MEMO

To:	The PPC9 Hearings Panel
From:	Jeff Smith – Manager Science Ellen Robotham – Policy Planner
Date:	10 June 2021
Subject:	**APPENDIX 11 - PLAN CHANGE 9 S42A REPORT**

Background

Appendix 11 to the Hawke's Bay Regional Council S42A Hearing Report is a memorandum that summarises hydrological information relevant to proposed Plan Change 9[1]. The Appendix 11 memo was not subject to full technical review and was inadvertently lodged with the Section 42A Report with errors and factually inaccurate information.

After writing this technical memo, the main author of the memo (Mona Wells) has resigned from Hawke's Bay Regional Council and is no longer available to inform the PPC9 hearing process.

Here, we attach a revised version of the Appendix 11 memo. We also provide a summary of major technical revisions and implications of those revisions for the Section 42A Report and evidence that has been lodged by submitters.

Major technical revisions to the Appendix 11 memorandum

Major revisions to the Appendix 11 memorandum include:

1. Deletion of planning evidence or advice that was provided by the technical expert. This includes statements regarding "sustainability" and degradation of a resource, which in this case are considered inappropriate for a technical expert to assert in expert witness evidence.
2. Irrelevant information (for example, discussion of the stream depletion calculator) has also been deleted.
3. Deletion of assessment of the groundwater resource based on water budget analysis. In the Appendix 11 memo, the author asserts that the purpose of groundwater management is to ensure that discharge from an aquifer does not exceed recharge (referred to as *Out>In* by the author).

   While the water budget may be contemplated in groundwater management, decisions on limits to groundwater development should primarily consider the size of discharge that can be captured without causing unacceptable effects. For example, effects of groundwater abstraction on hydraulically connected surface water bodies are considerably important in PPC9.

   Groundwater capture is largely independent of recharge, but depends on the dynamic response of the aquifer system to pumping – which is best identified using groundwater

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[1] The s42A Appendix 11 memorandum is titled *Summary of Key Elements of Science Pertaining to Water Quantity in Proposed Plan Change 9 – TANK* and was authored by Mona Wells and Rosa Kirkham.

models[2]. This modelling approach was used to assess the effects of groundwater abstraction (capture) on surface water bodies and other dynamic responses, to inform PPC9.

4. Irrigation water use in Figure 12 is substantially over-estimated from 2015-2019 due to an inappropriate "adjustment factor" that the author applied. This has subsequently been corrected in Robert Waldron's evidence in reply[3] (dated 19 May 2021).

Policy Implications

The memo was intended to be a summary of the science relied upon to inform the provisions of PPC9 as described in paragraph 1200 of the Section 42A report. As such, reporting officers did not change PPC9 planning provisions based on Appendix 11, bar one exception.

The one exception to this approach is in relation to the definition of Actual and Reasonable. Based on the over-estimated irrigation water in Figure 12 of the memo, reporting officers changed the definition of Actual and Reasonable. This error has since been amended based on the evidence of Mr Waldron.

The water quantity provisions of PPC9 as notified are justified by the Section 32 Report which references relevant scientific reports or TANK Group meeting decisions specifically. Amendments to the water quantity provisions of PPC9 through the Section 42A Report and the Section 42A Addendum Report have been based upon submissions and expert evidence provided by submitters or the Council's experts.

Submitters who reference Appendix 11

The following table identifies evidence that has been lodged by submitters which references Appendix 11.

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[2] Bredehoeft, John. (2002). *The Water Budget Myth Revisited: Why Hydrogeologists Model*. Ground water. v40(4). pp 340-5.

[3] Appendix 10 to the HBRC s42A Addendum Report

Submitter evidence	Evidence compiled	Page & Paragraph	Excerpts – references to Appendix 11	Affected by the amendments
Andrew Dark HB Winegrowers	Part 1	Page 41 para 80-86	The Appendix 11 Technical Water Quantity memo (pg 18) refers to the "dry climate" scenario that was run with the Heretaunga Aquifer Groundwater Model. In this scenario, climate conditions and pumping that are representative of the 2012 – 2013 irrigation season were repeated every year for the next hundred years. This is a conservative scenario, as it assumes that water use is high every year, rather than varying from year to year….. I note that In Figure 12 of the Appendix 11 memo, water use for the 2019 – 2020 irrigation season (a drought year) has been estimated at around 105 Mm³. The memo states that irrigation water use for this season was based on model results. No further details are provided, however, on how the updated volumes in this figure were derived.	Unlikely Mr Waldron's evidence addresses the error with actual water use estimation.
		Page 121 Para 91-94	However, since the publication of these reports, a further five years of data, overlapping with the period of enforced measurement and reporting, is now available. I refer to Figure 12 in Appendix 11 to the s42A Report which illustrates total groundwater pumping (Mm³ /year) per water cycle year between 2010/11 to 2019/2020. The data in the figure demonstrates that for the years 2010/2011 through to 2018/2019 inclusive, that total groundwater pumping is at or below 90Mm³.	Unlikely As above
Gerard Willis Lowe Corporation	Part 2	Page 44 Para 72	Here I consider it instructive to note that Figure 1 of the technical memo attached to the s42A report (Appendix 11) very clearly shows industrial use (as a whole) has been static over the past two decades while irrigation use has grown significantly. Similarly, Figure 12 of that memo shows that over the past decade, municipal take has grown markedly while industry has	Unlikely

			remained static. In other words, now that PCC9 requires allocation to phased out, industry is bearing a considerable burden of that reduction. It is, in effect being penalised for not using more of its consented allocation when it could have, in order to now address an over-allocation problem caused by significant growth by other sectors.	
Morry Black Te Taiwhenua o Heretaunga	Part 3	Page 86 Para 172	Appendix 11 to the s42A report in reference to the Heretaunga Aquifer refers to a water balance as being where water going in is equal to water coming out. What it fails to include in this equation is that water storage should stay the same to achieve sustainable management of the resource. Water storage is being gradually lost as is confirmed by Harper 2015 (Figure 4-1) and various regional council SOE reports.	Likely
		Page 96 Para 220 - 221	Page 2 of the s42A report Appendix 11 Memo under the sub-heading “Sustainability / Sustainable”, confirms that the science reports and the language therein are predicated on the Brundtland report of 1987, where the focus was on sustainable development, not sustainable management of natural and physical resources, which is the purpose of the Act. This implies the s42A report is relying on science backed by sustainable development principles, rather than sustainable management.	Likely
		Page 109 Para 280 - 287	The Appendix 11 Memo from the s42A report summarises the key elements and concepts that informed the freshwater quantity provisions in PPC9. Diagram A (page 1) shows that 180 Mm^3 has been allocated from an aquifer system that until recently was thought to be recharged at an average rate of 188 Mm^3 per annum.	Unlikely PPC9 acknowledges and addresses this over allocation
Gillian Holmes Hort NZ	Part 4	Page 385 Para 33-34	Numerous investigations have been undertaken into the groundwater and surface water within the TANK catchment as	Unlikely

			part of the PC9 process as summarised in Appendix 11 of the Section 42A report. 34. The main investigations and modelling work completed that have relevance to my evidence are as follows: a) Development of a SOURCE model (WWLA 2018) and subsequent scenario running using calibrated SOURCE model (HBRC, 2018 c); b) Development of a groundwater model of the Heretaunga Plains groundwater (HBRC, 2018a) and subsequent scenario modelling (HBRC, 2018b); and c) Development of stream flow depletion calculator (HBRC, 2021b).	
Lay Evidence Week 1				
Witness	Link	Page & Paragraph	Excerpts – references to Appendix 11	Affected by the amendments
Ngaio Tiuka NKII	Here	Page 14 Para 36-44	The biggest environmental and cultural issue in Heretaunga is disappearance of freshwater. Section 42A appendix 11 summed it up well: “groundwater levels and river and stream flows are decreasing due to water use”[13], the condition of freshwater resources in the Heretaunga Plains is degrading, and Out > In entails that this circumstance is not sustainable.	Likely
		Page 33 Para 83	Regulatory measures and hard limits need to be established based on environmental and cultural limits and sustainability to give effect to the hierarchy. For example, a total limit for the aquifer as discussed later in my evidence, would be based on ground water budget of ins and out as initially described in appendix 11 to the Section 42 report. Instead, it is based on irrigation demand, i.e. the last consideration in Te Mana o te Wai NPS FM 2020 hierarchy.	Likely
		Page 35 Para 92-97	The logical accounting consideration for the management of groundwater quantity, is don’t take out more than what’s going	Likely

			in. In = Out principle as described in the section 42A, appendix 11 report, page 1. It also states, page 2 “groundwater levels and river and stream flows are decreasing due to water use” 31 , the condition of freshwater resources in the Heretaunga Plains is degrading, and Out > In entails that this circumstance is not sustainable.	
Shade Smith NKII	Here	Page 6 Para 19 – 34	The memo in Appendix 11 of the Hearings report titled “Summary of Key Elements of Science Pertaining to Water Quantity in Proposed Plan Change 9 (PPC9) – TANK” outlines the general scientific basis for the policies and objectives of PPC9 that relate to water allocation. The Appendix 11 memo generally lacks detail on groundwater levels showing the extent of the decline that has already occurred historically, e.g. the past 70 years, despite this being of prime importance in being able to contextualise the current groundwater level situation. I also note the description of recharge source to the aquifer in the Appendix 11 memo is out of date. There is no recognition of hydrochemistry and isotope data showing robustly that the groundwater signature in the southern half of the aquifer is predominantly inconsistent with recharge from rivers (GNS 2018). Returning to the Appendix 11 memo there appears to be an unstated assumption that there is a background “steady state/equilibrium” condition which will simply be resolved by placing a limit on groundwater (and river) pumping. This is by no means certain given, as mentioned previously, the amount of drainage that has been undertaken (and continuing), changes to	Likely

			the river recharge mechanism, climate change, change in catchment vegetation, and soil loss.	
		page 12 Para 57 - 65	In continuance of the above discussion on the Paritua/Karewarewa and in relation to specific references in the Appendix 11 memo in PPC9, and in policy 44 to the Paritua/Karewarewa Stream, I note that the memo 'call[s] into question whether it [Paritua Stream] is very well connected with groundwater', and states that instead of declining groundwater levels, 'stream flow may be more closely related to rainfall'.	Likely

MEMO

To:	Ellen Robotham, Policy Planner, Strategic Planning Group, HBRC
From:	Mona Wells, Hydrology and Hydrogeology Team Leader, and Rosa Kirkham, Scientist Hydrology, Integrated Catchment Management Group, HBRC
Date:	15.04.2021 – **Revised 10.06.2021**
Subject:	**REVISED: Summary of Key Elements of Science Pertaining to Water Quantity inProposed Plan Change 9 – TANK**
File Ref:	NA

I. Background and Purpose of Memorandum

The *Proposed Plan Change 9: Tūtaekurī, Ahuriri, Ngaruroro and Karamū Catchments* (PPC9, Hawke's Bay Regional Council/HBRC, 2020), for catchments collectively referred to as TANK, recognises that fresh water is a finite resource in the Heretaunga Plains of Hawke's Bay. Figure 1A shows annual groundwater pumping takes from 1980–2013 (in million metres cubed or Mm^3) compared to water allocated for use(TCSG, 2017a). The three major uses of abstracted ground water are for public water supply, industry,and irrigation, the latter two of which have increased since 1980. Figure 1B shows the projected effect that the current level of pumping will have on groundwater levels in future if the trends in Figure 1A continue (blue line). For comparison, a crisis prevention outcome is shown (red); this result eventuates by taking action to cap allocated pumping takes at the maximum level from 2012/2013 (HBRC, 2018a, 2018).

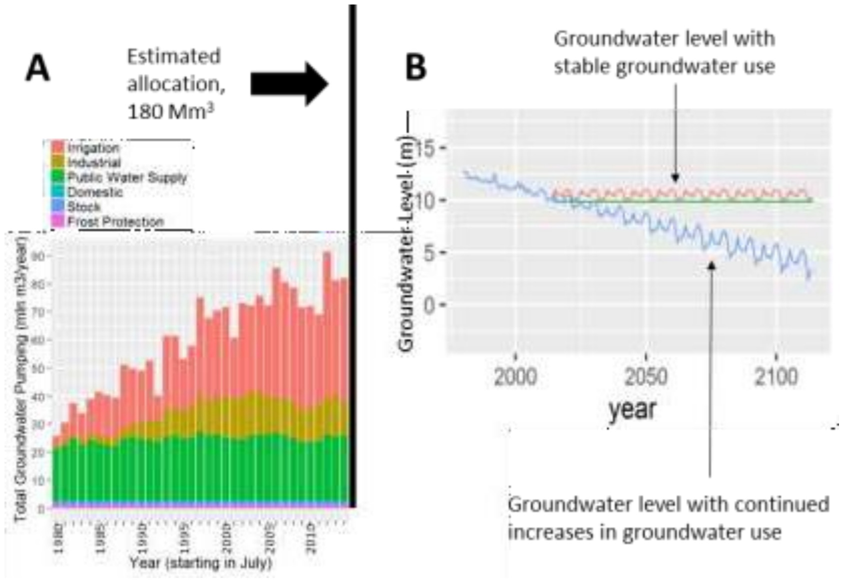

Figure 1. (A) Graph showing history of groundwater pumping by use type compared to estimated total groundwater allocation. (B) Graph showing groundwater depletion if increases in panel A continue infuture (blue) compared to change if static (red). The groundwater bore modelled is located on the southwest edge of Hastings.

Proposed Plan Change 9 amends the Hawke's Bay Regional Resource Management Plan to address various environmental issues and prepare for future needs of socioeconomic development in the TANK catchments area, while safeguarding the environment for future generations (HBRC, 2020). The fundamental science that underlies and informs PPC9 is complex and the product of many years work, which is described in thousands of pages of reports and other documents. The purpose of this memorandum is to summarise some key elements of science that informed freshwater quantity provisions of PPC9, in a single place, and in a form suitable for an informed, non-specialist reader. The contents of this memorandum are not intended to be comprehensive, and instead specifically focus on elements of science that relate to points commonly raised in submissions responding to PPC9. Aspects of PPC9 that are primarily matters of policy decisions are not dealt with herein. The next three sections provide an explanation of key terminology, followed by a summary of key elements of science informing knowledge on the consequences of water allocation and takes, and a section addressing specific rules in PPC9 that were widely mentioned in submissions.

II. Key Elements of Science Relating to Water Allocation and Takes in the Context of Proposed Plan Change 9 – TANK

One way to understand what is happening to water supplies is to collect monitoring data, e.g. surface water flows, groundwater levels, etc. HBRC have surface water and groundwater monitoring data extending back to, for some locations, the 1950s. As issues of water quantity and allocation have become more prominent, monitoring activity has increased apace in terms of the number of sites monitored, the frequency, and the focus on obtaining high quality data to meet needs. There are, however, two major shortcomings of relying on monitoringalone. First, monitoring is extremely costly. Distances are large, equipment is specialised, and the skill-level needed by monitoring personnel is relatively high. It is never practically possible to obtain an optimal amount of monitoring data. Second, and more importantly, monitoring tells us something about what has happened and what is happening; it does not tell us what we might expect in the future.As such, HBRC also have extensive modelling projects to complement monitoring efforts. The next two subsections provide brief summaries of HBRC’s monitoring and modelling work for surface waterand groundwater resources, followed by topics concerning the consequences of surface water- groundwater connectivity and some key points concerning what we currently know about water resource use.

a. Summary of Heretaunga Plains surface water monitoring and modelling

The surface water component of PPC9 includes the major river (Tūtaekurī, Ahuriri, Ngaruroro) and stream (Karamū) features, as well as a number of tributaries within these catchments (Figure 3, HBRC, 2018c).

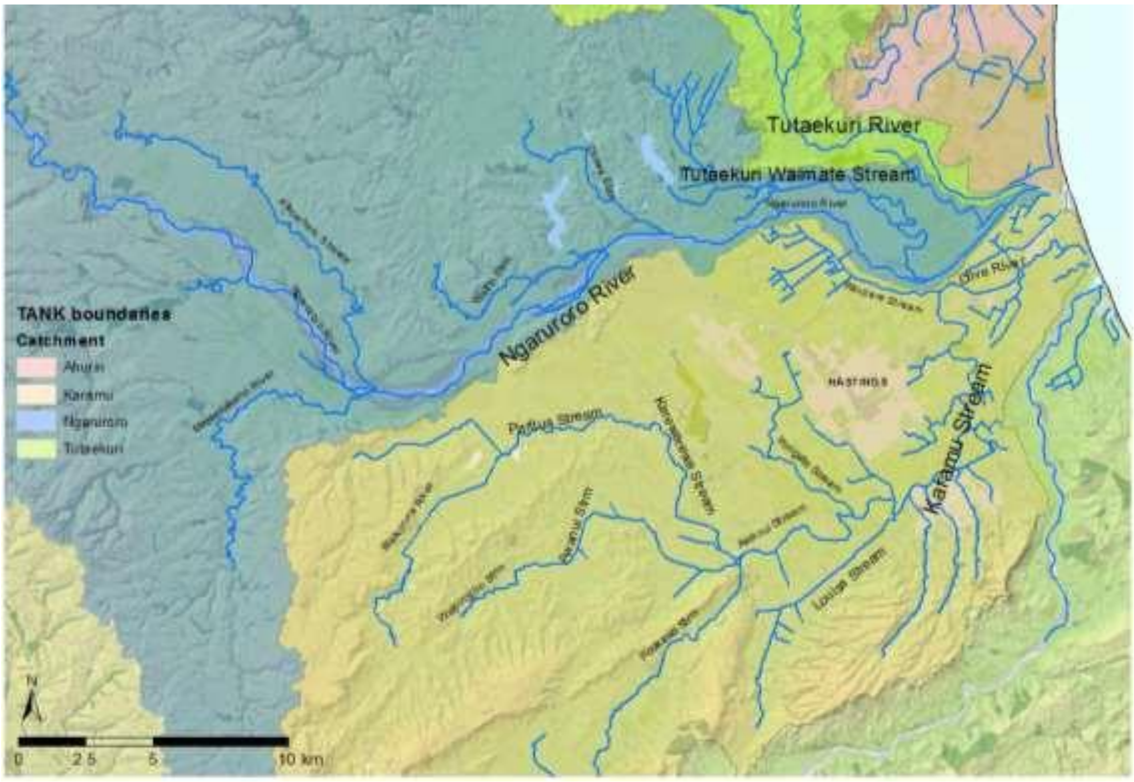

Figure 3. Map showing primary TANK catchments with rivers and streams that contribute surface water to theTANK groundwater.

Draining the Ruahine and Kaweka mountain ranges, both the Tūtaekurī and Ngaruroro are large rivers, with surface water catchment areas of 836 km^2 and 2,000 km^2, respectively (HBRC, 2016). These rivers are characterised by gravel beds, forming wide braided channels in the lower reaches. The Karamū Stream and Ahuriri catchments are smaller, being 500 km^2 and 86 km^2, respectively; both of these catchments primarily drain lowland country, with stream beds often comprised of fine gravels or sandy/silty substrate (HBRC, 2016). The Tūtaekurī, Ngaruroro and Clive rivers all flow into the Waitangi Estuary after uplift from the 1931 Napier earthquake caused the Tūtaekurī River to change its course to the south (HBRC, 2016).

Consideration of surface water river flows involves some key terminology that requires clarification in regard to usage in PPC9. “Minimum flow”, as used by PPC9, refers to a low-flow threshold at which water takes are restricted for the purpose of ecological protection. This minimum flow should not be interpreted to mean that a river or stream flow will always remain above this minimum flow, which is not always the case (HBRC, 2018d). A more appropriate term, adopted for clarity in some HBRC technical reports (HBRC, 2018c and 2018d) is “cease-take trigger flow”, indicating the flow at which a cease-take management response to reduce the rate of flow diminution is triggered, albeit sucha response does not ensure that flow will not continue to decline after the cease-take, for instance, during times of prolonged low rainfall. The term “trigger flow” also refers to high-flow takes described in PPC9. The terminology is used in a similar manner with respect to management intervention. In the case of high flow, trigger flow refers to the flow level above which water can betaken/harvested. Once a river’s flow drops below the high “trigger flow”, takes must cease.

HBRC have a number of sites within the TANK catchments where continuous monitoring of river and stream flow occurs Flow monitoring data are used for environmental reporting and assessment of flow levels for cease-take trigger flow and high flow management purposes. In addition to obtaining continuous flow data, it is important to physically measure flows and assess river and stream factors that affect flows through a process referred to as gauging. HBRC regularly perform gaugings to support surface water investigations, and river gauging is coupled with the continuous monitoring of select key sites for quality control purposes (HBRC, 2018d). The distribution of relevant surface water monitoring sites is shown in Figure 4 below. All telemetered sites are gauged for quality control purposes, however some have been identified for concurrent flow investigations, marked in red (concurrent gaugings further detailed in Section II.c).

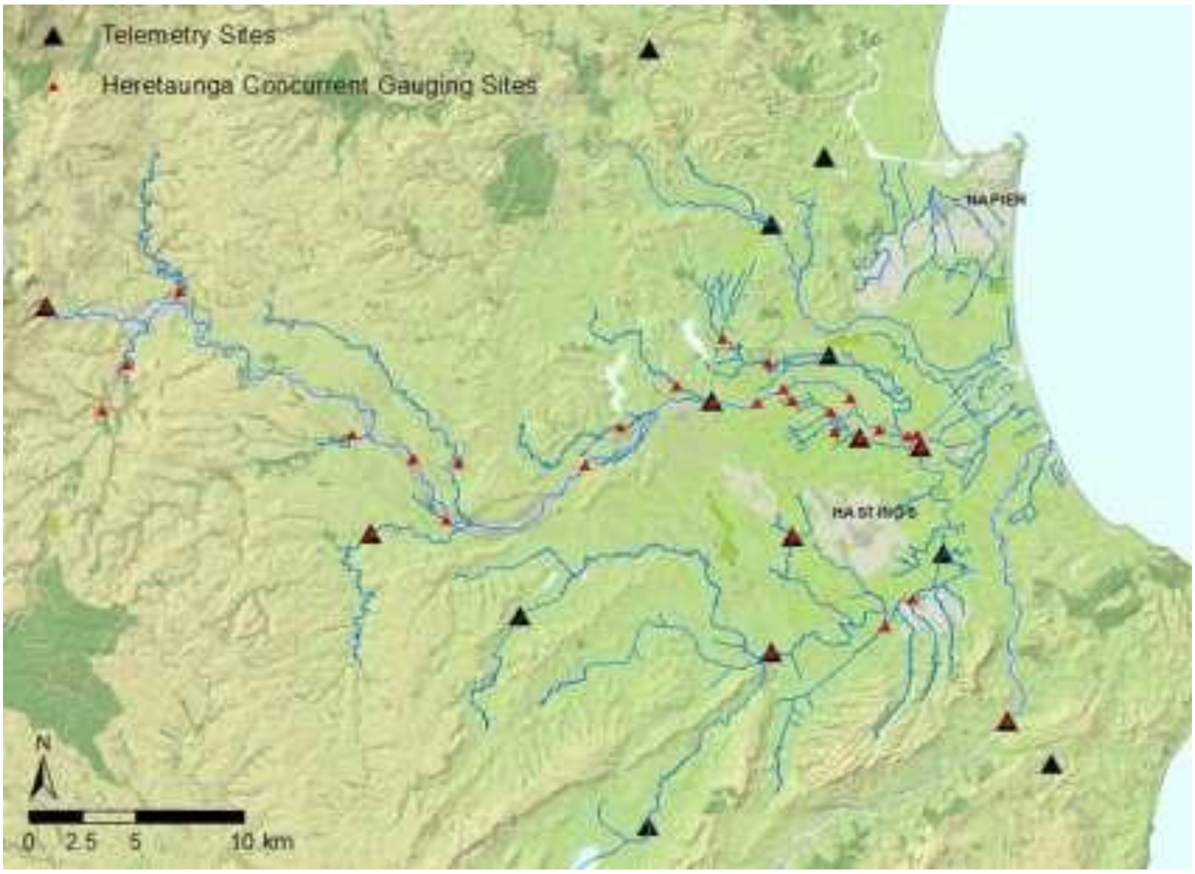

Figure 4. Heretaunga Plains map showing locations of surface water continuous monitoring telemetry sites and concurrent flow gauging sites.

To assess the future of the surface water resource, monitoring data is used in the development of models to simulate and predict surface water flows across TANK catchments, excluding the Ahuriri catchment and Poukawa sub-catchments that are being dealt with as separate packages of work. The surface water model was calibrated with data from 40 gauging sites (Williamson & Diack, 2018), representing a high level of coverage for this type of model, and the results were assessed by making comparisons between modelled simulated flow to theactual measured flow (Williamson & Diack, 2018). The performance of the model to simulate the river flows was assessed using measures that are well-accepted internationally and represent standardpractice for surface water modelling (Moriasi *et al*., 2007; Williamson & Diack 2018).

Following model construction, calibration and validation, a number of scenarios were run to simulate the surface water system under different environmental management protocols and future use (HBRC, 2018c). The various scenarios modelled included the following:

- The “base case” scenario simulates the TANK catchments as they have been in recent times, under current water use practice and management rules; this enables simulating the effects of current estimated water use on river flows and abstraction[4] restrictions.

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[4] For the purposes of this report, the term abstraction refers to any taking of surface water or groundwater, regardless of the purpose of the take.

- The "naturalised" scenario simulates what river flows would be without human water takes. The primary purpose of the scenario is to allow comparison with the base case scenario, in order to understand the cumulative effect of water takes on river flows under current practices.
- The "base case with maximum allocation" scenario simulates the effects of abstraction if all of the water currently allocated were to be used, while still subject to the application of current flow management rules.

- Various other scenarios were run to understand the effects of altering management rules such as cease-take trigger flow and high-flow trigger flow, to simulate the effects changes in management may have on the catchment and rivers. Results from these scenario runs were compared to the base case scenario.

Key findings from surface water modelling were drawn from comparisons of flow statistics between different scenarios. Under the base case scenario, for the Tūtaekurī River the pertinent low flow statistic (discussed further in Section III.d) differs from the naturalised conditions by less than 10%. The Ngaruroro River base case compared to the naturalised scenario shows substantively more impacts than for the Tūtaekurī River. This is due to coupled surface water-groundwater effects (Section II.c below) combined with the larger total surface water abstraction in the Ngaruroro River.The average modelled surface water abstraction for upstream of Ngaruroro River at Fernhill is 770 L/s, whereas average surface water abstractions upstream of the Tūtaekurī River at Puketapu is 450 L/s (HBRC, 2018c).

Following the assessment of the predicted impact of abstractions on the surface water network, various cease-take trigger flows were assessed. The results for the Tūtaekurī River and Ngaruroro River are summarised in Table 1 below in terms of water use restrictions that would occur in different scenarios. For the Ngaruroro River, the model predicts that increasing the cease-take trigger flow from the current 2,400 L/s to any of the larger trigger flows (the largest being 4,700 L/s) results in progressively larger effects on restriction, reducing the reliability of supply for existing water abstractors. The ecological effects of changes to flow regimes, for both high and lowflows, are discussed further in Sections III.c–e.

Table 1. Modelled restriction resulting from different cease-take trigger flows.

River	Cease-take trigger flow modelled (L/s)	Days of restriction predicted	Relative restriction per year (%)
Tūtaekurī	2,000[a]	0	0
Tūtaekurī	2,500	0	0
Tūtaekurī	2,800	< 5	0.3
Tūtaekurī	3,900	24.8	9.1
Ngaruroro	2,400 [a]	5.9	2.2
Ngaruroro	3,600	12.9	4.7
Ngaruroro	4,400	19.5	7.1
Ngaruroro	4,700	21.8	8

[a] Current cease-take trigger flows.

High-flow surface water allocation enables water to be harvested during the wet season and stored for later use. Much of the high-flow scenario modelling focuses on how to take surface water during times of high flow without disrupting high flows in a manner that adversely affects ecological habitat. The discussion of high-flow allocation scenarios modelling is coupled with discussion on ecological flows in Section III.e. Additionally, part of the high-flow allocation scenario assessment concerned modelling of the Ngaruroro River to identify ways to meet the irrigation demand for 3,500 ha with 17.5 Mm^3 storage to understand the possible scale of future demand and potential storage options (the relevance of these targets is described in HBRC, 2018c). The Ngaruroro River has the highest flows and is therefore a logical source for high-flow takes in the Heretaunga Plains. Results from high-flow allocation modelling indicate that there is greatest certainty for providing for potential future demand to irrigate 3,500 ha occurs for the scenario of a total high-flow allocation of 8,000 L/s. Furthermore, a total high-flow allocation of 8,000 L/s is the most likely scenario to provide additional volume to store water for environmental purposes, such as augmentation of surface water bodies during low flow periods (HBRC, 2018c).

b. Summary of Heretaunga Plains groundwater monitoring and modelling

Understanding groundwater resources in the Heretaunga Plains requires an understanding of the subsurface geology (HBRC, 2018a). We have a reasonable understanding of subsurface geology through decades of drilling that has occurred to instate groundwater bores. The Heretaunga Plains is bound to the east by the Pacific Ocean, and to the north, west and south by low-lying hills composed primarily of limestone and sandstone. Over time, flows from the Tūtaekurī, Ngaruroro, and Tukituki rivers have deposited sediments on top of the limestone and sandstone. Together with lagoonal and estuarine deposits, this deposition has gradually formed what we now call the Heretaunga Plains. At 300 km^2 in area, the plains cover a relatively small area compared to the sources of water and sediments in the catchments that drain to this plain (Section II.a). The deposits covering the Heretaunga Plains are approximately 900 m deep and perhaps as much as 1,600 m deep in some places(Ravens, 1990; Beanland *et al.*, 1998). The deposits consist generally of a layered structure with coarse permeable gravels alternating with fine, semi-impermeable clays.

Groundwater collects in the permeable portions of the Heretaunga Plains subsurface. At depths greater than approximately 250+ m, deep and older groundwater is present. Above this is the shallower groundwater system that has been developed for groundwater abstraction (HBRC, 2018a). In some places in the Heretaunga Plains, extending from approximately east of Flaxmere to the coast, a wedge of fine marine, estuarine and lagoon sediments lies above older gravel/permeable deposits. This denser layer of material acts to “confine” groundwater. Groundwater bores placed in these confined areas are artesian, i.e. wells for which groundwater is at pressure greater than atmospheric and hence may flow to the surfacewithout pumping (HBRC, 2018a).

In the course of groundwater monitoring, and to support HBRC’s groundwater research programmes, pumping tests of groundwater bores are often performed, from which the HBRC now has a large set of data. One behaviour that can be better understood via pumping tests is how fast groundwater is able to travel through the subsurface, i.e., how transmissive the subsurface is to groundwater, and how interconnected different parts of the subsurface are (HBRC, 2018a). Water flows quite well through large gravels, such as those found at the surface in Heretaunga Plains braided rivers, and likewise in the subsurface. It is no surprise, therefore, that in many places in the Heretaunga Plains groundwater system, there is high groundwater transmissivity (HBRC, 2018a).

Long-term changes in groundwater levels may be difficult to detect as they may be masked by the natural variability in groundwater levels between seasons. Monitoring of groundwater levels in the Heretaunga Plains groundwater system shows that declines have occurred slowly over time. Persistent declines are mainly located in the area northwest of Hastings, notably in groundwater levels between Roy’s Hill and Fernhill (HBRC, 2018a). Overall, Heretaunga Plains groundwater levels during summer have declined by an average of 5 centimetres per year between 1989 and 2018. While climaticinfluences may have played a part in the groundwater declines, abstraction from the aquifer system hasincreased substantially over this period.

Per Section I, the majority of groundwater abstracted from the Heretaunga Plains groundwater systemis used for public water supply, industry and irrigation, with smaller volumes of water estimated for frost protection, stock water and non-public water supply/domestic purposes (HBRC, 2018a). As at 2015, groundwater abstraction for public water supply averages approximately 22 Mm^3 per year[5](Mm^3/year) and has been relatively stable since 1980. Industrial use appears to have stabilised by the year 2000 at a level of approximately 13 Mm^3/year. A major review of metered pumping data for irrigation was undertaken in preparation for groundwater modelling efforts, from which numerous problems were encountered (HBRC, 2018a). Metered data is likely to underestimate the total abstraction for irrigation use due to metering requirements being relatively recently introduced.

Though there is large year-to-year variability in groundwater abstraction due to climate and other factors, in summer periods up to 50% of all groundwater abstraction from the Heretaunga Plains is estimated to be for irrigation (HBRC, 2018a). On average, approximately 35 Mm^3/year was estimated to be abstracted for irrigation between the years 2006 and 2014.

A numerical groundwater model was developed to evaluate current and future impacts caused by groundwater pumping. The groundwater model was also coupled with the surface water model to deal with understanding surface water-groundwater connectivity, discussed in Section II.c below, however, not all groundwater modelling was coupled with surface water models. Exceptions are listedas relevant below. The details of groundwater modelling have been published in a number of reports that are too extensive and technically complicated to capture fully here. Key points about the construction and the performance outcome of the model are summarised (Knowling *et al.*, 2018; HBRC, 2018a; Middlemis, 2018a and b).

Data that went into construction of the groundwater model include the following:

- A 3-dimensional geological model of the Heretaunga Plains. This geological model was constructed using data from several thousand HBRC bore logs (records logging geological material collected during drilling by depth), topographic data, the geological map of Hawke's Bay, radiocarbon age data and information from published seismic studies.
- Based on the geological model, groundwater was represented in the model in two vertical layers. The first represents the shallower layer of groundwater from which most abstraction occurs. The second layer represents deeper deposits to a maximum depth of 250 m.
- Groundwater levels in the Heretaunga Plains have been extensively monitored and the model utilised data from 101 monitoring points having time-series data.
- A comprehensive and systematic review of the entire stream network of the Heretaunga Plains was conducted and identified all significant surface water features that needed to be incorporated in the model as rivers, streams, springs and drains that interact with groundwater (HBRC, 2018d).
- Land surface recharge to groundwater is estimated using data based on rainfall records, soil data, climatic data, crop data and irrigated area, which resulted in 3,108 recharge daily time-series. Recharge from rainfall can only occur in the unconfined area of the aquifer, which amounts to a land surface area of ~240 km^2.
- The model also included data on groundwater pumping. This data was collected for different abstraction types obtained using different sources and methods: measured and (for irrigation use) modelled. Modelled irrigation demand was shown to be in reasonable agreement with recent water use measurements and was therefore used to compensate for lack of accurate

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[5] Measured in terms of a hydrological year or water year, which begins on July 1, and ends on June 30. Hydrological years are used because this enables each dry season to be evaluated in one interval, and the hydrological year also results in a better correspondence between rainfall, runoff, and relationships of surface and groundwater.

historical measured data.

- Other hydrological data are also needed to construct a groundwater model, for instance, hydraulic conductivity (i.e. a way to quantify the ability of fluid to pass through the subsurface material) is an important quantity. Hydraulic conductivity is an example of a quantity that, in modelling terms, is referred to as a parameter. Parameters contribute to the mathematical description of conditions determining how a system operates.

Once the basic description underlying model construction is formulated and needed input data is assembled, the model was calibrated to ensure the needed level of accuracy. Groundwater model construction, calibration, coupling with surface water models and subsequent use was overseen by a Technical Advisory Panel of national and international experts in groundwater modelling. As a result of this level of oversight, the desired outcome was achieved whereby the final calibrated model is able to replicate observations for the Heretaunga Plains groundwater system (i.e. match field-observed values, including seasonal variability and long-term variability) to a level that is difficult to achieve in groundwater modelling and is fit for decision support (Middlemis, 2018a and b). Example calibration plots are presented in Figure 5. The model technical reports summarise remaining uncertainties in the model, as well as a way forward to address these, however, the performance of the existing model is of a calibre that represents a step-change in terms of having an evidence basis on which to evaluate the effect of human activities on water resources in the Heretaunga Plains (Middlemis, 2018a and b).

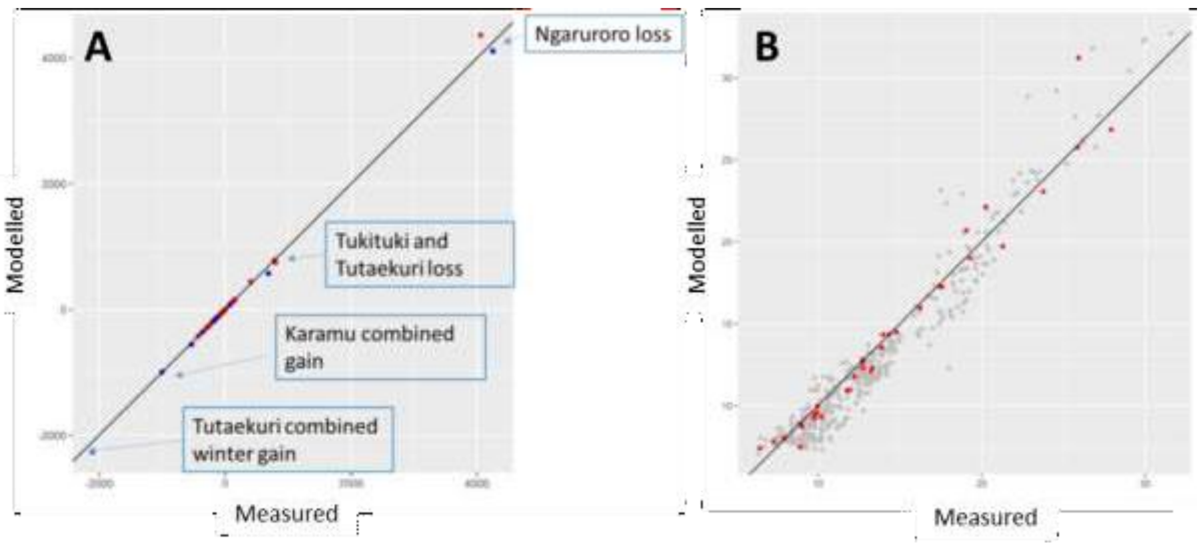

Figure 5. Example calibration plots for the Heretaunga Plains groundwater system model showing agreement betweenmodelled and measured (A) gains and losses of surface water to groundwater, and (B) groundwater levels.

After finalisation of the construction and calibration of the Heretaunga Plains groundwater model, a number of scenarios were run (HBRC, 2018b) to simulate 1) what the state of groundwater would be in the absence of abstractions and 2) a number of different use scenarios, including “business as usual” as well as scenarios under different environmental management protocols and forfuture use. Some key findings from these simulations are summarised as follows:

General observations regarding behaviour of the Heretaunga Plains groundwater system

- Groundwater recharge is highly variable seasonally, with most of this recharge occurring in winter months, and, under any scenario, much less recharge during the summer period.
- There is also variation in groundwater recharge between years, depending on rainfall.

- The major source of recharge to groundwater is through loss of water from rivers. Over 70% of the total recharge to groundwater in the Heretaunga Plains occurs through rivers losing water to groundwater, most of which is from the Ngaruroro River, with the remainder from the Tukituki River and Tūtaekurī River. In contrast, land surface recharge provides less than 30% of the total recharge to groundwater.
- Modelling was also used to quantify the decline in groundwater levels as a result of groundwater pumping for the period 1980 to 2015 (not coupled to surface water models as the model inputs and outputs exclusively reflect groundwater abstraction). The decline was generally larger in summer periods (December to February) than during winter (June to August). As compared to the naturalised scenario, the average drawdown in winter was 0.49 m in 1980/1981 increasing to 1.35 m for 2014/2015. For summer the average drawdown was 0.68 m in 1980/1981 increasing to 2.34 m for2014/2015. The areas most affected by groundwater pumping are near large public water supply takes in Napier and, to a lesser degree in Hastings, where drawdown of groundwater levels can exceed 4 m in the summer.
- About two-thirds of the groundwater depletion effect in the summer can be attributed to irrigation pumping. Some of this effect can be seen after the summer irrigation stops and continues into winter.

c. Explanation of surface water-groundwater connectivity and its consequences

Sections II.a and II.b discussed the prevalence of gravels and coarse deposits that constitute part of the surface and subsurface geological environment of the Heretaunga Plains and how a consequence ofthis geology is that water flows quite well through such materials. Accordingly, results from groundwater models show how losses of water from rivers to groundwater constitute a major source ofgroundwater recharge. There are many other, more extensive, implications of surface water- groundwater connectivity that are reviewed in this subsection.

Stream depletion – what it is, why it matters

Because of the distinct and prevalent connections between surface water and groundwater in the TANK catchments, when groundwater is pumped, this results in a reduction of flows to surface waters, including rivers, streams and springs. This reduction in flow is referred to as stream depletion.Stream depletion occurs to a greater or lesser extent when substantial surface water-groundwater connectivity exists and when groundwater is pumped. If the quantity of groundwater pumped is large and occurs in areas where subsurface flow occurs easily (high connectivity between surface water andgroundwater), stream depletion is greater, and vice versa. Here, the issue of stream depletion is first discussed conceptually, followed by presentation of data from HBRC studies on stream depletion in the Heretaunga Plains groundwater system.

Due to exchanges between connected surface water and groundwater, rivers, streams and springs may have areas of gains, losses, and stable flow (neither losing nor gaining). A losing river or stream reach has an underlying bed material and geology that allows water to infiltrate into the subsurface and groundwater system. River or stream flow will be reduced through a losing reach. Conversely, gaining reaches are areas where the river or stream bed is lower than the adjacent water table and consequently water flows into the river from the groundwater system. The importance of identifying and understanding areas of surface water gains and losses is most apparent during the low-flow seasons.

The occurrence of lower rainfall during summer months, combined with increased water demand over time, produces a regular seasonal decline in some surface water levels. As the river and stream flows are crucial for maintaining ecological habitat, losing reaches are at particular risk of dropping to flow levels that do not support local ecology, or in some cases dry up entirely. The dynamics of gains and losses provide information concerning surface water-groundwater connectivity and were built into the Heretaunga Plains groundwater system model.

Summary of data on gaining and losing areas of the Heretaunga Plains surface water network
Concurrent gaugings, where river discharge is measured at two or more sites on the same day and flow differences calculated, identify losing and gaining reaches (HBRC, 2018d). The Ngaruroro River is the most intensively gauged river in the Heretaunga Plains with 336 concurrent gaugings. The lower Ngaruroro includes a losing reach, recharging the Heretaunga Plains groundwater system, which in turn feeds and sustains many of the springs in the surrounding area through summer (HBRC, 2018a). Much of the flow loss occurs between Roy’s Hill and Fernhill (Section II.b), termed the major loss reach, where the underlying material consists predominantly of coarse gravels (HBRC, 2018a). Other areas of surface water gain and loss are shown in Figure 6; surface water gains and losses are colour-coded according to the figure legend. The Tūtaekurī River has a losing reach between Hakowia and Silverford; similar to the Ngaruroro River, the loss appears to be to an unconfined portion of groundwater. This Tūtaekurī River loss is a potential source of water to nearby springs and spring-fed streams, notably the nearby Tūtaekurī-Waimate Stream. Losses from the Tukituki River are shown for reference to the discussion below, however, are not discussed further as this river is not covered in PPC9.

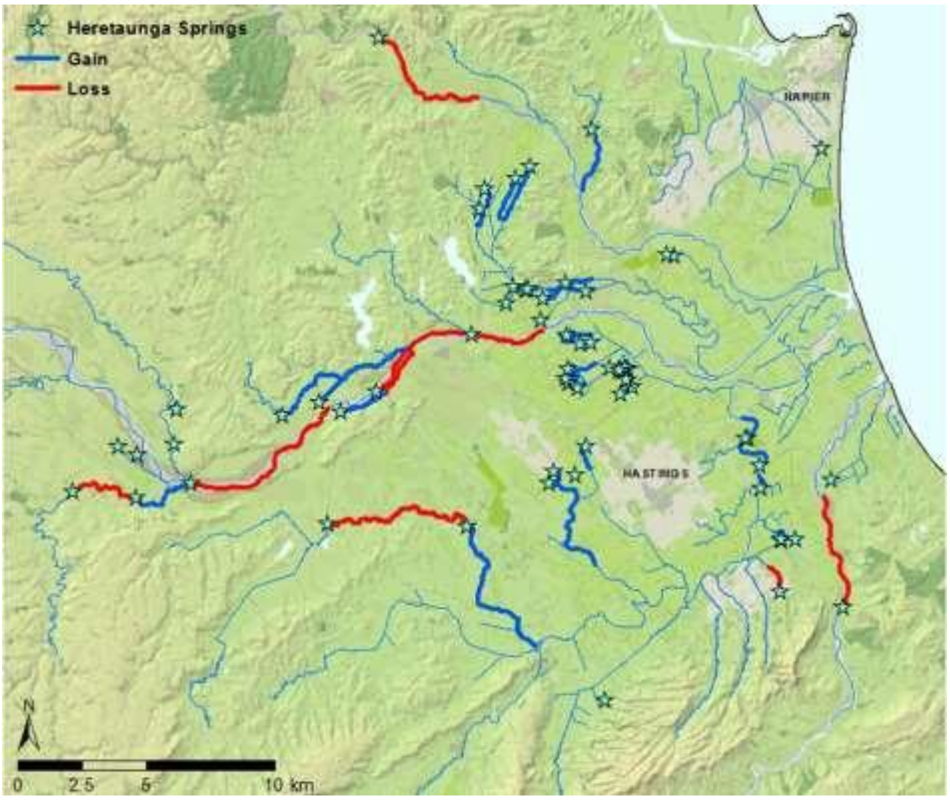

Figure 6. Areas in the Heretaunga Plains where major surface water gains, losses, and springs are known to occur.

In addition to the Tūtaekurī-Waimate Stream, some other notable spring-fed streams in the Heretaunga Plains that are discussed in groundwater modelling reports include the Karamū, Waitio, Raupare, Irongate, Mangateretere, Karewarewa and Paritua (Figure 3). A full discussion of possible surface water-groundwater connectivity would be lengthy. For brevity, the Karamū Stream and Paritua Stream are discussed herein, as there were multiple submissions concerning these for PPC9.

A large component of flow in the Karamū Stream cannot be accounted for by inflows of its tributaries alone. In other words, flows from streams that feed the Karamū Stream, such as the Irongate Stream and the Awanui Stream, are not sufficient to account for the total flow observed in the Karamū Stream. The amount of flow that is not accounted for is estimated to be between 570 L/s and 920 L/s (HBRC, 2018a). Work by HBRC (2018d) posits that the extra water to the Karamū Stream comes from groundwater inflows. Depletion to the Karamū Stream from groundwater pumping isdiscussed further below.

The Paritua Stream drains hill country to the west of Bridge Pa. Downstream of Bridge Pa, the Paritua Stream becomes the Karewarewa Stream. There are two distinct sections of the stream. The upper section, below Washpool Station bridge, loses water for around 7.5 km (HBRC, 2018a). This section can become dry at times. Further downstream from this, there is a gaining reach after the Paritua becomes the Karewarewa. The Paritua Stream losses occur where the stream flows across unconfined gravels that are perched several metres above the groundwater table (Rabbitte, 2009), and one investigation found that a layer of weakly cemented cobbles and gravels causes the streambed to be of lower permeability (Hughes, 2009; Rabbitte, 2009).The observed low permeability is consistent with a low measured loss rate for the Paritua Stream and this, coupled with the perched nature of the stream, call into question whether it is very well connected with groundwater in the upper reaches. Instead, stream flow upstream of Bridge Pa may be more closely related to rainfall. The sources of flow and causes of flow loss for the Paritua Stream are not well understood, and hence represent another area where more investigative work is underway.

Stream depletion – how it is quantified

Because stream depletion causes a reduction of surface water flows, it represents an environmental impact that must be quantified and addressed. HBRC use a Stream Depletion Ratio (SDR) to quantify stream depletion (HBRC, 2019). The SDR may be thought of as the percent of groundwater pumping that is equivalent to pumping surface water from any given stream, river or spring. An SDR of 50%, for instance, means that when pumping groundwater at 100 L/s, this will decrease surface water flow by 50 L/s. Behind this simple explanation, however, is a more complicated story. To understand this story in more detail, it is useful to consider the matter in the context of time and space.

With regard to issues of time in stream depletion, obviously when groundwater pumping is more intense, stream depletion will increase, and groundwater pumping is most intense during the period of the year that is driest and subject to greatest water-use demand, typically December to April (HBRC 2018a, 2019). When surface water is pumped, response is instantaneous, for instance, if water is pumped out of one side of a stock tank, the water level will immediately decrease across the whole tank. For groundwater, in contrast, flow occurs through the porous material in the “ground” (e.g. soil, gravels). This creates a lag time in the reaction of surface water levels to pumping, and the lag time will vary according to how easy or hard it is for water to flow through the subsurface material.

Typically, when a groundwater bore is pumped, water levels will first decrease around the bore, as shown in Figure 7. As the bore continues to be pumped, reduction in groundwater levels farther away from the bore occur, as well as stream depletion. As a result of this delayed effect, when a groundwater bore in a high connectivity environment that is not immediately next to a stream is pumped, there is no immediate stream depletion at the very moment that pumping starts. The longer the groundwater bore is pumped, the greater the stream depletion, as groundwater responds to the effect of pumping pressure. This means that, even for a bore with some subsurface connectedness to astream, the SDR is zero at the very moment that groundwater pumping begins, increasing to some maximum over time thereafter. The lag time for stream depletion is also the reason why, even if pumping ceases, groundwater levels will require some time and additional recharge to recover to pre-pumping levels. An example of the effect of time on the SDR starting from a condition of zero pumping and then showing the effect of SDR in response to pumping over time is shown in Figure 8 (HBRC, 2019).

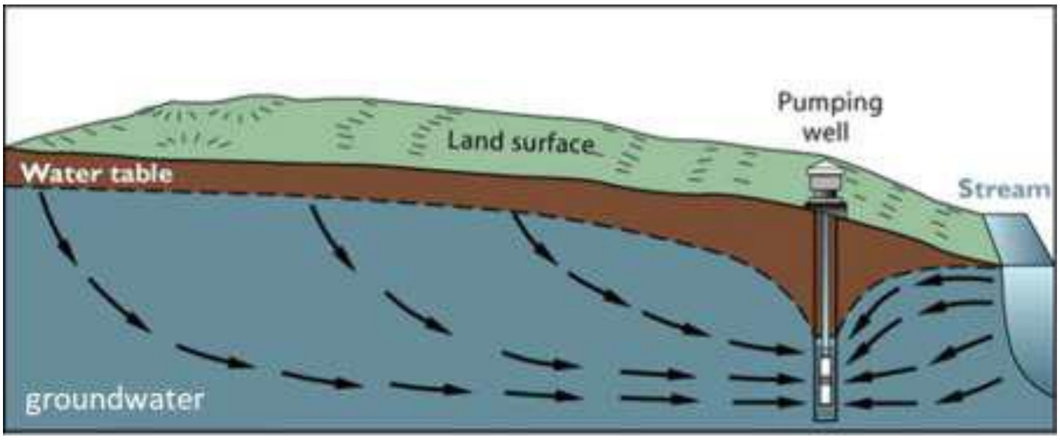

Figure 7. Schematic diagram showing how groundwater responds to pumping. As groundwater is pumped from a bore or well, groundwater levels initially decrease in the immediate vicinity of the bore. As pumping continues, the lowering of the groundwater table extends further away from the well and may begin to cause stream depletion as well.

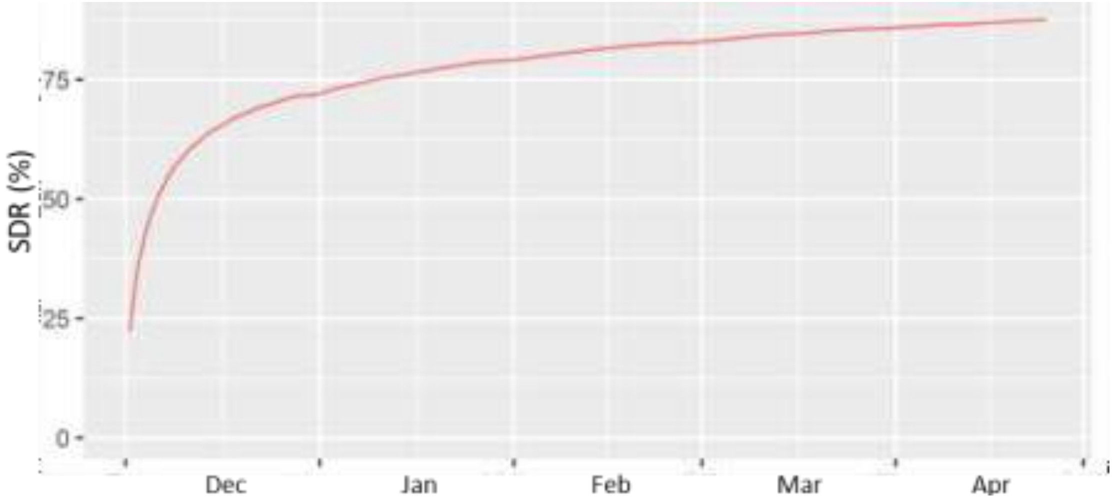

Figure 8. Graph of representative data showing how the Stream Depletion Ratio (SDR) increases over time for a constant rate of sustained groundwater pumping. An SDR of 100% indicates that for every unit of groundwater pumped, surface water is depleted by the same amount, i.e., all groundwater pumped is being removed from springs, streams or rivers.

The discussion of how time affects stream depletion is also useful to understand the issue of how spatial considerations relate to stream depletion. Using the stock tank example, pumping water out of one stock tank clearly does not affect the level in a second, unconnected, tank. Groundwater in the Heretaunga Plains system however is remarkably connected in most places in the aquifer because many parts of the subsurface are constituted of gravels and porous materials. This is the same reason why surface water and groundwater are intimately connected in most parts of the TANK groundwaters. As a consequence of spatial considerations, the SDR will be higher if a bore is close toand well connected (subsurface) with a given stream. Distance and reduction of subsurface permeability then will cause lower SDRs.

Extending the discussion beyond the conceptual, the methodology for determining the SDR is based on calculating the flow from a stream to a groundwater bore as a result of pumping over time. This is determined by first calculating surface water-groundwater exchanges in the absence of pumping (a naturalised flow scenario, Section II.a). Second, the exchange for a given pumping rate over time at a selected location is calculated. Stream depletion is the difference between the two calculations, i.e. how much water travels from the stream, though the ground, and out of the bore during pumping compared to what groundwater flow would be if no pumping were to occur (HBRC, 2019). Studies onstream depletion have shown that, since the subsurface connectivity in the Heretaunga Plains groundwater system is considerable, therefore pumping from any given bore can have wide-ranging effects that affect more than one surface water body.

Heretaunga Plains stream depletion zones

For modelling purposes, three Stream Depletion Zones (SDZ) within the Heretaunga Plains groundwater system were classified (HBRC, 2019). The zone classifications, given in Table 2 below recognise the dependence of stream depletion on both time and space. Thus, SDZ 1 is the zone where a given bore will have sufficient proximity and connectivity to nearby streams as to result in a SDR of greater than 90% after a pumping period of only seven days. In other words, surface water and groundwater are so intimately connected in this zone that groundwater flow lag times are low and, after seven days, pumping from the ground is effectively the same as pumping directly from the affected springs, streams and rivers.

In SDZ 3, in contrast, there is less connectivity, such that even after 150 days continuous pumping, less than 60% of the water pumped could be said to be depleting streams. However, there is considerable uncertainty associated with modelling parameters and inputs for much of the Zone 3 areas shown in Figure 9 and any interpretation of Zone 3 needs to consider this uncertainty.

Figure 9 shows a map of SDZs across the Heretaunga Plains groundwater system (HBRC, 2019). SDZ 2 predominates, with the highly stream depleting SDZ 1 being limited to specific areas, mainly limited reaches of the Ngaruroro and Tūtaekurī rivers, with smaller SDZ 1 areas near Maraekakaho Stream and in the Moteo valley. The less stream depleting SDZ 3 also has a limited extent, begin mainly present in the upper Ngaruroro valley upstream of Maraekakaho, the Tūtaekurī valley between Puketapu and the Heretaunga Plains, coastal and offshore areas, and other small peripheral valleys.

Table 2. Stream Depletion Zone (SDZ) classifications.

SDZ number	SDR (%)	Pumping period (days)
1	> 90%	7
2	> 60%	150
3	< 60%	150

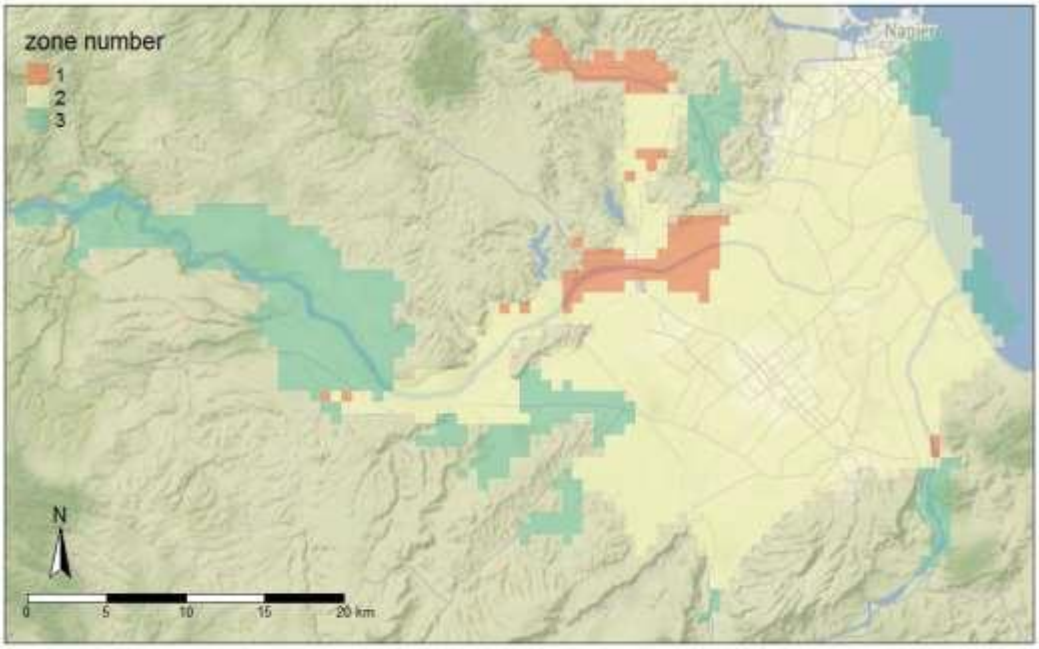

Figure 9. Map of SDZs superimposed upon a map of the Heretaunga Plains. SDZ 1 (red) shows areas where groundwater pumping is highly stream depleting whereas SDZ 3 (green) comprises areas where pumping results in the least depletion. The majority of the Heretaunga Plains aquifer system falls within SDZ 2, a consequence of which is that the majority of the Heretaunga Plains groundwater system is interconnected and subject to greater or lesser stream depletion as a result ofgroundwater pumping.

The extensive nature of SDZ 2 entails that stream depletion is not restricted to limited areas around streams and rivers, but instead occurs throughout the groundwater system. The majority of groundwater abstraction from the Heretaunga Plains groundwater system falls into a zone wherein more than 60% of groundwater pumped over the irrigation period of 150 days will be, according to the operative definition of SDR, removed from rivers, streams or springs. HBRC's stream depletion report estimates that an annual abstraction rate of 90 Mm^3 (equivalent to 2,800 L/s if pumped at a constant rate over 365 days), across the Heretaunga Plains groundwater system will result in more than 54 Mm^3(1,700 L/s) of stream depletion across the area shown in Figure 2A/Figure 9 (HBRC, 2019). In actual use, the pumping rate is higher during the irrigation period, thus the amount of stream depletion is not reasonably divisible over 365 days and instead will be higher than 1,700 L/s, on average, during later months of the irrigation period. Another consequence of the widespread and contiguous extent of SDZ 2 is that any sustained period of groundwater pumping causes stream depletion, to some extent or another, during periods of low rainfall, and avoiding stream depletion is effectively impossible without halting all abstraction.

General observations regarding behaviour of the Heretaunga Plains groundwater system with respect to surface water-groundwater connectivity and stream depletion

Summarising the impacts of groundwater abstraction during dry periods on stream depletion, the extent of surface water-groundwater connectivity in the Heretaunga Plains entails that the more groundwater that is abstracted over time, the greater will be the gradual and cumulative impact on stream depletion. Important conclusions from HBRC's surface water-groundwater monitoring and modelling programme are as follows (HBRC 2018a, 2018b, 2019):

- Model results generally match monitoring history well and show that, for the period 1980 until

2015, increased groundwater pumping has caused reduced streamflow, particularly during summer, for all major rivers analysed (the Ngaruroro, Tukituki, and Tūtaekurī rivers).

- Spring gains have also declined in lowland streams (the Irongate, Karamū, Karewarewa, Mangateretere, Raupare, Tūtaekurī–Waimate streams).
- The most affected surface water bodies include the spring-fed Paritua-Karewarewa stream system and Karamū Stream, with some other streams having lost a significant portion of flow, and a projected loss of up to 50% of low flows in the Ngaruroro River.

Findings for future scenarios[6]

- Future scenario modelling indicates that further decline in groundwater levels and streamflow will not occur if groundwater use is carried forward at the 2006–2014 levels used in the model scenario report (HBRC, 2018b).
- When groundwater pumping is assumed to increase in the future according to the trend in increasing abstraction observed up to the time of the scenarios report (HBRC, 2018b), the projected result shows significant future decline in streamflow and groundwater levels, with drying out of some streams and rivers, including Hawke’s Bay’s largest, the Ngaruroro River.
- A dry climate scenario was run to repeat conditions from the dry year 2012–2013 every year for the next 100 years. Results indicate that groundwater levels and river flows remain at low levels, but there is not a long term declining trend, provided the groundwater pumping continues at the rates applied in 2012–2013 (90 Mm^3/ year across the Heretaunga Plains groundwater system), which is about 20% higher than average pumping between 2005–2015 (76 Mm^3/ year).

Findings for mitigation and management scenarios

- Simulations to evaluate the benefits of the historical Roy’s Hill Managed Aquifer Recharge operation suggest its benefits were localised and of limited effectiveness.
- Streamflow augmentation, wherein groundwater is pumped and discharged into streams to enhance streamflow, was tested as a potential way to temporarily increase or restore streamflow, for example during periods of drought. Augmentation of the Ngaruroro River was not included in model simulations, as it would require excessively large, and thus likely infeasible, levels of augmentation. Augmentation is projected to be effective in improving flows, to some extent, for the Karamū, Mangateretere and Raupare, but there is considerable uncertainty with modelling for the Paritua-Karewarewa stream system. Augmentation appears to be effective for short-term ameliorisation of low flows from active groundwater abstraction, however, pumping higher volumes and/or longer pumping times will result in negative impacts. Also, augmentation is unlikely to be effective for mitigating the effects of increased groundwater allocation.
- A scenario was designed to identify the benefit of short-term bans on groundwater pumping during times of low surface water flows. Results indicate that the benefits of short-term pumpingbans are relatively minor, mainly because such bans reduce total groundwater abstraction by a small amount compared to the time it takes for the ban to manifest as increased streamflow. A year-round ban on all abstraction, including public water supply, industrial, and irrigation takes, would

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[6] Note – groundwater models for future scenarios were not run coupled with surface water models. If surface water abstractions were to change markedly in future this would be expected to affect groundwater. Mitigation and managementscenarios, which includes scenarios discussed in greater detail in Sections II.d and II.e, were run with surface water coupling.

be needed to fully eliminate abstraction impacts.

- A number of scenarios were constructed to investigate management options for groundwater and surface water takes on surface waters during a 17-year period (2015 to 2032). Scenarios examined effects from different pumping regimes, different cease-take trigger flows for low flow bans, the effect of SDZ management, and varying stream augmentation. The largest offsets to stream depletion effects result from changes in how stream depletion zones are managed, in particular the adoption of SDZ 1 described herein as a no-pumping zone. In most locations, the results indicate that at PPC9 cease-take trigger flows, augmentation is likely to be required for a large part of most irrigation seasons and at non-trivial rates.

Regarding model input data, model calibration, and how these affect output sensitivity and uncertainty

- Results indicate that increased pumping will have negative effects on stream flows. Conversely, a large reduction in pumping would be required to generate a meaningful improvement in lowland streamflow.
- A comprehensive uncertainty analysis was conducted to understand what effect uncertainties in model inputs would have to the model predictions (Knowling *et al.*, 2018). Results from this uncertainty analysis show there is some over- or under-prediction of pumping impacts on some rivers, however, even when including uncertainty and bias, the results indicate there is significant impact from groundwater pumping on streamflow and groundwater levels historically and in the future. In some instances, stream flows are understood, with high confidence, to be much lower than what would be expected in the absence of any water abstraction activities.

d. Estimated maximum groundwater abstraction in the Heretaunga Plains groundwater system in recent history

Scientifically, it is common to try and set quantitative bounds of problems, however, this practice is not limited to scientists. When obtaining an indicative price for goods or services, for instance, one would also want to know, what is the maximum price? i.e., to plan for the worst-case cost scenario to within reason and based on foreseeable variations. With respect to groundwater abstraction, uncertainties exist concerning actual abstraction, whether determined via measurement or modelling. In addition to these uncertainties, year-to-year use is variable, particularly with respect to abstraction for irrigation as a result of variations in weather conditions. These uncertainties notwithstanding, in order to manage groundwater resources, HBRC ask the question "In view of uncertainties concerning groundwater abstraction, what estimate of maximum annual abstraction would be reasonable to use in order to safeguard current users to continue their activities that depend on water supply?"

A simple, and therefore easy to understand, yet also factual answer to this question is seen in Figure 1A for the year spanning the 2012–2013 irrigation season. For the time span used in the Heretaunga Plains groundwater systems model scenarios report (HBRC, 2018b), this year was particularly dry, hence abstraction activities for 2012–2013 exceeded those of the other years shown for data available up to that time. In round terms, this amounts to an annual maximum of 90 Mm^3 for the Heretaunga Plains groundwater system. As noted in Section II.c, and detailed further in the reports cited herein, 90 Mm^3 is about 20% higher than the annual average for groundwater pumping between 2005–2015. PPC9 refers to the number of 90 Mm^3 as an interim allocation limit.

III. Scientific Matters Pertaining to Specific Rules and Schedules in Proposed Plan Change 9 – TANK

Some rules in PPC9 generated more submissions than others, and submitters also generally commented on some of the scheduled limits. This section addresses items in PPC9 rules and schedules that were the subject of frequent commentary.

a. Resource Management Act Section 14 groundwater takes

Section 14 groundwater takes were estimated for human and stock consumption and dairy shed washdown according the method of Buchanan (2013). According to this estimate, the total amount of this water use is negligible (Figure 1A) compared to takes for other uses. As permitted takes, this use is not metered and how the estimate compares to actual is not known.

b. Frost protection groundwater takes

The Heretaunga Plains groundwater system model (HBRC, 2018a) uses estimated frost protection takes, because the number and reliability of existing measurements are insufficient to modelling needs.By the method of estimation, the total volume of groundwater taken for frost protection is almost insignificant (HBRC, 2018a, Appendix A) compared to the total sum for irrigation, public water supply, and industrial takes (Figure 1B). Takes for frost protection are expected to be comparatively minor, since they only occur for limited periods (a few hours at most) and because frosts occur infrequently (an average of five frosts per month for September). PPC9 and provision for recognised ecologically relevant flow features.

River and stream flows, beyond supplying water for residential, commercial, and industrial purposes,also influence many aspects of stream ecology, with various sections of a flow regime affecting different ecological functions (TCSG, 2017b). Figure 13 is a conceptual schematic showing the various ecologically relevant flows (TCSG, 2017b). If flow drops too low or if low flow persists for too long, this results in a so-called habitat bottle-neck effect that results in sharp reductions in species population. This reflects, in part, how low flow reduces wetted habitat, i.e. if instream species do not have sufficient habitat, they die or are otherwise adversely affected.

Large floods are referred to as channel forming as they maintain channel form through large scale sediment transport and control of encroachment of woody weeds. Channel forming floods are typicallyidentified as approximately the mean annual maximum flow. Flushing flows are smaller floods that flush fine sediment, accumulated algae, and other aquatic vegetation. These flushing flows help maintain quality of habitat for small insects and other animals on which fish feed, thereforebenefiting resident fish species by protecting their food source. A flushing flow is commonly categorised as three times the median flow of the river.

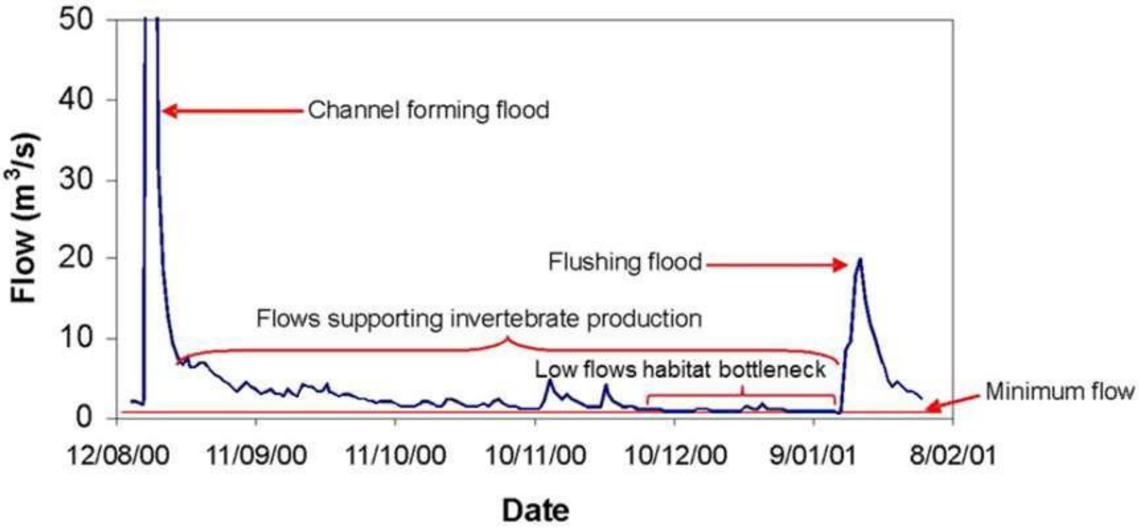


Figure 13. Schematic showing the various ecologically relevant flows.

In the course of technical assessment of surface water flows, a range of summary river flow statistics were calculated. Relevant metrics and terminology used here and in Sections III.d and III.e are as follows:

- **Median flow** is the flow value in the middle of all flow measurements over a given time period, i.e. for a given time period, half of the flow measurements are above the median, and half below.Because weather patterns, and thus flows, may change from year-to-year the median may change according to the time period over which it is assessed.

- **Mean flow** is an average of all flow values over a given time period.

- **Naturalised flow** is a modelled river flow calculated using results from the “naturalised” scenario model data (Section II.a). This is the flow that is expected in the absence of any water takes/abstractions.

- Mean annual low flow (**MALF**) is a number that represents the lowest flow periods in a year. Because flow can be highly variable, the annual low flow (ALF) is calculated as the lowest 7-day average flow over the year and MALF is the mean ALF over a period of years.

- A **naturalised MALF** is calculated using results from the “naturalised” scenario model data (Section II.a), i.e. the MALF expected if water abstraction/takes were not occurring.

- **Q95** is a low flow statistic where Q is a letter often representing flow and Q95 means that 95% of the time a river or stream flow will be higher than this.

- **FRE$_3$** is a high flow statistic often used in New Zealand (Harkness, 2010), where FRE is an abbreviation for frequency. FRE$_3$ is calculated as the average annual number of high flow events that exceed three times the daily median flow (Figure 14) and is formally defined for the purposes of PPC9 (HBRC, 2020) as *“the frequency of floods that are three times above the median flowfor a river as determined by the Regional Council records.”*

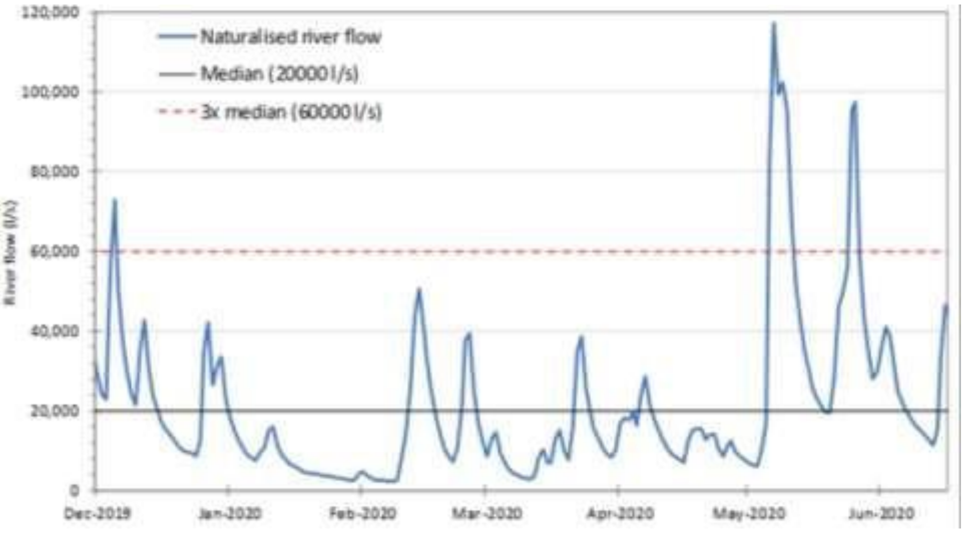


Figure 14. Graphic illustrating the concept of FRE_3 (HBRC, 2018c). The blue line shows naturalised river flow in time (modelled for the Ngaruroro River at Fernhill). The solid black horizontal line shows the medianflow is, i.e. the flow value in the middle of all flow measurements shown on the blue line. The median flow is 20,000 L/s, such that three times the median flow is 60,000 L/s, a flow level shown by the red dashed-line.There are three events when the flow (blue line) is larger than the red dashed-line: the first in December 2019,a second in May, 2020, and a third in late May/early June, 2020.

c. Surface water low flows and ecological habitat protection

Aquatic organisms, importantly fish and other organisms that constitute the ecosystems on which fish are dependent, require certain flow levels for the protection of their habitat, i.e. to ensure that organisms dependent on freshwater habitats will continue to survive. Maintaining cease-take trigger flow levels during dry periods when water is needed for irrigation is ecologically beneficial, however,requires restrictions on surface water takes (Section II.a). These restrictions can have adverse economic impacts for water users. PPC9 takes these two factors of habitat protection and the impacts of abstraction restrictions on water users into consideration when specifying cease-take trigger flows. This section summarises information on the basis for assessment of effects of different flow regimes on surface water habitats. Information concerning how flow management scenarios affect restrictionsto water users is given in Section II.a.

Habitat protection levels were established using a hydraulic habitat model that predicts the change in flow speed and river or stream depth with flow based on field surveys of a chosen river reach (HBRC, 2018e). Predictions of flow speed and depth are then compared to the ideal/preferred depth and speed of resident fish species, i.e. habitat criteria for different kinds of fish (HBRC, 2018e). This process produces so-called habitat-flow curves or habitat-suitability curves that relate, for instance, habitat available (area of habitat in m^2 per m of river reach, m^2/m) to flow (L/s). A representative example of a habitat-flow curve is shown in Figure 15 below. Data from these curves are used to calculate a single number that reflects combined habitat suitability for any given river or stream reach (HBRC, 2018e). In order to relate this overall number to flow, an ecologically relevant flow statistic is needed. For fish, habitat retention is expressed either 1) in terms of the naturalised MALF or 2) to the flow at which the overall habitat suitability number is optimum, whichever of these two is lower. In other words, if a particular fish requires low flows, option 2 would apply. Conversely, for fish that require higher flows, option 1 applies and naturalised MALF is the flow assigned as 100% habitat protection.

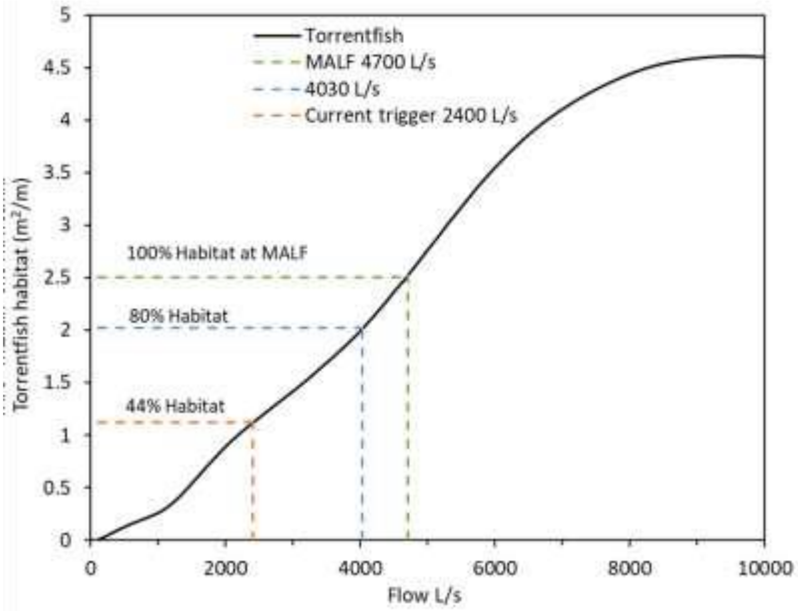
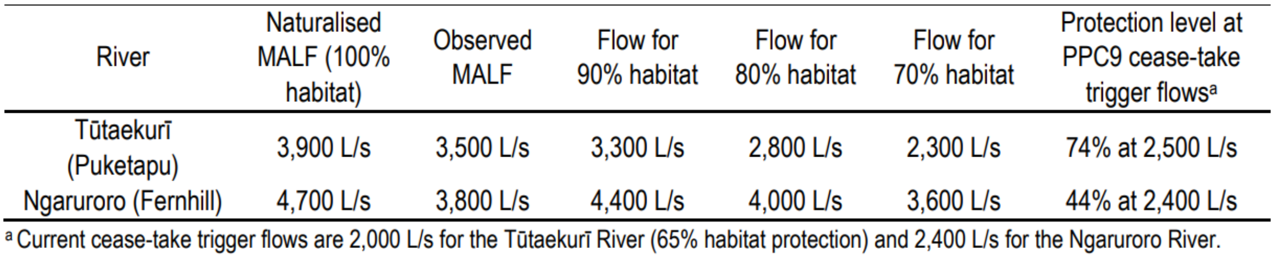


Figure 15. A representative example of a habitat-flow curve for torrentfish in the Ngaruroro River. This example shows habitat suitability in terms of area habitat (m^2) per m of river reach. Various measures of habitat suitability are combined into a single measure that is then rated according to flow regime (coloured lines).

For PPC9 it was assumed that naturalised MALF represents idealised habitat, i.e. naturalised MALF is 100% habitat protection. Table 3 gives a summary of ecologically relevant flow data and associated habitat protection levels for 1998–2015. For the Ngaruroro River, the naturalised MALF calculated at Fernhill is 4,700 L/s for 1998–2015, so 4,700 L/s is the flow that represents 100% habitat protection or no degradation to habitat. The observed MALF, however, is 3,800 L/s. Thinking about how this relates to protection of fish habitat, standard practise is to base cease-take trigger flows on the protection levels of the resident species with the highest flow requirements, as this provides a community-level protection by meeting or exceeding the flow requirements of other species as well.

The highest flow requirement species determined through the habitat modelling for the Ngaruroro River is for torrentfish, for which a flow of 4,400 L/s is estimated to provide a 90 % habitat protection level. The current cease-take trigger flow of 2,400 L/s sets an estimated 44% habitat protection level. In contrast, the highest flow requirement for the Tūtaekurī River is for trout, for which a 90% habitat protection level corresponds to a flow of 2,300 L/s. Under the current cease-take trigger flows (2,000 L/s) the protection level provided for the trout in the Tūtaekurī River is 65% (Table 3).

Table 3. Summary of cease-take trigger flows and the coinciding habitat protection levels for the time period of 1998–2015 (HBRC, 2018e).



River	Naturalised MALF (100% habitat)	Observed MALF	Flow for 90% habitat	Flow for 80% habitat	Flow for 70% habitat	Protection level at PPC9 cease-take trigger flows[a]
Tūtaekurī (Puketapu)	3,900 L/s	3,500 L/s	3,300 L/s	2,800 L/s	2,300 L/s	74% at 2,500 L/s
Ngaruroro (Fernhill)	4,700 L/s	3,800 L/s	4,400 L/s	4,000 L/s	3,600 L/s	44% at 2,400 L/s

[a] Current cease-take trigger flows are 2,000 L/s for the Tūtaekurī River (65% habitat protection) and 2,400 L/s for the Ngaruroro River.

After habitat modelling, the surface water model was used to simulate river flows under different management rules, including current cease-take trigger flows (HBRC, 2018c). Results from these simulations were compared to flows revealed by habitat modelling to be optimal for ecological protection. For the Ngaruroro River, cease-take trigger flow scenario modelling predicted that increasing the cease-take trigger flows would result in progressively larger effects on restriction, consequently reducing the reliability of supply for water users. At the highest cease-take trigger flow modelled (4,700 L/s), this increase in cease-take trigger flow predicts a small improvement to MALF of 3.3% (HBRC, 2018c).

The Ngaruroro River MALF and Q95 under 70% habitat protection levels increase by 2.4% and 0.2%, respectively, compared to the base case conditions (HBRC, 2018c). Therefore, for the Ngaruroro River, which currently has cease-take trigger flows corresponding to 44% habitat protection, increasing the cease-take trigger flows to 70% habitat protection provides very little benefit toward improving low flow statistics. Problematically, the increase to the cease-take trigger flows does not prevent the river from continuing to drop after water abstraction ceases. Comparison of naturalised to observed flows for the Ngaruroro River at Fernhill provides greater insight of how the current cease- take trigger levels of 2,400 L/s impacts and relates to the Ngaruroro flow regime. An analysis of the flow regime under a naturalised case indicates that the flow of the Ngaruroro River would fall below this cease-take trigger flow even with no surface water and groundwater takes (Figure 16). The dry season of 2012–2013 is used as an example of a drought year. During this summer period the model predicts that the Ngaruroro River ALF under a naturalised case is 2,300 L/s (extracted from data summarised in HBRC, 2018c).

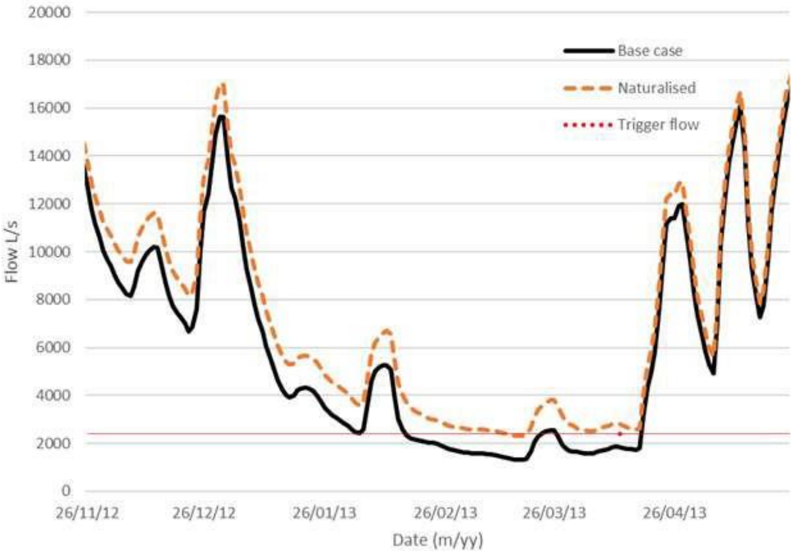


Figure 16. Comparison of the base case Ngaruroro River flow at Fernhill for2012–2013 (black line) to naturalised conditions (orange dashed-line). The current and PPC9 proposed trigger flow of 2,400 L/s is plotted as a red dotted- line.

For the Tūtaekurī River, modelling predicts that water restrictions will not occur up to 2,500 L/S, and at a cease-take trigger flow of 2,800 L/s there is a small proportion of restriction days per year (0.3%), while providing a relatively high level of habitat protection (80%).

d. Surface water high-flow takes

High flow events serve an important ecological role, providing flushing flows that remove excessive algae growth and limit algae accumulation, which in turn helps maintain habitat for the small animals on which fish feed. Through the process of modelling high-flow allocation scenarios that would minimise the adverse effects to instream ecological requirements, Harkness (2010) identified FRE_3 as a key metric. PPC9 high-flow take allocation limits are based on keeping the change to the naturalised FRE_3 to less than 10%, per the recommendation made by Harkness (2010). High flow allocations that reduce the FRE_3 flood frequency by less than 10% would be a suitable allocation methods/threshold for maintaining ecological instream values of the Ngaruroro River as the resulting flow regime would still be able to provide a flushing effect (HBRC, 2018e).

The range of high-flow scenarios modelled for the Ngaruroro River are listed in the first column of Table 4 below. The PPC9 high-flow allocation of 8,000 L/s (HBRC, 2020, Schedule 32) is the highest scenario modelled. As shown in Table 4, the allocation of 8,000 L/s is predicted to change FRE_3 by 5% below the recommended threshold of no more than 10% change in FRE_3. This leaves an additional5% change as a safety margin.

When the Ngaruroro River flow reaches the 20,000 L/s high flow trigger (HBRC, 2020), high-flow takes could begin. As the high-flow event comes to an end and the river levels drop below the 20,000 L/s trigger flow, all high flow takes must cease. A number of submitters expressed concern that high flow allocation takes would cause flat hydrographs, i.e. the peaks of floods above the trigger flow would be flattened due to the volume of water harvested. Modelled high flow allocation takes do not flatten the peaks of high-flow events, however the return to normal levels after the high flow event may be more rapid as the high flow takes potentially lower the flow over this high-flow period.

Table 4. Ngaruroro River high flow allocation scenarios modelled with the corresponding changes to FRE_3 and percent change to FRE_3 compared to a zero-allocation scenario.

High-flow allocation* (L/s)	FRE_3 (No. of 3x median flow events per year)	% Change from zero allocation
0	12.6	-
2,000*	12.4	-1.5%
4,000	12.4	-1.5%
6,000	12.1	-3.5%
8,000	11.9	-5.0%

* Current high flow allocation

In addition to flushing flows, channel forming floods are also ecologically important to maintain appropriate habitat (Figure 14). Maintenance of braided character through the Ngaruroro River flow regime involves not disrupting these channel-forming floods. This channel-forming flow regime wasnot explicitly discussed in the modelling report.

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