e) is determined by the total volume of water allocated at the date the resource consent application is notified. The phrase "total volume of water allocated" in Rules 23(c) to (e) includes the water that is allocated through current resource consents, the water that is proposed to be taken under consent applications that have been notified and the additional water proposed to be taken by the consent applicant.

(g) Notwithstanding Rules 23(c), (d) and (e) above, where:

(i) the rate of take of any abstraction and use of groundwater exceeds 2 litres per second; and

(ii) there is a direct, high degree or moderate degree of hydraulic connection between the groundwater source and an adjacent surface water body, as defined in Policy 29 "Stream Depletion Effects",

The stream depletion effect component of the groundwater abstraction and use, calculated in accordance with Policy 29 "Stream Depletion Effects", shall be considered in accordance with Rule 18 as though the abstraction and use was from the adjacent surface water body.

Fractured Rock Aquifers

Two groundwater management zones in the Southland Region, the Catlins and Hokonui zones, are defined as fractured rock aquifers. Maximum allocation volumes for the Catlins and Hokonui groundwater management zones are not specified in the plan (i.e. in Appendix A) due to thought that there is limited potential for large scale groundwater development in these management zones given the low permeability of Southland's fractured rock aquifers.

In 2010, Environment Southland commissioned a review of existing policy for confined and fractured aquifers, which was aimed at recommending sustainable management practices of these aquifers. Only the fractured rock aspects on this review are covered in this report as confined aquifers by virtue of their confined status have limited impact on surface waters.

The work concluded that the lack of allocation limits for fractured rock aquifers in Southland was not generally an environmental issue due to the low hydraulic conductivity and limited interconnection between water bearing fractures that restrict aquifer sustainability and associated environmental effects. However, the work raised concerns, that the absence of allocation limits may become an issue in the future following applications for large scale or competing development (Liquid Earth, 2010).

Liquid Earth (2010) recommended development of the policy surrounding fractured aquifers into a tiered framework to bring the management of fractured aquifers in line with the management of other aquifer types in the Southland Region. It was also recommended that fractured rock aquifers are managed on a localised rather than aquifer-scale basis, e.g. per landholding. This is similar to the existing policy used to define permitted use under Rule 23. Criteria for allocation from fractured rock aquifers recommended by Liquid Earth (2010) is shown below.

- **Table 1: Criteria for allocation from fractured aquifers proposed by Liquid Earth (2010)**

Activity Status	***Criteria***	***Information Requirements***
Restricted Discretionary	*Takes less than 2L/s where allocation is up to 25% of estimated groundwater recharge on the relevant landholding.*	▪ *Assessment of potential aquifer recharge on relevant landholding* ▪ *Aquifer test results to identify local hydraulic characteristics*
Discretionary	*Takes from fractured rock aquifers where the allocation is between 25% to 50% of the estimated recharge on the relevant landholding.*	▪ *Assessment of cumulative effects of water abstraction on neighbouring landholdings* ▪ *Aquifer test results adequate to characterise long-term aquifer response to abstraction* ▪ *Assessment of potential effects of abstraction on hydraulically connected surface water*
Non-complying	*Takes from fractured rock aquifers where the allocation is greater than 50% of the estimated recharge on the relevant landholding.*	▪ *Detailed hydrogeological assessment including aquifer recharge and discharge characteristics* ▪ *Analytical or numerical modelling of long-term effects of abstraction*

Following the Liquid Earth (2010) report, Environment Southland has proposed a plan change to the Regional Water Plan (Water Plan Change: Fractured Rock and Confined Aquifers and Community Water Supplies). A discussion document was made available to the public in 2011, and consultation with key stakeholders carried out in mid-2011. Environment Southland has received submissions, and aims to hold a hearing in June 2012.

The recommendation regarding localised rather than aquifer-scale management is applicable to basalt aquifers, especially considering the variable nature of the geology and hydraulic parameters, i.e. with respect to fractures, scoria and unfractured basalt that occurs with basalt flows. The numerical modelling outlined in **Sections 5** and **6** will further investigate the applicability of the concept of localised versus aquifer-scale management in a basalt aquifer.

2.15. Summary

The matrix below summarises the main methods prescribed in the polices and rules throughout New Zealand's Regional and Unitary Councils regarding surface water and groundwater interactions. The matrix also shows whether the Regional or Unitary Councils have identified volcanic and/or fractured rock aquifers as important from a regulatory perspective, although the current policy that addresses the nature of surface water and groundwater interaction has not been specifically developed for basalt aquifers.

	Analytical Methods	Numerical Methods	Specified Guidelines*	Set Back distances*	Sustainable Yields*	Volcanic and/or fractured rock
Auckland Council					★	★
Waikato Regional Council	★					
Bay of Plenty Regional Council						
Hawkes Bay Regional Council						
Horizons Regional Council	★		★			
Taranaki Regional Council				★		
Greater Wellington Regional Council					★	
Tasman District Council					★	
Nelson City Council						
West Coast Regional Council						
Environment Canterbury	★		★			
Otago Regional Council	★			★	★	★
Environment Southland			★		★	★

Notes: Specified Guidelines - to classify the degree of aquifer connectivity to surface water resources. Set Back Distances - from surface waterways. Sustainable Yields - for groundwater zones

Overall, the review indicated that many Regional and Unitary Councils throughout New Zealand are taking a pragmatic approach to the management of the interconnection between surface water and groundwater. This approach is shown by:

- the implication of specified guidelines to aid applicants in determining the level of interactions (e.g. Horizons Regional Council, Environment Canterbury and Environment Southland); and
- the acknowledgement of the potential varying degrees of interconnection in aquifers with regards to the resulting effect on surface water (i.e. acknowledging potential lag effects) as has been acknowledged by Tasman District Council. This information is an important component in the assessment of surface water and groundwater interactions.

A review of analytical methods for the calculation of stream depletion effects is provided in **Section 4**, while numerical modelling will be undertaken to determine whether localised management (including set back distances from surface water bodies) is applicable to managing surface water and groundwater interactions in basalt aquifers (**Section 5**).

3. Review of Australian Policy

3.1. Introduction

To broaden the understanding of current policies and rules regarding the interactions between surface water and groundwater, particularly with respect to basalt and/or fractured rock aquifers a review of current regulations and licensing in Australia was conducted. The regulations for several regions in Australia are outlined below.

3.2. Queensland

In Queensland, the Department of Environment and Resource Management (DERM) is responsible for the management and administration of water licensing and development permit requirements for the Region's water resources. In particular, DERM monitors the implementation of Water Management Plans (WMPs), which are designed to plan for the allocation and sustainable management of water to meet Queensland's future water requirements. WMP's establish a framework to share water between human consumptive needs and environmental values, as well as non-consumptive uses such as fisheries, grazing and tourism.

WMP's are developed through detailed technical and scientific assessments as well as community consultation, and will generally apply to the area's rivers, lakes, dams and springs (and if required groundwater). Through the development of the plan, the size of the resource is assessed to ensure that the water is allocated within sustainable boundaries (i.e. a sustainable yield approach as adopted by many of New Zealand's Regional Councils).

In Queensland, a number of sub-artesian areas (i.e. groundwater zones) have been declared under the *Water Act 2000.* Some have been declared within WMPs, while most have been declared under the Water Regulation 2002, both of which are subordinate legislation of the Act.

An example of a declared sub-artesian area that is volcanic is the Atherton Basalt Aquifer in Far North Queensland (AGE, 2007). This volcanic aquifer is comprised of a vertical series of vesicular lava flows, with each lava flow representing a specific eruption event. Most of the basalt rock is hard and dense, although weathered rock can be present at the top and bottom of individual lava flows.

AGE (2007) identified that potential environment issues associated with the use of groundwater in the Atherton Basalt Aquifer was the interaction between surface water and groundwater, as well as the dependency of ecosystems on groundwater. However, it is acknowledged that there is a lack of detailed groundwater level information available in the area, and hence a detailed assessment of interaction with surface water bodies and ecosystems can not be undertaken. AGE (2007) stated that prior to further development of the groundwater resources in the aquifer, a better understanding of the groundwater dependent ecosystems and interaction is required.

Overall, this approach is consistent with the sustainable yield approach adopted by New Zealand Regional Councils, as outlined in **Section 2**.

3.3. New South Wales

The New South Wales Government Office of Water manages groundwater in distinct groundwater zones. Allocation from each groundwater management zone is managed with a Water Sharing Plan. The *Draft Water Sharing Plan NSW Murray Darling Basin Fractured Rock Groundwater Sources* (NSW Office of Water, 2010) is the latest Water Sharing Plan to be developed for fractured rock aquifers (including basalt aquifers). This plan manages only the water from fractured rock aquifers within the defined area, and excludes water from other aquifer types within the area. Different rules apply for these aquifers depending on the classification of the groundwater source. Under this plan, groundwater volume available for allocation within the fractured rock aquifers is determined by:

Long term average annual abstraction limit = recharge x sustainability factor

where the sustainability factor is the percentage of the recharge volume that has been reserved as environmental water and is dependent on the overall risks arising from abstraction.

While an objective of the Water Sharing Plan is to recognise the interconnectivity of surface and groundwater resources, the plan contains only high level policy relating effects of groundwater takes on surface water bodies as outlined in Clause 38 below:

38 Rules for water supply works located near sensitive environmental areas

(1) A water supply work approval shall not be granted or amended to authorise the construction of a water supply work which, in the Minister's opinion, is located:

(a) within 100 metres of a high priority groundwater dependent ecosystem listed in clause 1 of Schedule 3 in the case of a water supply work used solely to take water pursuant to basic landholder rights; or

(b) within 200 metres of a high priority groundwater dependent ecosystem listed in clause 1 of Schedule 3 for water supply works not used solely to take water pursuant to basic landholder rights; or

(e) within 40 metres of the top of the high bank of a stream

Overall, this approach is consistent with the sustainable yield approach adopted by New Zealand Regional Councils, as outlined in **Section 2**.

3.4. Victoria

In Victoria, the Department of Sustainability and Environment (DSE) leads the Victorian Government's efforts to sustainably manage water resources and catchments, climate change, bushfires, parks and other public land, forests, biodiversity and ecosystem conservation. Groundwater is managed through the Groundwater Management Unit (GMU), which is organised into Water Supply Protection Areas (WSPA), Groundwater Management Areas or Unincorporated Areas.

Groundwater is allocated for commercial and irrigation purposes under strict licensing arrangements under the *Water Act 1989*, with the consumption of groundwater from Victoria's aquifers managed according to geographical area.

SKM (2010) reviewed the policies and regulations for a site with fractured basaltic geology known as Black Hill, located near the town of Gordon in Southern Victoria. Black Hill is situated in an area characterised by the flat plains of Late Cainozoic volcanic rocks, and partly dissected early palaeozoic sediments. Black Hill is an extinct volcano characterised by a crater, and consists of scoria, tuff and a series of individual basalt flows, which represent different phases of volcanic activity. Black Hill falls within the Bungaree Water Supply Protection Area (WSPA) that is overseen by Southern Rural Water Authorities. Overall, the WSPA includes both confined and unconfined aquifers in the area but does not include any specific regulatory mechanisms for the basalt aquifers in this area.

Overall, this approach of assigning Groundwater Management Units is consistent with the sustainable yield assessments currently undertaken by some New Zealand Regional Council's.

3.5. South Australia

The Department for Water (previously Department of Water, Land and Biodiversity Conservation (DWLBC)) is responsible for the management of authorisations and licences within South Australia. Currently, there are 27 prescribed water resources in South Australia, with 20 being managed through existing water allocation plans (WAPs), four managed under the Water Resources (Penrice Exemption) Regulation 1997, and water allocation plans are being prepared for the remaining areas.

One example of a WAP is a draft plan currently under discussion for the Adelaide and Mount Lofty Area. The geology of the aquifers in this area includes fractured rock, limestone, and quaternary sediments. The groundwater is managed through defining the aquifer resource capacity (calculated through hydraulic and hydrochemical modelling, observed groundwater levels and baseflow in water courses) and the calculation of the water extraction limit. The underground water extraction limit is the difference between the underground water resource capacity and the sum of baseflow, existing non-licensed underground water use (including deemed commercial forestry water use) in a given underground water management zone.

Once again, his approach is consistent with the sustainable yield assessments currently undertaken by some New Zealand Regional Council's. As such, there would appear to be no significant learnings or innovative management approaches that could be gained from the work currently being implemented in South Australia.

3.6. Western Australia

The Department of Water (DoW) is responsible for the management of water resources in Western Australia. The DoW is responsible for authorisations, licences and permits under the *Rights in Water and Irrigation Act 1914* (RIWI). RIWI licensing is required for all regulated or "proclaimed" areas (and artesian groundwater wells). There are 45 groundwater and 22 surface water areas proclaimed under the RIWI Act (DoW, 2010b). Licensing is granted within proclaimed areas as long as the abstraction is within the specified allocation limit. As such, with the other Australian regions, the management of groundwater in Western Australia is undertaken using a sustainable yield approach.

3.7. Tasmania

Tasmania has an extensive groundwater resource contained within igneous, sedimentary and metamorphic rocks, as well as unconsolidated sediments. There are three main types of aquifers within Tasmania:

- Fractured rock aquifers (such as dolerite, a medium grained basalt) – underlying approximately 85-90% of the land surface. These aquifers have relatively low porosities (less than 10%) and permeabilities, and hence low yields that limit their development;
- Sedimentary rock aquifers (such as sandstone) – provide high yields, possibly due to the dual porosity effects; and
- Intergranular aquifers (such as gravel and sand) – underlying only 10-15% of aquifers in the State.

The linkage between surface water and groundwater is not well understood in Tasmania, although anecdotal evidence exists to suggest that groundwater extraction may be influencing river flows in a number of areas. In addition the interaction between surface water and groundwater is recognised as one of the key data gaps of information in Tasmania.

There is a significant national impetus (the National Water Initiative) towards integrated management of surface water and groundwater (named whole of water resource management). The Department of Primary Industries, Parks, Water and Environment have developed an Implementation Plan that describes groundwater initiatives and essentially will involve the development and implementation of Water Management Plans. This approach is consistent with the approach currently undertaken by other Regions across Australia.

3.8. Summary

This review has highlighted that there is limited information available regarding the level of interaction between surface water and groundwater in many catchments across Australia. As such, the Authorities have adopted methods of assigning groundwater management areas, with the management of the groundwater resources in these assigned areas being undertaken through Water Management Plans. This approach is conducted for aquifer types including basalt aquifers and is consistent with the sustainable yield approach currently implemented by many of New Zealand's Regional and Unitary Councils as outlined in **Section 2**. Hence it would appear to be limited significant learnings or innovative management approaches that could be gained from the work currently being implemented throughout Australia with regards to basalt aquifers.

4. Stream and Spring Depletion Analytical Methods

4.1. Introduction

Stream depletion analytical methods use mathematical solutions to calculate the effects of stream depletion as a result of groundwater abstraction from a bore screened in an aquifer unit.

All stream depletion methods are ultimately based on well flow theory, which was first promulgated by Theis in 1935 and became known as the Theis Solution. The Theis Solution is applicable to confined aquifers and can be used as an approximation to calculate drawdown in unconfined aquifers. In 1941, Theis progressed this solution to enable the calculation of stream depletion rates for a fully penetrating stream in the unconfined aquifer.

In 1954, Glover and Balmer rewrote this solution to include more recent mathematical notation. The solution was further developed by Hantush (1965) to include an aquitard lining on the stream boundary. Jenkins (1968) and Wallace et al. (1990) provided improvements to include more general pumping schedules.

These earlier analytical methods have not been reported in this work because they are variations of the original Theis model, which makes the assumption that the stream fully penetrates the aquifer. This assumption tends to overpredict the impact and hence renders the methods overly conservative. Despite this assumption, the Jenkins (1968) method is very commonly used because of its simplicity. The models outlined in this review supersede these older methods and provide more realistic assumptions around the structure of the aquifer and the stream.

The Bouwer (1997) and Hunt (1997) methods consider cases where streams partially penetrate the aquifer and are perched above the static water table. Both methods provide an indication of whether stream seepage will change under the influence of abstraction with increasing depth to the groundwater table. These methods provide an indication of the depth to the groundwater table where abstraction has no influence on the rate of seepage from the stream. These methods are explained in **Section 4.2.1** and **Section 4.2.2**.

Where streams are depleted by the effects of abstraction, several models have been developed by multiple authors to quantify the magnitude of impact observed as a result of this abstraction. These models are specific to the type of aquifer being considered. Methods are considered for stream depletion from unconfined aquifers, leaky aquifers and unconfined aquifers with deep aquifer recharge in **Section 4.3**, **Section 4.4** and **Section 4.5**. One method for quantifying spring depletion in a leaky aquifer is also considered in **Section 4.6**.

The solutions for each of these methods are complex and can be time consuming and technically challenging to implement, requiring knowledge in coding and numerical mathematics. Methods that are already developed in existing software have significant advantages with respect to ease of implementation.

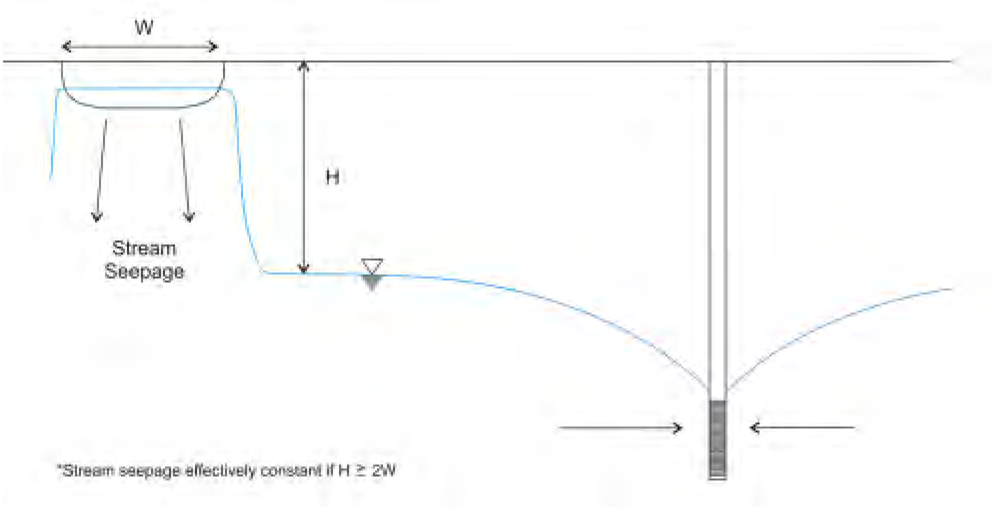
4.2. Perched Stream Depletion Methods

In some situations, the stream can be perched above the groundwater table, causing it to lose water through the bed of the stream. In these situations, for the purposes of stream leakage calculation, it is useful to know whether or not abstraction will have any influence on the leakage rate and what the leakage rate is.

4.2.1. Bouwer (1997) Method

The Bouwer (1997) method described in ECan (2000) aims to quantify stream depletion rate for a stream perched above the water table where the depth of the water table is known and to provide a check as to whether or not abstraction is likely to affect stream depletion rate.

It compares the depth of the water table below ground level at the stream location (H) to the width of the stream (W) to calculate the stream depletion rate. This method indicates that when $H \geq 2W$, the rate of stream bed leakage is independent of H, meaning that if the water table is deep, stream seepage rates will remain unchanged with abstraction.



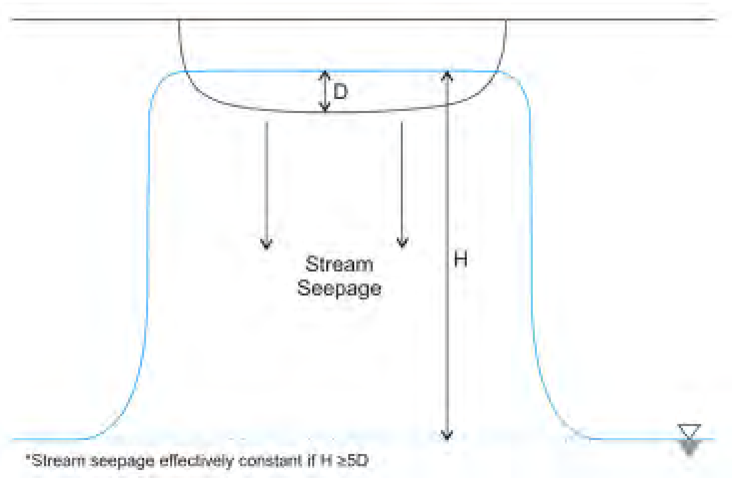
- **Figure 1. Bouwer stream seepage schematic.**

This method is useful in situations where it is known that the stream is situated above the water table. Given the width of the stream and the depth of the water table, it allows the stream depletion rate to be calculated and performs a check on whether or not abstraction is likely to have any effect on stream depletion rate. The limitation of this method is that if abstraction is likely to affect stream depletion, it does not allow any quantification of the stream depletion rate under the abstraction conditions.

4.2.2. Hunt (1997) Flow Net Analysis Method

The Hunt Flow Net Analysis (1997) method described in ECan (2000) like the Bouwer (1997) method indicates whether abstraction is likely to impact on stream seepage rates where the stream is perched above the water table.

It compares the depth of the water table below the water surface (H) in the stream to the depth of the water in the deepest point of the stream (D). If H ≥ 5D, then flow from the stream is expected to be vertically down and further lowering of the water table due to abstraction is not expected to have any influence on seepage rates.



- **Figure 2. Hunt Flow Net Analysis schematic.**

This method is useful where it is known that the stream is situated above the water table and it is not certain whether or not it has a good connection with the water table.

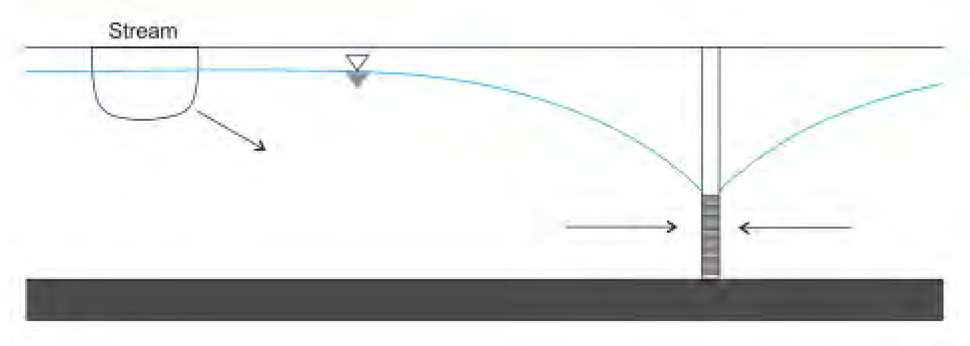
4.3. Unconfined Stream Depletion Methods

4.3.1. Hunt (1999) Stream Depletion Solution

The Hunt (1999) solution aims to predict stream depletion rates with time as a result of constant abstraction from a bore off to one side of a partially penetrating stream in an unbounded unconfined aquifer underlain by an aquiclude.

It is based on the Theis solution of groundwater flow and assumes that the aquifer is unconfined with the stream partially penetrating the water table, with a pumping bore off to one side. The aquifer is assumed to be infinite in extent and to have homogeneous hydraulic properties.

No software implementing this model could be found in a background search.



- **Figure 3. Hunt (1999) stream depletion schematic.**

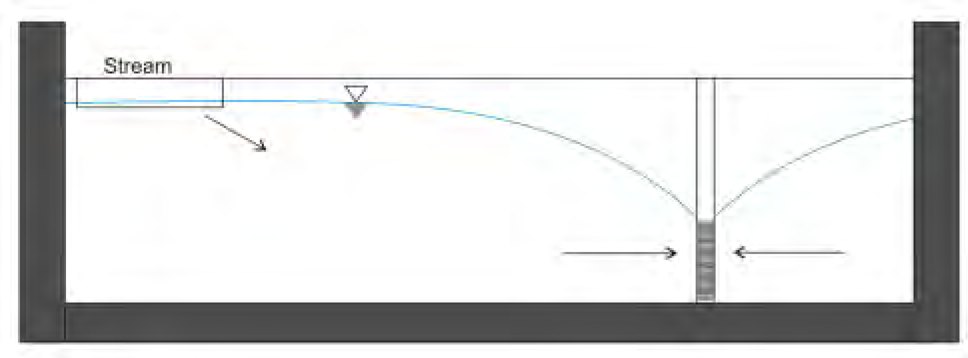
This model is likely to be of limited use in basalt lava flow setting because it does not allow for bounds on the aquifer, which are likely to result from changes in permeability distribution throughout the basalt.

4.3.2. Butler, Jr. et. al. (1999) Stream Depletion Solution

The Butler, Jr. (1999) solution aims to predict stream depletion rates as a result of abstraction from a bore off to one side of the partially penetrating stream in an aquifer bounded in both directions perpendicular to the stream.

The solution was based on the same principals as the Hunt (1999) solution, but has several improvements. The Butler solution allows for a bounded aquifer in the direction perpendicular to the stream and for a stream of finite width, whereas the Hunt (1999) solution assumes an infinitely thin stream.

Software implementing this model is known as StrpStrm and is available from the Kansas Geological Survey[13].



- **Figure 4. Butler (1999) stream depletion schematic.**

The advantage of this solution is that it is bounded, allowing for the extents of the permeable basalt units. This is likely to be one of the most useful models for this setting.

4.4. Leaky Aquifer Stream Depletion Methods

In some cases, it can be necessary to use leaky aquifer methods to assess stream depletion effects. This can be necessary in cases where there are multiple geological units of alternating hydraulic characteristics. For example, these methods may be useful where there is a weathered layer near the surface containing the water table, underlain by higher conductivity layers from which water is to be abstracted. Methods for handling this conceptualisation are discussed below in **Section 4.4.1** to **Section 4.4.4**.

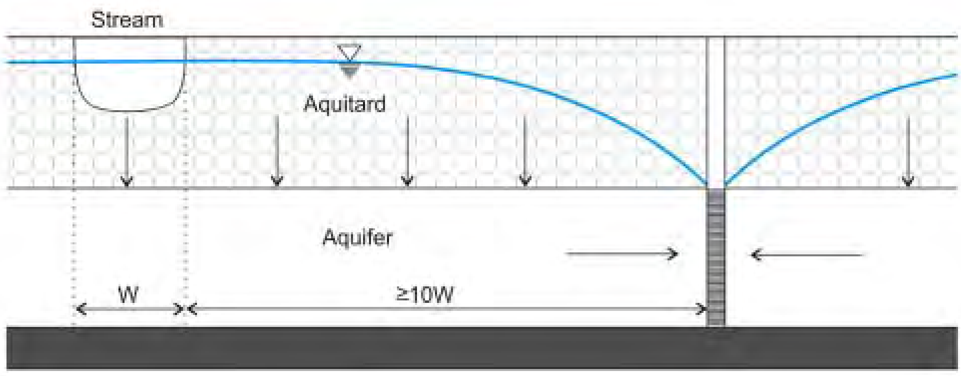
4.4.1. Hunt (2003) Stream Depletion Solution

The Hunt (2003) solution described in Hunt (2008) aims to predict stream depletion due to abstraction where the stream partially penetrates an aquitard that overlies a permeable aquifer unit from which abstraction takes place. This setup was developed from a pump test model known as the Boulton model, where drawdown is predicted in an aquifer unit overlain by an aquitard containing the water table. The Hunt (2003) model assumes that the aquifer is infinite and that flow is only able to move vertically in the aquitard layer and horizontally in the aquifer layer as in the Boulton model.

[13] http://www.kgs.ku.edu/StreamAq/Software/strp.html

To use Hunt (2003), the pumping bore must be at least 10 stream widths away from the stream and the stream must be located in the aquitard unit, which should have a significantly lower horizontal conductivity than the pumped aquifer unit. The aquitard unit can be used to model layers of different geology under the condition that the top layer that is penetrated by the stream is an aquitard layer, preventing significant horizontal flow to or from the stream.

A function for calculating stream depletion for this model called Q_4 is available from Bruce Hunt's website[14] within the excel spreadsheet "Function.xls".



- **Figure 5. Hunt (2003) stream depletion schematic.**

This method is limited in that it is unbounded, so may not model long term behaviour or scenarios where the well and or the stream are in close proximity to the aquifer boundaries. However, this limitation is addressed in **Section 4.4.2** below.

4.4.2. Hunt (2007) Stream Depletion Solution

The Hunt (2007) solution described in Hunt (2008) aims to predict stream depletion due to abstraction in a leaky aquifer where abstraction takes place in a permeable aquifer unit and the water table and stream are located in an upper unit. The extent of the aquifer perpendicular to the direction of the stream is limited in this method.

This is likely to be a useful solution method in a basalt aquifer setting because it allows flows in the aquifer to be bounded such as a narrow valley situation. This solution may also be applicable to valley infill basalt lava flows, particularly where pulses of volcanism have created stacked discrete lava flows, the shallower of which may be confining the deeper lavas.

[14] http://www.civil.canterbury.ac.nz/staff/bhunt.shtml

A function for calculating stream depletion using this model called Q_13 is available from Bruce Hunt's website[15] within the excel spreadsheet "Function.xls".

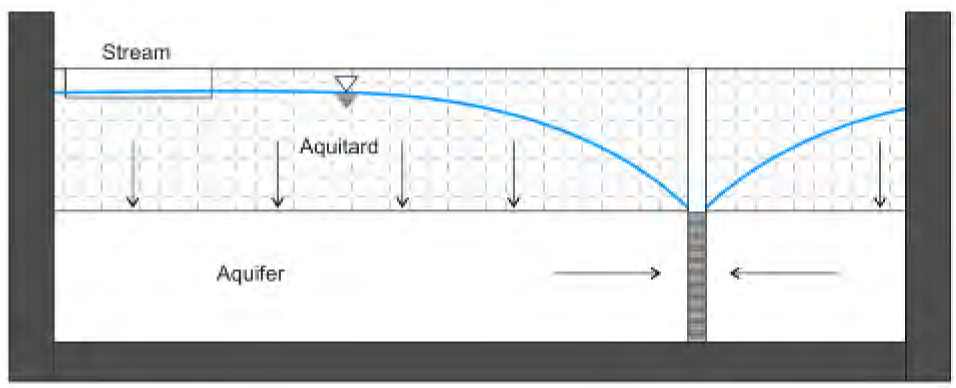


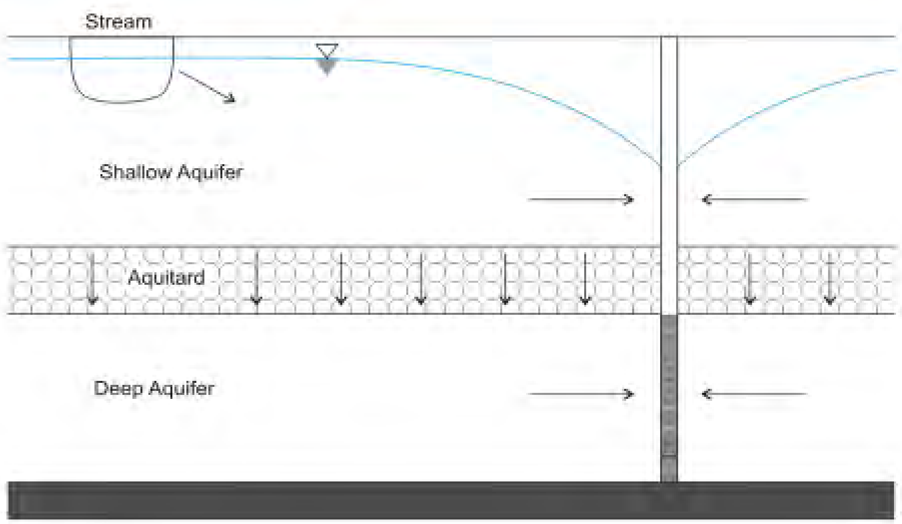
Figure 6. Hunt (2007) stream depletion schematic.

The advantage of this method is that it is bounded, so able to take into account the aquifer extents. This is likely to be one of the most useful models for this setting.

4.4.3. Ward and Lough (2011) Stream Depletion Solution

The Ward and Lough (2011) solution aims to predict stream depletion due to abstraction in a two-layer leaky aquifer made up of a shallow aquifer and a deep aquifer separated by an aquitard as shown in **Figure 7**. Abstraction takes place in the deeper aquifer unit while the water table and the stream are located in the shallow aquifer unit.

[15] http://www.civil.canterbury.ac.nz/staff/bhunt.shtml



■ **Figure 7. Ward and Lough (2011) stream depletion schematic.**

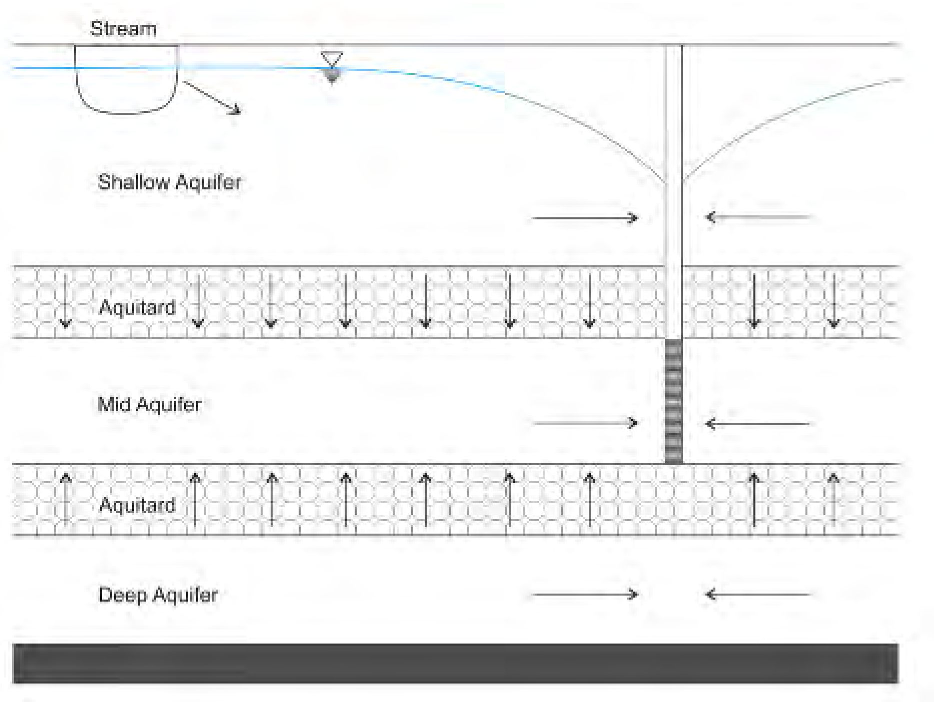
This solution assumes that the flow in each of the aquifer units is purely horizontal and that pressure is communicated between the two layers through vertical flow through the aquitard unit. Software for this model is available from the Otago Computational Modelling Group[16]. However, to use this program, the user needs to have access to a licensed version of MATLAB.

The advantage of using this method is that it will produce more realistic late time behaviour as the stream is located in an aquifer unit as opposed to an aquitard, as in the Hunt (2003) and Hunt (2007) models.. The disadvantage of this method is that it is not bounded, so will be of limited use in bounded scenarios.

4.4.4. Ward and Falle (2011) Stream Depletion Solution

The Ward and Falle (2011) solution aims to predict stream depletion due to abstraction in a three-layer leaky aquifer made up of a shallow aquifer, containing the stream and the water table, a mid aquifer from which water is abstracted and a deep aquifer. Each aquifer unit allows for horizontal flow and communicates with adjacent aquifers through the aquitard units which allow for vertical flow. The conceptual layout of this method is shown in **Figure 8**.

[16] http://www.ocmo.co.nz/matlab_code.html



- **Figure 8. Ward and Falle (2011) stream depletion schematic.**

The OCMO website[17] is referenced by Ward and Lough (2011) as having MATLAB code for their models, however at the time this review was performed, no code was available on this website for the calculation of stream depletion using this model. However, if this code were available, the user would need to have access to a licensed version of MATLAB.

The advantage of this method is that it extends the Ward and Lough (2011) solution to allow for deep aquifer recharge if this should be necessary. The disadvantages are that this model is complex and will require hydraulic parameters for all three aquifer units and the two aquitards. It will require some certainty about the geological structure of the system and is unbounded so will be of limited use in situations where aquifer boundaries are in close proximity to the production bore or the stream. This limits the method’s usefulness to conceptualisation and hypothetical testing, unless detailed field data are available.

4.5. Stream Depletion with Deep Aquifer Recharge

Deep aquifer recharge can have a significant impact on stream depletion rates. This is where a shallow aquifer unit containing the stream and the screened section of the abstraction bore is

[17] http://www.ocmo.co.nz/matlab_code.html

underlain by an aquitard and a deep aquifer. When abstraction takes place from the bore, drawdown from the shallow aquifer can be recharged from the deep aquifer unit. This recharge reduces the drawdown reaching the stream, reducing stream depletion. If the bottom of the shallow aquifer is considered impermeable where this situation is relevant, stream depletion rates will be over predicted.

Methods considering deep aquifer recharge are discussed below in **Section 4.5.1** and **Section 4.5.2**.

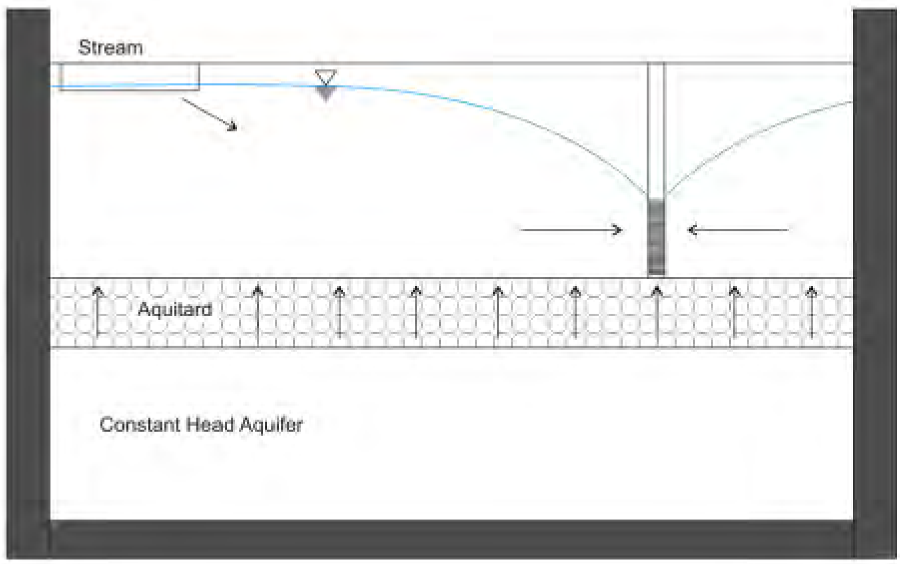
4.5.1. Butler (2007) Stream Depletion Solution

The Butler (2007) method aims to calculate stream depletion as a result of abstraction where both the stream and abstraction are in a shallow aquifer unit underlain by an aquitard and a constant head deep aquifer unit thus allowing for deep aquifer upwelling to provide a component of the abstraction. This is shown schematically in **Figure 9** (Butler, 2007). This solution is similar to the Butler (1999) solution in **Section 4.3.2**, but lacks the assumption of an impermeable model base.

Stream depletion in this model is strongly affected by the distance of the bore from the stream and conductivity of the aquitard unit. If the pumping bore is sufficiently distant from the stream, deep aquifer recharge may become very significant. Consistent with this finding, the properties of the aquitard become more important as the bore is moved further away from the stream.

The authors indicate that this solution should not be used in practical situations unless it can be shown that the head in the lower aquifer are relatively stable under pumping and a gradient is induced within the aquitard unit. By assuming a constant head, it assumes an infinite water supply from the deep aquifer, which may not be an appropriate assumption for all situations.

No software implementing this model could be found in a background search.



- **Figure 9. Butler (2007) stream depletion schematic.**

The main advantage of this model is that it is bounded, which will allow aquifer extents to be taken into account. However, this model is unlikely to be of much practical use because it is not known whether an implementation of this model exists and is readily available, it is not valid if drawdown significantly influences the deeper aquifer unit and it requires experimental testing to confirm whether or not this is the case.

4.5.2. Hunt (2009) Stream Depletion Solution

The Hunt (2009) solution aims to calculate stream depletion rates where both the stream and the abstraction are in a shallow aquifer near the surface and are underlain by an aquitard and a deep aquifer of variable head.

The method allows for horizontal flow in both the shallow and deep aquifer units towards the location of the pumping well located in the shallow aquifer. The pressure difference between the shallow and the deep aquifer induced from abstraction within the shallow aquifer causes water to flow from the deep aquifer upwards through the aquitard.

A function for calculating stream depletion for this model called Q_15 is available from Bruce Hunt's website[18] within the excel spreadsheet "Function.xls".

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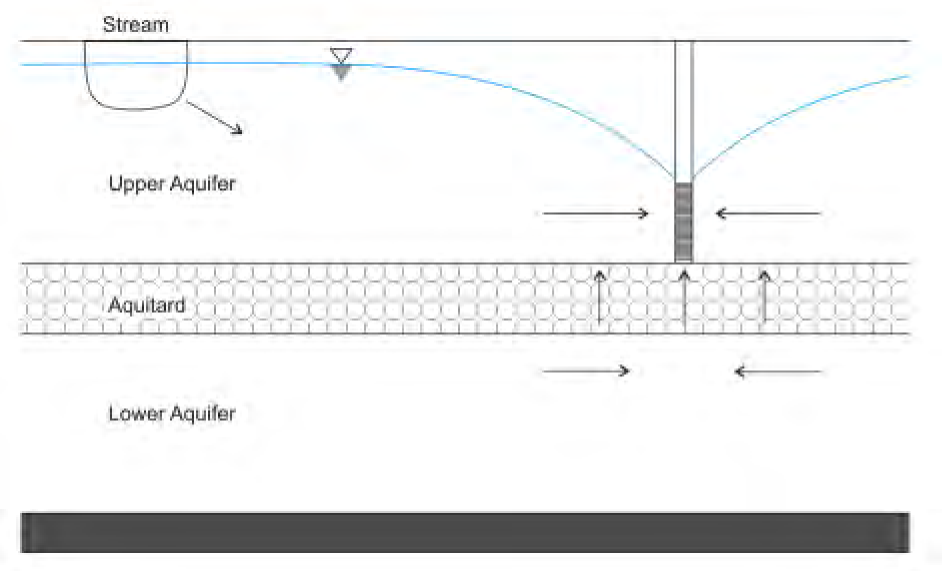
[18] http://www.civil.canterbury.ac.nz/staff/bhunt.shtml



- **Figure 10. Hunt (2009) stream depletion schematic.**

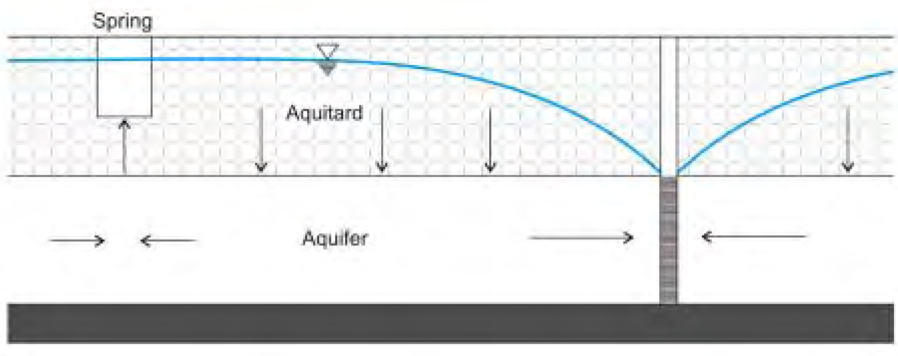
The advantages of this method are that it allows for flow in the deep aquifer unit, meaning that it is less limited than the Butler (2007) model and does not require experimental testing. The main limitation of this method is that it is unbounded meaning it will under predict drawdown in cases where either the bore or the stream are in close proximity to the bounds of the aquifer or in cases of long term abstraction.

4.6. Spring Depletion

In some situations, abstraction may interfere with springs, which for the purposes of the methods that are discussed in the following are differentiated from streams by forming a connection to the surface at a single point as opposed to spanning the length of the aquifer as in the case of a stream. In these situations it is useful to quantify this effect so that decisions can be made about abstraction limits and timing.

4.6.1. Hunt and Smith (2008) Spring Depletion Solution

The Hunt and Smith (2008) solution for spring depletion is similar to the Butler (1999) model for stream depletion presented in **Section 4.3.2**, but aims to calculate spring depletion where the spring partially penetrates an aquitard unit and abstraction takes place from a deep aquifer unit underlying the aquitard as shown in **Figure 11**.



- **Figure 11. Hunt and Smith (2008) spring depletion schematic.**

Hunt and Smith (2008) assume there is only vertical flow in the aquitard and only horizontal flow in the aquifer unit. The spring depletion rate (Q_d) is modelled as being proportional to the drawdown (s) produced by the pumping bore at the spring location. This requires the calculation of a spring depletion coefficient (α), which relates the spring depletion to the drawdown at the spring location by the following equation, where T is the aquifer transmissivity.

$$Q_d(t) = \alpha T s(t)$$

The spring depletion coefficient can be calculated from the below equation, where K'' is the vertical conductivity of the aquitard, B'' is the thickness of the aquitard directly below the spring and x_0 is the effective spring radius.

$$\alpha = \frac{\left(\frac{K''}{B''}\right)\pi x_0}{T}$$

However, the effective spring radius is often unknown and the flow system near the spring is complex due to non-laminar flow in the spring fissures, meaning that this value is best found experimentally, which adds some complexity to the implementation of this model.

A function for calculating spring depletion for this method called Q_5 is available from Bruce Hunt's website[19] within the excel spreadsheet "Function.xls".

The advantage of this solution is that if appropriate test pumping data are available and the bore and spring are not in close proximity to the model boundaries, it should give a first pass

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[19] http://www.civil.canterbury.ac.nz/staff/bhunt.shtml

approximation to spring depletion. Its limitations are that it is unbounded and testing needs to be done to determine the spring discharge coefficient, which will require the use of extra resources.

4.7. Summary

The matrix below summarises the main stream depletion analytical methods outlined above, and includes information on the main input parameters required to undertake these methods.

Method	Abstraction Rate	Distance to Stream \Spring	Aquifer Transmissivity/Transmissivities	Aquifer Storativity	Stream Depletion Factor/ Spring Discharge Coefficient	Streambed Conductivity	Stream Width	Streambed Thickness	Aquitard Conductivity/Conductivities	Aquitard Thickness(es)	Distance to Aquifer Boundaries	Notes
Hunt (1999)	★	★	★	★	★							
Butler (1999)	★	★	★	★		★	★	★			★	
Hunt (2003)	★	★	★	★	★				★	★		
Hunt (2007)	★	★	★	★		★	★	★	★	★	★	
Ward and Lough (2011)	★	★	★	★	★				★	★		Two aquifer units
Ward and Falle (2011)	★	★	★	★	★				★	★		Three aquifer units and two aquitards
Butler (2007)	★	★	★	★		★	★	★	★	★	★	
Hunt (2009)	★	★	★	★	★				★	★		Two aquifer units
Hunt and Smith (2008)	★	★	★	★	★				★	★		

A review of stream depletion analytical methods has come to the following conclusions based on the ease of use and appropriateness of each method:

- For a basalt aquifer setting, the Butler Jr. (1999) and Hunt (2007) methods discussed in **Section 4.3.2** and **Section 4.4.2** are considered to be of most relevance. These methods complement each other, with one allowing for unconfined aquifer conditions where there is very good connection to the surface and the other allowing for leaky aquifer conditions, where the surface may be weathered. Both methods allow bounds to be set perpendicular to the stream, which is useful because different basalt flows will have heterogeneities with high permeability material alternating with lower permeability material. These bounds can be set either as the edge of the aquifer unit or as a boundary between high and low permeability material. These models have both been implemented in software programs that are readily available.

- While there are methods available for deep aquifer recharge, these methods are very limited. The Butler (2007) solution described in **Section 4.5.1** allows for bounding of the aquifer, which will be useful in this setting, but assumes constant heads in the deep aquifer that have to be verified experimentally before it can be used. There is also no known software that uses this model. The Hunt (2009) solution in **Section 4.5.2** allows for flow in the deep aquifer and has a readily available software implementation, but is unbounded, meaning that it may be of limited use in this setting for late time results. This will be dependent on the distance of the bore and the stream to the aquifer boundaries.
- Only one known spring depletion implementation was found in this work. This solution assumes a leaky aquifer setting with the spring screened in the leaky aquifer and abstraction taken from the deeper aquifer unit and has an implementation that is readily available to the public. This method also requires experimentation to quantify the stream leakage parameter and is unbounded making it of limited use for long term analysis or where the stream or bore are in close proximity to the aquifer bounds.

5. Stream Depletion Assessment for Northland Basalt

5.1. Introduction

The average amount of groundwater abstraction from an aquifer system will in most instances[20] result in that same amount of water being depleted from surface water bodies within the catchment at some point and time, regardless of where a bore is located or the variation of abstraction rate. The timing and magnitude of stream depletion, however, is variable depending on a range of factors including conceptual aquifer setting, take location and depth.

If the groundwater abstraction is shallow and perfectly connected with the stream, impacts of the abstraction will have no attenuation and will be observed as depletion from the stream within a short period of time. Conversely, if there is a poor connection between the take and the stream, the effects of the take will be attenuated and the maximum depletion rate from the stream will be closer to the average abstraction rate than a take with a better connection.

As indicated above, the attenuation in the system will be controlled by the nature of the geological setting and the depth and distance of the bore from the stream. These parameters can be assessed with the use of numerical models and analytical methods. It is also important when selecting models or methods to consider the limitations of the input data. As previously indicated NRC has acknowledged data limitations for some of the aquifers and as such NRC currently has a preference for appropriately simplistic and conservative models and methods.

The section aimed to assess whether an analytical method for assessing groundwater-surface water interaction specific to Northland basalts could be developed. The work undertaken involved three stages described as follows:

- ***Aquifer Conceptualisation*** –identification of four typical geological settings found within Northland basalt, from analysis of the typical geological settings within the Maungatapere, Whatitiri, Maunu and Monument Hill basalt complexes;
- ***Numerical Modelling*** **-** Development and simulation of conceptual numerical models to represent the four conceptual aquifer settings;
- ***Analytical Methods*** – Development of an analytical method and calibration to the numerical models for assessment of stream depletion effects.

[20] The exception to this is in some very deep groundwater systems where submarine discharges to the ocean floor occur.

5.2. Conceptual Aquifer Settings

To aid the identification of four typical geological settings found within Northland basalt, the geology of both the Maunu, Maungatapere, Whatitiri and Monument Hill complexes were reviewed. In particular, the characteristics of the geology in specific groundwater catchments were investigated. As part of this review, a groundwater divide map for the Maunu, Maungatapere, Whatitiri aquifers was constructed based on the work completed in SKM (2010) as shown in **Figure 12** . Overall, this assessment identified that the aquifers comprised of localised basalt flows and hence compartmentalised basalt catchments.

- **Figure 12. Groundwater Divide Map**
  (See A3 attachment at rear)

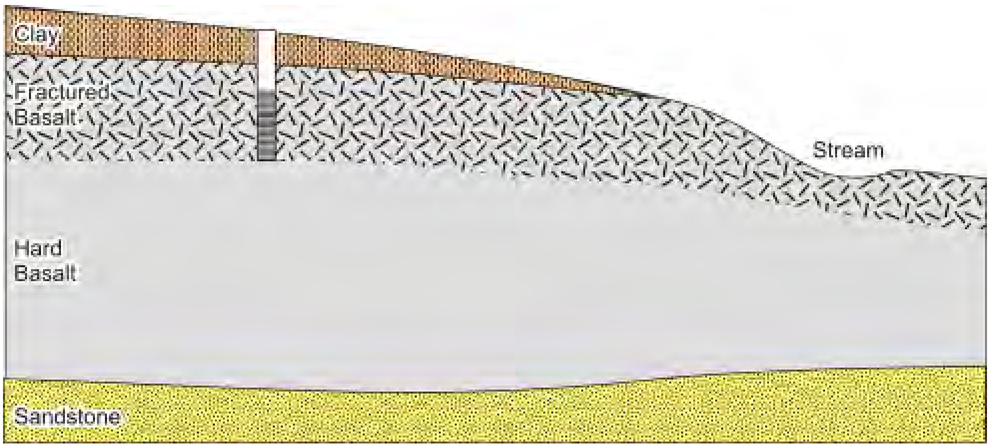
Based on this review, the following four geological settings were identified (see **Figure 13** to **Figure 16**):

i) fractured basalt underlain by hard basalt;

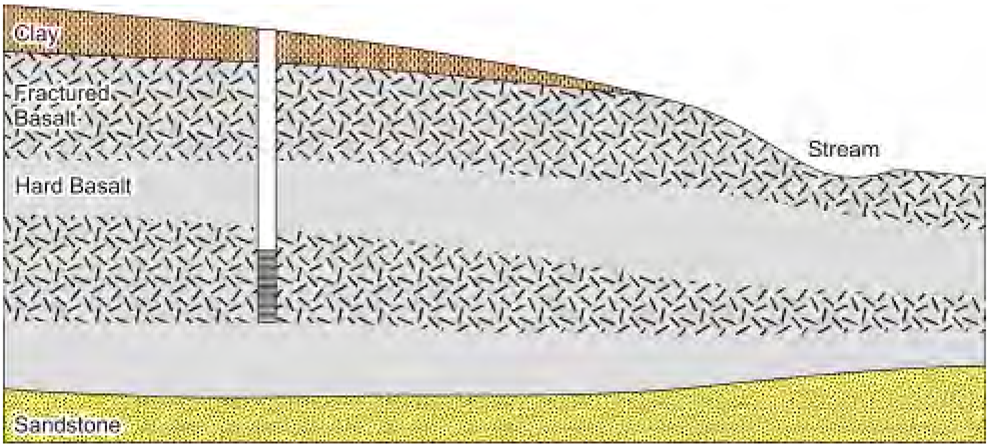
ii) layers of fractured and hard basalt;

iii) fractured basalt underlain by hard basalt with a localised fractured zone; and

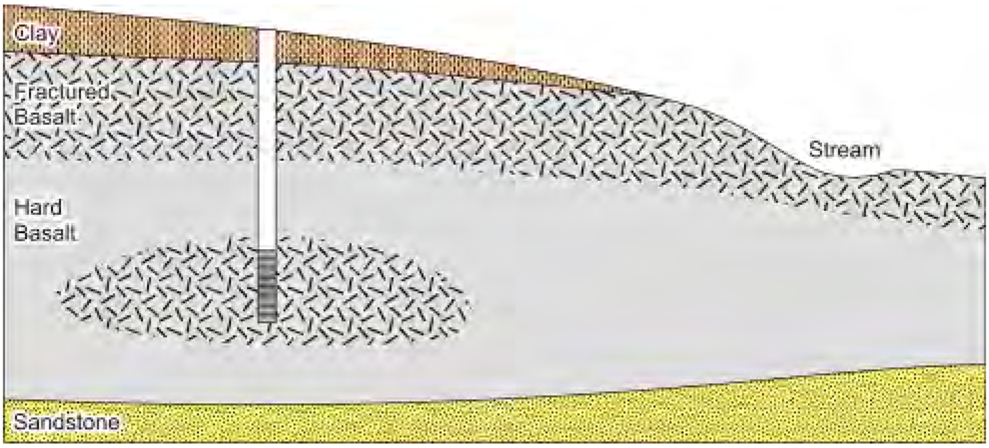
iv) hard basalt with a zone of scoria.



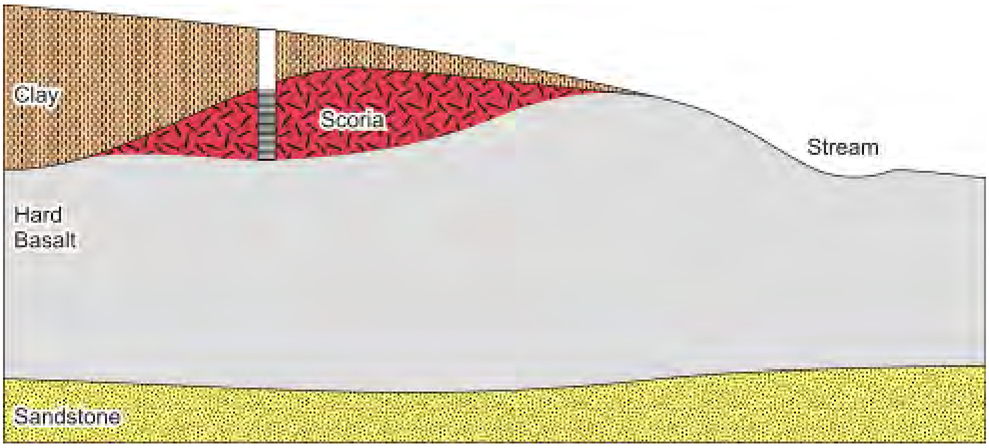
- **Figure 13. Fractured basalt underlain by hard basalt.**



- **Figure 14. Layers of fractured and hard basalt.**



- **Figure 15. Fractured basalt underlain by hard basalt with a fractured basalt zone.**



- **Figure 16. Hard basalt with a scoria zone.**

5.3. Numerical Model Analysis

In order to determine the appropriateness of analytical methods, numerical models were developed to represent and simulate the conceptual aquifer settings presented in the previous section. The intention is to then compare the outputs from these numerical models with analytical methods.

A single generalised numerical model was set up using the FeFlow package[21]. Use of a generalised model allowed for speed of implementation while taking the complexities of the flow system into account. The layer structure was designed to be adaptable to each of the four geological settings allowing a single model to be used for each. The complexities of each geological setting have to be accounted for to assess their respective impact on attenuation of groundwater abstraction effects. These complexities were determined through a review of the geology of the Maunu, Maungatapere, Whatitiri and Monument Hill complexes, as outlined above, and include:

i) meandering streams running along the boundaries of basalt flows;
ii) smaller streams branching into main streams through tributaries;
iii) an aquifer basement that rises towards the edges of the basalt flow; and
iv) a catchment area that grows radially towards the edges of the basalt, consistent with the nature of basalt flows (moving radially outwards from a volcanic cone).

The final model setup is shown in **Figure 17**.

[21] A fully three dimensional finite element modelling system developed by WASY-DHI in Germany.

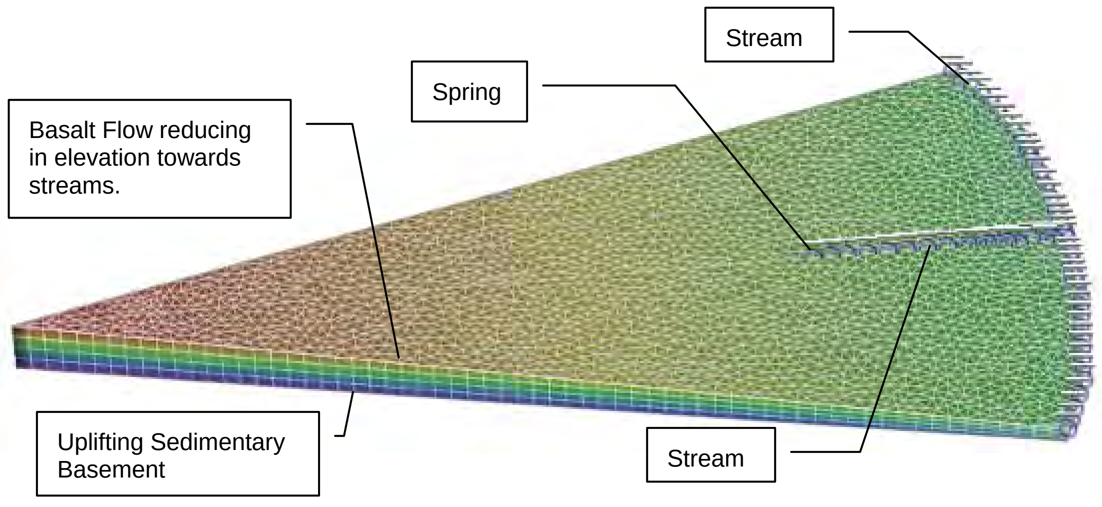


Figure 17. Generalised model structure.

Each of the four geological settings was assigned an individual set of hydraulic parameters, which include hydraulic conductivity, storativity and specific yield of the rock. Given the heterogeneity in aquifer hydraulic parameters that occur in nature, particularly in basalt aquifers, a representative set of parameters was chosen so that the simulations give a good indication of results that can be reasonably expected.

The hydraulic parameters assigned were based on the two previous modelling exercises completed for the Maunu, Maungatapere and Whatitiri aquifers in SKM (2010a) and for the Monument Hill (Kaikohe) aquifer in SKM (2010b).

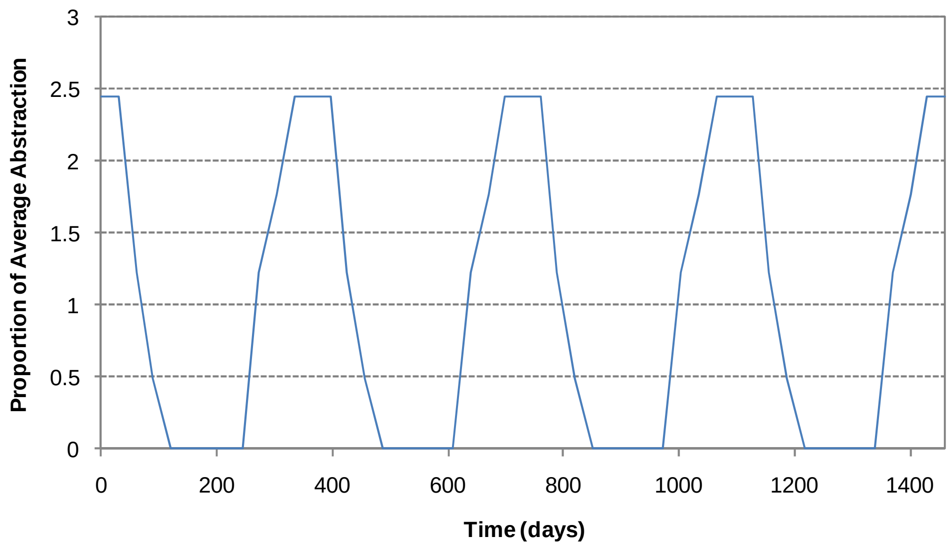
The geological settings and their associated parameters used in this investigation are summarised in **Table 2**.

Table 2. Summary of hydraulic parameters.

Rock Type	K_h (m/s)	K_h/K_v	S_y	S_s (1/m)
Scoria	1.7×10^{-5}	3	0.1	5×10^{-6}
Hard Basalt (minor fractures)	1.7×10^{-6}	10	0.01	5×10^{-6}
Fractured Basalt	1.5×10^{-5}	10	0.01	5×10^{-6}

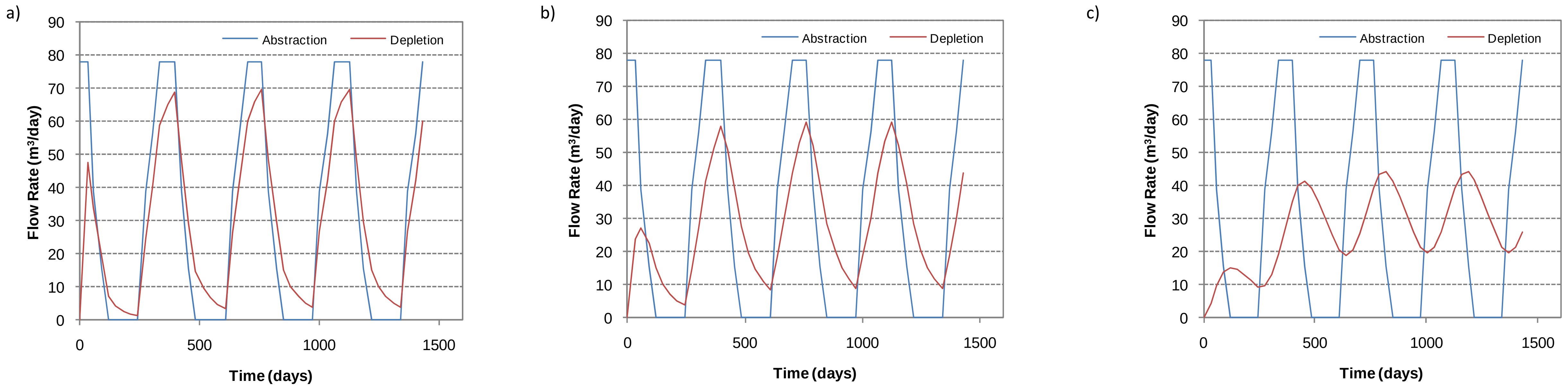
To assess stream depletion, simulations utilising bores at various distances upgradient from the stream/spring of 35 m, 200 m and 1000 m were assigned in the model within the geological unit under investigation for each particular simulation, as shown in **Figure 13** to **Figure 16**.

A typical irrigation flow profile was applied to an abstraction bore in the model. This profile is shown in **Figure 18**, with increased abstraction during the summer months and no abstraction during the winter months. The average abstraction rate applied was 32 m^3/day, hence peak abstraction was approximately 80 m^3/day. This abstraction rate represents approximately 2% of mean annual rainfall recharge within the model domain and was selected after initial sensitivity testing as a suitable flow that did not aggressively depressurise the model domain.

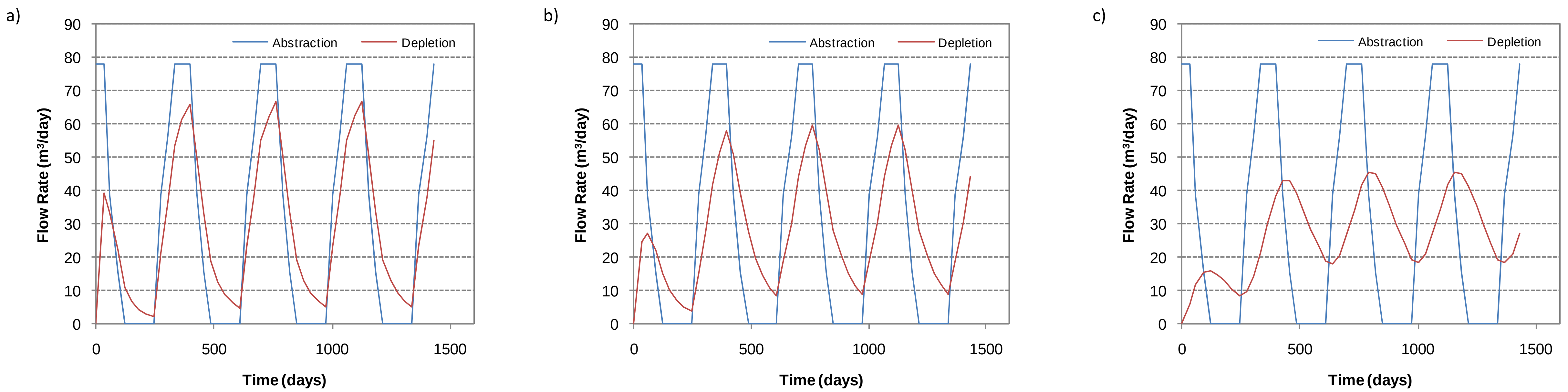


- **Figure 18. Modelled irrigation profile.**

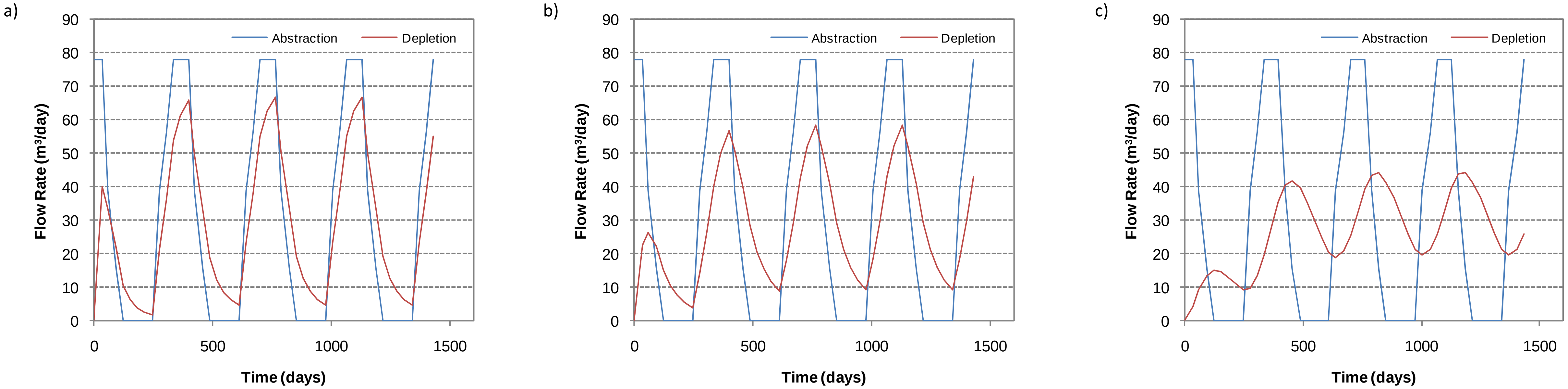
Stream depletion plots for the simulation of each of the three different abstraction rates and the four geological settings are shown in **Figure 19** to **Figure 22**. The irrigation profile is shown in blue and the stream depletion rate is shown in red.



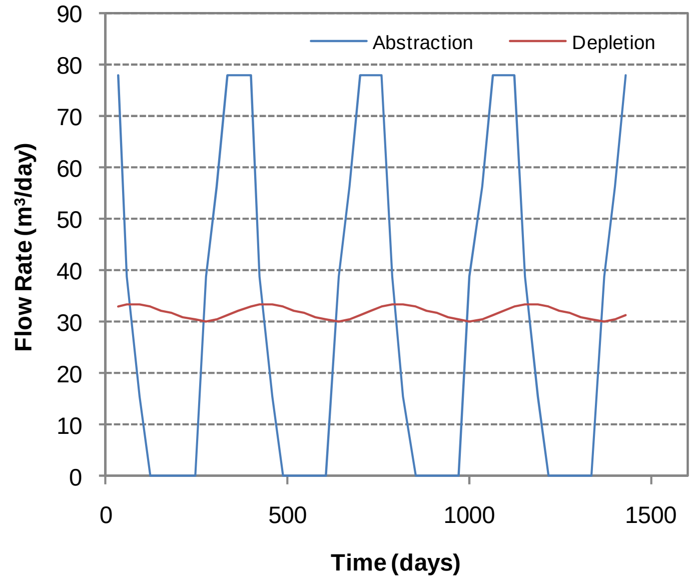
- **Figure 19. Abstraction and depletion rates for fractured basalt underlain by hard basalt with a) 35 m bore displacement, b) 200 m bore displacement and c) 1000 m bore displacement.**



- **Figure 20. Abstraction and depletion rates for layers of fractured and hard basalt with a) 35 m bore displacement, b) 200 m bore displacement and c) 1000 m bore displacement.**



■ **Figure 21. Abstraction and depletion rates for fractured basalt underlain by hard basalt with a fractured basalt zone with a) 35 m bore displacement, b) 200 m bore displacement and c) 1000 m bore displacement.**



b)

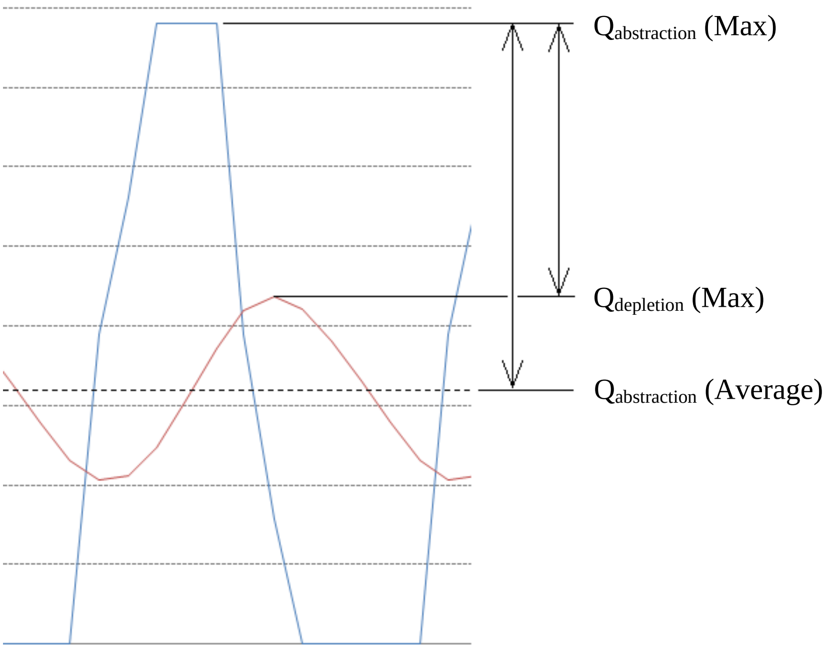
■ **Figure 22. Abstraction and depletion rates for hard basalt with a scoria zone with a 200 m bore displacement.**

5.3.1. Analysis of Modelling Results

In the processing of the results for each setting, an attenuation factor was developed for scenario comparative purposes. The attenuation factor for the purposes of this study is defined by the following equation, which essentially is a ratio of the difference between maximum abstraction and maximum depletion, and the difference between maximum abstraction and average abstraction.

$$A_f = \frac{Q_{abstraction}(Max) - Q_{depletion}(Max)}{Q_{abstraction}(Max) - Q_{abstraction}(Average)}$$

Where A_f is the attenuation factor, $Q_{abstraction}$(Max) is the maximum abstraction rate, $Q_{depletion}$(Max) is the maximum depletion rate and $Q_{abstraction}$(Average) is the average abstraction rate. This is shown graphically in a time varying graph of abstraction and stream depletion, in **Figure 23**.



- **Figure 23. Attenuation description.**

The following explains the range in values expected for the attenuation factor:

- **A_f = 1-** If the attenuation factor is one, the stream depletion rate is equal to the average abstraction rate, and hence the stream depletion rate is fully attenuated.
- **A_f = 0-** If the attenuation factor is zero, the maximum stream depletion is equal to the maximum abstraction, hence there is no attenuation. All cases are expected to lie between these limits.

The values of attenuation factor should be considered an indicative index only, as the scale is not proportional (i.e. a doubling in attenuation factor will not always equal a doubling in stream depletion rate).

The attenuation factors for these settings are summarised in **Table 3**. As separation increases between the bore and the stream, there is an increase in the resistance to flow between the two, resulting in increased attenuation of the stream depletion rate resulting from abstraction. This is seen from the reduced oscillation in stream depletion rates with increasing distance in the above figures.

- **Table 3. Attenuation factors.**

Geological Setup	Bore Separation		
	35 m	200 m	1000 m
Fractured basalt underlain by hard basalt.	0.184	0.402	0.730
Layers of fractured and hard basalt.	0.242	0.398	0.700
Fractured basalt underlain by hard basalt with a fractured basalt zone.	0.241	0.423	0.730
Hard basalt with scoria zone.	-	0.963	-

The attenuation factors for each of the first three geological settings are similar for the same separation between the bore and the stream. This is likely due to the good connection between the stream and the bore created by the fractured basalt at the surface.

Only one separation was tested for the hard basalt with a zone of scoria because changing bore location would mean having to move the scoria zone, altering the geological setting of the model significantly. This simulation gave the highest attenuation factor, with the hard basalt providing a significant barrier to flow, attenuating the pressure signal observed at the stream. This is further evidenced in that it took approximately 16 years of irrigation cycles before a steady pattern was observed in stream depletion results as shown in **Figure 24**, which shows results from the numerical model running over a period of 40 years.

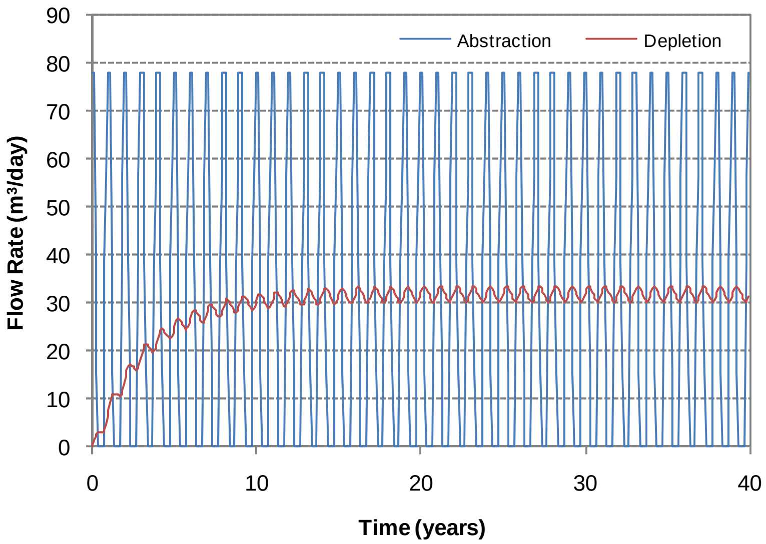


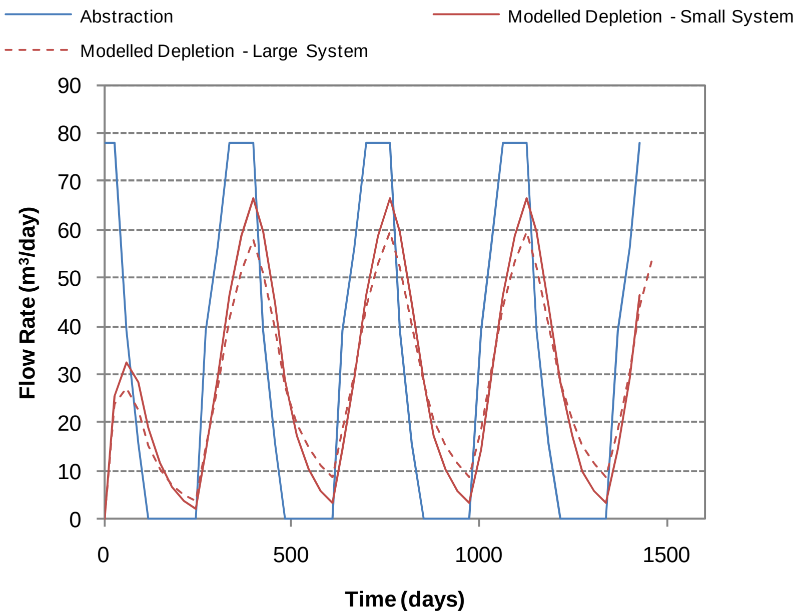
Figure 24. Stream depletion for hard basalt with a scoria zone (200 m bore displacement) over a period of 40 years.

5.3.1.1. Effect of System Size on Attenuation

There are several details in the numerical model that need to be considered when implementing an analytical method to perform the same role. One of the differences is that the numerical model will often have boundaries, whereas in most cases an analytical method is unbounded (as outlined in **Section 4**), and even where boundaries are present, they are simplified. The impact boundaries have on stream depletion is of potential significance, because they reduce storage available in the modelling domain and can focus the pressure drawdown created by abstraction towards the stream, resulting in reduced attenuation.

An additional simulation was run to test the effect of reducing the domain size. The boundaries of the model were reduced to no more than 100 m from the bore, with the abstraction bore remaining 200 m from the stream. A simulation in which the domain size was increased was not undertaken during this assessment, as increasing the size of model would not fit with the localised basalt flows, and hence compartmentalised basalt catchments identified through the review of Northland's basalt complexes.

Implementing this change reduces attenuation as expected, as shown in **Figure 25**. This is observed from the reduction in attenuation factor from a value of 0.402 in the original setup to a value of 0.248 in the reduced setup.



- **Figure 25. Stream depletion with varying model domain (200 m bore displacement).**

5.4. Comparison of Numerical Models to Analytical Methods

5.4.1. Hunt (2009) Method

As previously inferred, analytical methods can prove very time efficient for assessing stream depletion rates. Data can be entered quickly and results obtained with very little setup and computation time, avoiding potential complications in these areas with numerical models.

Initial analytical modelling was performed based on the setting with fractured basalt underlain by hard basalt only. This setting is representative of the first three settings given that numerical modelling results were comparable between these settings (as shown in **Figures 19** to **21**). The first analytical method chosen for this is the Hunt (2009) solution outlined in **Section 4.5.2** and **Figure 10**.

This method was chosen because it allows for horizontal flow at the surface as would be expected in a fractured basalt setting and it is available in Excel format, which can be quickly adapted to a varying abstraction rate.

To be consistent with the numerical model, several simplifying assumptions were made in deploying the analytical method for this application. Since the analytical method does not have the same level of detail as the numerical model, several of the details had to be generalised such as layer aquifer thickness, and stream geometry and separation from the bore. These assumptions are as follows:

- The thickness of the top aquifer is constant throughout the entire model;
- The hard basalt is separated into two to match the model conceptualisation;
- The top half of the hard basalt models vertical flow between the hard basalt and the fractured basalt;
- The bottom half of the hard basalt models the horizontal flow of water in the hard basalt unit;
- The stream is straight and has no branches or tributaries; and
- The stream leakage parameter is very large (facilitating unrestricted water transfer) and is not considered to be a parameter of importance in this modelling exercise.

The specific parameters used in the analytical method, resulting from the hydraulic parameters outlined in **Table 2**, the above assumptions and the structure of the Hunt (2009) model are summarised in **Table 4**.

- **Table 4. Summary of Hunt (2009) model parameters for fractured basalt underlain by hard basalt.**

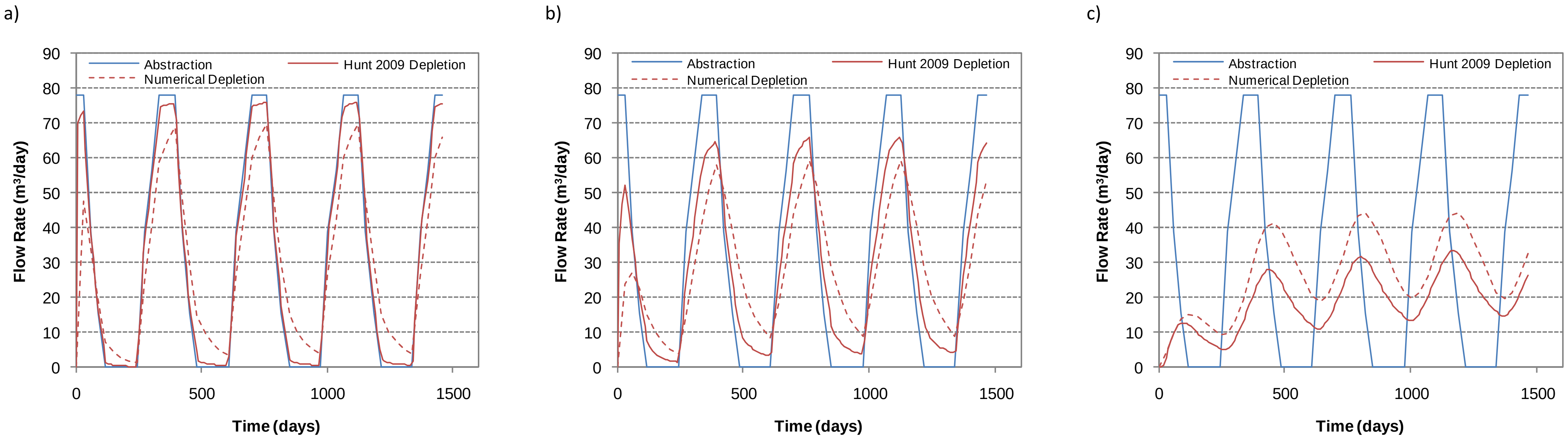
Layer	T (m^2/s)	S	K_v (m/s)	Thickness (m)
Fractured Basalt	4.05×10^{-4}	0.01	-	27
Hard Basalt (minor fractures)	-	-	1.70×10^{-7}	12.1
Hard Basalt (minor fractures)	2.06×10^{-5}	6.06×10^{-5}	-	12.1

Modifications to Hunt (2009) method were undertaken to enable simulation of variable abstraction rates. The primary modification comprised the addition of super-positioning functionality to the code.

The same irrigation abstraction scheme outlined for the numerical model was applied with bore to stream separation distances of 35 m, 200 m and 1000 m, producing the results shown in **Figure 26**. The attenuation factors for each of these simulations with their numerical counterparts are shown in **Table 5**.

- **Table 5. Comparison of numerical and analytical attenuation factors for fractured basalt underlain by hard basalt.**

Geological Setup	Bore Separation		
	35 m	200 m	1000 m
Numerical Model	0.184	0.402	0.730
Hunt (2009)	0.046	0.261	0.814



■ **Figure 26. Stream depletion rates for numerical and Hunt (2009) analytical methods for fractured basalt underlain by hard basalt with a) 35 m bore displacement, b) 200 m bore displacement and c) 1000 m bore displacement.**

The Hunt (2009) solution produces stream depletion curves consistent with the abstraction profile, albeit slightly larger in the summer months and lower in the winter months, hence the Hunt (2009) method predicts less attenuation than the numerical model for both the 35 m and 200 m bore spacing. This indicates that the Hunt (2009) method is conservative for the purposes of analysing stream depletion.

One key reason for this conservatism is the way in which the Hunt (2009) method has been applied, i.e. it has been assumed that there is an essentially perfect connection between the aquifer and the stream. Entering a lower streambed connectivity value into the method will increase the predicted attenuation, allowing it to be calibrated to experimental data where available.

In the 1000 m case (**Figure 26c)**, the reported attenuation for the Hunt (2009) method is greater than the numerical model. This is because the analytical method has not fully reached its equilibrium cyclic state. The Hunt (2009) method was run for up to 40 years without fully reaching such a state to the point at which the method became inefficient (taking ~10 minutes to compute). This is due to the assumption that there are no boundaries in the analytical method. This assumption is not met for Northlands basalt aquifers and hence this method should only be used if the bore is in close proximity to the stream.

The large distance between the bore and the stream means that the bore will take a large proportion of abstracted water from storage before its effects are fully felt at the stream. A very long lead in period will therefore have to be simulated using the analytical method before it is able to adequately simulate stream depletion.

Overall, this work indicates that the Hunt (2009) method is appropriate for the setting of fractured basalt overlying hard basalt where the bore is located within approximately 500 m of the stream.

5.4.2. Hunt (2007) Method

A second analytical method was tested to address the issues resulting from infinite storage within the Hunt (2007) method. For this analysis the Hunt (2007) method was tested (see **Section 4.4.2** and **Figure 9**).

Hunt (2007) assumes that water is abstracted from an aquifer unit overlain by an aquitard containing both the stream and the water table. In the geological setting of fractured basalt overlain by hard basalt, there is no aquitard unit. However, this model was adapted to model the desired setting by making the aquitard unit as thin as possible while still containing the water table for the abstraction rates used for irrigation (i.e. making sure that the unit was thick enough to encompass anticipated drawdown) and by assigning hydraulic parameters of fractured basalt to the aquitard unit. For the purposes of this assessment, this aquitard is referred to as the shallow aquifer.

This method allows for boundaries to be placed on the aquifer unit, making it more likely to be able to accurately model the situation where the bore is located far from the stream.

In the numerical model, the very end of the wedge shaped domain was 2,200 m from the stream and 1,600 m from the spring. As the Hunt (2007) method is unbounded in the direction parallel to the stream, it was assumed that it was most appropriate for the boundary to be placed halfway between the end of the numerical model and the stream location (i.e. between 800 m and 1,000 m away from the stream). The pumping bore may be placed at the location of the boundary in some situations. However, this does not inhibit the method from operating correctly.

This model additionally makes the following assumptions:

- Flow is vertical only in the aquitard unit;
- Flow is horizontal only in the aquifer unit;
- The stream is of finite sized and must be defined; and
- The stream is straight and has no branches or tributaries.

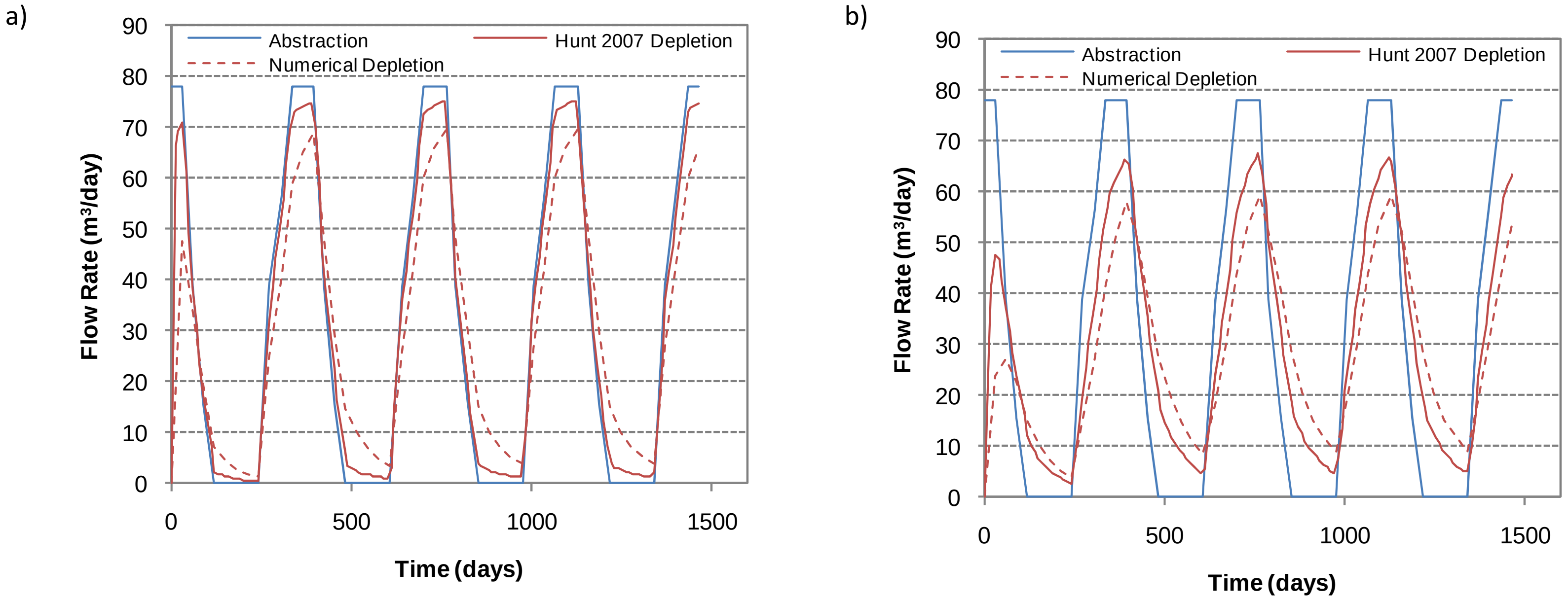
Several parameters were required for entry into this model and are outlined in **Table 6**.

- **Table 6. Model parameters for Hunt (2007) analytical solution.**

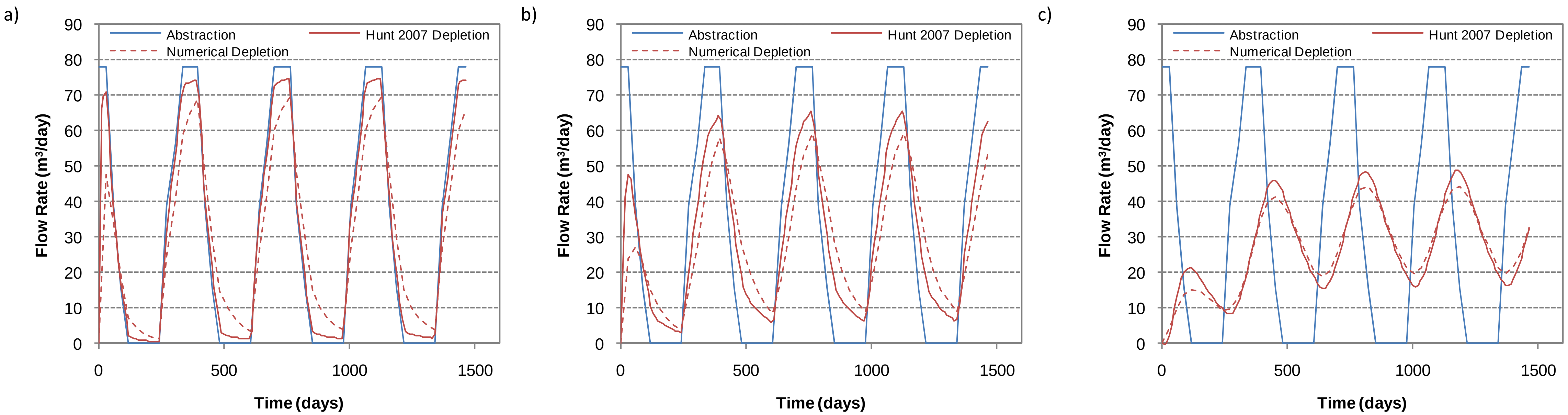
Parameter	Value
K_h (m/s)	1.5×10^{-5}
K_v (m/s)	1.5×10^{-6}
Aquitard Storativity	0.01
Aquifer Storativity	0.01
Aquitard Thickness (m)	5
Aquifer Thickness (m)	22
Stream Separation (m)	35, 200, 1,000
Right Boundary Separation (m)	800, 1,000
Left Boundary Separation (m)	20
Stream width (m)	20
Stream depth (m)	4.5

The same modification to the Hunt (2007) code was implemented to enable transient simulation of abstraction rates.

The same irrigation abstraction scheme outlined for the numerical model was applied with stream separations of 35, 200 and 1,000 m producing the attenuation factors summarised in **Table 7** and the plots of stream depletion rates shown in **Figure 27** and **Figure 28**.



- **Figure 27. Stream depletion rates for numerical and Hunt (2007) analytical methods for fractured basalt underlain by hard basalt with: a) 35m bore displacement, and b) 200 m bore displacement, with a boundary at 800 m.**



- **Figure 28. Stream depletion rates for numerical and Hunt (2007) analytical methods for fractured basalt underlain by hard basalt with: a) 35m bore displacement, b) 200 m bore displacement, and c) 1,000 m bore displacement with a boundary at 1000 m.**

These stream depletion traces in **Figure 27** and **Figure 28** and attenuation factors in **Table 7** show that for both boundary distances of 800 and 1,000 m, the results produced by the Hunt (2007) method are conservative (i.e. less attenuation predicted) than the numerical model. This strongly suggests that the Hunt (2007) method with boundary conditions applied provides results that are more applicable than the Hunt (2009) method, which is unbounded or comprises infinite storage.

In a Northland context, this suggests that bounded analytical methods such as Hunt (2007) are appropriately conservative for high level or first pass assessment of stream depletion effects in localised basalt flows or compartmentalised basalt catchments.

- **Table 7. Comparison of numerical and analytical attenuation factors for fractured basalt underlain by hard basalt for the Hunt (2007) model.**

Geological Setup	Bore Separation		
	35 m	200 m	1000 m
Numerical Model	0.184	0.402	0.730
Hunt (2009)	0.046	0.261	0.814
Hunt (2007) – 800 m Right Boundary	0.062	0.229	-
Hunt (2007) – 1000 m Right Boundary	0.069	0.268	0.634

Note: Recall an attenuation factor of 0 = no attenuation, while 1 = fully attenuated.

5.5. Conclusions

The aim of this section was to assess whether an analytical method could be utilised to assess stream depletion effects from groundwater abstraction in a range of geological conditions.

The work indicated that:

- Preliminary testing of the three fractured basalt settings all produced very similar results for stream depletion in numerical simulations and as such can all be represented using the fractured basalt setting;
- Scoria settings likely to occur in the Northland basalt aquifers are likely to have the water body (either a spring or stream) situated at the edge of the boundary between the scoria and the less permeable units at its boundary, making the scoria setting similar to the fractured basalt setting with the hydraulic properties of basalt replaced with those of scoria; and
- Use of a bounded aquifer tool such as the Hunt (2007) method would be appropriate for determination of stream depletion effects in localised basalt flows or compartmentalised basalt catchments. This concept is explored further in **Section 6**.

6. Stream Depletion Tool

6.1. Introduction

The previous section aimed to assess whether analytical methods for assessing groundwater-surface water interaction specific to Northland basalts could be developed. The work indicated that use of a bounded aquifer tool such as the Hunt (2007) method would be appropriate for determination of stream depletion effects in localised basalt flows or compartmentalised basalt catchments, and for all geological settings considered.

With this understanding, the Hunt (2007) method was further developed with the purpose of producing a prototype Stream Depletion User Interface Tool for NRC to evaluate its usefulness in assisting applicants or Council staff in water allocation applications or decisions.

This section describes the development of the tool and in particular the key features and assumptions.

6.2. Description of the Prototype Tool

As inferred above, a tool for the assessment of stream depletion rates within basalt aquifer settings has been developed for Northland Regional Council to trial. The tool predicts a stream depletion rate from input parameters in a consent or consent application, such as proposed peak and average abstraction rates, the distance of the bore from the stream, aquifer setting type, and the thickness of the aquifer.

This tool implements an adaptation of the Hunt (2007) method discussed in **Section 5.4.2**. Several methods were assessed against numerical simulations, however this method was chosen because:

- It allows for the extent of the aquifer to be limited. This is necessary because the catchment and geological boundaries of the aquifer focus depletion into the stream.
- It is available in excel format and can be easily modified.
- It can be distributed on the condition that the original source (Bruce Hunt) is acknowledged.
- It produced good results on the slightly conservative side when it was compared against numerical simulation results for the same settings.

The tool contains three spreadsheets. The first is an instruction sheet, which lists information about the model, how it is used and what its outputs are. The second sheet assists the user in selecting an appropriate thickness for the upper unit of the model (shallow aquifer thickness). Finally, the third sheet allows application parameters to be entered, presents plots of the output and reports the peak stream depletion rate for the provided input parameters.

The peak stream depletion rate is considered to be the parameter of most importance, as it provides an indication of the worst possible impact that could result in the stream.

The tool contains two geological settings to choose from; fractured basalt and scoria. The original work documented in **Section 5** considered four geological scenarios:

- fractured basalt overlying hard basalt;
- layers of fractured and unfractured basalt;
- fractured basalt overlying a layer of unfractured basalt with a fractured lens from which abstraction is taken; and
- an unconnected scoria lens overlying hard basalt.

There were two reasons for reducing the number of settings. Firstly, preliminary testing of the three fractured basalt settings all produced very similar results for stream depletion in numerical simulations and can all be represented using the fractured basalt setting defined in the tool.

Secondly, the scoria settings likely to occur in the Northland basalt aquifers are likely to have the water body (either a spring or stream) situated at the edge of the boundary between the scoria and the less permeable unit at its boundary, making the scoria setting similar to the fractured basalt setting with the hydraulic properties of basalt replaced with those of scoria.

The tool requires a boundary distance to be entered to limit the aquifer to a finite extent. A map dividing the Maungatapere aquifer into surface water catchments is shown in **Figure 29,** with each catchment assigned a boundary distance for entry into the tool. In the assessment of a typical application, the location of the proposed take should be found on this map and the boundary distance assigned to appropriate catchment should be entered into the tool.

- **Figure 29. Boundary distance map.**

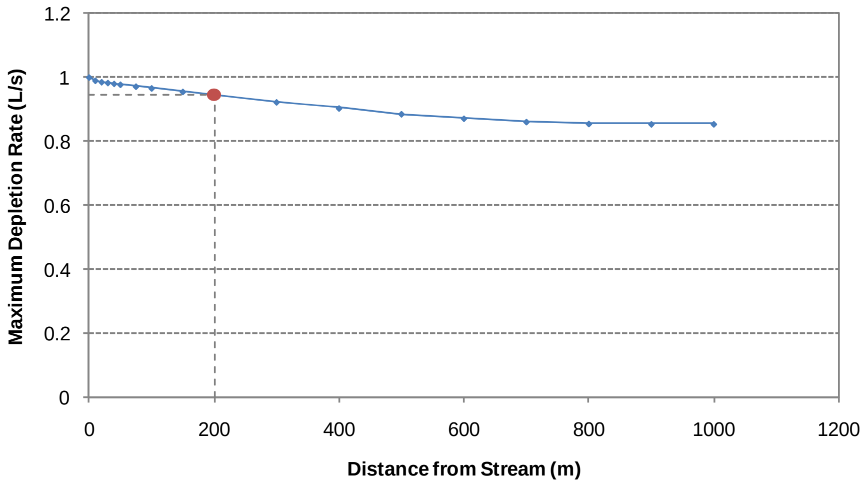
(See A3 attachment at rear).

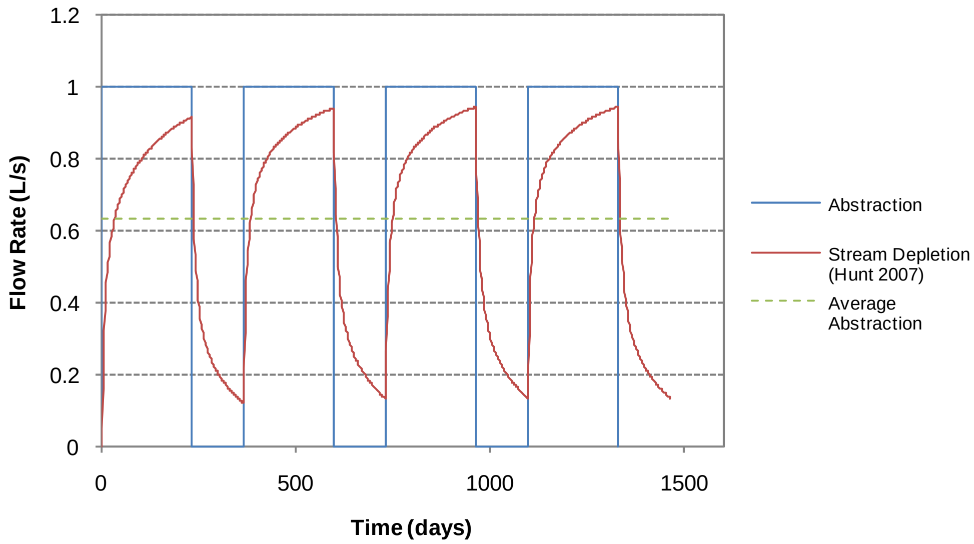
In order to assess stream depletion, the selected geological setting is conceptualised into two units:

- an upper unit at the surface – allowing vertical flow only; and
- an underlying aquifer.

In a basalt setting, there is likely to only be a single aquifer unit with no overlying material. Due to this, the upper unit is assigned the vertical hydraulic properties of the aquifer. In addition, this method assumes that the water table sits in the upper unit, with the thickness estimated using the second spreadsheet based on the input abstraction rate and aquifer thickness (ensuring the unit is thick enough to encompass anticipated drawdown).

The output from the tool consists of two plots and a table of key statistics. The two plots, as shown in **Figure 30**, plot 1) the maximum stream depletion rate expected from the stream against the distance that the take is from the stream and 2) flow rates over a four year period including peak rate abstraction, average abstraction rate and the resulting stream depletion.





- **Figure 30. Example result plots from Stream Depletion Tool.**

The key output statistics calculated using the tool are as follows:

- *Peak Stream Depletion* – this is a maximum stream depletion predicted from the chosen input parameters over the first four years of irrigation;
- *Average Abstraction*– this is the average flow rate that will be depleted from the stream if this irrigation profile is continued indefinitely;
- *Calculated Stream Depletion* – this is the average stream depletion predicted by the method in the last year of the first four years of irrigation. It is calculated as a check to ensure that the abstraction has been allowed adequate time to reach the stream.
- *Balance Check*– this is the difference between the average abstraction rate and the average stream depletion rate calculated by the method. The balance check is premised on the assumption that the total volume of abstracted water will ultimately result in an equivalent volume of stream depletion in the long term (recognising that it is peak (i.e. short term) stream depletion that is important for water allocation purposes). The spreadsheet will produce a warning if this value is more than 10% of the abstraction rate as this will indicate that the results may not be reliable.

7. Recommendations on Potential Policy Development

As stated in **Section 1**, the specific objective of this project is to provide appropriate methodologies to determine groundwater and surface water interaction in basalt aquifers in Northland, recommend appropriate surface and groundwater interaction policy, and provide a draft of how these policies may be framed and transferred to basalt aquifers in Northland.

The previous sections have outlined the development of an analytical method, with a prototype Stream Depletion User Interface Tool being produced for NRC. Following the development of this tool, recommendations for changes to the current Regional Plan with regards to groundwater-surface water interaction in basalt aquifers are as follows:

- The first step of the process is to define the minimum flow requirements for the stream of interest. In order to keep this assessment conservative, the minimum flow recommendations in the Proposed National Environmental Standard on Environmental Flows and Water Levels (Ministry for the Environment, 2008) could be used.
- It is recommended that the Stream Depletion User Interface Tool, if considered appropriate, be incorporated into the Regional Plan via a Schedule. This Schedule could be developed in a similar format as Schedule 5A of the Proposed Plan Change 1 C for the Otago Regional Council (see **Section 2.13**). As such, this Schedule would overview the tool and provide advice on matters such as:
  - situations where stream depletion effect in basalt aquifers is unlikely;
  - use of analytical equations other than Hunt (2007); and
  - use of numerical flow models to determine streamflow depletion effects.

It should be noted that an initial review of the current NRC policy on the Effects on Surface Water Resources (Policy 10.5.7) was undertaken and it is considered that this Policy covers all of the relevant factors that need to be considered.

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