MEMO

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Date:	15.04.2021
Subject:	**Summary of Key Elements of Science Pertaining to Water Quantity in Proposed Plan Change 9 – TANK**
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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. Management of the quantity of this freshwater resource is governed by the simple principle of *Out* = *In*, i.e. we cannot take more water out of the system than is coming in without encountering potentially serious consequences. *Out* represents processes such as runoff of water to the sea or use for human activities, and *In* would be, for instance, rainfall. When *Out* > *In*, the amount of resource dwindles, with consequences to both ecosystems and human activities. 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 substantially 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).

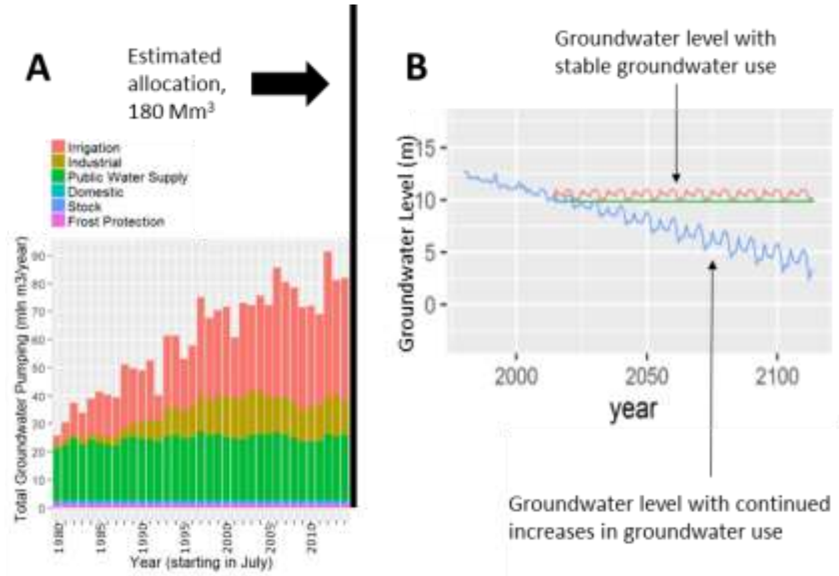

Figure 1. (A) Graph showing history of groundwater pumping by use type compared to estimated total groundwater allocation. (B) Graph showing groundwater depletion if increases in panel A continue in future (blue) compared to change if static (red). The groundwater bore modelled is located on the southwest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

Key terms used in PPC9 and how these relate to the conceptual scientific underpinnings of PPC9 are discussed below. Specific technical terms and definitions are given as needed and are not covered in this section.

Sustainability / Sustainable –
In the context of environmental issues, the words sustainability and sustainable are used in different ways and have a number of definitions. The oldest, and common usage, relates to sustainable development, which was defined by the World Commission on Environment and Development's 1987 Brundtland Report (WCED, 1987) as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". The use of the phrase sustainable in the scientific reports that support and inform PPC9 is consistent with the Brundtland Report's usage. The general aim of managing water quantity in PPC9 is to ensure that future generations have access to water and may enjoy an environment that is not degraded by overuse of water or water shortages. In terms of the science that backs PPC9, this involves achieving the simple balance of *Out* = *In*.

Over-allocated –
The New Zealand National Policy Statement for Freshwater Management (2020) states that

> *"over-allocation, in relation to both the quantity and quality of freshwater, is the situation where: (a) resource use exceeds a limit; or (b) if limits have not been set, an FMU* [Freshwater Management Unit] *or part of an FMU is degraded or degrading."*

The science research underpinning PPC9 uses the term over-allocated in a sense that is consistent with this definition, with the further proviso of sustainable use, as discussed above. At present there is no specified limit on groundwater resource use, however, as groundwater levels and river and stream flows are decreasing due to water use (HBRC, 2018b), the condition of freshwater resources in the Heretaunga Plains is degrading, and *Out* > *In* entails that this circumstance is not sustainable.

Steady-state / equilibrium –
In science these two terms, formally, have very specific definitions. The two terms are different, however, in some cases are used informally in a manner that might seem similar, as both involve a type of balance. When considering groundwater levels (stream flows, etc.), these may rise in the winter, and fall in the summer, but if year-on-year there is neither an overall decline nor an overall increase in groundwater levels (stream flows, etc.), the system is often referred to as being in dynamic equilibrium or long-term steady-state.

Interim allocation and sinking lid –
PPC9 uses the term interim allocation to refer to an amount of water to be pumped annually from the Heretaunga Plains groundwater system. The science behind the concept of interim allocation reflects what we know with very high confidence (i.e. effective certainty) and what we know with less certainty. To within very high confidence, the Heretaunga Plains groundwater system is sufficiently over-allocated (McKay, 2020) that there is a well-founded basis for concern of environmental and economic crises if immediate action is not taken. While the circumstance of over-allocation is well understood, there remains uncertainty around what the exact value of the allocation limit should be in

order to achieve a sustainable level of use (McKay, 2020). As such, interim allocation addresses the immediate need to establish a limit that is within reasonable bounds (discussed further in Section III.d), while also allowing for future refinement to arrive at an allocation limit in which we have greater confidence. A consequence of the interim allocation, as provided for in PPC9, is that existing permit holders will not be able increase the quantity of water that they are allocated, and any substantive new net groundwater takes will be prohibited. Permit renewals will be subject to "*actual and reasonable use*" (HBRC, 2020), which in many cases is less than current allocation. Over time, this should effect a reduction of annual allocation in the direction of the interim allocation limit, an effect that has been referred to as a "sinking lid" for total water allocation.

Actual and reasonable use as defined in PPC9 –
The term "*actual and reasonable*" with reference to water use is defined in detail in PPC9 Chapter 9, Glossary of Terms (HBRC, 2020). Summarising, actual and reasonable will require permit applicants for new groundwater takes to justify their use need via accurate metered records of use or a justification of irrigation needs based on modelling. The modelling approach specified (Rajanayaka & Fisk, 2018; ARL, 2020) is based on an approach that has been demonstrated to be reliable and accounts for the specific water use given a specified high level of irrigation efficiency. An examination of Figure 1 reveals how reducing the total allocation of ~180 Mm^3 (see black bar in panel A) to what is in actual recent year-on-year use (remaining coloured bars in the figure) will ensure that worst-case unsustainable use (blue line in panel B) will be avoided.

Heretaunga Plains Groundwater System versus TANK Catchments –
The exact boundaries of the Heretaunga Plains groundwater system are a subject of current investigation, however, we know with reasonable confidence where the main areas of utilisable groundwater resource lie. This area is shown on a map in Figure 2A. The portion of this area that is managed by PPC9 and comprised of groundwaters within the TANK catchment is shown in Figure 2B, an area that has been referred to in some HBRC reports (e.g. 2020, Schedule 31E) as the Heretaunga Plains FMU or GMU. For the purposes of this memorandum, the Heretaunga Plains groundwater system references Figure 2A, whereas the TANK groundwater references Figure 2B. Studies on the Heretaunga Plains groundwater system have considered the contribution of the Tukituki River and groundwater in the Tukituki catchment, however, the Tukituki River and groundwater managed separately from.

Figure 2. Maps showing (A) the spatial extent of the Heretaunga Plains groundwater system model (light yellow) and (B) the spatial extent of TANK groundwater resources (light blue) (HBRC, 2018a and 2020, Schedule 31).

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

As discussed in Section I, for the Heretaunga Plains groundwater system, which includes TANK groundwater, there is a substantive and potentially serious future risk that the demand for surface and groundwater will increasingly exceed supply. The best 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 monitoring alone. 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 water and 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). 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 catchments. The Karamū Stream and Ahuriri River 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 Karamū Stream was previously a tributary to the Ngaruroro River until the lowermost reach of the Ngaruroro River was diverted and canalised after severe flooding in 1867 (HBRC, 2016). Currently the name of the Karamū Stream changes to Clive River for the part of the reach downstream of the diversion. The Ahuriri River flows into the Ahuriri Estuary, whereas 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 habitat 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 such a 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 be taken/harvested. Once a river's flow drops below the high "trigger flow", takes must cease.

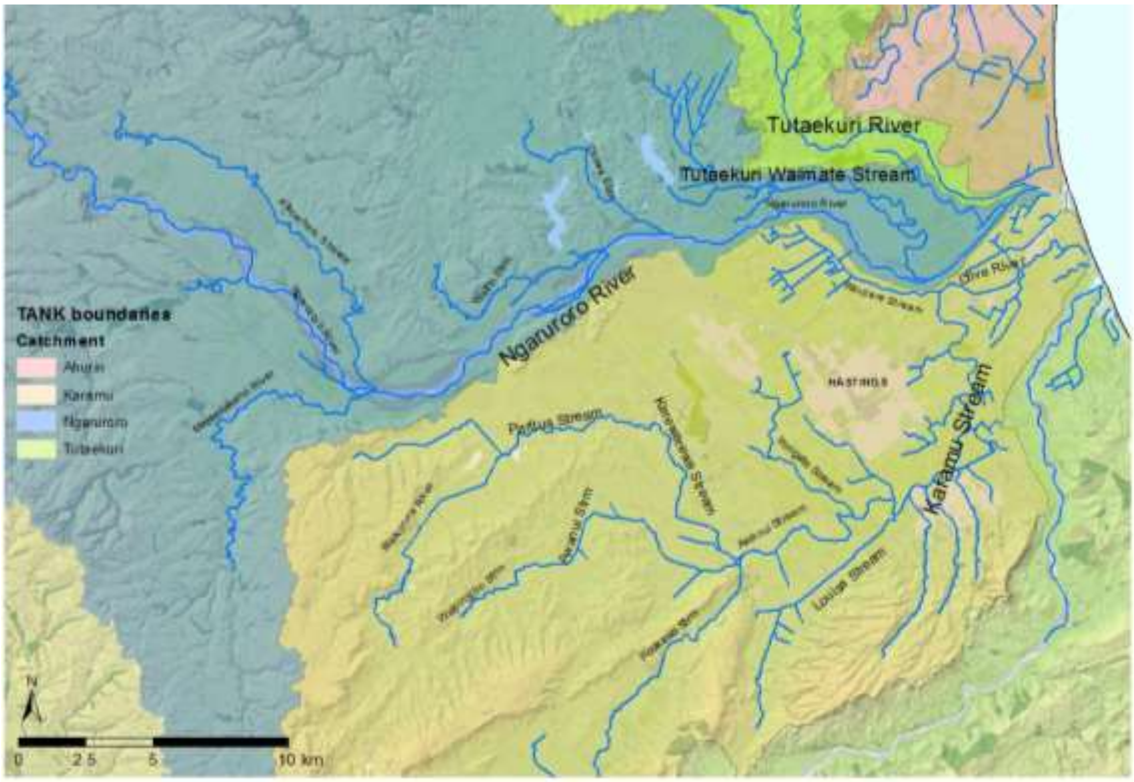

Figure 3. Map showing primary TANK catchments with rivers and streams that contribute surface water to the TANK groundwater.

HBRC have a number of sites within the TANK catchments where continuous monitoring of river and stream flow occurs through a process referred to as telemetry (electronic transmission of continuous flow, HRC, 2013). Telemetry provides a significant amount of continuous water level and flow data key to assessing river flow trends for State of the Environment reporting, as well as providing near real-time assessment of flow levels for cease-take trigger flow and high flow management purposes. In addition to obtaining telemetered 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 through telemetry for quality control purposes (HBRC, 2018d). The distribution of relevant surface water monitoring sites is described 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 III.c).

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. Data inputs provided for the model runs (Williamson & Diack, 2018) included daily rainfall, evaporation, and loss of water to the atmosphere from plants (a process called transpiration, akin to respiration in animals). For the surface water model to best represent the TANK catchments and simulate river flows to a satisfactory level, additional catchment characteristics were utilised within defined sub-catchments. Slope, geology, land use, and soil class where assigned to sub-catchments based on the current data for the area. Other inputs including soil infiltration rate and soil moisture where assigned within sub-catchments and optimised during a process referred to as model calibration, which is used to ensure the needed accuracy of models. 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 the actual 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 standard practice for surface water modelling (Moriasi *et al*., 2007; Williamson & Diack 2018).

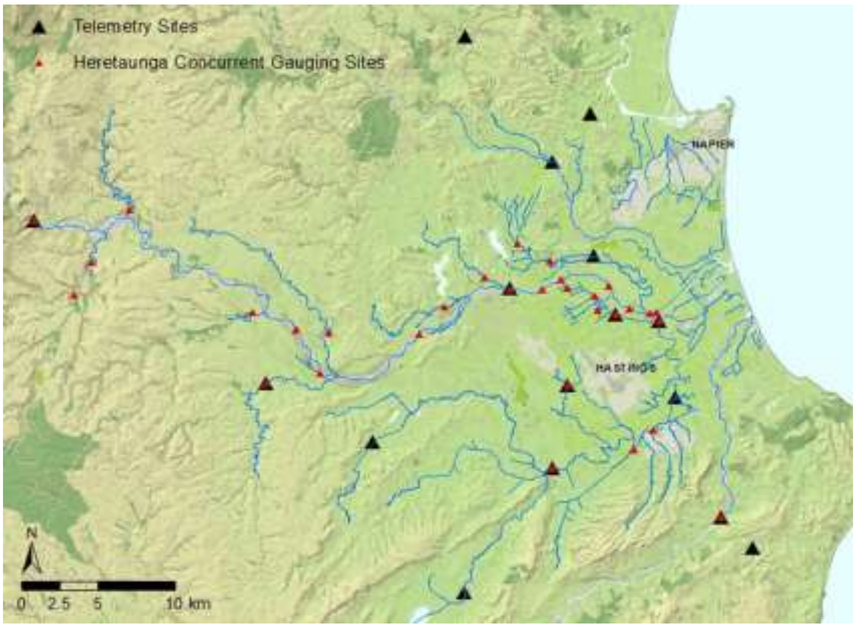

Figure 4. Heretaunga Plains map showing locations of surface water continuous monitoring telemetry sites and concurrent flow gauging sites.

Following the construction, calibration and validation of the surface water model, 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[1] restrictions.
- 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 surface 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

[1] 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.

statistic (discussed further in Section IV.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 III.c below) combined with the larger total surface water abstraction in the Ngaruroro River. The modelled surface water abstraction for upstream of Ngaruroro River at Fernhill is 770 L/s, whereas 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. As the low-flow regime in the Tūtaekurī River is relatively less impacted than that of the Ngaruroro River, the Tūtaekurī is relatively more resilient to raising cease-take trigger flows without incurring high levels of restriction on water takes. 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 low flows, are discussed further in Sections IV.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 scenarios modelling focuses on how to take surface water during times of high flow without disrupting high flows in a manner that degrades ecological habitat. The discussion of high-flow allocation scenarios modelling is coupled with discussion on ecological flows in Section IV.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 III.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 highly 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 under pressure and hence will flow to the surface without 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 climatic influences may have played a part in the groundwater declines, abstraction from the aquifer system has increased substantially over this period.

Per Section I, the majority of groundwater abstracted from the Heretaunga Plains groundwater system is 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[2] (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 irrigation use due

[2] 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 calendar year also results in a better correspondence between rainfall, runoff, and relationships of surface and groundwater.

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). Approximately 50 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 III.c below, however, not all groundwater modelling was coupled with surface water models. Exceptions are listed as 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).
- 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 modelled). Modelled data was shown to be in reasonable agreement with recent measurements and was therefore used to compensate for lack of accurate 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 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).

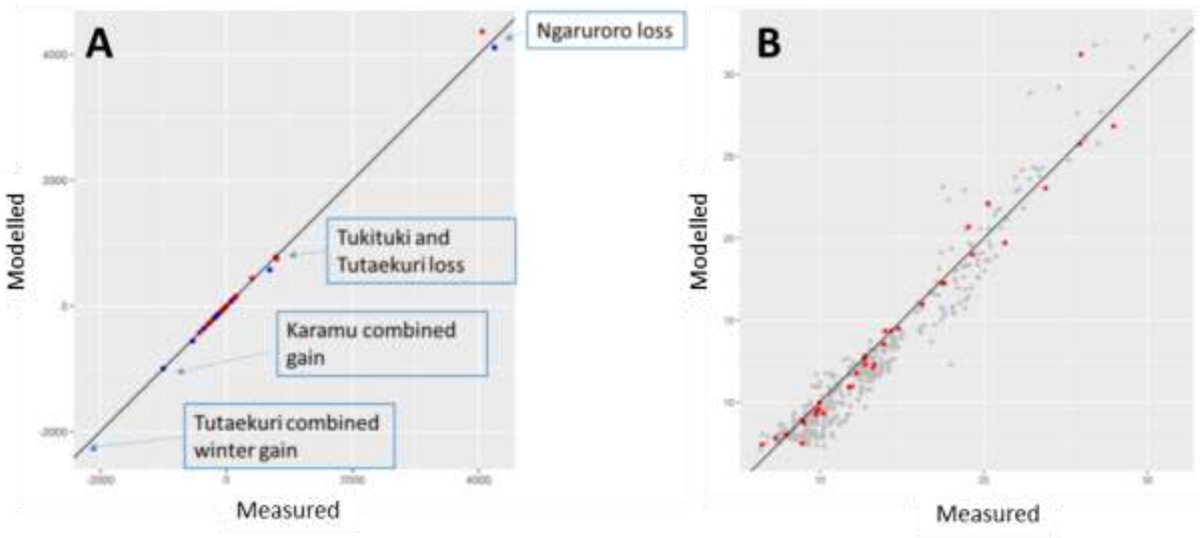

Figure 5. Example calibration plots for the Heretaunga Plains groundwater system model showing agreement between modelled and measured (A) gains and losses of surface water to groundwater, and (B) groundwater levels.

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 human activity/abstractions and 2) a number of different use scenarios, including “business as usual” as well as scenarios under different environmental management protocols and for future 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 input data reflects surface water 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 for 2014/2015. 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 long after the summer irrigation stops and sometimes continues into winter.

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

Sections III.a and III.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 of this 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 of groundwater 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 and groundwater), 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 is 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 III.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.

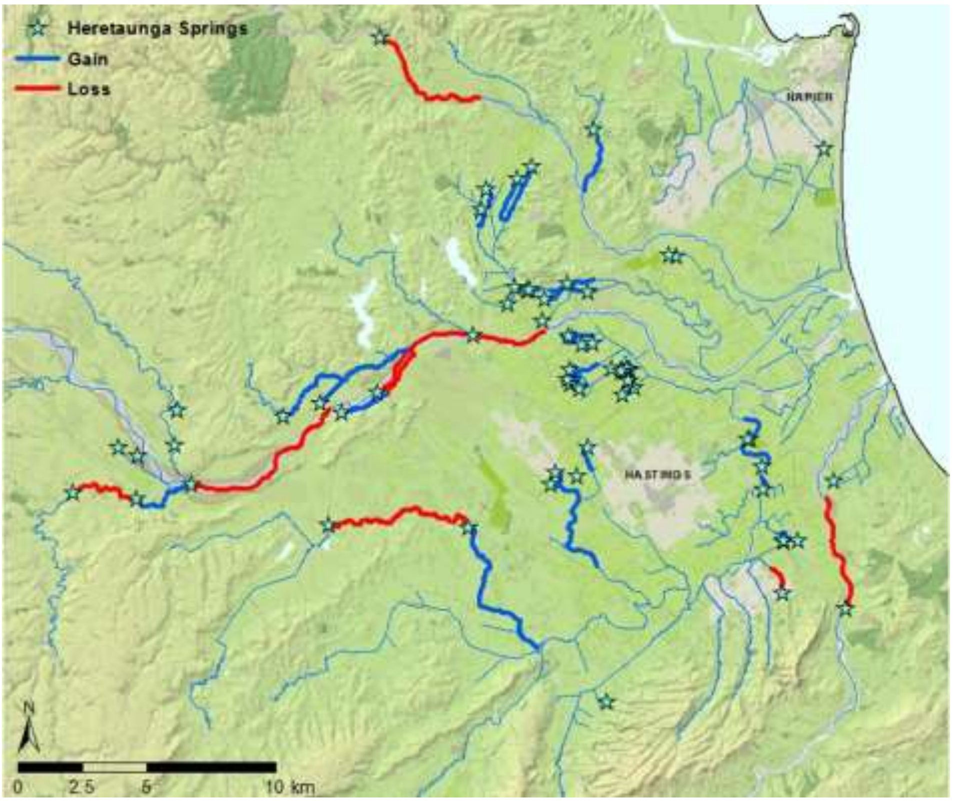

Figure 6. Areas in the Heretaunga Plains where major surface water gains, losses, and springs are known to occur.

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. The two most likely sources of groundwater inflows are linked to losses from the Tukituki River or losses from the Ngaruroro River. In respect of subsurface connectivity and other data, groundwater fed by the losing reaches of both rivers could be a source of water to the Karamū Stream. One possibility is that losses to groundwater from the Tukituki River are the dominant source of groundwater flow to the Karamū Stream during summer low flows, whereas losses to groundwater from the Ngaruroro River are increasingly important as inputs to the to the Karamū Stream during winter. More investigative work is needed and is underway, in order to understand

Karamū Stream flows more fully. Depletion to the Karamū Stream from groundwater pumping is discussed further below.

The Paritua Stream drains hill country to the west and south of Te Tua Station, which lies west of Hastings. 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. Instead stream flow 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 a stream, 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).

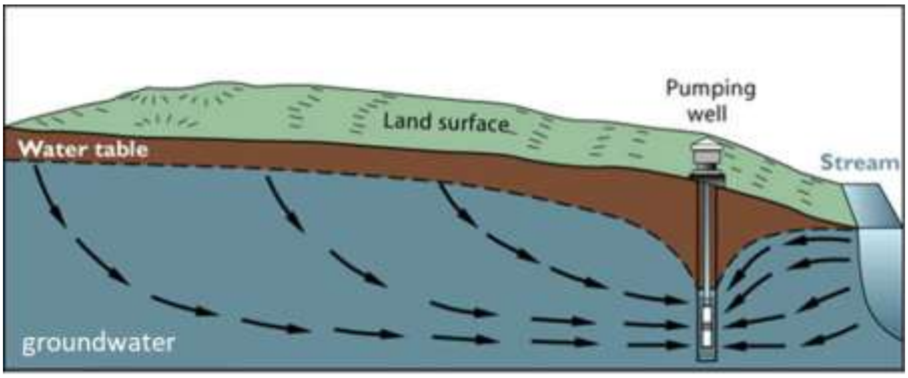

Figure 7. Schematic diagram showing how groundwater responds to pumping. As groundwater is pumped from a bore or well, groundwater levels initially decrease in the immediate vicinity of the bore. As pumping continues, the lowering of the groundwater table extends further away from the well and may begin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

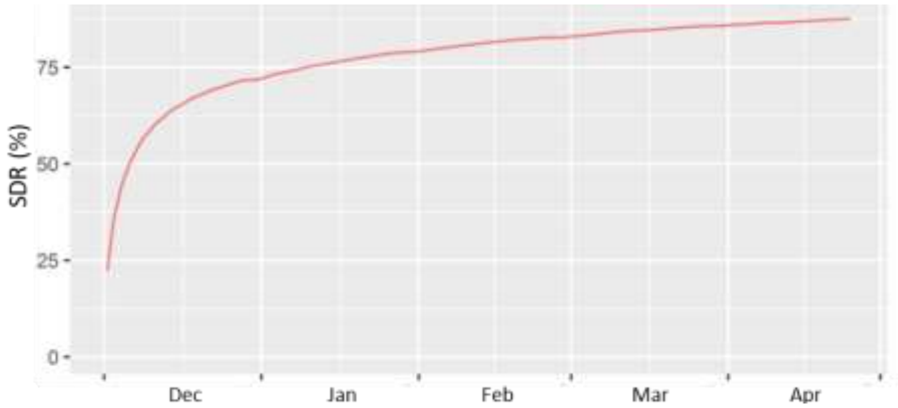

Figure 8. Graph of representative data showing how the Stream Depletion Ratio (SDR) increases over time for a constant rate of sustained groundwater pumping. An SDR of 100% indicates that for every unit of groundwater pumped, surface water is depleted by the same amount, i.e., all groundwater pumped 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 to and 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 III.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 on stream 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

To apply a systematic standard to stream depletion effects, HBRC have classified three Stream Depletion Zones (SDZ) within the Heretaunga Plains groundwater system (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. 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

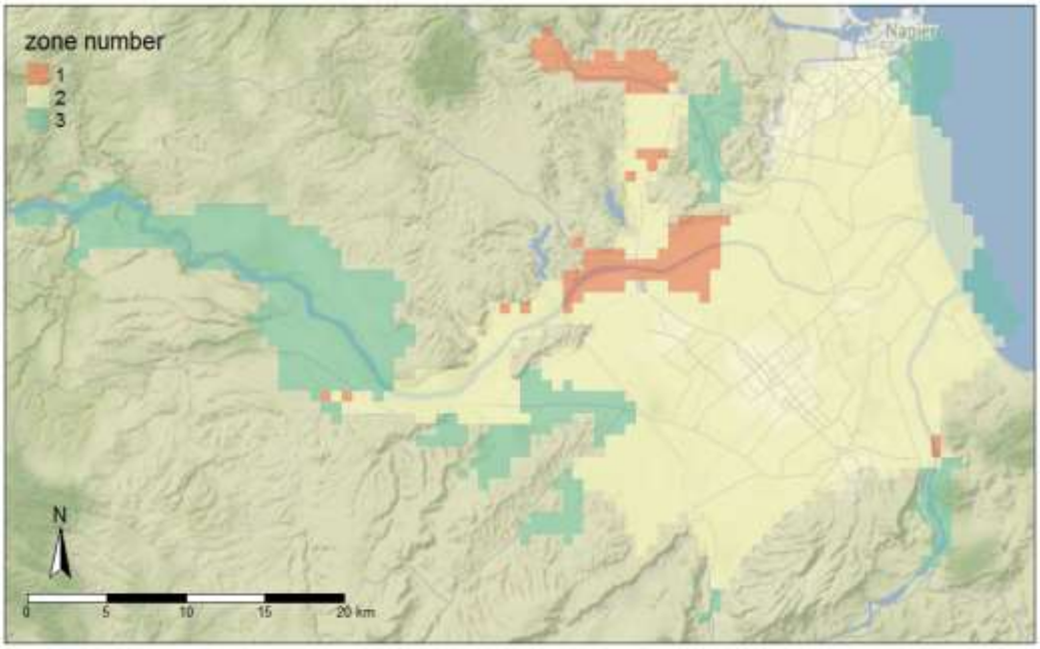

Figure 9. Map of SDZs superimposed upon a map of the Heretaunga Plains. SDZ 1 (red) shows areas where groundwater pumping is highly stream depleting whereas SDZ 3 (green) comprises areas where pumping results in the least depletion. The majority of the Heretaunga Plains aquifer system falls within SDZ 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 of groundwater 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 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.

Heretaunga Plains stream depletion Calculator

To help community members and stakeholders understand and participate in the management of their activities that cause stream depletion, HBRC have developed an online Stream Depletion Calculator (HBRC, 2021). Results from this calculator are the same as what would be obtained from running a calculation based on a groundwater model that has been trialled, tested, and internationally reviewed as fit-for-purpose, however, without the need for the deep technical and specialist expertise needed to use the model itself.

Figure 10 shows two illustrative examples of results from using the online Stream Depletion Calculator. Figure 10A shows stream depletion caused by pumping 10 L/s over 150 days that would occur from a groundwater bore at the intersection of Taihape and Swamp Roads, i.e., near the bridge over the Ngaruroro River at Fernhill. Figure 10B shows stream depletion caused by pumping 10 L/s over 150 days that would occur from a groundwater bore at the Hastings Golf Club at Bridge Pa. Comparing Figure 10A to 10B illustrates issues of variable and cumulative effects in the Heretaunga Plains groundwater system. Of the two examples, the former shows a circumstance in which one surface water feature is primarily or disproportionately affected. The SDR for this case is 1 (100% of groundwater pumped coming from surface water), and most (93%) of the depletion is coming from the Ngaruroro River. For a bore at Hastings Golf Club, in contrast, the SDR is lower (0.77) and stream depletion occurs across both the Ngaruroro River and Karamū Stream, with lesser stream depletion of 7.6, 13, and 11%, respectively, coming from the Raupare Stream, the Tūtaekurī-Waimate Stream, and the Tukituki River.

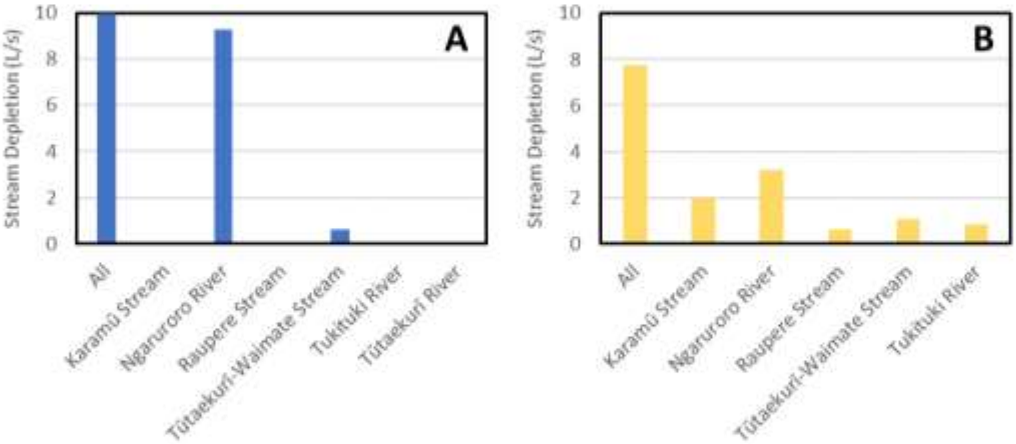

Figure 10. Calculated stream depletion for hypothetical groundwater bores place at two sites, and assuming pumping at a rate of 10 L/s over 150 days during the December to April irrigation season. (A) Stream depletion for a bore located at the intersection of Taihape and Swamp Roads. (B) Stream depletion for a bore located at the Hastings Golf Club at Bridge Pa.

Springs and how the Stream Depletion Calculator deals with them

A number of submissions in response to PPC9 specifically address the issue of springs, i.e., as separate and distinct from streams and rivers. In water science, the term spring refers to a point or specific area on the ground surface where water flows from groundwater to the surface. There are different types of springs, ranging, for instance, from a highly localised point where water springs from the ground to a more extensive and diffuse area that may release enough water to form a spring-fed stream.

Due to changes in the amount of water in the environment season-to-season, seasons cause fluctuations in subsurface groundwater levels, and hence also potentially affects springs. In the Hawke's Bay area, even aside from human activities that abstract surface water and groundwater, the differential amount of rain in the winter versus the summer, combined with the permeability of the ground to flow in many places, result in higher groundwater levels in winter than in summer. Figure 11A below shows a representative example of changing groundwater levels with season, and Figure 11B shows a conceptual graphic illustrating how seasonal changes in groundwater levels might affect springs. In Figure 11B, when groundwater levels are high in the winter, flow from springs may be distributed over a larger spatial scale (all blue symbols), whereas in summer, when groundwater levels are low, only the lowest elevated region of the spring (darker blue symbol) might be active. It is important to note that the representation in Figure 11B is general to much, but not all, of the Heretaunga Plains groundwater system. In regions where there is less subsurface connectivity, stream flow might be more dependent on localised rainwater inputs.

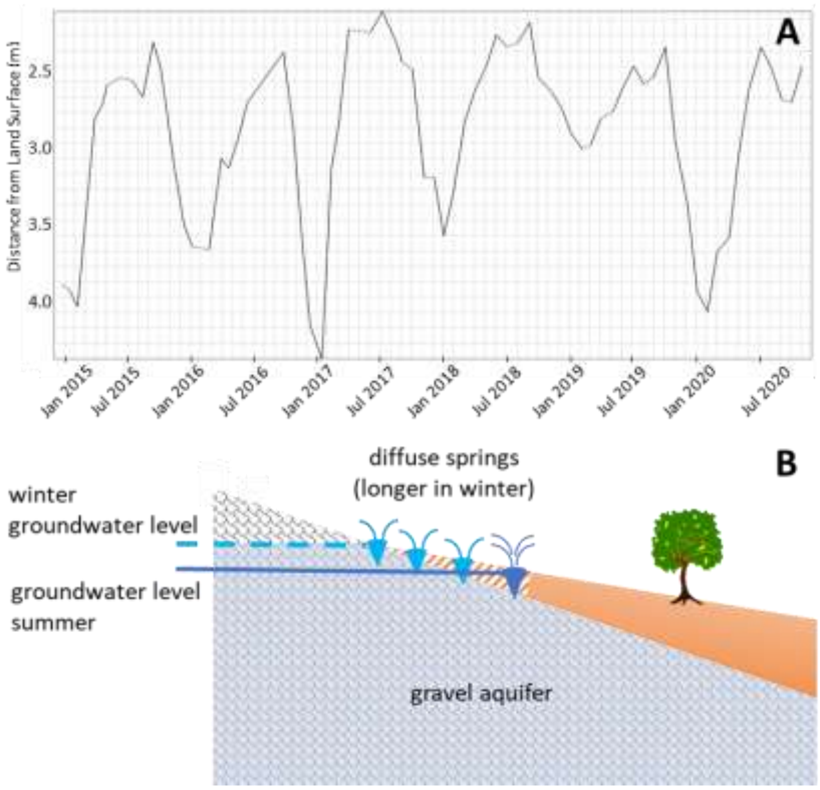

Figure 11. (A) Representative data from a Hawke's Bay monitoring well showing how groundwater levels fluctuate seasonally as weather fluctuates from cooler and wetter to hotter and dryer; (B) Conceptual schematic illustrating a common scenario of how diffuse springs may react to seasonal fluctuations in groundwater levels. All blue spring symbols might represent locations with active springs in winter, whereas in summer, when groundwater levels are low, only the lowest elevated region of the spring (darker blue symbol) might be active.

There are a number of areas in the Heretaunga Plains groundwater system that behave as diffuse streams, and hence are explicitly accounted for in model calculations as such. This is described in various HBRC reports (HBRC, 2018a, 2018b, and 2019), however, may not be generally understood by the public inasmuch as, for instance, the online Stream Depletion Calculator does not differentiate spring-fed surface waters. The areas that represent diffuse springs or spring-fed streams (in whole or part) include the Tūtaekurī-Waimate, Karamū, Waitio, Raupare, Irongate, Mangateretere, Paritua, Karewarewa streams, and a number of other small springs.

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, with the exception of some very localised areas (e.g. SDZ 3, green portions of the map in Figure 9), 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. The degree of stream depletion can be highly variable, and for this reason the online Stream Depletion Calculator offers an innovative option to rapidly quantify the effect of any particular abstraction scenario, such that the effects of single and cumulative abstractions might be assessed and managed. 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 (more than 90% decrease of natural flow) and Karamū Stream (over 60% of flow), with some other streams having lost a significant portion of flow (between about 40 and 80%), and a projected loss of approximately 50% to the Ngaruroro River.

Findings for future scenarios[3]

- 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).

[3] 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 management scenarios, which includes scenarios discussed in greater detail in Sections III.d and III.e, were run with surface water coupling.

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 relatively small 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 not 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 pumping bans 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 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 even a small increase in 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 (80 Mm^3 of which came from TANK groundwater in 2012–2013, Figure 2B). As noted in Section III.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.

e. Effective date

In PPC9, actual and reasonable is measured on the basis of water meter records for ten years' preceding August 1, 2017 or on the basis of the amount of water used for irrigation over the same period. This effective date sets a standard by which future sustainable use is managed. The data in Figure 1A (Section I) reflects groundwater pumping used as an input to groundwater model calculations (HBRC, 2018a and 2018b). Since the publication of these reports, five more years of data have accrued. Figure 12 below shows water use data for the three major categories of greatest water use, updated to the most recent complete year of records (2019–2020 water cycle year, i.e. from July 1, 2019, to June 30, 2020). Per comments in Section III.b, metered data for Public Water Supply and Industrial use is reasonably accurate, and data for irrigation is based on model results. Because there are increasing numbers of consents for which frost protection water use is combined with irrigation water use, these two use categories are combined. The data in the figure, however, does not capture all frost protection use, and frost protection use is estimated to be much less than for irrigation (see Section IV.b). Water use for the major use categories varies from year to year. Generally, irrigation is consistently the largest water use, with notably higher proportion of use during dry years.

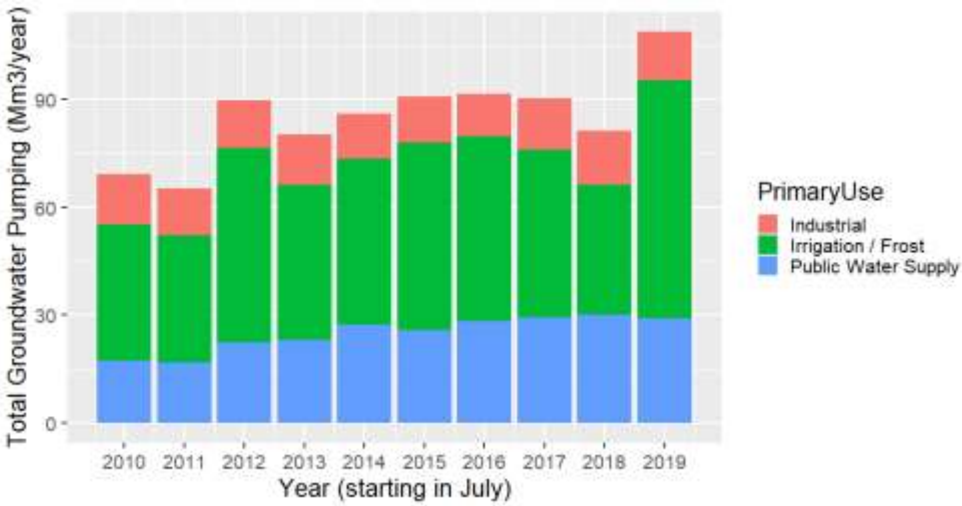

Figure 12. Water use for the three major categories of greatest use, updated to the most recent complete year of records (2019–2020 water cycle year, i.e. from July 1, 2019, to June 30, 2020).

IV. 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). There are two sources of uncertainty regarding frost protection takes. First, HBRC (2018a, Appendix A) noted several ways in which the estimate might be biased to lower than actual values. Second, the groundwater model is not able to account for the effects due to the high instantaneous rate of take for frost protection (HBRC, 2018a). For frost protection, a large amount of water must be pumped over a relatively short period of time.[4] The stream depletion calculator estimates effects according to sustained pumping at a relatively low rate (10 L/s). The impact of such high-rate takes on the instantaneous flow of a stream is assumed to be negligible given the short duration of the take, however, this, along with the potential effects of the timing of frost takes (reductions in flow at times when spawning fish may be sensitive to drying out) were not explicitly tested (HBRC, 2018a).

c. 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 typically identified as approximately the mean annual maximum flow. Flushing flows are smaller floods that

[4] Large frost protection takes on HBRC consent records include 800 L/s for surface water, tied to Ngaruroro River flow of 15,000 L/s at Whanawhana, and 168 L/s for groundwater, taken from one well in the Meeanee area; P. Barret, HBRC Consents, *Pers. Comm*.

flush fine sediment, accumulated algae, and other aquatic vegetation. These flushing flows help maintain quality of habitat for small insects, worms and other animals on which fish feed, therefore benefiting resident fish species by protecting their food source. A flushing flow is categorised as usually three times the median flow of the river.

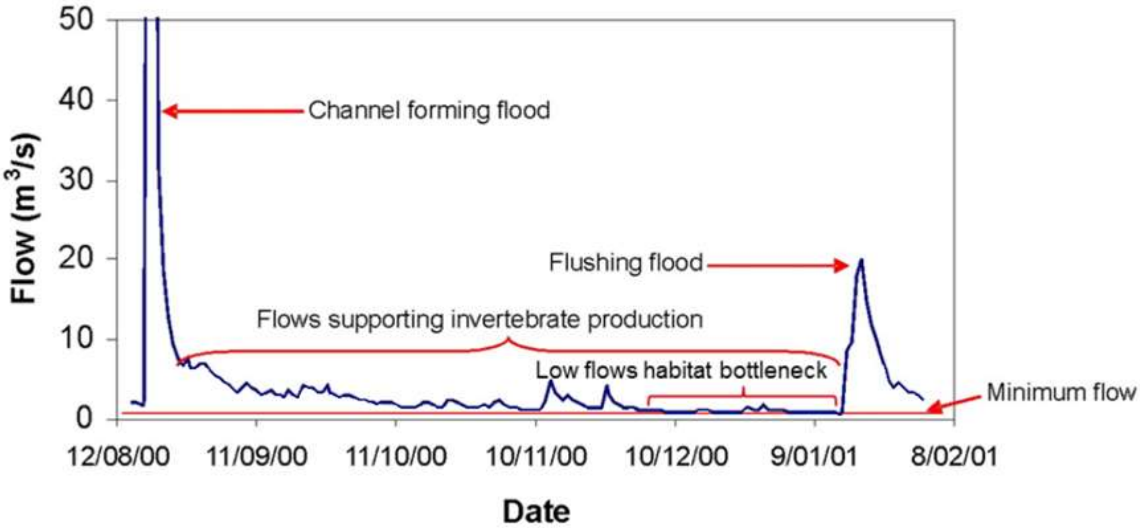

Figure 13. Schematic showing the various ecologically relevant flows.

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 IV.d and IV.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 III.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, MALF is calculated as the lowest 7-day average over the year.

- A **naturalised MALF** is calculated using results from the "naturalised" scenario model data (Section III.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 from 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 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 flow for a river as determined by the Regional Council records."*

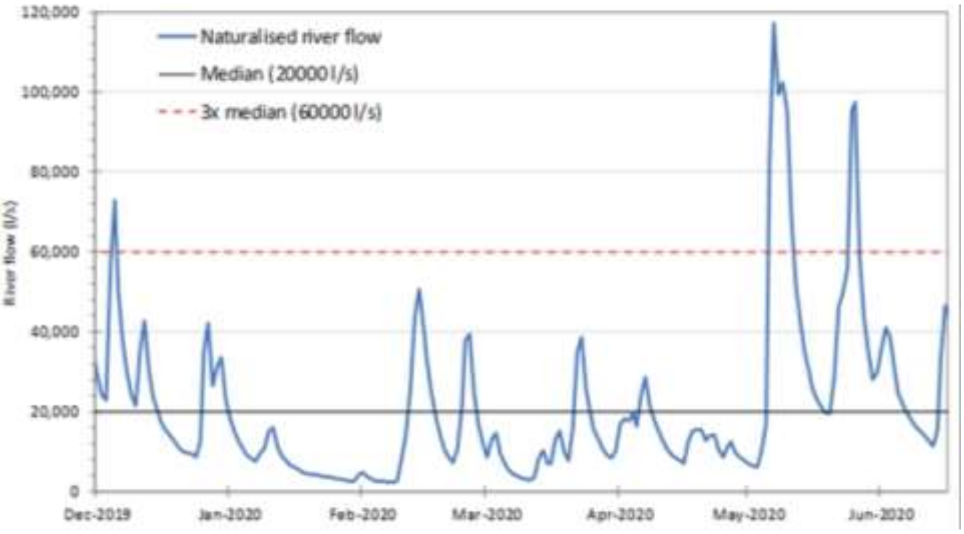

Figure 14. Graphic illustrating the concept of FRE_3 (HBRC, 2018c). The blue line shows naturalised river flow in time (modelled for the Ngaruroro River at Fernhill). The solid black horizontal line shows the median flow is, i.e. the flow value in the middle of all flow measurements shown on the blue 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. For this data, FRE_3 = 3.

d. 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 III.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 restrictions to water users is given in Section III.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.

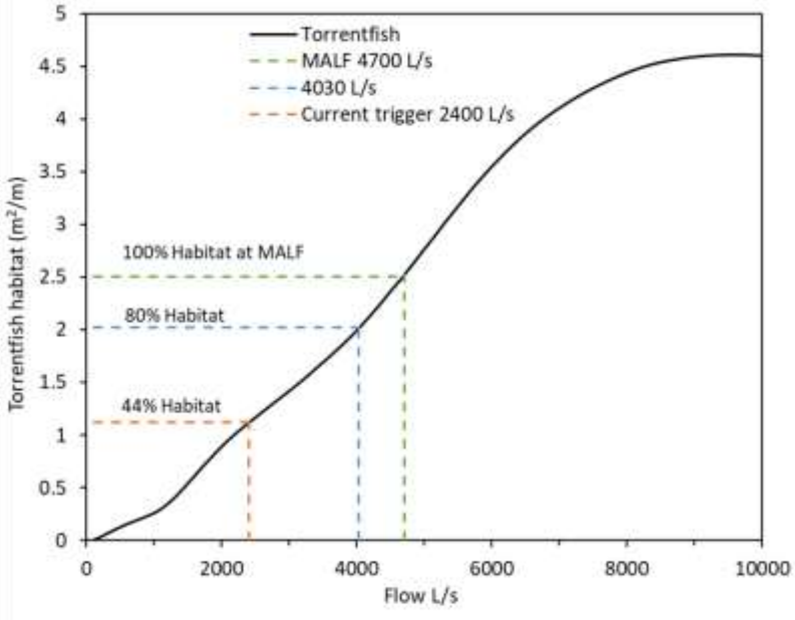

Figure 15. A representative example of a habitat-flow curve for torrentfish in the Ngaruroro River. This example shows habitat suitability in terms of area habitat (m^2) per m of river reach. Various measures of habitat suitability are combined into a single measure that is then rated according to flow 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% 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 MALF under a naturalised case is 2,300 L/s (extracted from data summarised in HBRC, 2018c).

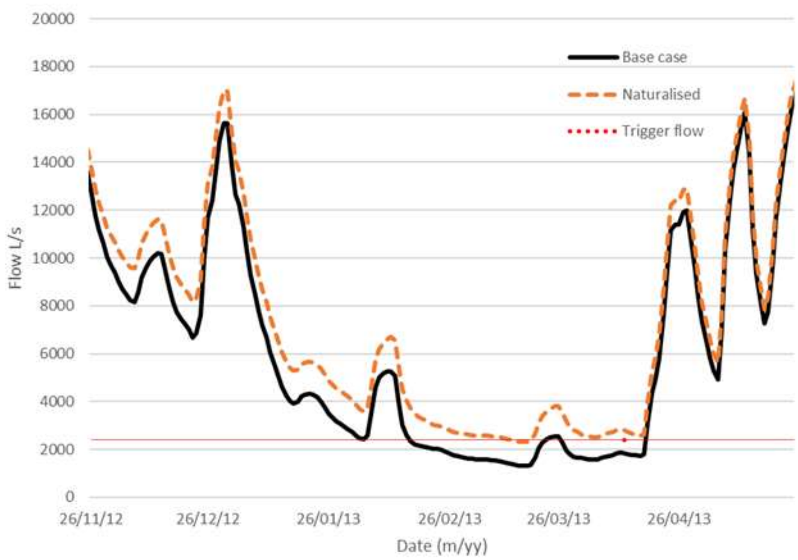

Figure 16. Comparison of the base case Ngaruroro River flow at Fernhill for 2012–2013 (black line) to naturalised conditions (orange dashed-line). The current and PPC9 proposed trigger flow of 2,400 L/s is plotted as a red dotted-line.

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%).

e. 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 additional 5% 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 trigger

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 was not explicitly discussed in the modelling report.

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