  

Groundwater allocation methods and operational experience in New Zealand and Europe

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Executive Summary

KSL was engaged by Waikato Regional Council (WRC) to review and summarise the methods that have been used to define groundwater allocation zone boundaries and limits by regulatory bodies in New Zealand and Europe and to obtain insights from regulatory staff on their operational experience with groundwater allocation limit setting and implementation. This information will be used to help WRC technical staff to scope and plan science work in support of their regional plan review process.

Groundwater allocation zones are generally defined according to either environmental constraints or management objectives. Allocation zone alignment with the spatial extent of water-bearing geological units is an example of the former; zone delineation to encapsulate high groundwater usage areas and the use of modelling to define the area of an aquifer within which groundwater abstraction is likely to deplete stream flows beyond a certain threshold within a certain period time are examples of the latter. A combination of both approaches is used in some instances.

Because groundwater allocation zone boundaries often have significant implications for water users, the method used to define the boundary can become contentious. Challenges often arise where water users on one side of a boundary are more restricted and face greater economic impacts than those on the other side. The biggest challenges arise where previously unrestricted water users face new restrictions and where the boundaries are based on modelling (be it conceptual or mathematical) because modelling is inherently uncertain and open to challenge.

Use of a fixed percentage of long-term average rainfall or estimated groundwater recharge rates has been the most common method used in New Zealand to set allocation limits. This has been superseded in some regions (typically those with higher intensity groundwater usage) by value judgement-based limits or those based on specific effects thresholds (e.g. a maximum rate of stream depletion or maintenance of a 2 m head at the coast). The European Water Framework Directive, as implemented by the Environment Agency in England, uses a comprehensive four test system comprising a Groundwater Balance Test, a Surface Water Dependent Test, a Groundwater Dependent Terrestrial Ecosystems Test and a Saline and Other Intrusions Test.

Challenges associated with use of a fixed percentage of groundwater recharge include uncertainty over the recharge rate, the potential for significant adverse effects to occur in multi-year groundwater droughts (especially if a high percentage of groundwater recharge is allocated, e.g. 50%) and the possibility of adverse effects on sensitive waterbodies (e.g. wetlands and springs) occurring under relatively small changes in groundwater level. Resource-intensive technical assessment/modelling and stakeholder and community engagement is often required to define allocation limits via a value judgement process.

Managing stream depletion effects is often the most challenging aspect of groundwater allocation and limit-setting. Some of the main areas of difficulty highlighted in this report are: a) understanding lag times between groundwater abstraction and stream depletion effects coupled with the requirement to conclusively demonstrate that imposition of low flow restrictions will deliver a sufficient level of benefit to counteract economic impacts; b) apportionment of consented water take rates between groundwater and surface water for allocation accounting in the face of stream depletion modelling uncertainty; c) incomplete information on actual groundwater abstraction rates and hence imprecise knowledge of the effects of current abstraction on stream flows; and d) managing the conflict between regional plan simplicity plus implementation efficiency versus provision of both sufficient differentiation/discretisation in rules and policies to manage a wide range of possible effects and a sufficient degree of equality for water users.

Solutions deployed to address some of these challenges include use of common expiry dates and five year water take consent durations to provide a mechanism for a more adaptive management approach; investment in rigorous numerical modelling of stream depletion with uncertainty quantification to provide a firm platform for decision-making, double counting of water takes (within both surface water and groundwater allocation blocks) to mitigate the risk of over-allocation following updated estimates of stream depletion rates and the use of plan rules which provide a mechanism for updates as improved information and knowledge become available.

Consideration of the effects of global warming and climate breakdown is recognised as an important challenge for groundwater allocation limit-setting, but no specific solutions were found within the information obtained for this study.

Contents

1. BACKGROUND

KSL was engaged by Waikato Regional Council (WRC) to review and summarise the methods that have been used to define groundwater allocation zone boundaries and limits in New Zealand and overseas and to provide insights into operational experience with groundwater allocation limit implementation.

The Water Allocation component of the Waikato Regional Plan is scheduled for review in 2022; WRC wish to obtain information on how allocation limits and boundaries have been defined both across NZ and overseas as part of their preparatory work. The main questions of interest are:

1. What approaches have been used to define allocation limits and boundaries?
2. Which approaches have been successful; which have been problematic at implementation stage and how have problems been overcome?
3. What science information is required to robustly define allocation limits under the different approaches?

This information will be used to help to scope and plan science work in support of the regional plan review process.

2. GROUNDWATER MANAGEMENT OVERVIEW

Determination of the impacts of groundwater abstraction on water users, the long-term groundwater resource and environmental receptors is a core requirement for effective groundwater management in areas of high water demand. The impacts of groundwater abstraction are often considered in terms of direct local effects and diffuse cumulative effects. Examples of direct local effects include drawdown in a neighbouring well, dewatering of a wetland or depletion of a spring due to a new groundwater abstraction. Examples of diffuse cumulative effects include the combined effects of long-term pumping from all wells within a catchment on groundwater levels, stream baseflows and sea water intrusion.

Direct local effects are often assessed and managed through field investigations and/or modelling as part of the Assessment of Environmental Effects required under the Resource Management Act to support determination of consent applications. Although cumulative local effects are sometimes managed within the consenting process (e.g. Environment Canterbury's WQN10 well interference method – see Section 4.1.11), this can be challenging. Cumulative effects are often managed through groundwater allocation limits. Allocation limits typically define the volume of water that can be extracted from a given geographic area (sometimes referred to as Groundwater Allocation Zones or Groundwater Management Zones) over a given time period (typically a year, but sometimes for shorter periods).

3. GROUNDWATER MANAGEMENT CHALLENGES IN THE WAIKATO REGION

Groundwater Management Zone boundaries were defined several decades ago in the Waikato Region with the primary aim of identifying areas with high resource utilisation, where more detailed science investigations should be prioritised. In 2014 the Groundwater Management Zone boundaries were reclassified as groundwater allocation zones during an Environment Course process. Because the boundaries were not defined with this purpose in mind, a number of issues have arisen:

1) Some groundwater GAZs are very large and have accordingly large allocation limits. These large limits coupled with the current Regional Plan rules do not provide a mechanism by which the direct and cumulative local effects of single large abstractions or groups of small abstractions can be adequately managed.
2) Aquifer morphology in the Waikato region is variable; some aquifers discharge at the coast but many of the large aquifers are found within inland basins and discharge only to surface water at outlet gorges. This presents challenges under the current allocation framework
3) The presence of multi-layered aquifers in the region, with varying degrees of connectivity with surface water resources, create challenges for determination of effects-based allocation limits
4) The current GAZ boundaries do not cover all groundwater resources within the region. The current Regional Plan rules impose severe restrictions on groundwater abstraction outside of allocation zones.
5) The current method to define sustainable yield in accordance with stream baseflow protection goals assumes that the effects of groundwater abstraction on surface water occur evenly over a 12-month period. The potential lag effects between irrigation season abstraction and the depletion of stream flows are not accounted for.

3.1. Scope of work

The focus of this project is to gather and summarise information on groundwater resource management practices have been implemented by regulatory bodies and to provide insights into any difficulties that have been encountered and the solutions that have been found. The scope of work is to provide:

1. A summary of methods used within NZ and overseas to define allocation limits;
2. A summary of methods used within NZ and overseas to define groundwater allocation zone boundaries with a focus on groundwater management in the absence of hydrological boundaries;
3. Discussion of the potential implementation challenges and solutions associated with different approaches based on the experience of operational staff;
4. An overview of the science data, analysis and knowledge required to define allocation limits and boundaries under relevant options; and
5. A SWOT[1] analysis of the allocation methods and options

Section 4 of this report covers items 1-2 above. Section 5 summarises the methods used to define groundwater allocation zones and to set allocation limits which have been used by the authorities who contributed to this study, the technical assessment requirements for these methods and provides a SWOT analysis of each. The methods used by each regulatory authority together with challenges and solutions are summarised in Appendix A.1.

[1] Strengths, Weaknesses, Opportunities and Threats

4. ALLOCATION METHODS

4.1. Introduction

The following sections provide a summary of the information collected via phone conversations and email correspondence with staff at regional councils in New Zealand, the French Geological Survey and the Environment Agency in England.

4.1.1. Northland

Allocation methods - zone boundary delineation

Productive groundwater resources in the Northland Region are found in both a large number of small coastal aquifers, which are delineated through their geological extent and usage areas and in more extensive formations such as the Aupouri aquifer to the north of Kaitaia. The Aupori aquifer is laterally extensive and has been split into separate management zones based on high usage areas and aquifer property data from pumping tests. The management zone boundaries are not operated as allocation zones because they do not represent hydraulically separate units. A radius of influence method is used to manage the rate/spatial intensity of groundwater abstraction in order to minimise the risk of seawater intrusion.

Allocation methods - setting limits

Allocation limits have been defined based on the Proposed National Environmental Standard on Ecological Flows and Water Levels (MfE, 2008) using groundwater recharge estimates derived from a soil water budget model. Limits have been set at 10% of rainfall recharge for coastal aquifers and 35% of recharge for the large inland basalt aquifers. Allocation was capped at the allocated volume in aquifers where consented groundwater abstraction exceeded these percentages at the time of limit setting. Further investigations have been prioritised for these aquifers to support determination of aquifer-specific limits.

New water take consent applicants are required to assess the sustainable yield of any aquifer for which no limits have been set.

Stream depletion effects are generally managed through the consenting process

Permitted Activity private water supply abstractions and municipal supplies are included in groundwater allocation accounting because these represent a significant proportion of total abstraction in many of the small coastal aquifers.

Challenges and solutions

The “gold rush” effect of the limit setting process coupled with a rapid expansion in water demand for avocado orchards has been a major challenge in the Northland Region.

4.1.2. Auckland

Allocation methods - zone boundary delineation

Auckland Council defined 121 Aquifer Management Areas (AMAs) via a hierarchical zone delineation approach using the following variables in order of priority: 1) geology; 2) surface water catchments; 3) aquifer piezometric contours and 4) administrative boundaries (e.g. boundary with Northland Regional Council).

Allocation methods - setting limits

Water allocation limits were defined for High Use Areas[1] in the Auckland Unitary Plan. These areas were delineated based on the following criteria:

Some aquifers are highly allocated, providing water to users as well as being major sources of spring and stream flow. They are currently adversely affected by over pumping or are likely to become highly allocated over the life of the Plan, particularly in areas of high potential growth. These aquifers are identified as High-use Aquifer Management Areas.

Some of these areas are now fully allocated but other areas that were expected to become highly allocated have experienced little increase in usage.

Annual groundwater allocation limits were defined for these aquifers based on a percentage of estimated groundwater recharge. The allocation limits are defined as *water allocation and availability guidelines* in the Auckland Unitary Plan rather than as strict limits. I discuss this approach further under the *Challenges and solutions* heading below.

For all other AMAs the allocation limits have been defined using the interim limits for groundwater defined in the Proposed National Environmental Standard on Ecological Flows and Water Levels (MfE, 2008), as follows:

For shallow, coastal aquifers (predominantly sand) an allocation limit of whichever is the greater of:

- 15% of the average annual recharge as calculated by the regional council
- the total allocation from the groundwater resource on the date that the standard comes into force less any resource consents surrendered, lapsed, cancelled or not replaced.

For all other aquifers an allocation limit of whichever is the greater of:

- 35% of the average annual recharge as calculated by the regional council
- the total allocation from the groundwater resource on the date that the standard comes into force less any resource consents surrendered, lapsed, cancelled or not replaced.

For groundwater that is shown to be connected to adjacent surface water, the environmental flow or water level set for the surface water body will also apply to the management of groundwater takes.

[1]
See:https://unitaryplan.aucklandcouncil.govt.nz/Images/Auckland%20Unitary%20Plan%20Operative/Chapter%20M%20Appendices/Appendix%203%20Aquifer%20water%20availabilities%20and%20levels.pdf

The Unitary Plan does not provide a definition for shallow coastal aquifers. Allocation limits for very deep and/or confined aquifers are currently based on 65% of the annual average recharge rate.

Challenges and solutions

Auckland Regional Council defined the groundwater allocation limits in the High-use Aquifer Management Areas as guideline values in recognition of the limited knowledge of groundwater recharge rates and sustainable yields. The aim of this approach (which I refer to hereon as a "floating cap") was to provide a mechanism by which the limits could be updated as improved science knowledge became available. In practice the guideline status of the limits and associated regional plan rules have led to a situation under which consent applicants are able to advocate for higher allocation limits based on technical assessment work undertaken to support new water take consent applications. Several applicants have used this approach to obtain groundwater take consents in excess of the guideline values specified in the plan. A possible outcome of this situation is that groundwater allocation limits will continue to be increased in response to technical work undertaken by practitioners working in the interests of their clients.

The lack of definition for shallow coastal aquifers and absence of allocation limits for deep coastal aquifers has created some challenges.

4.1.3. Bay of Plenty

Allocation methods - zone boundary delineation

110 groundwater allocation zones have been defined in the Bay of Plenty (BOP) region. Groundwater allocation zone boundaries for water balance assessments were generally based on surface water catchment boundaries, simplified hydrogeological units and groundwater flow paths.

Three-dimensional groundwater models have been, or are in the process of being, developed as part of the more recent groundwater limit setting studies. In these instances, the boundaries of the study area have been based on sub-regional 'water management areas' (WMAs) developed by the council and/or simplified hydrogeological units. WMAs are based on several factors including physical surface water catchment area. Groundwater boundaries were not a significant factor in determining WMA boundaries. Aquifers extend across WMA boundaries. These boundary conditions are considered in the development of the groundwater models.

Allocation methods - setting limits

Interim groundwater allocation limits have been defined for areas where groundwater take consents are concentrated and are based on a water balance approach. Of the 110 groundwater management zones, eight have no assessment of availability.

The water balance approach defines the Groundwater Available for Allocation (GAA). The aim of the GAA / 'Residual Annual Aquifer Recharge' (RAAR) water balance approach was to establish a high level of protection for surface water bodies connected to the groundwater system. In the Region-wide Water Quantity Plan Change (Plan Change 9), 35% of the GAA value is adopted as the interim allocation limit

Residual Average Annual Recharge is calculated as follows:

1. Calculate average annual flows into the relevant aquifer or zone.

2. Subtract from this flow an allocation to sustain stream flow, where it is determined that there is connection between groundwater and surface water (Note that this is not necessary for the deeper groundwater zones, where there is unlikely to be connection to surface water).
3. The groundwater remaining is referred to as the 'Residual Average Annual Recharge' (RAAR).
4. The allocation limit is set at 35% of RAAR as shown in Figure 4-1.

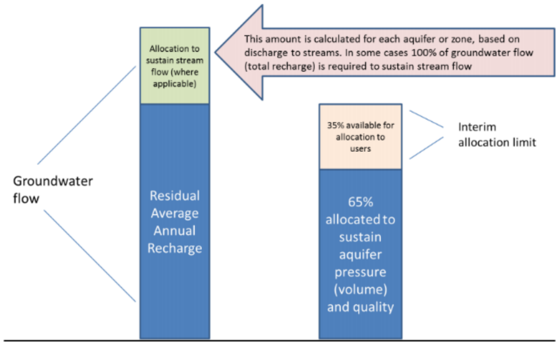

Figure 4-1 Groundwater allocation limit setting approach in BOP

The water balance approach seeks to protect all connected surface water bodies including groundwater-fed wetlands. However, it must be noted that many lowland groundwater-fed wetlands have historically been drained and are the subject of ongoing drainage schemes. Making a relatively small proportion of groundwater recharge available for groundwater abstraction the allocation limits prevents a significant reduction in offshore flow rates and therefore provides some protection against seawater intrusion.

Multi-layer aquifer allocation zones are present within the BOP Region. The water balance model approach adopts pro-rata allocation volumes for the two layers. It is based on the proportion of the geological units within the separate spatial allocation zones identified that have been determined to contribute recharge to the respective layers. Further information on the implementation of this method is available from BOP regional council staff.

Well interference effects are not managed explicitly under the water balance approach to limit-setting, but as per seawater intrusion, the relatively low allocation limits provide constrain the potential for widespread groundwater level declines. Local well interference effects associated with individual consents effects are considered as part of individual resource consent applications.

Stream depletion assessments are required for new / replacement consents, on a case by case basis where the council has identified it as an issue. For groundwater accounting all groundwater takes are conservatively assumed to be taken from groundwater (even if in some instances a proportion is determined to be coming from surface water). Surface water accounting has not been developed to the same extent. Surface water accounting is likely to account for proportion of groundwater taken that is determined to be coming from surface water.

Challenges and solutions

Most of the groundwater allocation zone boundaries in the water balance assessments are not based on hydrogeological units. In these instances, the groundwater allocation zones are not separate aquifers and zone boundaries do not align with aquifer boundaries. Groundwater moves between allocation zones. Anomalies can arise at zone boundaries where water maybe available on one side of the line and not on the other side. The smaller the allocation zone the greater the potential for this anomaly.

In some cases, because of the size of the zones and volume of base-flow within it, negative RAAR/GAA values were derived. In these groundwater allocation zones the allocation limit is conservatively determined to be zero, effectively creating an exclusion zone around some parts of surface water bodies. Because groundwater was previously allocated in some of these areas it has resulted in over-allocation in terms of the interim allocation limits, despite there being very little water allocated in some instances.

The water balance approach aims to establish a 'high level' of protection for surface water bodies connected to the groundwater system. The water balance and 35% of GAA approach in Plan Change 9 results in interim allocation limits that are not spatially uniform across the region / groundwater allocation zones in terms of % of annual aquifer recharge. Interim allocation limits within allocation zone range from 0 to 35% of annual aquifer recharge. Most are less than 25% and the average is approximately 10%.

The water balance approach is more qualitative (judgement-based) that quantitative. The high level of protection adopted was a function of council decisions and were subject to the first schedule process of the regional plan variation. The water balance model does not consider lag time between groundwater abstraction from deep wells and the associated reduction in stream flow rates.

BOP Regional Council is seeking to address some of these challenges by setting allocation limits for the broader Water Management Areas via numerical groundwater modelling studies.

Under the groundwater limit-setting study for the Kaituna area, for instance, a numerical groundwater model is being used to explore several management scenarios. These include criteria for 0-1%, 5% and 10% base-flow reduction, as well as no more than 0.5 m groundwater level drawdown below mean sea level at the coast. These management option scenarios and the result have recently been discussed with community groups to determine their preference(s). The process is ongoing; limits based on the model predictions have not been decided yet. The model simulations were designed to avoid mixing of water between different hydrogeological units. Therefore, abstraction from deeper units is not expected to influence baseflows. The model will be used to define specific allocation limits for each aquifer within multi-layer groundwater systems.

4.1.4. Gisborne

Allocation methods - zone boundary delineation

Groundwater allocation limits have been defined for four Freshwater Management Units (FMU) within the Waipoa Catchment (Poverty Bay) in the Gisborne region: Waipaoa Hill Country, Te Arai, Poverty Bay Flats and Gisborne Urban. Water quantity zones within the Poverty Bay Flats FMU include; shallow aquifers associated with and including Te Hapara Sands and the Waipaoa River, the deep aquifers (Makauri and Matokitoki) and the Taruheru River.

Bore log data has been used to delineate shallow alluvial aquifers; new water takes are assessed on a case-by-case basis to determine connectivity with the river. Geological maps, well log data and pumping test data are used to determine connectivity and hence whether a new take can access the Waipaoa River and associated shallow aquifers allocation (which is the only FMU currently with water available for allocation). Geological maps, well log data and pumping test data were also used to define which existing takes are within this FMU for allocation accounting purposes.

The boundaries of the deep aquifers and shallow coastal aquifer were defined using well log data.

Allocation methods - setting limits

Allocation limits were generally set at the allocation at the time of the regional plan notification. However, as the deep aquifers are identified as being in decline, successive annual allocation reduction targets in 2020 and 2025 have also been set. Allocation reduction targets are also set for the Waipaoa and Te Arai Rivers and also Te Hapara Sands Aquifer. Groundwater recharge for Te Hapara Sands Aquifer from surface watercourses was not accounted for and hence the allocation limits are likely to be somewhat conservative for those aquifers with potential surface water loss rates. The allocation limits do not account for any groundwater inflows from outside the FMUs or outflows (e.g. offshore groundwater discharge). Groundwater level data and existing use rates were also used to support allocation limit decision-making. Progressively declining seasonal low water levels in the deep Makauri aquifer highlighted the need to reduce abstraction or increase recharge rates in order to maintain the groundwater resource, for instance.

For aquifers outside of the Waipaoa catchment the regional plan states that where no catchment plan or catchment plan objectives have been developed groundwater abstraction shall be at a rate no greater than the capacity of the aquifer to replenish.

Challenges and solutions

Water take consents (with the exception of large storage reservoirs) have been assigned a common end-date with a maximum five-year duration in order to provide mechanisms by which over-allocation of the deep aquifers can be recovered and water take rates can be maintained within sustainable limits. Although this creates a significant staff resource burden at the time of expiry, the council has been able to manage this and consider that the water resource management benefits outweigh the resourcing challenges. The need to manage the water resource carefully and sustainably was found to be more important than consent-holder concerns about investment uncertainty for water resource development, although this was and is still a significant challenge. Although development of new kiwi fruit orchards is challenging with short duration consents due to investment requirements, the local community overall have generally accepted the need for short-duration consents.

Over-allocation of the deep Makauri aquifer is being managed through the plan requirement for consent holders to reduce water take allocation in both 2020 and 2023. Council is also investigating Managed Aquifer Recharge (MAR) and is currently progressing stage 2 of a MAR pilot study. Some existing consent holders are struggling to adapt to the proposed future lower water allocation take volumes.

Recovery of over-allocation has driven improvements in irrigation efficiency. Further intensification of the Poverty Bay Flats has seen an impact on the water quality within the Taruheru River a key surface water body which flows through the Poverty Bay Flats.

4.1.5. Taranaki

Allocation methods - zone boundary delineation

Groundwater allocation zones have not previously been defined in the Taranaki region; a plan change process is currently underway to define allocation zones. Freshwater management units (FMUs) have been proposed for the region in the draft plan; these have been delineated primarily based on land use and its regulation (e.g.

dairy areas vs. hill country farming etc.). The areas of the predominant aquifer systems within each FMU have been defined as groundwater management zones, but this work is still in progress and is subject to change.

Although multi-layer aquifers are present in the region, these are not well characterised and hence the stratified aquifer system is managed as a single unit at present.

Allocation methods - setting limits

The currently proposed allocation limits comprise 15% of the estimated annual average rainfall recharge volume. This is believed to be reasonably conservative. Groundwater utilisation is relatively low in the Taranaki Region; the most heaving allocated groundwater zone has only 28% of its sustainable yield currently allocated. Other zones are generally in the single figures in terms of proportion allocated as a percentage of rainfall recharge and well interference effects are managed through the consenting process for individual groundwater takes.

Challenges and solutions

The main groundwater management challenge in the Taranaki Region at present is devising an allocation framework that best aligns groundwater management with that of surface water and land use. This is required to support holistic water resource management. Development of a water resource management response with a level of complexity proportional to resource pressures is another key objective.

Under the currently proposed groundwater allocation zone delineation approach there are several small areas of aquifers spread across a number of FMUs, because the FMU and aquifer boundaries do not align. This results in many groundwater allocation zones and the management of land use activities may be different across each of these if regulation differs across FMUs. It is recognized that this may prove to be overly complicated. Delineation of allocation zones based on aquifer boundaries may ultimately be found to be a better approach. Taranaki Regional Council is currently considering the potential operational/management issues under various allocation zone delineation approaches in order to minimise the risk of unintended consequences.

4.1.6. Horizons

Allocation methods - zone boundary delineation

The Horizons region is split into 10 groundwater management zones which are based on the surface water management zones. The groundwater management zones follow surface water catchment boundaries and, where they extend inland, include areas of relatively impermeable strata.

Allocation methods - setting limits

Groundwater allocation limits have been defined for seven of the 10 groundwater zones. Allocation limits are currently based on 5% of average rainfall across the area of each zone; none of the groundwater management zones are fully allocated at present.

A review of groundwater allocation limits on the Horizons Region undertaken by PDP in 2019 (which is the source for much of the information presented below) concluded that allocation of 5% of average annual rainfall for groundwater abstraction is generally a conservative approach to setting groundwater allocation. However, in the Horizons region, it can result in inflated volumes of groundwater allocation as it includes higher rainfall amounts across inland areas where limited groundwater is available across impermeable strata, and which do not contribute rainfall recharge to the groundwater resource.

The PDP study found that 5% of rainfall across the groundwater management zone area amounts to between 36% and 90% of land surface recharge across the permeable areas of the zone and hence use of rainfall as a basis for allocation could lead to allocation of a high proportion of total groundwater recharge in some areas. Those zones with very high proportions of recharge allocated to groundwater abstraction generally comprise those with very limited groundwater abstraction, however. The report suggested that it would be prudent to reduce the allocation limits in those zones and recommended that allocation limits should be set at a maximum of 50% of land surface recharge as default generic criteria across the area of permeable strata within each zone, noting that individual assessments may reduce that value.

Groundwater and surface water bodies have separate allocation regimes within the region, but groundwater takes can be partly or wholly allocated to the surface water allocation block depending on the degree of hydraulic connection to a surface waterway.

Policy 16-6 in the One Plan classifies surface water depletion effects and specifies management approaches. Those abstractions that have a high or greater effect (i.e. a greater than 50% surface water depletion effect after 100 days pumping) are included in the surface water allocation regime with flow restrictions. The effect on surface water of takes with a surface water depletion of between 20% and 50% after 100 days (a medium effect) is also included in the surface water allocation regime, but without flow restrictions.

Groundwater takes calculated as having a <20% stream depletion effect after 100 days' pumping and those with a 'medium' stream depletion rate are included in the groundwater allocation regime.

Challenges and solutions

Long term groundwater level declines in the order of 1-2 m have been observed in a number of wells in the Rangitikei groundwater management zone. This zone covers a coastal plains area and an inland hillslope catchment and is 79% allocated under the One Plan allocation limit. Modelling studies indicate that the declines are likely to relate to increased abstraction in the area since 2007. Most of the bores showing declining groundwater levels are located towards the coast. Management responses have included trigger levels for some consents, where the total abstraction in each season depends on winter recovery levels in the preceding winter/spring. Modelling work undertaken as part of the PDP (2019) report indicated that groundwater levels could continue to occur in the long term under current abstraction rates and that increased abstraction could cause significant long-term declines. This could impact on water availability in existing wells, saline intrusion risks at the coast and flows in surface water courses. On this basis my interpretation is that the current allocation limit may not be suitably protective.

Under the current surface water and groundwater allocation system for the Tarurua zone (an inland basin aquifer which discharges to the Manawatu River where it flows through the Manawatu Gorge) the surface water and groundwater allocation blocks are currently treated separately. Groundwater takes that have a less than 20% stream depletion effects after 100 days pumping are classified as groundwater takes and included in the groundwater allocation block, although those takes will still have some effect on surface water. Groundwater takes with stream depletion effects of more than 20% are partly or wholly included in the surface water allocation block. Because all groundwater abstraction will eventually affect surface water flows, and the timing of these flow reductions could potentially occur during low flow periods, the PDP (2019) report concluded that it may not be possible to meet the surface water flow targets if the groundwater allocation block were to be fully utilised. The report concluded that, given the relationship between groundwater and surface water in this zone, it would be appropriate to consider an integrated groundwater and surface water allocation regime, whereby groundwater and surface water takes are allocated together from a single, combined allocation block

4.1.7. Greater Wellington

Allocation methods - zone boundary delineation

Groundwater allocation limits have been set for all areas with significant known groundwater resources in the Greater Wellington Region: Wairarapa Valley, Hutt Valley and Kapiti Coast. Zone limits were defined through a conceptualisation process based on workshops with geologists and hydrogeologists followed by numerical modelling.

Allocation methods - setting limits

Groundwater allocation limits have been set through consideration of water budgets, stream depletion, seawater intrusion and in some instances management of effects on groundwater-fed wetlands.

Groundwater allocation limits have been set at 25% of annual average groundwater recharge in catchments where the cumulative effects of groundwater abstraction on stream depletion was not the key control on groundwater allocation.

Cumulative stream depletion effects were the key driver for allocation limit-setting in catchments where groundwater and surface water resources are connected. In these catchments the allocation limits account for stream depletion effects by making 1-5% of mean annual low flow (MALF) available for large rivers and 20% of MALF for smaller stream, the latter being mainly based on the existing level of depletion rather than being determined as a ‘safe limit’. A modelled irrigation season stream depletion rate of 60% is generally used as an important threshold for determining management response.

GWRC are in the process of evaluating the issue of lags between pumping and stream depletion effects in order to provide clearer information on the benefits of restricting groundwater takes at time of low flow. This has proven to be the most contentious issue during the plan development process.

Challenges and solutions

Although there has generally been good agreement with and acceptance of the main aquifer lateral zone boundaries, the boundaries which define the transition from high connection to low connectivity groundwater (both lateral and with depth) have been disputed during the Regional Plan development and hearing process and have been the subject of an appeal. The main issues arose where the proposed plan rules required previously unrestricted consent holders to reduce groundwater abstraction during low flow conditions. In order to justify the plan rules GWRC were required to demonstrate that imposition of the water take restrictions would result in a beneficial improvement in stream flows within the period of low flows. Providing a sufficient degree of proof in the context of modelling uncertainty and the potential for significant economic impacts on consent holders proved challenging. The appeal process was ultimately resolved through revision of the groundwater-surface water connectivity definitions. The differing effects of groundwater abstraction from the lower part of the catchment, where surface water flows are greater and the impacted reach length is shorter than stream depletion from abstractions in the upper catchment, were also identified in plan submissions and ultimately lead to a change in policy. The coarseness of stream restriction bands has also been contentious. The plan rules require all water takes with a modelled irrigation season stream depletion rate of ≥60% to take no more than 50% of their consented rate under low flow conditions. Submitters noted that the depletion effects at 60% are much less than depletion rates at 95%, for instance, and hence consent holders with lower depletion rates should be less restricted. This situation highlights the challenges of providing plan rules which balance the need to manage activities in accordance with the magnitude of their effects on the one hand and the need to provide a planning framework which can be implemented efficiently on the other.

4.1.8. Hawkes Bay

Allocation methods - zone boundary delineation

The main groundwater resources in the Hawkes Bay region occur within the Tukituki Catchment and the Heretaunga Plains aquifer system. The Tukituki Catchment is split into three groundwater allocation zones.

Delineation of the Ruataniwha Plains into two zones was primarily based on flow path modelling. For the Heretaunga Plains the allocation zone represents the entire aquifer system.

Allocation methods - setting limits

Groundwater allocation has been set for the main groundwater systems in the Tukituki Catchment and proposed for the Heretaunga Plains aquifer system. For small groundwater systems there is no allocation limit.

Allocation limits in the Hawkes Bay Region have not been set (or proposed) based a percentage of groundwater recharge. Numerical models were developed for each groundwater system and several scenarios used to evaluate pumping impacts. The effects of groundwater abstraction on surface water bodies have ultimately been the main driver of the limits but other impacts were assessed such as cumulative drawdown. Seawater intrusion impacts were considered but the risk was ultimately considered to be low.

Numerical modelling was used with surface water modelling (SOURCE) to evaluate the reduction in surface water caused by groundwater pumping. The effect on aquatic eco-systems and security of supplies were also evaluated. The cumulative impacts were assessed against minimum flows, with minimum flow being the key focus for the Tukituki Catchment/Ruataniwha limit-setting process. Surface water and groundwater allocation limits were ultimately based on the existing volume of consented abstraction (Tranche 1 allocation block). The Regional Plan also enables additional groundwater to be abstracted as a discretionary activity (Tranche 2), provided that river flows are augmented to maintain the relevant minimum flows commensurate to the scale of effect of the Tranche 2 groundwater take.

The Heretaunga Plains limit-setting process (known as TANK; Tūtaekurī, Ahuriri, Ngaruroro and Karamū Catchments) used a collaborative planning approach whereby stakeholders were more involved in determining “acceptable limits”. These sought to manage impacts on surface water flows and associated ecological values whilst seeking to meet the needs and aspirations of local stakeholders. This process is ongoing at the time of writing.

The lag time between groundwater abstraction from deep wells and the associated reduction in stream flow rates was considered by evaluating the time to reach a new equilibrium. The lag time was also considered when setting policy to assess direct stream depletion effects.

Regional Plan rules protect stream flows through allocation limits set in the plan and temporary restrictions when "minimum flow" triggers are breached. Allocation limits are based on dry year scenarios rather than an average year. Consecutive driest year scenarios were explored during the Heretaunga Plains science programme in conjunction with various scenarios of actual use versus total paper allocation in order to provide information on potential outcomes during the periods under which water resources are subjected to most stress. The council is exploring MAR and augmentation to provide added management tools for protecting stream flows.

The Heretaunga and Ruataniwha groundwater systems comprise multi-layer aquifers and were modelled as such. Because the systems are leaky and connected, they are managed as a single system (allocation is set for the entire system not as individual layers). Further details of how stream depletion effects are managed are provided in the following documents:

- Heretaunga (https://www.hbrc.govt.nz/assets/Document-Library/Plans/TANK-Draft-Plan-Change-v7-20180808.pdf)
- Ruataniwha (https://www.hbrc.govt.nz/assets/Document-Library/Tukituki/Tukituki-Plan-Change-6.pdf)

The Regional Resource Management Plan does not currently set groundwater allocation limits for the TANK catchments. An allocation limit for the Heretaunga Plains groundwater has been proposed, but this is somewhat controversial at present. The Plan proposes a non-numerical limit based on existing use (and limited to use before 2017). The Plan also takes a staged approach in determining the final numerical allocation limit for the Heretaunga Plains: better information on current allocation is required before the costs of further reductions in take rates can be assessed if the proposed stream depletion management solutions (see discussion below) prove ineffective. The plan provides for water to be re-allocated to existing permit holders on an 'actual and reasonable' basis that considers existing water/land use.

All of the other groundwater takes in the TANK catchments (including Ahuriri, Poukawa and both the Tūtaekurī and Ngaruroro catchments outside of the Heretaunga Plains are also limited to existing use only. Those areas are not considered over-allocated, just fully-allocated.

In both the fully and over-allocated catchments new water takes will be considered prohibited activities. The amount of water allowed for new permitted activities has been decreased to 5 m^3/day (down from 20 m^3/day).

Challenges and solutions

Intensive land use and high rates of groundwater abstraction from the Heretaunga Plains aquifer have caused significant degradation of the lowland streams which drain this catchment. A numerical modelling study found that, contrary to previous views and assumptions, all groundwater takes within the catchment are likely to be contributing to stream depletion within a 150-day period to some degree (regardless of well depth and distance). The technical work also showed that significant reductions in both the allocation limit and the actual rates of groundwater abstraction will be required to improve stream flows and ecological health. Minimum flow triggers would need to be activated much earlier in the irrigation season in order to be effective. Economic modelling showed that these actions would have a major impact on the local horticultural industry.

Previous stream augmentation experience in Hawkes Bay and groundwater modelling results suggest that low flows in streams can successfully be addressed by pumping groundwater into streams at times of low flows. This approach uses water stored in the aquifer to maintain flows over relatively short periods (e.g. several months) during the irrigation season. Aquifer storage is then replenished in the off season. HBRC has drafted a planning framework which includes a Stream Flow Maintenance and Habitat Enhancement Scheme. Some of the key elements of this approach are:

- A web app[2] which calculates the stream depletion rate for any well or groups of wells within the catchment
- A global water take consent
- Flexibility for water users to contribute to the scheme in different ways, e.g. by undertaking additional stream habitat improvement work (beyond the riparian improvement work required in the proposed plan), contributing to the stream augmentation fund or by reducing water take rates.
- Provision of technical support and enabling mechanisms by HBRC with the scheme being led and managed by stakeholders.

Some of the advantages of this approach include:

- Equity: water users with the greatest impact on stream flows would be required to make the greatest contribution towards stream restoration and vice-versa
- Encourages efficient and optimal value water usage: low volume high value water usage is incentivised, high volume low value water uses are disincentivised.
- Lower economic impact: analysis indicated that the capital and operating costs of stream augmentation are significantly less than the costs associated with reduced water usage.

Tangata whenua are not supportive of the stream augmentation proposal at present. Successful implementation of the proposed a Stream Flow Maintenance and Habitat Enhancement Scheme is expected to be challenging. The TANK plan has not yet been publicly notified.

4.1.9. Tasman

Allocation methods - zone boundary delineation

There are seven hydrological catchments in the Tasman District. Groundwater allocation zones have been defined for areas of high groundwater usage; a default policy applies elsewhere. The Buller catchment is managed under a Water Conservation Order which treats surface water and groundwater as a single resource. Surface water and groundwater also treated as a single resource in small catchments.

The Waimea aquifer is split into lower and upper confined units and managed as separate aquifers. River gravel aquifers adjacent to the Waimea River (and the unconfined part of the Waimea aquifer at the gorge) are managed as per the surface watercourse.

Allocation methods - setting limits

Groundwater abstraction from the Waimea and Central Plains aquifers is managed to achieve minimum flow targets and to maintain a positive head at the coast. The limit-setting process was informed by a groundwater

[2] https://aelwan.shinyapps.io/stream_depletion_calculator/

model which was used to evaluate allocation based on a stream depletion limit and maintaining 2 m head at coastal sentinel well.

The deep Motuere aquifer is recharged from a hillslope catchment and does not discharge to surface water. The primary groundwater management objective for this very low transmissivity aquifer is to control well interference effects. This is achieved through a requirement to implement large separation distances between wells and an allocation limit set to manage well interference.

Challenges and solutions

Management of water during drought periods is a key challenge in the Tasman Region. The Regional Plan empowers a Dry Weather Task Force to manage water restrictions during dry periods. The management framework comprises trigger-based reductions of 20, 35, 50% and 100% (C state). Compliance with these restrictions, when active, is checked on a weekly basis. Management at weekly resolution presents challenges in timing: weekly metering data resolution is not sufficient to check compliance, so a new water metering database has been commissioned to improve data resolution.

In response to high demand for groundwater the Regional Plan includes a Bona Fide review clause to determine water take consent limits on renewal. If use is >80% in any one year within 15-year period the consent holder is able to keep their full consented water take. If usage is <80% a proportion of the water must be surrendered. If metering records show that no water has been uses in the last 5 years the consent is not renewed and if a water take consent is not used within five years of grant the water must also be surrendered. The Council maintains a formal waiting list for new water users and any water made available through the Bona Fide review process is allocated to those on the waiting list.

Tasman District have produced a “Global Assessment of Environmental Effects (AEE)” for controlled activities in the region. This approach avoids the various consenting process challenges associated with a “Global” consent whilst still achieving efficiencies in the consenting process by avoiding the need for a new AEE to be drafted for each consent application.

4.1.10. Marlborough

Allocation methods - zone boundary delineation

Seven Freshwater Management Units (FMUs) have been defined in the Marlborough region for the purposes of setting groundwater allocation limits. The FMUs include three river valley aquifers (known as the Southern Valley aquifers), which are hydraulically separated from one another but discharge to the Wairau Aquifer FMU. The Riverlands Aquifer FMU is also hydraulically connected to the Wairau Aquifer but is less transmissive and susceptible to much larger pumping-induced drawdowns than the Wairau aquifer and is therefore subject to an allocation limit reflective of these local conditions. The Rarangi Shallow Aquifer FMU is separated from the underlying Wairau Aquifer by a confining layer. The Southern Springs FMU was historically part of the Wairau Aquifer and does have an annual volumetric allocation limit in the same manner as the other aquifer-based FMUs. It is geographically located at the base of the Benmorven FMU, and notably (unlike other aquifers) it has a restriction based on the flow of a surface waterbody within the FMU.

Some of the FMUs have been split into sub-units for management of specific effects. The Wairau Aquifer, for instance, is sub-divided into a Recharge Sector, a Lower Wairau Sector and a Coastal Sector. These sub-units have been delineated in recognition of variation in the effects of groundwater abstraction on stream flows.

Pumping from wells in the Recharge Sector, for instance, will ultimately reduce discharge rates to the downgradient springs, but these effects are likely to take several months to occur. This means that inclusion of minimum flow-based pumping cessation or reduction conditions in groundwater take consents in this area are unlikely to be beneficial: the effects of reduced pumping will not be realised until the winter months, when stream flows have recovered from their summer and autumn lows. Groundwater usage in the Recharge Sector is therefore best managed through allocation limits. Conversely, abstraction from the Lower Wairau Sector is likely to have a more rapid impact on spring flows and hence inclusion of minimum water level conditions on groundwater take consents here will have a beneficial effect for maintenance of spring flows under low flow conditions. The long-term cumulative effects of abstraction from wells in this area are again managed via allocation limits.

Outside of these FMUs the science work has shown that groundwater resources are closely connected to surface water bodies and hence management of the groundwater resource in accordance with the surface water management regime is the best approach.

Allocation methods - setting limits

Allocation limits have generally been determined through a combination of historic and recent monitoring data analysis and modelling. The historic data set provides some baseline information on flows and groundwater levels at lower rates of groundwater abstraction which can be compared to more recent data to provide insights into the effects of current abstraction. Modelling has been used to assess higher groundwater abstraction scenarios and to understand effects where monitoring data are limited. Consented rates have proven to be generous in the region, such that most consent holders use a relatively small proportion of their maximum permitted rate, even in dry years. This means that much higher rates of groundwater abstraction could potentially occur within the existing allocated volume and modelling the effects of this scenario was an important part of the limit setting process.

Challenges and solutions

Inclusion of minimum flow or level-based water take restrictions on previously unrestricted water takes was one of the most contentious aspects of the limit-setting process. Consultants working on behalf of consent holders proposed an alternative zonation for minimum flow restrictions and this was debated during the hearing process which is still in progress at the time of writing.

Subdivision of the Wairau Aquifer FMU into stream depletion-based management zones reduces the need for stream depletion effects to be undertaken for every water take consent. Although an up-front investment in technical work was required to provide a basis for delineation of the zones, this is likely to deliver a long-term saving because significant resources are often required to review individual stream depletion assessments provided by water take consent holders and to liaise with their consultants to agree on suitable modelling inputs and assumptions.

Analysis of climate records showed that rainfall in the Marlborough region was above average between 2008 and 2012 (when much of the technical assessment work to support the limit-setting process was undertaken), and hence the effects of groundwater abstraction on environmental receptors had been mitigated to some extent by above average recharge and below average water demand. It was important to consider the relative lack of environmental effects associated with the increase in groundwater abstraction over that period in the context of this climate variability.

Groundwater allocation and management in the context of climate change is an ongoing and unresolved challenge in Marlborough (and elsewhere). In some instances, minimum flow limits have been based on historical low flow measurements and the effects of water take restrictions on water users and the viability of their operations were assessed under the assumption that the frequency of these low flow events remains unchanged. Climate science has consistently predicted that climatic variability and extremes will increase, and these predictions have been borne out by recent events in both the northern and southern hemisphere. This means that the impacts of water take restrictions on water users could be significantly greater than expected in the years ahead. Further work is required to determine how best to manage groundwater resources and set limits in the context of a more severe climate.

4.1.11. Canterbury

Allocation methods - zone boundary delineation

30 Groundwater Allocation Zones (GAZs) in the Canterbury Region were originally defined in the Natural Resources Regional Plan (NRRP), predecessor to the Canterbury Land and Water Regional Plan (LWRP). Zone boundaries were defined through a combination of groundwater flow line analysis, geological maps and expert judgement.

The region was subsequently delineated into 10 land and water management zones under the Canterbury Water Management Strategy (CWMS). A series of sub-region Plan Changes have been implemented or are in process to tailor some of the land and water management rules and policies to achieve environmental outcomes and meet the needs and goals of local iwi, communities and stakeholders within each zone. Some of the GAZ boundaries were modified and new allocation zones defined[3] in order to manage specific local issues. For example, under proposed Plan Change 7 of the LWRP the boundaries of some GAZs have been extended to include the adjacent foothill catchments in the Waimakariri and Orari, Temuka, Opihi and Pareora (OTOP) water zones. Although significant groundwater development is unlikely in these foothill areas, this approach avoids a “no man’s land” scenario and provides clarity during the consenting process for all groundwater take applications. It also recognises that groundwater seepages from these areas contribute to the overall groundwater recharge of the downgradient aquifer system.

Allocation methods - setting limits

Interim allocation blocks were originally determined for all zones based on 15% of average annual rainfall (the so-called 1st order approach). These were later superseded by a 2nd order approach which defined allocation limits as 50% of groundwater recharge from rainfall plus irrigation (land surface recharge). More recently the allocation limits for GAZs within many of the CWMS zones were revised during the CWMS zone-based Plan Changes. For GAZs with water still available for allocation under the 2nd order assessment-based limits, capping groundwater allocation at the currently allocated volume or with a small additional percentage allowance for new development has been used in some instances. Rules and policies have been implemented or proposed to recover over-allocation where required.

[3] A total of 83 GAZs are currently defined

Scenarios-based groundwater modelling has often been used to inform decision-making on groundwater allocation limits. In the Waimakariri zone limit-setting process (Plan Change 7c), for instance, a calibration-constrained stochastic groundwater model was used to simulate the effects of several groundwater allocation and usage scenarios on stream flows and the reliability of existing groundwater takes associated with groundwater level declines under the increased abstraction scenarios. The potential effects of predicted stream flow reductions on aquatic ecology and the economic impact of reduced reliability for existing groundwater users were evaluated for each scenario and the information was used to inform decision making.

Challenges and solutions

Delineation of GAZ boundaries using groundwater flow lines (as opposed to groundwater divides and hydraulic barriers) has caused some challenges. Although use of groundwater contour-based flow lines as a basis for delineating groundwater allocation zones provides an area within which water budgets can be calculated, the hydraulic effects of groundwater abstraction extend beyond the zone boundaries. Furthermore, flow directions can differ in deeper parts of the aquifer system, but this may not be apparent from piezometric contours derived predominantly from shallow wells. This has been recognised by some stakeholders in Canterbury. Farmers in the Waimakariri zone, for instance, have observed the drawdown effects of abstraction from neighbours' wells located in adjacent GAZs and questioned why their zone is fully allocated whereas new water is available in the adjacent zone. In other instances, irrigators located close to the boundary of fully allocated groundwater zones have drilled wells in the adjacent allocation zone (within which water is available) and piped water across the zone boundary.

The historic assumption that the Waimakariri River represents a hydraulic barrier between the Waimakariri and Christchurch – West Melton CWMS zones caused significant challenges in the PC7 work programme. Although these challenges related to the potential for transport of nitrate from the intensively farmed Waimakariri zone into Christchurch zone (within which farming land use intensification had been severely restricted), they highlight the problems that can occur when water management zone boundaries are not based on robustly-defined hydraulic units.

In some instances, the GAZ delineation issue has been managed by running a range of groundwater abstraction scenarios using groundwater models that are bounded by true hydraulic barriers (or with boundaries set sufficiently far from the areas of predictive interest) and which include multiple GAZs. This enables assessment of the cumulative effects of groundwater abstraction on stream flows, water levels and coastal discharge rates (as required) and determination of GAZ-based allocation limits which give due consideration to the impact of abstraction on water features in adjacent GAZs. Many GAZs in Canterbury are now fully allocated (and in some cases over-allocated) and hence the issue of cross-boundary hydraulic impacts is becoming less critical.

Derivation of groundwater allocation limits using 50% of long-term average land surface recharge has presented several challenges. During the multi-year drought associated with the 2016 Super El Niño event, for instance, land surface recharge was significantly below average (in some areas <50%) and groundwater usage was well above average. Groundwater usage represented a very high percentage of total groundwater recharge in some areas over this period. Groundwater levels declined significantly and flows in groundwater-fed streams became very low. The cessation of flow in the Selwyn River at a popular swimming location received a high degree of media coverage. Environment Canterbury also received a series of enquiries from owners of shallow wells that became dry over the drought. Concerns were raised about whether allocation of such a high percentage of average year recharge provided an appropriate degree of protection for spring and stream baseflows during extended periods of below average recharge.

Implementation of adaptive management groundwater take consent conditions has also presented challenges in Canterbury. A Hearing Panel granted consents for approximately 120 new water takes in the heavily allocated Selwyn Te-Waihora zone in 2008 and 2010 (spread across two hearing decisions) with conditions that restricted abstraction rates during periods of low groundwater levels. The consent conditions included two trigger levels in specific monitoring wells: an upper trigger below which abstraction rates were restricted and a lower trigger below which no water could be taken, with a linear reduction in take rates between the upper and lower triggers. These conditions have proven problematic because:

a. Water levels changed significantly in some of the monitoring wells during the Canterbury earthquakes and have not returned to pre-earthquake levels. This meant that abstraction became unrestricted for some and continuously restricted for others.

b. Significant resources are required to determine the restriction for each consent every year and to ensure that consent holders comply with the restrictions

Groundwater and surface water allocation limit-setting and accounting is challenging in the context of stream depletion. Environment Canterbury and consent applicants typically use the Theis-Jenkins or Hunt (1999/2003) stream depletion solutions to estimate the stream depletion rate for each well. For new consents or renewals of water takes from wells <50 m deep (deeper wells are currently assumed to have low stream depletion effects), consent applicants are required to undertake aquifer tests and to model stream depletion using the parameters derived from the test. Schedule 9[4] of the LWRP then dictates whether a minimum flow condition is required and how the annual water take volume should be apportioned between the surface water and groundwater allocation blocks. Because many groundwater consents pre-date the requirement to undertake a stream depletion assessment, Environment Canterbury use local aquifer parameters looked-up from the Aquifer Test Database to undertake an approximate stream depletion assessment for allocation accounting and limit-setting purposes.

Most aquifer test transmissivity values are derived from wells with short (e.g. 1-2 m) screens. Pumping test-based transmissivity values in the order of 1,000 – 5,000 m²/d are not uncommon for the Canterbury Plains. The low vertical hydraulic conductivity of the Canterbury aquifers means that aquifer tests undertaken on short screen wells typically only perturb a fraction of the saturated aquifer thickness, however, and hence the aquifer-test derived transmissivity values are generally much lower than the transmissivity of the full aquifer. This conclusion is supported by the findings of regional scale groundwater model optimisation work and by simple Darcy's Law calculations: transmissivity values in the order of 20,000 – 50,000 m²/d are typically required to align estimated aquifer recharge and discharge rates with the hydraulic gradient defined by groundwater level monitoring data. Because modelled stream depletion rates are directly proportional to aquifer transmissivity, this can (all else being equal) lead to a significant underestimation of stream depletion. Numerical modelling results also show that the infinite aquifer extent assumption of analytical stream depletion solutions can lead to underestimation of stream depletion rates, particularly for aquifers with limited

[4] https://eplan.ecan.govt.nz/eplan/#Rules/0/20/1/24931

lateral extents bounded by no-flow barriers. Furthermore, recent modelling work has indicated that a significant proportion of wells >50 m deep in Canterbury could potentially cause significant stream depletion. The validity of the 50 m depth criteria is now being reconsidered.

For water allocation purposes the uncertainty over stream depletion rates has been managed in some instances by including modelled stream depletion within the surface water allocation blocks but without discounting this volume of water from the groundwater allocation block (i.e. the full allocation volume for a given consent is accounted for as part of the groundwater allocation calculation but the modelled stream depletion component is also accounted for in the surface water allocation calculation, so some double-counting occurs). The aim of this approach is to avoid a situation where site-specific stream depletion assessments show lower rates of stream depletion. In the absence of double-counting, this would inflate the groundwater allocation and could lead to over-allocation and the requirement for “claw-backs”, which are challenging.

Protection of flows in the upper reaches of spring-fed streams is also challenging under the current groundwater management framework. The stream depletion management rules relate to the proportion of the water take that is modelled as stream depleting and the flow monitoring sites are usually located in the lower stream reaches. Although the relationship between flows at monitoring sites and the frequency and length of dry stream reaches has been characterised to some degree in a few water courses (e.g. the Ashley River/Rakahuri), gathering data for this purpose is resource intensive.

Environment Canterbury and Christchurch City Council received a significant number of enquiries from residents during the 2015-2017 drought, when flows ceased in the upper reaches of the Avon River/ Ōtākaro. Questions were asked about the effect of groundwater abstraction for the city water supply on stream flows and the need for water metering and usage restrictions during drought conditions was debated.

4.1.12. Southland

Allocation methods - zone boundary delineation

Groundwater allocation is managed using mapped “Groundwater Management Zones” for unconfined/semi-confined systems in Southland. These zones are mapped based on inferred hydraulic connections and areas of groundwater with similar hydraulic properties (riparian aquifers with substantial interaction with rivers are differentiated from terrace aquifers and lowland aquifers, for example). There are 30 zones mapped across Southland. The exact spatial boundaries of these zones have changed several times in the last 10 years.

Allocation methods - setting limits

Primary allocation or the volume of groundwater that is available for allocation from each zone is currently calculated as 35% of the mean annual rainfall recharge. For areas that fall outside of the groundwater management zones the same 35% of rainfall recharge rule is applied to calculate an allocation volume for the relevant land area for which the water take is associated (usually the property area).

Abstraction of groundwater is subject to consideration of numerous conditions as set out in Rule 54 of the proposed Southland Water and Land Plan (pSWLP). Two major considerations are stream depletion and bore interference effects these are assessed on a site by site basis following the guidance set out in the pSWLP. Calculated stream depletion is accounted for in the relevant surface water allocation regime.

Challenges and solutions

The plan recognises that stream depletion effects on rivers and lakes can occur, and provides a pathway for determining how much of the effect should be considered as surface water allocation, whether minimum flows in the river will be a suitable control or will be ineffective, and if the stream depletion effect is too small to be taken into account.

Because the stream depletion effect is a modelled effect, challenges arise around how new modelling or improved information will be incorporated after the consents have been granted. This issue has been addressed by specifying the stream depletion effect of the groundwater take in the resource consent (e.g. “this resource consent authorises abstraction of 11 litres per second of groundwater, of which 5 litres per second is stream depletion from the …. River”). This provides certainty about the consented allocation, and newly modelled figures can be incorporated through s128 reviews or upon replacement of the consents.

New plan provisions around modelling of stream depletion effects were not fully evaluated before notification of the plan to determine the effect on surface water allocation. This has led to over-allocation of surface water, which needs to be addressed through consent reviews.

Challenges arose when the confined aquifer allocation determination was changed from limits on potentiometric head reduction to an annual throughflow system. Essentially the consents were approved in accordance with the first set of plan provisions, but there were physical signs in the aquifer that there was an issue. The plan changed the allocation system, which meant that the consents shifted to being heavily over-allocated. However, the plan provided no framework to correct the existing allocation to the new system, which made it difficult to set up a system that relied in part on group management.

The older regional plan excluded stream depletion effects on intermittently flowing streams, partly because surface water allocation is based on MALF to protect surface water habitat and other values. So, if surface flow is zero for part of each year for an intermittent flow, then MALF is also zero. This caused problems for downstream allocation because there was often subsurface flow in the gravel bed. It also did not address whether the stream depletion effect exacerbated the frequency or length of periods when surface flow ceased.

Assessment of interference effects on neighbouring bores can also be an issue. It is common, especially for older bores or wells, for them not to fully penetrate the aquifer. The regional plan requires that interference effects be based on cumulative drawdown in the bore under the assumption of full penetration of the saturated thickness of the aquifer. Ambiguity in the wording of the plan rules causes confusion amongst applicants and their advisors leading to challenges during the effects assessment and consenting process.

Climate change effects are likely to present challenges going forward where groundwater allocation is based on estimates of annual aquifer recharge as a percentage of annual rainfall. Unusually low groundwater levels occurred recently in response to rainfall being three standard deviations lower than the 40 year rainfall record average.

Analytical models of stream depletion and interference effects from individual takes (e.g. the Hunt models as presented in the ECan online tools) have provided a reasonable way to estimate these effects based on sound, established science. Nonetheless, issues have arisen from the need to rely on analytical modelling, such as:

- Inability of limited duration pump tests to constrain estimates of the key parameters needed for analytical models.
- Uncertainty about parameter values and applicability of model assumptions for particular takes can mean that estimates of effects in particular cases are inaccurate e.g. actual interference by drawdown

in neighbouring bores may exceed model estimates and cause takes from those bores to become unreliable or unviable.

- Correlations of groundwater level with stream flow have been found in some cases to exceed modelled relationships, whereby stream depletion effects are implied in excess of analytical model predictions.
- Analytical models applied to individual takes may not be suitable for assessment or management of stream depletion effects that occur over longer time frames and/or cumulatively at catchment scales.
- Difficulties adjusting allocation controlled by established consents to incorporate new science and/or revised estimates of effects or available resource.

The regional plan now specifies methods by which pump testing must be carried out for determining stream depletion and interference effects. This was a major shortfall of previous plans that did not specify how tests should be undertaken.

There are also difficulties in providing for mitigation of effects of maximum consented use (rates of water take) which may seldom occur, while exempting more regular use from unnecessary restrictions. Compliance monitoring and enforcement generally are difficult, e.g. getting good water take information. Flexible, adaptive consent conditions and management systems which provide for more effective resource use may be yet more difficult to monitor and enforce. For example, consent conditions for limiting a take based on flow in an affected stream ('low flow cut-offs') are generally based on the effect of maximum rates of take. Effects of actual rates of take – variable, intermittent, and often inaccurately reported - are difficult to estimate.

4.1.13. The European Water Framework Directive

The overarching policy for water management in EU member states is defined in the Water Framework Directive (WFD) as follows:

- Define groundwater bodies (GWB) within river basin districts
- Identify GWB presenting a risk of not achieving WFD environmental objectives
- Establish registers of protected areas for habitats and species directly dependent on groundwater
- Establish groundwater monitoring networks to provide a comprehensive overview of groundwater chemical and quantitative status
- Set up a river basin management plan (RBMP) which must:
    i. Take into account the principle of recovery of costs for water services, including environmental and resource costs in accordance with the "polluter pays" principle; and
    ii. Establish a programme of measures for achieving WFD environmental objectives (e.g. abstraction control, prevent or control pollution)

Two examples of how the WFD has been implemented, in England and France, are presented below.

4.1.14. England

Allocation methods - zone boundary delineation

Allocation limits have been defined for 272 groundwater bodies in England. Groundwater body boundaries are defined in accordance with hydraulic boundaries, but aquifers are subdivided for management purposes in some instances. Transfer rate estimates between these sub-divided aquifers are estimated and accounted for in water budgets.

Allocation methods - setting limits

The WFD requires all groundwater bodies to achieve “good” status and for EU member states to put measures in place to achieve this status where it is not already met. Groundwater body “Quantitative Status” is assessed via four tests (SNIFFER, 2005):

- Groundwater Balance Test: the total abstraction from the groundwater body should not exceed the recharge to that groundwater body after an allowance for dependent ecosystems if no specifc assessment of these has been possible
- Surface Water Dependent Test: groundwater flows to dependent surface water bodies should not be diminished by groundwater body-related pressures to the extent that they do not achieve Good status, or their status is reduced from High to Good
- Groundwater Dependent Terrestrial Ecosystems Test: groundwater body pressures should not diminish flows or levels supporting groundwater dependant terrestrial ecosystems such that these ecosystems suffer “significant damage” in relation to conservation objectives.
- Saline and Other Intrusions Test: groundwater abstraction should not cause a reversal in groundwater flow direction which results in significant intrusion of saline or other poor-quality water into the groundwater body

Water bodies that fail one or more of the tests are classified as “poor” or “failing to achieve good status”. Member states can be fined by the EU if they allow status deterioration to occur.

<u>*Groundwater balance test*</u>

The following information on the Groundwater Balance Test is summarised from an internal Environment Agency guidance document entitled *WFD Groundwater Balance Test.*

The Groundwater Balance Test is important as it focuses on other issues not identified through the WFD assessments. Such issues include impact on lakes and level-dependent marshes, groundwater levels to maintain springs and river accretion, as well as discharges to the coast to maintain the saline interface and marine ecology.

The Groundwater Balance Test also allows for sensitivity testing around prolonged periods of dry weather. By adjusting the average recharge rate within the groundwater balance allows a quick methodology to interpret if groundwater is in deficit and there is a potential for the environment to be impacted.

The Quantitative Status of an aquifer with regard to the Groundwater Balance Test as follows: “The level of groundwater in the groundwater body is such that the available groundwater resource is not exceeded by the long-term annual average rate of abstraction.

The Available Groundwater Resource is defined as:

Available Groundwater Resource [Ml/d] = Long term average recharge - Net environmental flow allocation ± Groundwater Flux

The Groundwater Body Water Balance is defined as:

Groundwater Body Water Balance [Ml/d] = Available Groundwater Resource - Long term average abstraction

The environmental flow allocation is calculated from the naturalised Q50 flow x the baseflow index for all surface water courses overlying the groundwater body, generally based on data from the preceding six years. The Groundwater Flux term is based on estimates of cross boundary and offshore flow rates.

The water balance is calculated under both current abstraction rates (based on water metering records) and for consented volumes. Where long term average abstraction exceeds the Available Groundwater Resource the Groundwater Body Water Balance test is not met and the quantitative status is classified as Poor. Where the total consented groundwater volume exceeds the Available Groundwater Resource the quantitative status is classified as At Risk.

EC (2009) notes that because this test is a groundwater body-wide test it may not always be possible to clearly define the local flow needs of rivers and wetlands. Additionally, the available groundwater resource for the groundwater body (GWB) may not all be available for abstraction because hydrogeological conditions (e.g. transmissivity and storage) make it difficult to exploit economically and practically. Distribution of the 'available resource' across the GWB may also vary in relation to sensitive receptors. Therefore, status assessment will need to take this into account and in many cases the poor status boundary will not simply be where abstraction > 100% available resource but could be much lower. In some hydrogeological situations it could be as low as 20%.

More detailed information on the technical methods used to determine the water balance test is available on request.

Surface water dependent test

UKTAG (2012) note that surface water and groundwater bodies are intimately connected and pressures on one may impact on the other. The surface water dependent test addresses whether, at a local scale, the pressures from groundwater are having a significant effect on an individual surface water body, taking into account all the pressures on that surface water body. The impacts from groundwater are usually difficult to measure, and in practice they will be determined based on models of the systems or on expert judgement. Where the effects are believed to require remediation, such expert judgement should be tested, usually by some form of modelling or monitoring.

As part of the surface water characterisation, flow standards for the associated surface water bodies will be set on the basis of recommended flow criteria or using expert judgement.

It is rarely possible to make precise or timely measurements of the reduction in flow caused by groundwater pressures, as these increase slowly over extended periods after a new groundwater pressure is applied. The component of the surface water failure due to groundwater will therefore need to be estimated.

A failure to meet the required flow standard in any surface water body may be due to either groundwater or surface water abstractions. This significance test assesses the proportion of the problem that can be attributed to groundwater abstraction within the total upstream catchment. If greater than 50% of the allowable abstraction can be attributed to groundwater, then the groundwater body fails to meet good status for this test

The steps involved in classification are detailed below:

- Associate each groundwater body with a related surface water body or bodies.
- Determine whether any of these related surface water bodies failing their WFD flow standards

- If the flow standards are not being met for a surface water body, determine whether groundwater abstraction impacts on this surface water body are a significant component of the failure to achieve flow standards.
- If groundwater abstractions are considered to be significant in any related surface water body that is failing to meet its flow standards, then the groundwater body is at poor status for this test.
- If the flow standards are being met or groundwater abstractions are not considered to be causing a significant diminution of flow, then the groundwater body is at good status for this test.

Groundwater Dependent Terrestrial Ecosystems Test

UKTAG (2012a) explains that groundwater dependent terrestrial ecosystems (GWDTE) are wetlands which critically depend on groundwater flows and/or chemical inputs to maintain them in favourable ecological condition.

For groundwater bodies with GWDTEs, the body can be classified using the process outlines in steps (i) – (iv) below:

(i) Assess relevance of ecological impact: Assess which wetlands a) contain groundwater dependent communities and b) are significantly damaged which is likely due to a quantitative pressure from groundwater abstractions. The assessment of significant damage is an ecological evaluation of the significance of the ecosystem itself and the magnitude of the damage. This is defined within UKTAG, 2005 'Draft Protocol for determining "Significant Damage" to a "Groundwater Dependent Terrestrial Ecosystem" (GWDTE). If a groundwater body does not have wetland which meets these ecological criteria, then the groundwater body is at good status for this test. Otherwise, proceed to step (ii).

(ii) Further assessment of risk: Identify whether groundwater abstractions could impact on the site, using a number of desk-based methods. This step is a national screening level assessment and uses techniques such as applying a generic conceptual understanding of the groundwater body and whether there is likely to be a direct hydraulic linkage to the site, equivalent recharge circles from the abstraction to predict if any likely impacts and outputs from any pre-existing studies etc. If there is no evidence that groundwater may be causing the significant damage, then the groundwater body is at good status for this test. Otherwise, proceed to step (iii).

(iii) Carry out further investigation and classify: For those sites where there is both 1) relevant ecological damage and 2) evidence that a groundwater could be the cause, further investigation is needed. This step is a site-specific assessment. This investigation is to determine whether the GWDTE has been significantly damaged by pressures on the groundwater body. This investigation may require an ecological assessment to confirm the cause of damage and environmental supporting conditions, and/or a more detailed hydrogeological investigation to confirm a connection between the wetland and the groundwater body. This further investigation can include a simple walkover survey of the site, work between expert ecologists and hydrogeologists. The level of investigation required will depend on the ecological evidence and the confidence in the hydraulic linkage between the site and the groundwater body. If it is confirmed that the necessary environmental supporting conditions for the GWDTE are not being met as a result of pressures transmitted through the groundwater body, and this is the most significant reason for the failure to meet the environmental supporting conditions, then the body will be at poor status for this test.

Saline and Other Intrusions Test

An intrusion is interpreted to be intrusion of poor-quality water into a groundwater body from another water body. Types of intrusions that are considered in this test are illustrated in Figure 4-2.

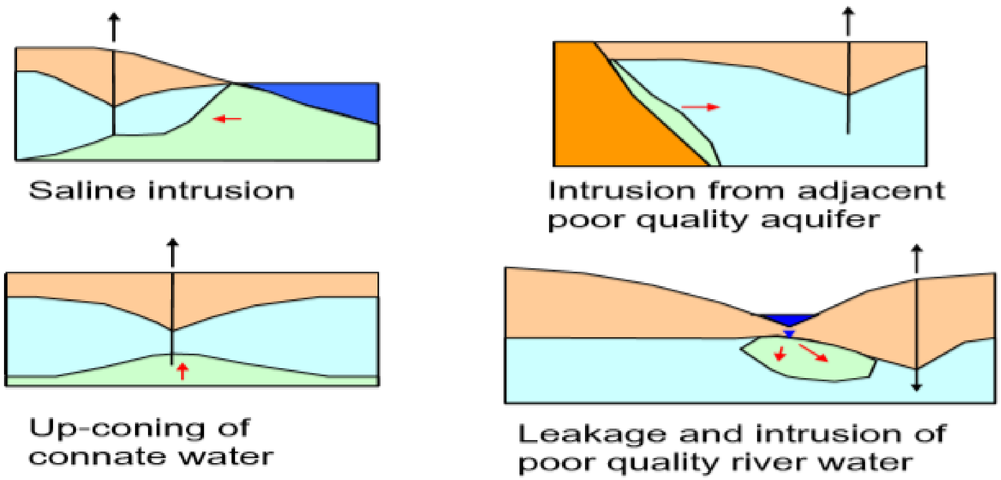

Figure 4-2 Types of intrusion considered for the intrusion test (from UKTAG, 2012b)

The process for assessing this test is described in UKTAG (2012b) as follows:

Status, and the presence of an intrusion of poor-quality water into the groundwater body, is determined through an assessment of trends in Electrical Conductivity (EC) or other indicator substances. The test is designed to detect the presence of an intrusion that is induced by the pumping of groundwater.

Threshold Values: Set at the upper limit of the natural background range for key determinands. Threshold values are only used in combination with trend assessment.

The conditions for good chemical status are not met when threshold values are exceeded and there is either a significant and sustained rising trend in one or more key determinands at relevant monitoring points; or there is an existing significant impact on a point of abstraction as a consequence of an intrusion

Challenges and solutions

The EA recognises that use of long-term average recharge estimates to determine the water budget test presents challenges for management of water resources in the context of climate change and increased climate variability. The increasingly hot and dry summers and increase in back-to-back groundwater droughts that are forecast for England over coming decades are expected to lead to a growth in water demand and a reduction in availability at the times of greatest stress. Groundwater modelling is being undertaken to assess these impacts. Drought management is challenging under current regulations: although a mechanism is available to restrict irrigation in the spring months if the detrimental impact of this abstraction on stream flows can be demonstrated, the delay between groundwater abstraction and stream flow effects and uncertainty over this make it difficult to provide sufficient proof that such restrictions are justifiable.

4.1.15. France

Allocation methods - zone boundary delineation

Water resources in France are categorised as a) surface water and associated groundwater; b) connected aquifers; and c) unconnected aquifers. Category a)[5] aquifers are defined where groundwater abstraction could impact on flows within the adjacent surface watercourse within 24 hours. Category b) aquifers are assigned where groundwater abstraction could impact surface water resources within an irrigation season (four months). Groundwater abstraction from category c) aquifers is not expected to impact surface water resources within a four-month period.

I was unable to obtain detailed information on how groundwater allocation zone boundaries are delineated, other than that they are based on analysis of hydrogeological data.

Allocation methods - setting limits

Allocation limits are set for the three water resources categories above plus off-line water storage schemes. Allocation volumes are subdivided into either dry season and wet season volumes, volumes for each of the four seasons or into monthly volumes.

Allocation volumes are calculated in order to leave enough water available to meet water demands and environmental flows in four out of five years. This means that restrictions are implemented one year in five, when environmental flows are not achieved. Water use restrictions are tiered and managed by a Drought Management Committee.

The environmental flow limits and groundwater level limits which trigger the implementation of restrictions are defined at catchment level by a Catchment Group. Irrigation restrictions are applied hierarchically based on the value of the crop. Low value crops, such as corn, are restricted first; high value crops such as fruit and vegetable cropping (which are in any case low volume users) are rarely restricted. Some high value crops are exempt from restrictions.

Challenges and solutions

The environmental flow limits and groundwater level limit-setting process is contentious. Methodologies vary between catchments and disagreements arise on where flows and groundwater levels should be measured. Regulatory authorities are currently undertaking work to streamline this process by reviewing operational practices around France so that those methods that work best can be applied more widely.

Allocation of available water between individual consents for farming is managed at catchment level through OUGCs (Single Agricultural Water User Associations). These associations are populated by local farmers working towards the goal of distributing water in order to maximise the greatest overall common benefit. A

[5] Category a-c is my terminology and is not necessarily the terminology used in France

key goal of this process is to move away from grandparenting of water rights to a collective pooling system. Water markets have been eliminated[6].

Exemption of high value crops in some catchments has led to disputes and in a few instances the conversion of large areas of the land to high value crops. This means that water use restrictions are not implemented, and hence environmental flow targets are not met.

5. TECHNICAL ASSESSMENT REQUIREMENTS AND SWOT ANALYSIS

5.1. Allocation zone delineation

The methods that have been used to define groundwater allocation zone boundaries (both laterally and vertically) are summarised in Table 1 below. Numbers 1-4 above have been evaluated within the SWOT analysis framework in Table 3.

Table 1 Allocation zone delineation methods and assessment requirements

No.	Method	Description	Technical assessment requirements
1	Surface water/topographic catchments	Groundwater management units aligned with surface water catchments.	Topographic contour or Lidar-based mapping.
2	Geological data (maps, well logs), used to define the lateral extent of transmissive material	Allocation zones aligned with spatial extent (lateral and vertical) of water-yielding geological units	Well log, geological map. May also include aquifer test data analysis and 3D geological modelling
3	Groundwater flow lines	Subdivision of aquifers into smaller management units based on groundwater flow lines. These smaller units are sometimes defined to encapsulate the recharge area for one or more groundwater-dependent surface water bodies.	Groundwater contour interpolation from piezometric surveys.
4	Degree of connectivity with surface water bodies	Several methods have been used to define allocation zones in accordance with effects on surface waters. These include delineation of alluvial aquifers immediately adjacent and closely connected to surface watercourses,	Collection and analysis of aquifer property data, stream depletion modelling with varying degrees of complexity

[6] Further information on the methodology used and challenges associated with this approach is available if required.

No.	Method	Description	Technical assessment requirements
		delineation using stream depletion time-based criteria (e.g. area of aquifer within which stream depletion rates exceed 60% of the abstraction rate within a given period).	(analytical modelling, deterministic numerical modelling, stochastic numerical modelling).
5	Administrative boundaries	Defining or clipping groundwater allocation zones to align with administrative boundaries – e.g. Regional Council boundaries.	None.
6	A combination of the above	Example: Development of a conceptual model of an aquifer system and defining allocation zone limits through consideration of geological, hydrogeological and surface water connectivity data, giving due consideration to the planning mechanisms that will be used to manage groundwater.	Combination of the above, sometimes in conjunction with expert judgement.

5.2. Allocation limit-setting

The methods that have been used to define groundwater allocation limits are summarised in Table 2 and are evaluated within the SWOT analysis framework in Table 3.

Table 2 Allocation limit determination methods and assessment requirements

No.	Method	Summary	Technical assessment requirements
1	Fixed percentage of annual average rainfall or groundwater recharge	Allocation limits defined as a fixed percentage of annual average rainfall (e.g. 5%) or estimated groundwater recharge (e.g. 10%, 50%).	Varies from rainfall data analysis to detailed recharge evaluation using soil water budget models, lysimeter data, satellite remote sensing data, water table fluctuation and environmental tracer analysis.
2	Existing consented use rates	Groundwater allocation is sometimes capped at current consented rates or current rates ± a given percentage, depending on whether current abstraction exceeds acceptable environmental effects thresholds.	Information on consented annual volumes and usage rates. Current state and trend analysis and evaluation of whether effects of current abstraction and/or potential future abstraction (e.g. within existing consent limits) are acceptable.
3	Maximum permissible stream depletion	Definition of allocation limits based on assessment of stream depletion rates and	Stream depletion analysis: Collection and analysis of aquifer property data, stream depletion modelling with varying degrees

No.	Method	Summary	Technical assessment requirements
		determination of the maximum acceptable rate of stream depletion.	of complexity (analytical modelling, deterministic numerical modelling, stochastic numerical modelling). Stream depletion limit determination: approaches include a fixed % of MALF, structured expert judgement and stream-specific ecological effects-based thresholds.
4	Prevention of seawater intrusion	Maintenance of positive coastal gradients and sufficiently high flux rates to prevent both active and passive seawater intrusion.	Examples include modelling maximum abstraction rates for maintenance of 2 m asl head in coastal sentinel wells and salinity monitoring-based approaches (e.g. England).
5	Value judgment based on scenario modelling	Simulation of multiple allocation scenarios and associated impacts on stream flows and/or groundwater levels coupled with cost/benefit analysis (economic and environmental) of higher/lower rates of abstraction.	As per No. 3 above + groundwater level modelling (ranging from spreadsheet calculations to numerical modelling) + economic benefit (increased abstraction) and/or cost (reduced abstraction) assessment + stream health impact analysis + science communication with stakeholders involved in value judgement process.
6	Adaptive management	Floating allocation set each year (typically in September) based on groundwater levels. Consent holders can access between 0 and 100% of their allocation.	Data analysis or modelling to determine relationship between groundwater levels and environmental effects. Level of complexity depends on local context.
7	Four test system (WFD)	Holistic evaluation of groundwater recharge, surface water connectivity + dependency and intrusion of poor-quality water.	Groundwater recharge analysis, stream depletion modelling, determination of stream flow standards and evaluation of groundwater abstraction effects on flow thresholds, evaluation of wetland dependency on groundwater and groundwater abstraction effects and assessment of water quality data for intrusion test.

Table 3 SWOT analysis for groundwater allocation boundary definition methods

Delineation method	Strengths	Weaknesses	Opportunities	Threats
Surface water/topographic catchments	Simple, low cost. Often the best option for topographically constrained river basin aquifers.	Aquifers often span multiple surface water catchments, especially on plains.	Potential to quickly define allocation zones for catchments with low usage rates. Potential to manage groundwater and surface water as a single unit (where appropriate). Extension of allocation zones to topographic boundaries, even where these include low productivity aquifers, avoids "no man's land" situation.	Unintended consequences if high groundwater abstraction from one surface water catchment depletes flows and/or groundwater levels in connected adjacent catchment.
Geological data (maps, well logs)	Well-suited to areas where aquifer extent correlates with geological boundaries. Ability to discretise multiple allocation zones in the vertical plain.	Lateral and vertical extent of aquifers may not be well-defined by available information. May required 3D geological modelling.	Potential to use as a basis for defining degree of connectivity with surface water and thereby define stream depletion rules and policies on an allocation zone (rather than per-consent) basis.	Lateral and vertical connectivity between adjacent units may be ignored, leading to unintended consequences.
Groundwater flow lines	Provides basis for water budget calculations and hence allocation limit setting as a percentage of recharge. Allows laterally extensive aquifers (e.g. coastal plains) to be discretised into smaller management units.	Flow lines do not represent hydraulic effect boundaries and hence effects on/from adjacent zones are likely. Groundwater flow directions can vary with depth but limited deep aquifer observations	Splitting large aquifers into smaller units can help to manage localised cumulative effects associated with high intensity usage areas. Scenario-based groundwater modelling can be used to assess environmental outcomes associated with abstraction from both within an allocation zone and within adjacent allocation zones.	Potential for unintended consequences if interference effects between adjacent allocation zones is not considered.

Delineation method	Strengths	Weaknesses	Opportunities	Threats
		make this hard to discern.		
Surface water connectivity	Stream depletion is often a key driver for allocation limit-setting. Allows for vertical discretisation of an aquifer.	Detailed technical analysis and modelling may be required.	Defining allocation zones in accordance with the degree of connectivity provides administrative units within which allocation limits and plan rules can be tailored to stream depletion management goals.	Challenges from water users on modelled estimates of connectivity and lag times between pumping and stream depletion during plan development process. Discounting the cumulative impacts of many low depletion takes can lead to unintended consequences.

Table 4 SWOT analysis for groundwater limit-setting methods

Delineation method	Strengths	Weaknesses	Opportunities	Threats
Fixed percentage of annual average rainfall or groundwater recharge	Relatively simple to determine allocation limits and easy to implement. Provides a means by which multiple effects can be managed, e.g. impact on lakes and level-dependent wetlands, groundwater levels to maintain springs and river accretion and discharges to the coast to maintain the saline interface.	Blunt tool, difficult to achieve specific environmental outcomes (e.g. protection of a certain level of stream baseflow) if used as the only groundwater allocation method.	Can be used in conjunction with other methods to provide for holistic management of groundwater and surface water resources. Fixed percentages can be varied in accordance with certainty over recharge estimates (e.g. use of lower percentages where recharge estimates are highly uncertain) and with protection requirements (e.g. use of lower percentages to provide higher degree of certainty over stream flow protection).	Use of long-term average recharge rate may not provide a suitable degree of protection during multi-year groundwater droughts, when stream baseflows are the most stressed. This could prove to be a significant limitation as the climate becomes more extreme in response to global heating.
Existing consented use rates	Relatively simple to determine allocation limits and easy to implement.	Full effects of existing abstraction may not be apparent from monitoring data due to lags and climate variability.	Could circumvent the need for significant investment of resources to evaluate relationships between groundwater abstraction and water resource impacts, particularly if reduction in actual abstraction rates beyond a certain percentage (e.g. 10%) within the life of the regional plan is unlikely to be achievable.	Uncertainty over actual use rates and translation of instantaneous, daily or monthly abstraction consent limits into annual limits is challenging. Assumes that effects of existing abstraction are acceptable.

Delineation method	Strengths	Weaknesses	Opportunities	Threats
Maximum permissible stream depletion	Ability to tailor groundwater abstraction to effects thresholds and ecological protection in surface waters.	Uncertainty over modelled stream depletion rates and lag times between abstraction and depletion. Significant investment in science work may be required, depending on method used.	Potential to require consent holders to contribute to contribute to delivery of stream health outcomes based on magnitude of depletion effects as per the proposed Hawkes Bay TANK plan. Can be used in conjunction with other methods to provide for holistic management of groundwater and surface water resources.	Challenges during consenting process due to modelling uncertainty and lag times. Defining flows required to achieve stream health objectives in the context of multiple stresses (e.g. nitrate, sediment, riparian habitat) can be challenging
Coastal head and groundwater flux constraints to prevent seawater intrusion	Specifically manages seawater intrusion risk.	Needs to be used in conjunction with other methods to manage broader effects of groundwater abstraction.	Can be used in conjunction with other methods to provide for holistic management of groundwater and surface water resources.	Potential for passive seawater intrusion in coastal wells can be overlooked if intrusion assumed to occur only with a hydraulic gradient from the ocean towards the coast.

Delineation method	Strengths	Weaknesses	Opportunities	Threats
Value judgment based on scenario modelling	Ability to involve stakeholders and communities in cost/benefit analysis of environmental versus economic outcomes. Can mitigate challenges associated with definition of effects-based thresholds for stream depletion where these are hard to determine due to multiple stream health drivers.	Resource-intensive. Does not define effects-based thresholds; lack of hard limits could support acceptance of environmental degradation in order to avoid economic impacts from reduced abstraction.	Education of stakeholders on effects of groundwater abstraction. This may lead to improved implementation/compliance rates. Potential for water users to go beyond the minimum requirements in order to improve the natural environment through improved understanding of impacts and solutions.	Value judgment can be dominated by water take interests due to higher rates of participation by this stakeholder group in engagement processes. Environmental interests can be under-represented.
Adaptive management	Allows more water to be taken at times of surplus and less during times of shortage.	Highest demand typically occurs at times of shortage and lowest demand at times of surplus. Can be resource-intensive to implement	Use of value-based restriction tiers, e.g. restrictions applied to low value crops before high value crops or inefficient before efficient water users. Provides opportunity to incentivise high value and efficient water usage.	Vulnerable to changes in monitoring well baseline (e.g. due to local abstraction or earthquakes) if groundwater levels are used as a trigger
Four test system (WFD)	Comprehensive management of water resources.	Resource-intensive.	Investment in improved understanding of hydrological systems and groundwater abstraction effects can provide a strong foundation for future proactive resource management.	Reliance on modelling and technical assessment, therefore open to challenge. Intrusion test is reactive and may only identify issues after the fact.

6. CONCLUSIONS

The main conclusions of this study are as follows:

- Definition of groundwater allocation limits as a fixed percentage of either long-term average rainfall or groundwater recharge has been the most common limit-setting method in NZ. This is being superseded in some areas by quantitative effects threshold (e.g. stream depletion at 5% of MALF) or value judgement-based limits.
- Assessment and management of stream depletion effects are often the most challenging aspects of groundwater allocation. Science work and associated plan rules have been contentious in some areas where previously restrictions are proposed for previously unrestricted water takes and where water user impacts differ significantly either side of a zone boundary defined through modelling
- A SWOT analysis has been undertaken to evaluate the various methods that have been used to define groundwater allocation zones and to set allocation limits.
- The Four Test system implemented by the Environment Agency in England to meet the requirements of the European Water Framework Directive provides the most comprehensive framework for assessment and management of groundwater abstraction effects. A significant investment in science work may be required to implement this, depending on the methodology used to assess each of the four tests.
- A wide range of challenges and solutions in both allocation zone delineation, limit-setting and implementation are documented in this report. Whilst some solutions may be applicable only in local circumstances, others could be useful in a broad range of settings.
- Although setting allocation limits in the context of climate change and the associated increase in extreme weather has been recognised as a challenge, limited work appears to have been done so far to manage the associated risks. Use of short duration consents (e.g. five years) with common end dates provides a mechanism for adaptive management and could offer a partial solution. But short consents are unpopular amongst water users seeking longer term certainty of supply for investment decision-making and present resourcing challenges for regulatory authorities.

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9. LIMITATIONS

Kōmanawa Solution Ltd (KSL) has prepared this Report in accordance with the usual care and thoroughness of the consulting profession for the use of Waikato Regional Council

This Report has been prepared in accordance with the scope of work and for the purpose outlined in our proposal dated 11th October 2019 and is based on generally accepted practices and standards at the time it was prepared. No other warranty, expressed or implied, is made as to the professional advice included in this Report.

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APPENDICES

A.1 Summary of challenges and solutions

The challenges and solutions deployed by the regulatory bodies covered within this report are summarised in Table 5 below.

Table 5 Summary of groundwater quantity management challenges and solutions

Challenge	Solution	Location	Comments
Zone delineation			
Zone delineation by flow lines: water movement between adjacent zones	Expansion of management zones and scenario-based groundwater modelling	Bay of Plenty	Original zone delineation and accounting method was challenging and contentious
Allocation zone delineation	Defined on basis of surface water connectivity	France	Allocation limits set to give $^4/_5$ year reliability
Allocation zone delineation	Extension to topographic divides in hill country	Canterbury	Recognises contribution of seepages from hill country into downgradient aquifers, avoids "no man's land"
Setting allocation zone boundaries within continuous aquifers	Scenario modelling to determine effects on/from adjacent zones	Canterbury	Capping allocation at current is becoming common; this makes zone boundary definitions less critical
Setting limits			
Uncertainty over recharge rate	Guideline cap	Auckland	Practitioners acting on behalf of water users have successfully argued for application of less conservative estimates of groundwater recharge, resulting in increasing rates of groundwater usage
Defining degree of groundwater-SW connectivity	Modelling studies	Greater Wellington	Demonstrating benefits of low flow restrictions & granularity of banding has been challenging
Allocation limit-setting	50% of recharge	Canterbury	Problematic during multi-year groundwater droughts
Allocation limit-setting	Groundwater trigger level-based allocations	Canterbury, Southland	Problematic in Canterbury due to earthquake changes + resource intensive. More successful in Southland
Allocation accounting	Double counting of stream depletion	Canterbury	Manages uncertainty over preliminarily modelled depletion

Challenge	Solution	Location	Comments
Uncertainty over water take rates	Staged approach to determination of allocation limit	Hawkes Bay	Work in progress
Allocation limit setting - holistic effects management	Four test process - WFD	England	Large body of technical literature available from EA
Allocation in context of climate change	N/A	Southland, Canterbury	Recognition that allocation as a fixed % of long-term recharge may not be suitable under a more variable and extreme climate but no solutions developed to date
Implementation			
Managing to allocation limits	Five-year consents with common end date	Gisborne	Experience to date is that benefits of ability to better manage the resource outweigh resourcing costs of simultaneous consent processing
Stream depletion effects	Recognised flow restrictions required at flows >min flow limits due to lag effects. Stream Flow Maintenance and Habitat Enhancement Scheme proposed	Hawkes Bay	Several challenges still to be overcome to finalise and implement proposed plan change
Stream depletion assessment	Analytical solutions with pumping tests	Canterbury	Results could underestimate stream depletion. Sensitive/vulnerable upper reaches may not be well-managed
Stream depletion assessment - intermittent streams	Excluded from previous regional plan	Southland	Caused problems for downstream reaches due to underflow and increased length/duration of dry reaches
Management of stream depletion effects	Variable quality pumping tests, lack of clarity during consenting	Southland & Canterbury	Specification of pumping test and technical assessment requirements