Representing the influence of dams on river flows

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Executive summary

The purpose of this work was to investigate data requirements and potential methods to quantify the influence of non-consumptive water use, such as hydro-electric dams, on downstream river flows - with an emphasis on in-stream environmental values. Many methods previously applied to accomplish this task compare natural and altered river flow time-series. There are at least three contrasting methods for analysis of such river flow time-series: 1) comparison of observed flow time-series data for periods before and after dam construction; 2) comparison of naturalised dam outflows (constructed from observed reservoir inflows) with observed reservoir outflows; and 3) analysis of flow time-series calculated from hydrological models representing natural and altered scenarios.

The US Nature Conservancy's Indicators of Hydrologic Alteration (IHA) software was used to calculate 33 hydrologic indices under pre- and post- alteration conditions for a catchment heavily influenced by hydropower operations. These hydrologic indices represent intra- and inter-annual variability, and magnitude, duration, frequency, timing and rate of change of river flows. The Range of Variability Approach was then used to compare pre- and post- alteration hydrological patterns. This method has been widely used in international literature to represent human-induced changes in flow regimes. However, standard application of the method does not provide a single quantification of hydrological impact or water allocation pressure, because contrasting aspects of a dynamic flow regime are considered. This is in contrast with pressures resulting from consumptive water allocation which has been previously calculated and mapped across New Zealand. It is concluded that the IHA provide a transparent and objective method for quantifying the influence of non-consumptive water use, including hydropower schemes, on downstream river flows. However, inputs of natural and altered river flow time-series must be available to apply the IHA method. Further hydrological indices can be added to the standard set of indices applied within the IHA. In particular, indices linked to ecosystem state or habitat availability may be provide useful comparators.

The main disadvantages of the IHA include: a) a high demand for accurate estimated or observed flow data; b) lack of an overall indicator of pressure on flow regimes exerted by dam operations; and c) lack of explicit linking of flow regime components to ecosystem states or in-stream values.

The Waitaki catchment was used to demonstrate how data requirements can be met and potential methods applied when quantifying the hydrological influence hydro-electric dams. It should be noted that the purpose of this report was to provide generic methodological guidance regarding the influence of dams on flow regimes. The purpose of this report was not specifically to investigate hydrological impacts of water management infrastructure in the Waitaki catchment.

1 Introduction

The Ministry of the Environment (MfE) previously contracted NIWA to produce a pressure-state-impact model for freshwater flows and allocation. Subsequently, MfE contracted NIWA to complete additional modelling and refinement of the model at a national level. Following further development of the freshwater policy work, based on these earlier contracts, MfE required further analysis and advice on the model to assist with policy and planning processes at national and regional levels and aiding the implementation of the National Policy Statement for Freshwater Management (NPS-FM). This report improves on previous work by identifying methods for representing the likely impacts (i.e. pressures and altered states) on river flows downstream of large dams.

Previous work by Booker et al. (2016a; 2016b) for MfE included the development of models and associated analysis to allow a pressure-state-impact framework to be applied to river flows across New Zealand. That work sought to provide spatial information to quantify pressures on New Zealand's river flows resulting from consents to abstract water from surface and groundwater. Maps of pressure on river flows were developed by analysing consents to abstract water for consumptive use. Results were presented at national, regional and spatially continuous scales. Booker (2018) provided further details of how pressure was calculated by comparing naturalised median flow with the sum of upstream consents for all locations across the New Zealand national river network.

Booker et al. (2016a) defined consumptive water use as encompassing all abstractions that did not return the abstracted volume to the location from which the water was taken. They defined consumptive hydro-power schemes as those that depleted river flows for some length of the river network over the long term. This definition meant that diversions within the same catchment, inter-catchment diversions, and diversions to the sea were represented when calculating pressure from consumptive consents to abstract water on river flows. Non-consumptive consents, including those describing non-consumptive hydro-power schemes, were removed from the previous analysis of Booker et al. (2016a). This meant that the influence of dams that store water and subsequently release that water immediately downstream were not represented when calculating pressure on river flows. The hydrological impacts of dams and the downstream pressures that they create were therefore not included in the previous analysis of Booker et al. (2016a) and Booker (2018).

The aim of this project was to develop a methodology to quantify the influence of dams on downstream flows with respect to their influence on in-stream values. Most methods used to accomplish this task require natural and altered river flow time-series as input. There are several contrasting methods that could be used to derive these river flow time-series.

1. Observed flow time-series data for periods before and after dam construction can be analysed to quantify the influence of dams on downstream hydrology. However, care must be taken to account for different climatic influences between the two periods (e.g., frequency or duration of droughts).

2. Observed data or calculated flow time-series for lake inflows (upstream of a hydro-power dam) can be used to reconstruct naturalised downstream flow time-series and therefore allow quantification of the influence of dams on downstream hydrology.

3. Flow time-series data calculated using hydrological models can be used to simulate both natural and altered flows downstream of hydro-power dams.

In this report we consider the above options for gaining river flow time-series for an example catchment, and also complete the following components:

1. Review potential impacts of dams on in-stream river values and methods available for representing downstream impacts of dams on river flows (Section 2);
2. Clarification of current treatment of non-consumptive (and consumptive) dams within the national TopNet model (a component of NIWA's New Zealand Water Model; NZWaM-Hydro) (Section 3);
3. Where possible develop techniques for assessing pressure and altered state of flows from dams (Section 4.2 and 4.4);
4. Develop methods for extracting, summarising and incorporating simulated naturalised river flow time-series (supplied by a national hydrological model) (Section 4.5);
5. Apply a method that quantifies hydrological alteration resulting from non-consumptive hydro-electric dams to an example highly impacted catchment (Section 4);
6. Critically assess applicability of available methods for assessing environmental flows downstream of dams (Section 5); and
7. Provide recommendations on the utility of available methods (Section 6).

We selected the Waitaki catchment as our example catchment. The Waitaki was selected because it contains several large hydro-electric dams and managed reservoirs of national significance, contains some highly prized in-stream values (e.g., biodiversity, aesthetic, and recreational) and because we gained permission from Meridian Energy Limited (MEL) to analyse flow data from the catchment for the purposes of this report. We note that the purpose of this report was to provide a generic methodological guidance regarding the influence of dams on flow regimes. The purpose of this report was not specifically to investigate hydrological impacts of water management infrastructure in the Waitaki catchment.

2 Downstream impacts of dams on river flows

The value of maintaining variable flows to benefit river, floodplain and estuary diversity and health has been increasingly recognized (Bunn and Arthington, 2002), yet dams are a prime example of anthropogenic stressors that have potential to significantly alter seasonality of flow in river systems (Tonkin et al., 2017). Dams impact rivers by changing the timing, magnitude and frequency of high and low flows; this has implications for river geomorphology, sediment transport, and instream ecology. For these reasons the functioning and diversity of existing habitats can be adversely impacted by dam-induced alteration of hydrological characteristics of downstream channels and associated areas (Graf, 2006). Molles et al. (1998) and Nislow et al. (2002) found that reduction in the number and magnitude of floods impacted riparian forest communities which led to further impacts on biodiversity. Wotton et al. (1996) determined that downstream food webs were similarly impacted, whilst Schmidt et al. (2008) suggest that such impacts may be found hundreds of kilometres downstream from larger dams.

Environmental flows have been defined as “the quantity and timing of water flows required to maintain the components, functions, processes and resilience of aquatic ecosystems and the goods and services they provide to people” (TNC, 2016). Environmental flows are often associated with environmental outcomes and are intended to maintain or improve the ecological condition of rivers, wetlands and estuaries (Horne et al., 2017). Ideally, environmental flows downstream of dams would be assessed in view of available scientific information to provide ecologically-based and socially acceptable outcomes (Stewardson et al., 2017). The Ecological Limits of Hydrological Alteration (ELOHA) is one framework that aims to aid the development, implementation and adaptation of environmental flows. This framework seeks to provide environmental flow recommendations through development of scientifically defensible and empirically testable relationships between flow alteration and ecological responses (Poff et al., 2010). ELOHA includes steps to: 1) build natural and altered hydrographs; 2) identify a set of ecologically-relevant flow variables; 3) determine deviation of natural to altered flows; and 4) develop flow alteration–ecological response relationships from literature, expert knowledge and field studies. See Mackay et al. (2014) for an example of how the first three of these steps has been undertaken in Australian catchments.

Given the dependence on ecological states on flow regimes and the prominent role of quantifying flow alteration in environmental flow setting frameworks, flow variability should be a particularly important consideration in managing water allocation in dam or storage facility development and operations. To assess potential downstream impacts of dam operations on river flows it is necessary to characterize natural and altered flow conditions in a reliable way so that the environmental conditions linked to in-stream values can be more accurately represented with and without hydrological alteration.

The choice of method used to represent downstream impacts will depend on the ultimate purpose for which the assessment is being made. For example, when assessing drivers of channel change, Schmidt and Wilcock (2008) utilized hydrogeomorphic indicators of downstream impacts including: changes to the balance between sediment transport capacity and sediment supply; the Shields number (a parameter representing the shear stress necessary for initiation of sediment motion); and the magnitude of flood reduction. More recently, Ngor et al, (2018), looked at the response of fish diversity patterns to hydrological modification caused by upstream damming. They ultimately found that temporal shifts in fish assemblage compositions indicated that dams altered seasonal flow patterns and thus favoured more generalist species. In a similar study, Jardine et al. (2015) demonstrated the fundamental role that flow rhythmicity has on riverine diversity. They showed that more rhythmic rivers support more diverse fish assemblages, more stable bird populations and greater riparian forest production. The approaches used in the above studies have the potential to be used to identify domain changes in geomorphological and/or ecological river character brought about by upstream impacts of dams.

Mialhot et al. (2018) point out that whilst dam construction creates changes to catchment hydrology, dam operation produces the dynamic alteration of river flow. Thus, attempting to represent the impact of dams to downstream flows using simplistic representations of dam specifications (e.g., operating capacity, spillway design, crest height, etc), will result in over-simplistic results. It is preferable to apply knowledge of dam operations incorporated into dam outflow time-series to represent dynamic variations in flow that can then be assessed using a range of hydrological indices. Miailhot et al. (2018) assess the unimodality of the daily flow distributions and developed a 'degree of regulation' index to describe dam influence. Whilst there is a range of studies that have assessed the impacts of dam construction on downstream flows (e.g., Magilligan and Nislow, 2005; Matteau et al., 2009; Mei et al., 2017; Hecht et al., 2018), there are fewer studies that focus on actual dam operations. Detailed studies of dam operations include White et al., (2005) who used wavelet analysis on hourly flow data to identify operating cycles related to hydroelectric power production. Zimmerman (2010) also used hourly flow data to identify potential impacts to sub-daily flow regimes.

The identification of specific ways in which a dam can influence downstream flow conditions is difficult, due to uncertainty in dam operation status and characteristics. Whilst in-river dams may be non-consumptive in the long-term (unless they are diverting water out of the catchment), they can severely impact flow regimes in the short term. Similarly, dam operation may occur in short bursts, making the representation of the temporal characteristics of any hydrological impacts difficult. Lu et al. (2018) assessed multiple dam influences on downstream hydrology using hydrological modelling and post-bias correction. They found that whilst impacted rivers experienced reduced high-pulse counts and increased daily rise-and-fall rates they might also exhibit relatively unchanged monthly discharges.

In the US, the Nature Conservancy developed the Indicators of Hydrologic Alteration (IHA) to support hydrologic evaluation (Richter et al., 1996, 1997). The IHA originally utilized 33 hydrologic parameters. These were chosen to represent human-induced changes in the flow regime and included descriptors of intra- and inter-annual variability, and magnitude, duration, frequency, timing and rate of change of river flows. The values were computed for each year of record to allow identification of both inter-annual variability and trends through time relative to known impacts. The indicators were also used to assess modelled time-series of naturalized flows. The method can therefore be used to compare post-impact conditions with natural inter-annual variability. Additional characteristics have since included intra-daily variability or flow duration statistics. However, five components of river flow regularly identified as important to ecosystem health are: extreme low flows, low flows, high-flow pulses, small floods and large floods (Mathews and Richter, 2007). These components indicate how hydrological alteration downstream of dams can occur at a variety of temporal scales. At the broadest temporal scale large dams can alter inter-annual or seasonal patterns by storing winter high flows or spring snow-melt to be released at other times of the year (Li et al., 2017). At shorter temporal scales, daily variations in flow are created when hydroelectric power plants are managed in response to sub-daily changes of the electricity market (e.g., Moreira et al., 2018). The IHA has been widely used in the international literature. For example, recent applications have included assessment of hydrologic alteration induced by the Three Gorges Dam, China (Cheng et al., 2018), and climate-induced alteration of hydrologic indicators in the Athabasca

River Basin, Canada (Eum et al., 2017). However, several studies have used other hydrological indices to characterise flow regimes in addition to the IHA parameters. For example, Biggs (2000) used the number of events exceeding three times the median flow when investigating periphyton growth, and Booker et al. (2015) used the ratio of the first and second linear moment of daily flows and the predictability index of Colwell (1974) when investigating invertebrate distributions. It should also be noted that many hydrological indices can be correlated with each other (Olden and Poff, 2003), and with other landscape-scale predictors (e.g., temperature, distance inland, slope) relevant to ecological state (e.g., Crow et al., 2012).

Spatial aspects of hydrological alteration may also be important when assessing potential impacts of dams. In catchments with only a single dam, hydrological alteration will always be largest immediately downstream of the dam and will decrease with distance downstream as flow is typically augmented by downstream tributaries and gains from groundwater. However, dams are often constructed as part of larger schemes designed to route water through a series of dams. These schemes can be placed in a variety of spatial configurations such as in series along a river main stem or on tributaries of a main stem. Large schemes can also transfer water between locations on the natural river network by diverting water through canals or pipes. These spatial issues mean that maps of hydrological alteration (e.g., Mailhot et al., 2018; Radinger et al., 2018) and spatial indices may be informative when assessing impacts of dam schemes across catchments (e.g., Grill et al., 2015). There may also be impacts of dams at the broader regional scale. The study of Macnaughton et al. (2017) indicated that biological impairment consisting of significant relative biotic alteration from unregulated rivers was directly related to increasing flow alteration scores.

3 Representation of dams in the TopNet model

Flow time-series data calculated using hydrological models can be used to simulate both natural and altered flows downstream of hydro-power dams. NIWA's TopNet model (Bandaragoda et al., 2004) is an example of a hydrological model that has been previously been used in the development of water allocation scenarios and to assess flow management options. At a national scale, an uncalibrated version of TopNet has been applied to river-reaches across New Zealand. The accuracy of various aspects of this national coverage model have been quantified by McMillan et al. (2010), Booker and Woods (2014), and McMillan et al., (2016). At the catchment scale, various TopNet parameters can be calibrated to improve predictive power (e.g., Singh et al., 2017). Recent improvements to TopNet have included inclusion of processes intended to better simulate surface water–groundwater interaction (Yang et al., 2017).

The TopNet model allows representation of dams and lakes and so can be used to aid interpretation of downstream impacts of such features within water management scenarios. The TopNet national runoff model currently includes representation of 3820 natural lakes or artificial dams (Figure 3.1). However, it is important to understand the limitations of how lakes and dams are represented in large-scale hydrological models. The representation of dams within the TopNet model is described below. Subsequent comparison of simulated and observed downstream flow characteristics (for the Waitaki catchment) are then described in the next chapter.

Figure 3.1: Location of water bodies (lakes and dams) in the TopNet national runoff model.

Lakes and dams in the TopNet model are defined as surface stores in which water particles have longer residence times than normal stream channels. Lakes are treated as river reaches with additional attributes of storage geometry and a water level-discharge relationship. Dam features receive water from upstream reaches and surface and groundwater flows. Currently only shallow groundwater flows are represented in this model but deeper groundwater inputs will be represented in an updated TopNet groundwater module (Yang, 2017). In addition, evaporation losses and precipitation gains to the dam are represented.

Where detailed information concerning reservoir geometry is available, it is used to determine a relationship between water level (*h*); surface area (A_l); and dam storage (S_l). When such information is not available, it is assumed that A_l varies with *h* according to the following relationship:

$$A_l = c_l h^{d_l} \qquad c_l, d_l > 0 \tag{3.1}$$

where *c* and *d* are shape parameters (e.g., in Lake Ohau, c=40451; d= 1.5).

There are currently 3820 surface water bodies represented using the above method in the TopNet national river simulation model. Of these, 2355 have c and d parameters defined. The relationship between lake storage and lake surface height is obtained from the following relationship (reservoir surface area is equal to the rate of change in volume with height):

$$\frac{dS_l}{dh} = A_l(h) \tag{3.2}$$

The change in lake storage S_l with time *t* is given by:

$$\frac{dS_l}{dt} = Q_{l-in} - Q_{l-out} + Q_{sub} + (p - e_{pot})A_l \tag{3.3}$$

where Q_{l-in} is the flow rate at the upstream reach junction (of which there may be more than one), Q_{l-out} is the outflow rate to the downstream reach junction, and Q_{sub} is the input to the lake from the adjacent basin. Discharge from the basin (Q_{sub}) is equal to $q_o A$. The inflow rate from an upstream reach is given by *qw*, where *w* is the reach width and *q* the discharge per unit width.

The outflow rate to the downstream reach is a function of water level height in the reservoir *h*. By default, the stage-discharge relationship is given by:

$$\begin{aligned} Q_{l-out} &= 0 && h \le h_l \\ Q_{l-out} &= a_l(h - h_l)^{b_l} && h \ge h_l \end{aligned} \tag{3.4}$$

where and a_l and b_l are constants, h_l is the height of the lowest point of the reservoir outlet above the reservoir bottom. Other stage-discharge relationships may be used where available.

4 Flow characterisation

For this project we used data from the following sources:

1. Simulated flow time-series from the national TopNet model as described above (where lake geometry is represented by empirical parameters). The daily data was derived from an hourly output time-series and the model used Strahler 1 sub-catchments, NZ digital network (version 2) and the 2018 updated evapotranspiration sub-model.
2. Observed or calculated inflows to dam reservoirs.
3. Observed flows recorded before and after establishment of hydro-power schemes.
4. Observed outflows from dams, including flows over the spillway.

The data were derived for several locations relating to the hydro-power generation scheme upstream of the Waitaki Dam, the most downstream part of the Waitaki Hydropower Scheme.

To demonstrate a methodology for assessment and quantification of downstream impacts of dams and managed storages on river flows, pre- and post- storage management flows (1928-1948 and 1993-2017 respectively) in the highly impacted Waitaki catchment (Waitaki Dam) were first compared. Modelled flows (produced by the TopNet model) were then compared against 'observed' flows, for the post-storage management period (1993-2017).

The water resources of the Waitaki River basin and associated lakes (Figure 4.1) are of national significance, not least because of the major electricity generation activities in the catchment, but also because of the recreational, ecological and cultural values associated with the river environment. Information relating to observed and simulated natural flows have previously been collated by Henderson et al. (2004) who were engaged by MEL to quantify the water resources of the Waitaki River above Waitaki Dam. The surface water management upstream of the dam is complex with three large natural lakes (Tekapo, Pukaki and Ohau), and four smaller lakes (Lake Aviemore and the three headwater lakes that form Lake Benmore).

The natural mean flow at the Waitaki Dam and Ohau Weir for 1926-2003 was determined by Henderson et al. (2004) to be 363.1 m^3/s and 81.5 m^3/s respectively. These estimates were based on analysis of flow, lake level and rain records from the Waitaki catchment and derived from the Water Resources Archive (NIWA); the Power Archive (Opus International Consultants on behalf of MEL); the Climate Database (NIWA); and Environment Canterbury. Lake inflows were inferred from records of upstream lake outflows and lake-level data which have been collected since 1925 in the Waitaki, and since 1926 at Ohau.

Observed and simulated naturalised lake outflow for the Waitaki Dam are shown in Figure 4.2 (the estimations were checked against an independent record measured by Environment Canterbury at Kurow). Flows over ten years were found to be consistent between the two sites by Henderson et al. (2004). The observed data can be broken into four distinct periods (A, B, C and D).

- In period A, there are no large controlled storages upstream of the Waitaki Dam, and strong correspondence between observed and naturalised flow time-series is evident (Figure 4.2). This is mainly because Lake Waitaki has a small volume relative to the flow regime

- Period B represents the period in which flows are impacted by construction of the early lake control structures at Lakes Pukaki and Tekapo (upstream of the Waitaki Dam) and subsequent storage management.
- Period C represents the period of time from which observations were taken at shorter intervals (sub-daily), and up to the commissioning of the Pukaki High Dam. This increased the amount of managed storage in the catchment significantly.
- Period D represents the relatively uniform period of operation and infrastructure since 1979.

The four periods have quite distinct characteristics due to the differing upstream conditions and sampling frequencies. Analysis of the impacts of dam and reservoir operations downstream of the Waitaki Dam can be achieved by comparing Period A (pre-impact) with Period D (post-impact), or by comparing simulated natural flows with recorded operational flows over the same period.

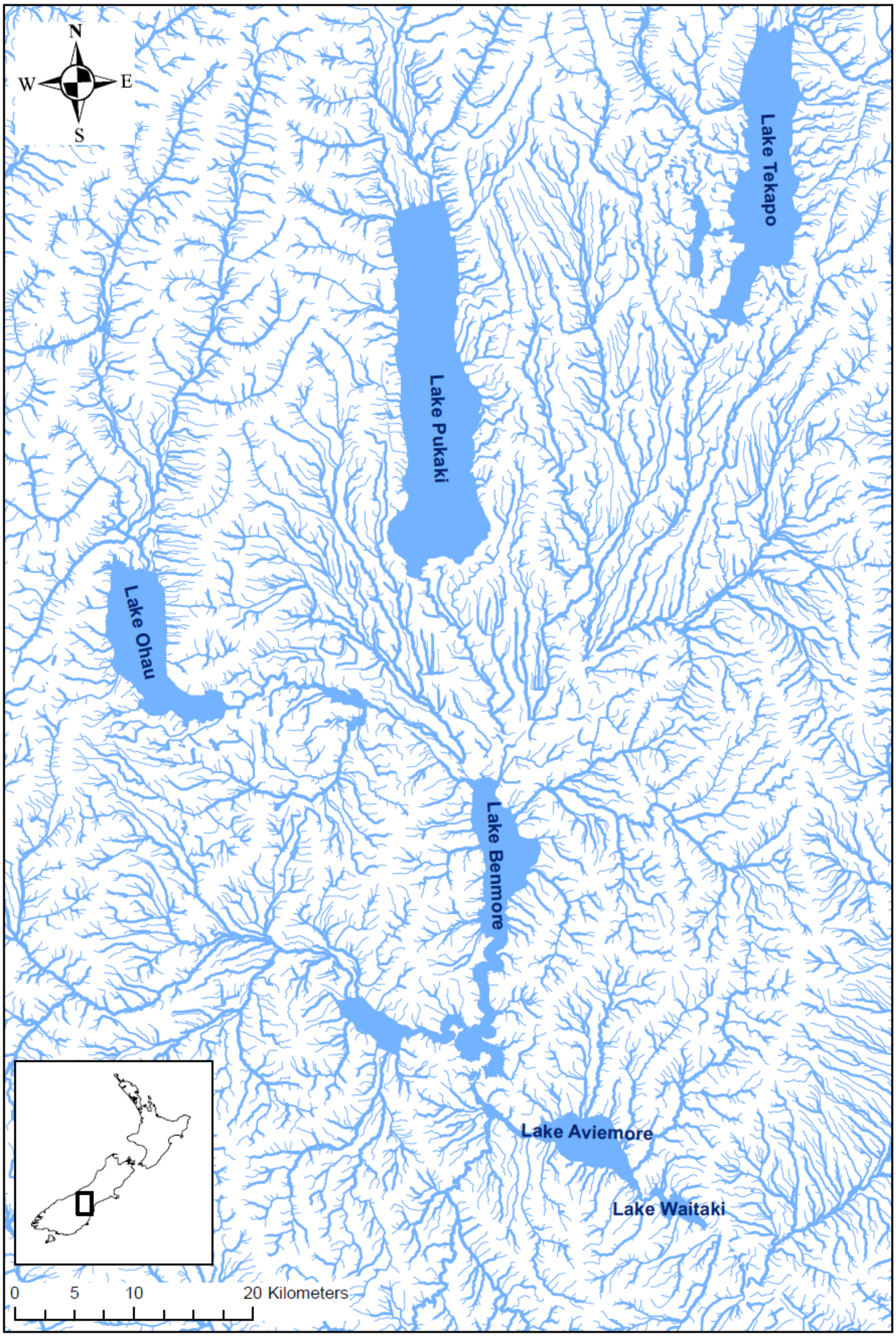

Figure 4.1: Location of Lake Tekapo, Lake Pukaki, Lake Ohau, Lake Benmore, Lake Aviemore, and Lake Waitaki.

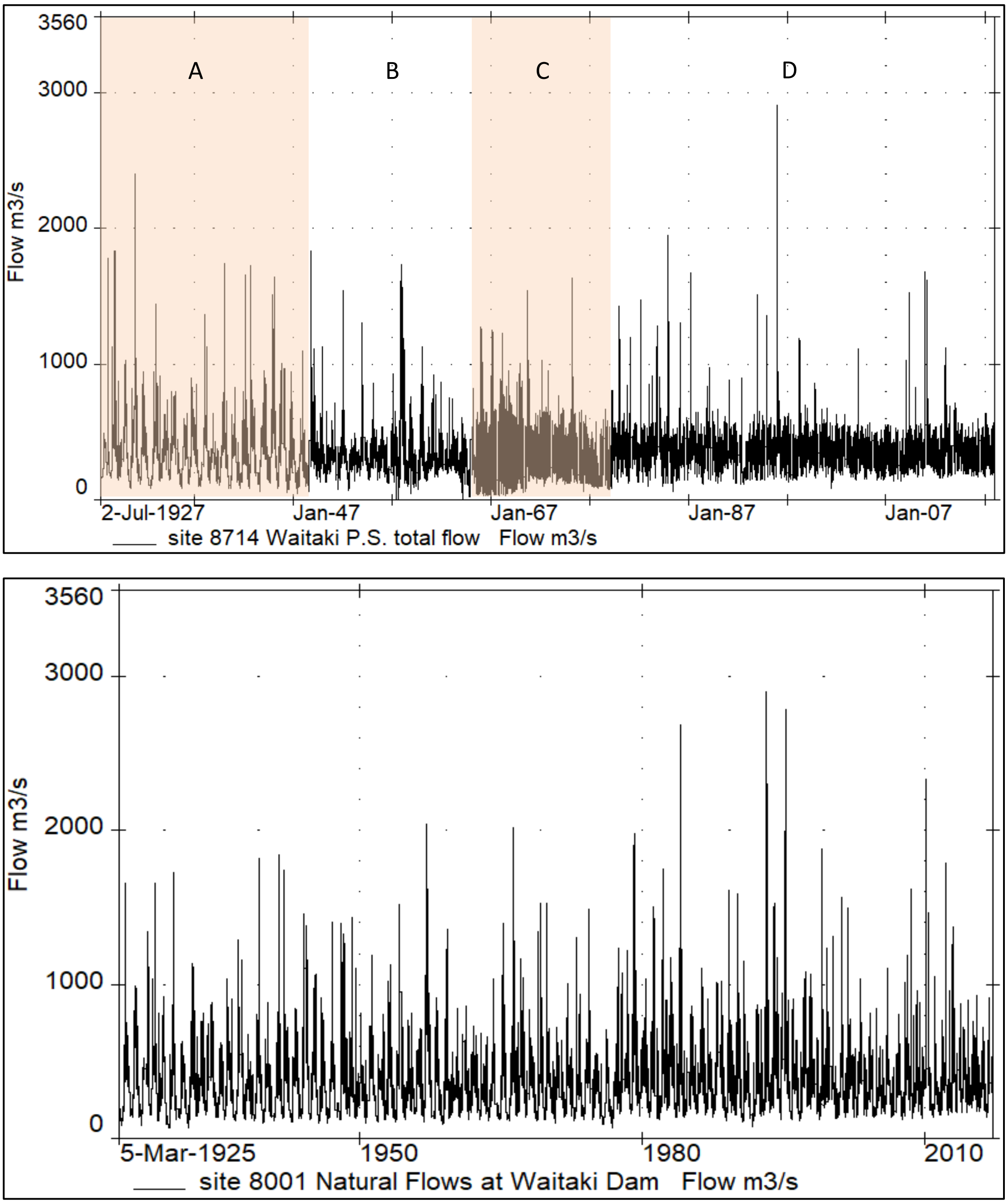

Figure 4.2: Observed (upper graph) and naturalised flows (lower graph) downstream of the Waitaki Dam. Shading represents periods used to represent pre-impact (A) and post-impact (D).

4.1 Dam flow attenuation

The impact of the Waitaki Dam on downstream flows can be seen by comparing simulated (naturalised) flows in the river below the dam (as shown in Figure 4.2 lower graph), against observed dam outflows combined with observed flows from the dam spillway. The (3-hourly) data from 1999 to 2002 (Figure 4.3) shows that large inflows to the reservoir occurred in 1999, 2001 and 2002. However, flow releases via the dam spillway are only seen in 1999 and 2001. Generally, there is very little flow above the dam outflow capacity, and spill events are managed to conserve water stored in reservoirs upstream of the dam for power generation. However, downstream winter flows are often higher than total inflows, as storage from upstream reservoirs is released for power generation during the winter.

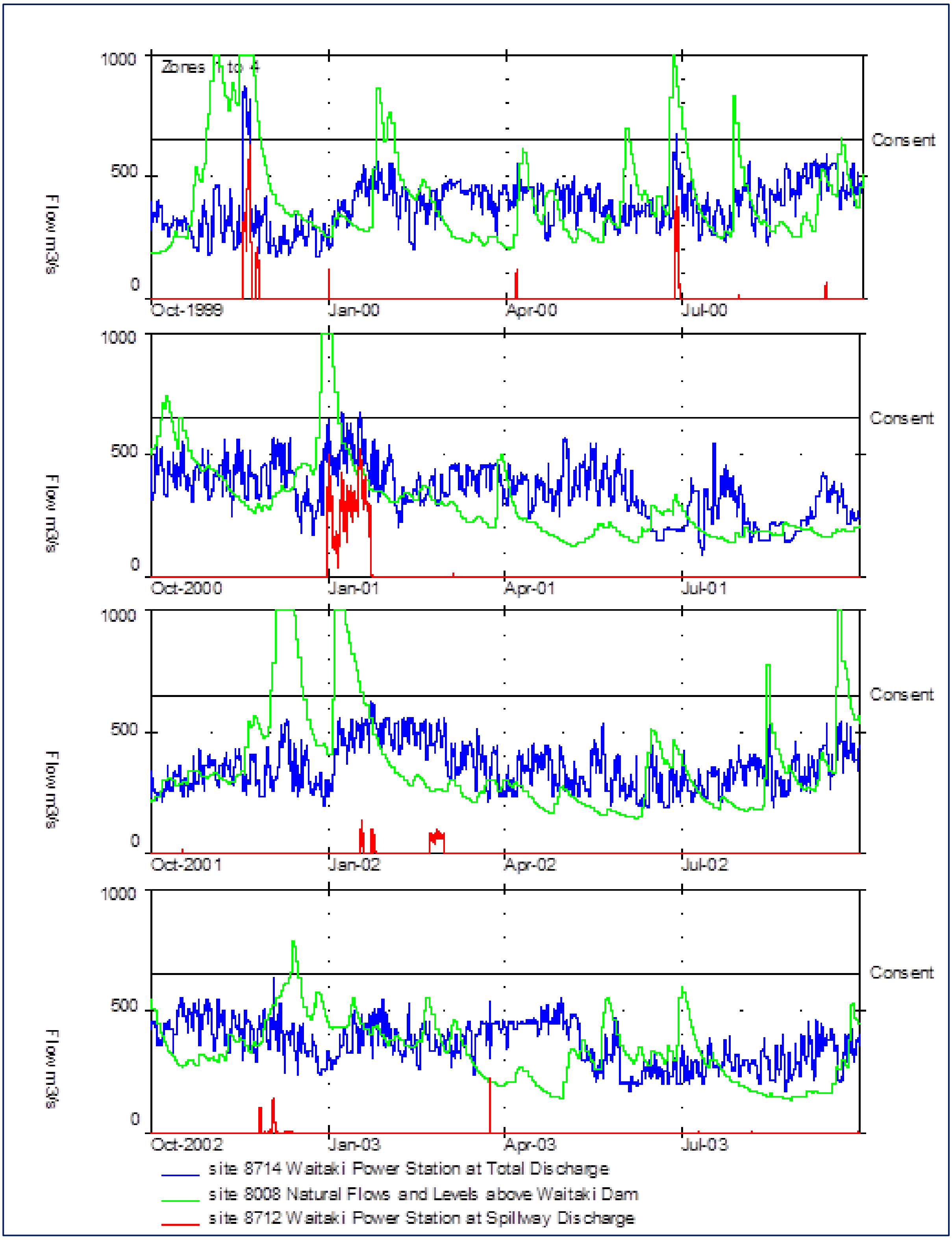

Figure 4.3: Flows at Waitaki Dam for the water years 2000-2003. Blue is recorded total flow past Waitaki Dam, green is natural flow, and red is recorded spill (included in total flow) (Henderson et al 2004)**.**

4.2 Statistical characterisation of downstream flows

The biologically relevant hydrologic attributes (or 'Indicators of Hydrologic Alteration (IHA)) of Richter et al. (2006) can be divided into five groups relating to mean monthly; annual maxima; timing of maxima; frequency and duration of high and low flows; and rate and frequency of change in flow conditions (rising or falling hydrographs). As these statistics represent inter-annual attribute variation, they present a good foundation to compare natural flow and attenuated flows. See Appendix A for full description of the IHA indices.

Some of the IHA indices are unambiguous because they have no input parameters (e.g., mean monthly flows). However, some of the IHA indices require input parameters for their calculation. For example, high and low pulses must be defined in terms of flow percentiles exceeded. We applied the default settings for determining all IHA indices. For example, we used the 30th and 70th percentiles to define the natural range of variability. See Appendix B for IHA parameter settings applied in this study.

In addition to the IHA indices, Richter's 'range of variability approach' (RVA) allows direct comparison of IHA indices between pre- and post-impact flows. This methodology consists of the following steps:

1. Define the data time-series for representation of pre- and post-impacted flows.
2. Calculate the hydrological statistics to be used for each year, for each of the given time-series.
3. Compute measures of central tendency and variation for each of the annual (and daily if required) statistics calculated in step 2.
4. Calculate the percentage change in annual (and daily if required) statistics between pre- and post-impacted flows.

We applied the IHA software (TNC, 2018) to calculate the IHA indices (Table 4-1) and therefore apply the RVA approach to flow time-series from the Waitaki catchment. See Richter et al. (1996) for a full explanation of the IHA indices. In its simplest form, the RVA method requires a time-series of flows for the river or site under investigation. A set of statistical parameters are used to characterise hydrological conditions in each year of the time-series. These parameters are known as the Indicators of Hydrologic Alteration (IHA), and provide information designed to describe fully the natural flow regime, including those components that are ecologically significant. Measures of spread are then used to quantify variation in these parameters between years. Different measures of spread can be employed depending on whether it is assumed that the data are parametrically or non-parametrically distributed. Richter et al. (1996) stated that the parameters and their range of variability are "intended for use with other [unspecified] ecosystem metrics" to inform management activities and for setting environmental flow regimes.

Table 4-1: Hydrological indices used in the Indicators of Hydrological Alteration (IHA; Richter et al., 1997) .

Group	Parameter description	Abbreviation
1) Magnitude of monthly flows	Mean value for each calendar month	eg. MeanSep
	Median value for each calendar month	eg. MedianSep
2) Magnitude and duration of annual extremes	Annual minima 1-day means	Mean1DayFlowMins
	Annual minima 3-day means	Mean3DayFlowMins
	Annual minima 7-day means	Mean7DayFlowMins
	Annual minima 30-day means	Mean30DayFlowMins
	Annual minima 90-day means	Mean90DayFlowMins
	Annual maxima 1-day means	Mean1DayFlowMaxs
	Annual maxima 3-day means	Mean3DayFlowMaxs
	Annual maxima 7-day means	Mean7DayFlowMaxs
	Annual maxima 30-day means	Mean30DayFlowMaxs
	Annual maxima 90-day means	Mean90DayFlowMaxs
	Number of zero flow days	ZeroFlowDays
	Base flow index	BFI
3) Timing of annual extremes	Julian day of annual maximum	JulianMin
	Julian day of annual minimum	JulianMax
4) Frequency and duration of high and low pulses	Number of low pulses within each water year	nPulsesLow
	Mean duration of low pulses	MeanPulseLengthLow
	Median duration of low pulses	MedianPulseLengthLow
	Number of high pulses within each water year	nPulsesHigh
	Mean duration of high pulses	MeanPulseLengthHigh
	Median duration of high pulses	MedianPulseLengthHigh
5) Rate and frequency of flow changes	Mean of all positive differences between daily values	meanPos
	Median of all positive differences between daily values	medianPos
	Number of all positive differences between days	nPos
	Mean of all negative differences between daily values	meanNeg
	Median of all negative differences between daily values	medianNeg
	Number of all negative differences between days	nNeg
	Number of hydrologic reversals	Reversals
6) Data checks	Number of days with no records	GapDays

A more advanced technique can be employed where pre-impact and post-impact scenarios are available. In these cases, the degree of hydrological alteration can be assessed by comparing the pre- and post-impact scenario distributions drawn from annual time-series for each of the parameters. In the case of proposed schemes, or where impacts have been in place since before hydrological records began, no pre- and post-impact data will be available. In these situations, synthetic time-series can be generated to represent the natural (or naturalised) and altered (or managed) situations which can then be compared.

4.3 Pre- and post-impact flows below Waitaki Dam

Analysis of two periods within the observed Waitaki Dam data demonstrates analysis that can be used to define the impact of dams on flow characteristics. Flow characteristics for the pre-dam construction period: 1928-1948 (Period A as shown in Figure 4.2) were compared with the post-dam construction period: 1993-2017 (within period D).

In Figure 4.4 , the variability of mean monthly flows downstream of the Waitaki Dam, before and after upstream dam construction are shown in a box and whisker plot. Mean monthly flows are greater in the post-construction period in the winter months (May to September) and lower in the four summer months (November to February). There are only minor between-month variations in mean monthly flows for the flow altered period. However, this pattern only partially explains differences in the flow regime between the natural and altered periods.

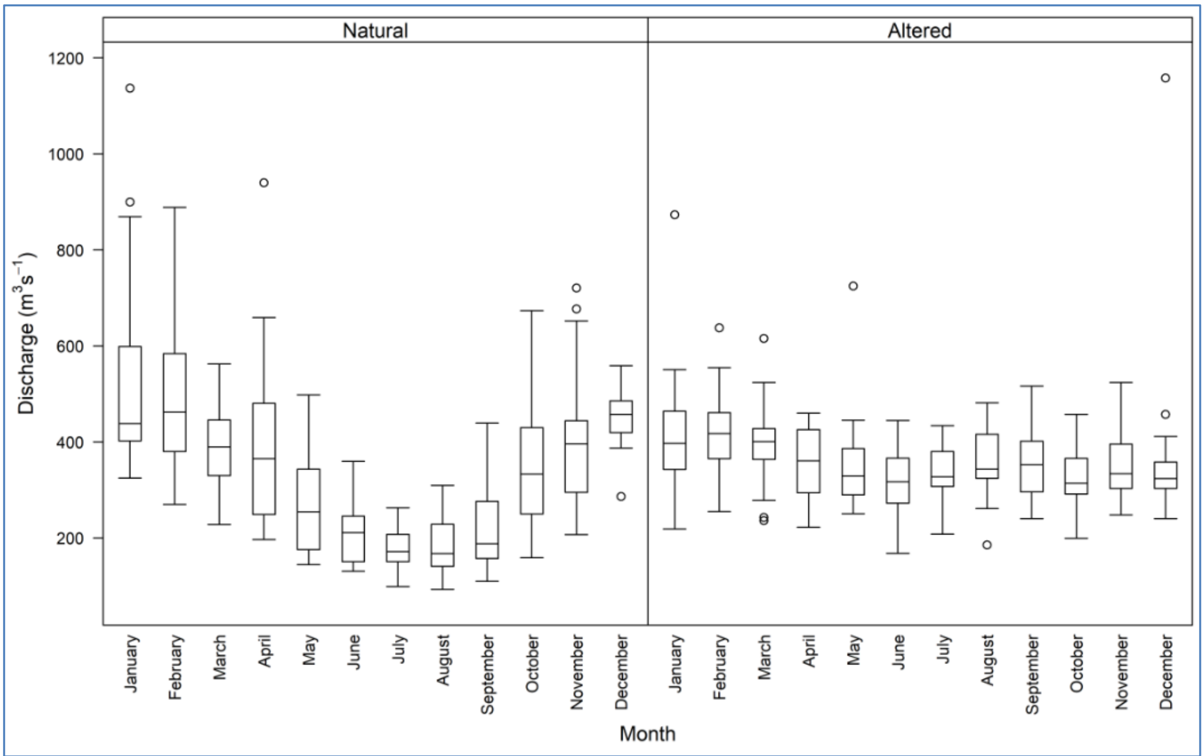

Figure 4.4: Box and whisker plot of mean monthly discharge downstream of the Waitaki Dam before and after upstream dam construction.

Figure 4-5 shows the frequency distributions of hydrological indices calculated for natural and altered flow conditions. The number of flow reversals that have occurred since the river has become more managed has increased, representing the increase in controlled flows. The mean rate at which the flow hydrograph both rises and falls is also increased within altered flows, indicating a more rapid increase and reduction of flows from the dam. Similarly, the altered flow hydrographs exhibit both shorter rising and recession limbs. The base-flow index also increases from a mean of 0.35 to 0.6 in the post-impact time-series, as the environmental flows released from the dam maintain higher low flows. It was also observed in the data that minimum flows occurred at any time of year under managed conditions (rather than just in Autumn as in the pre-impact data). Finally, the duration of both high- and low-flow pulses (defined as flows outside the median plus or minus 25% respectively) were reduced in the altered time-series; whereas the number of high pulses increased – this is again symptomatic of controlled releases from reservoirs or dams.

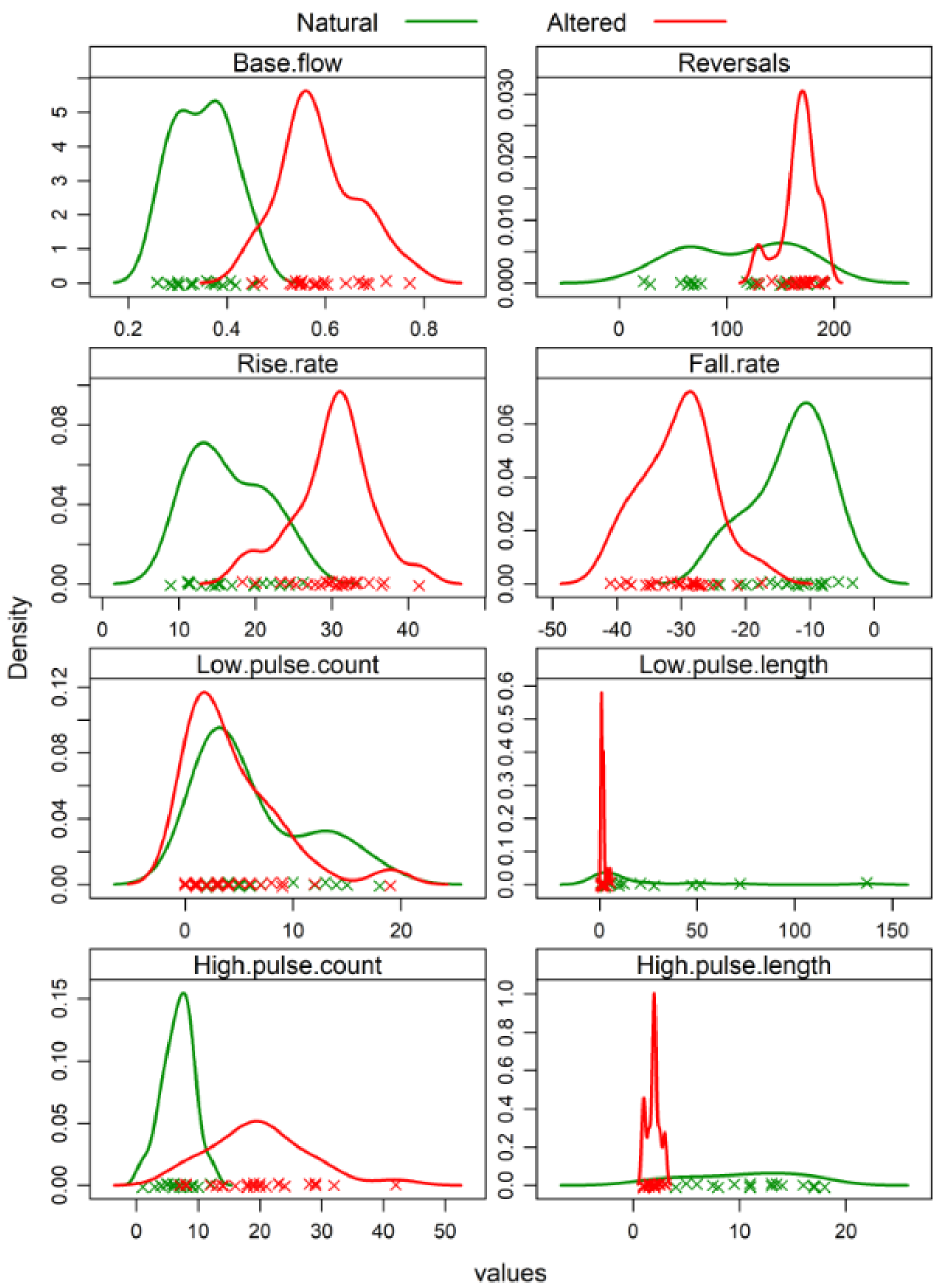

Figure 4-5: Pre- and post-impact flow characteristics on the Waitaki River. Crosses indicate x-axis values on which solid line is based.

The frequency distributions of the 1, 3, 7, 30 and 90-day minimum and maximum of natural and altered flows are shown in Figure 4.6. The data confirms that the predominant post-impacted flows exhibit a smaller range (i.e. they have higher low flows and lower high flows) regardless of the duration used to define these indices.

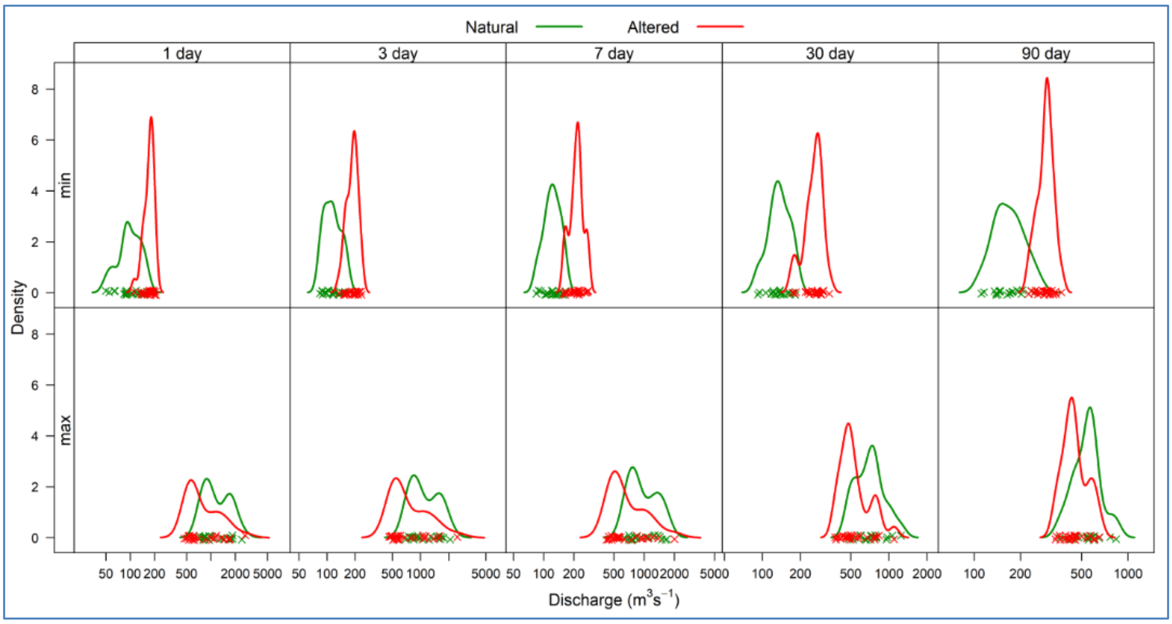

Figure 4.6: Frequency distribution of the 1, 3, 7, 30 and 90 day minimum and maximums of natural and altered flows. Crosses indicate x-axis values on which solid line is based.

Figure 4.7 shows pre- and post-impacted monthly median flows for the Waitaki. The figure illustrates the months in which the central tendency (median) of the post-impact situation falls outside of the range of the pre-impact natural variation (as defined by the 30th and 70th percentile boundaries), thus indicting that flow alteration that is outside the range of natural variability. The figure also illustrates the pattern seen in the three previous graphs whereby winter flows (May to September) are generally greater, and summer flows are lower.

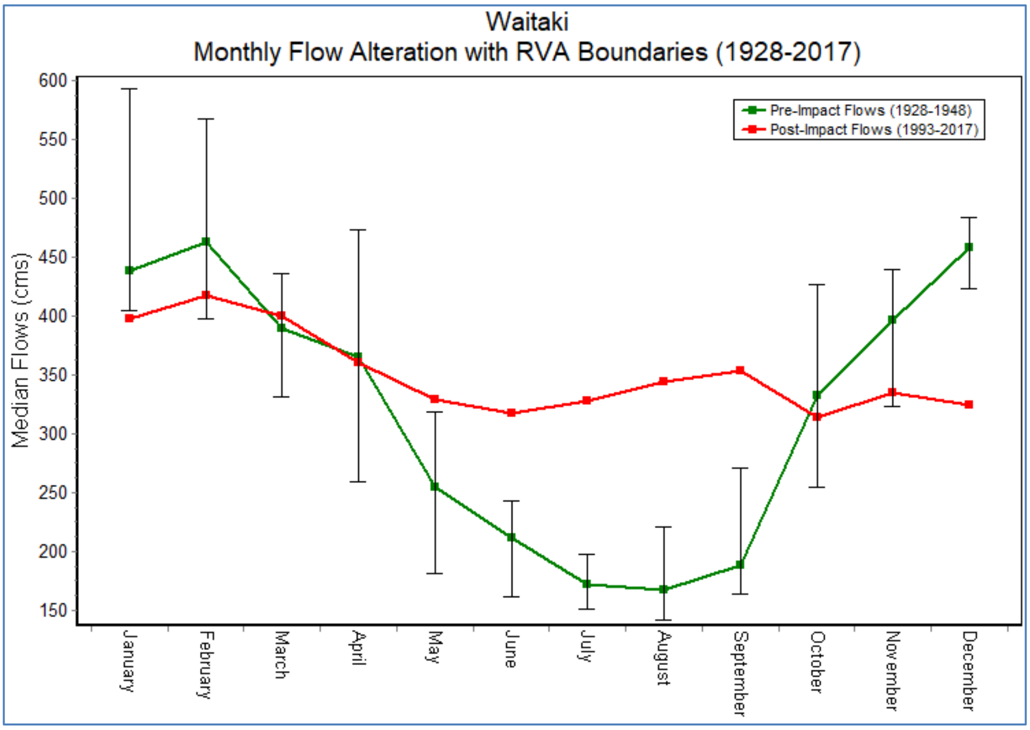

Figure 4.7: Monthly median flow before (1928-1948) and after (1993-2017) dam construction. Black bars show range of natural inter-annual variability as defined by the 30th and 70th percentiles.

The magnitude of flow alteration can also be seen in the changed flow duration curve characteristics in Figure 4.8.

As the comparison between pre- and post-impact flows compared different time periods (i.e. 1928-48 and 1993-2017) there is a possibility that some long-term differences could be caused by different climatic conditions experienced within each period. However, a small difference in mean flow between the two periods of 355.4 m^3/s and 366.5 m^3/s respectively indicates a similar long-term water balance. This difference indicates mean flow was 3% higher during the post-impact period.

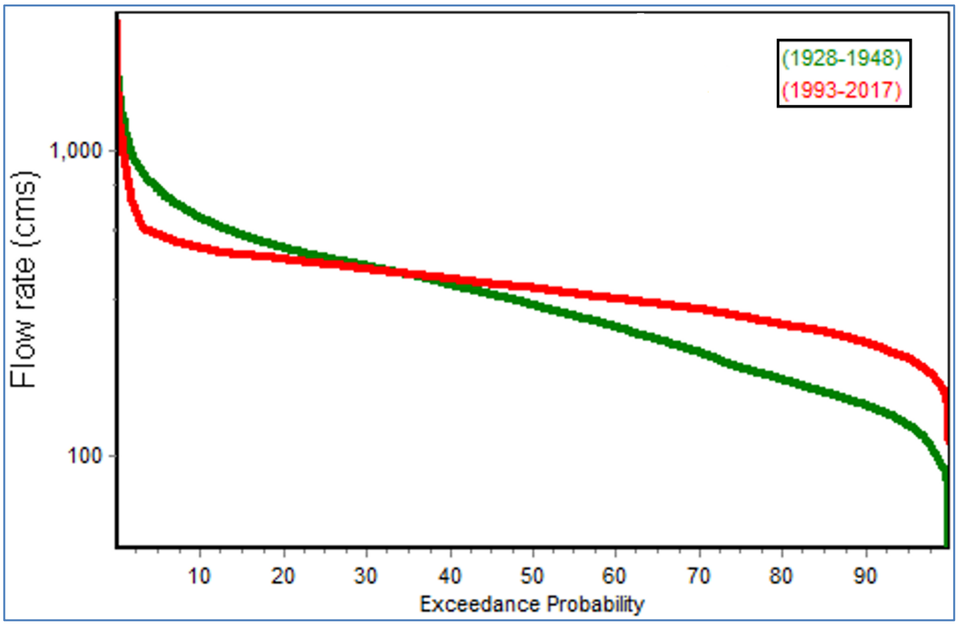

Figure 4.8: Flow duration curves before (1928-1948) and after (1993-2017) dam construction. The y-axis is a log scale.

4.4 RVA method

The RVA method can be used to compare pre-impact and post-impact IHA parameters whereby Hydrological Alteration Values (HAV) shown in Figure 4.9 represent the degree of alteration of each IHA index between pre- and post-impact such that:

$$\mathrm{HAV} = \frac{\text{post impact IHA} - \text{pre impact IHA}}{\text{pre impact IHA}} \tag{4.1}$$

RVA categories relate to the inter-annual range of each IHA observed in the pre-impact data, such that a low RVA category means that most observed values were ≤ the 30th percentile of the observed range; a medium RVA category means that most observed values were between the 30th and 70th percentile; and a high RVA category means that most observed values were > the 70th percentile. Figure 4.9 shows the highest HAV's calculated for the Waitaki where the colour of the bar indicates the RVA category. Positive HAV's therefore represent an increase of observations in the post-impact time-series that fell within the RVA category (of the pre-impact distribution), whilst negative values indicate a reduction in the number of observations. Interpretation of Figure 4.9 confirms decreased summer, and increased winter, post-impact flows; relatively large increases in the mean (1, 3, 7, 30 and 90-day) minimum flows, and relatively small decreases in mean maximum (1, 3, 7, 30 and 90-

day) flows. Also of note, (and not so far evident from the previous diagrams) is that there are expected rises in both the mean rate of flow increase and mean rate of flow decrease, and in the mean number of flow reversals per year.

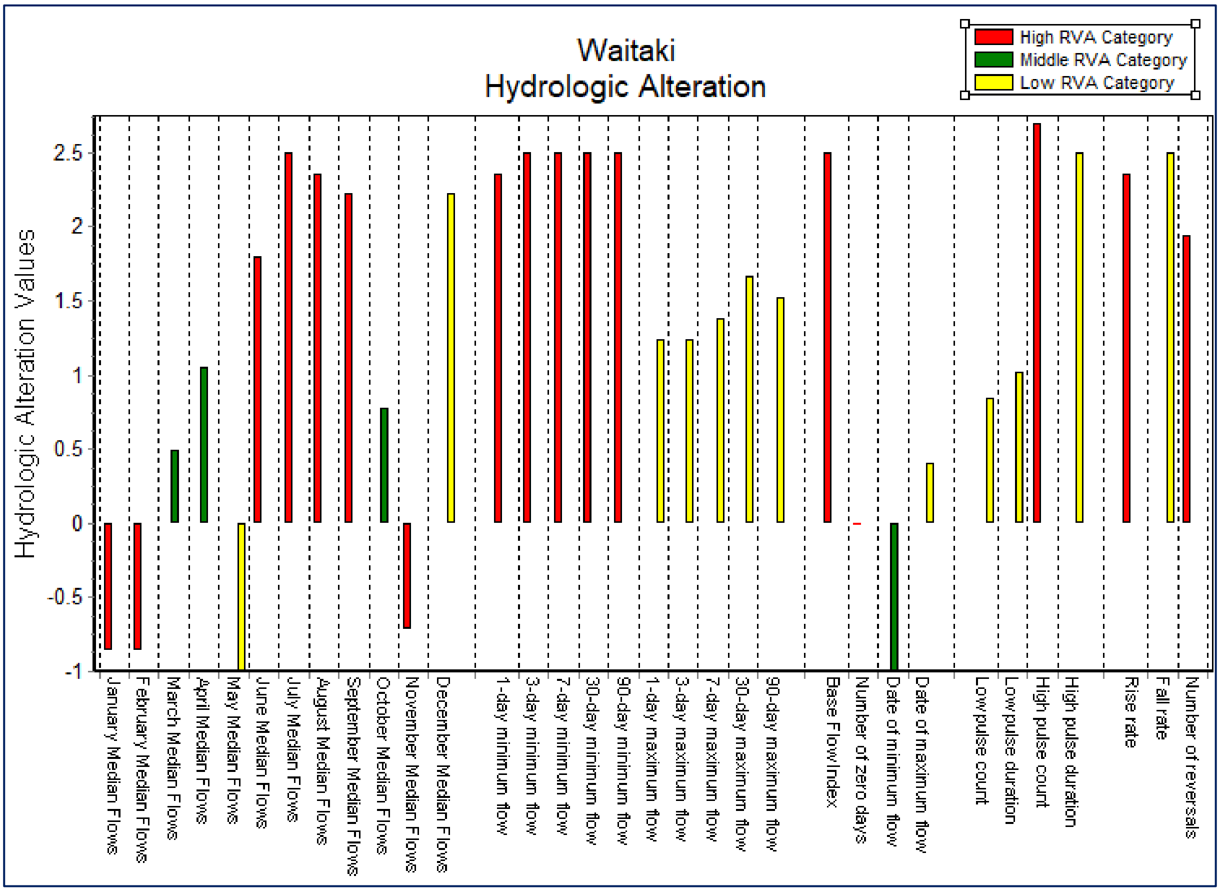

Figure 4.9: Highest Hydrological Alteration Values for pre- and post-impact on the Waitaki River.

4.5 TopNet modelled post-impact flows at Waitaki Reservoir

To assess the extent to which modelled flows (from the TopNet Model) can be used to represent the impact of dam characteristics, a comparison of observed and modelled flow time-series for the post-impact period (1993 to 2017) was made. Figure 4.10 shows that TopNet (uncalibrated national version) under-predicts the managed low flows downstream from the Waitaki Dam and over-predicts all but the largest managed peak-flows from the dam. This is because TopNet is simulating each dam within the Waitaki catchment hydroelectric scheme as a simple reservoir, for which the storage-area and storage outflow relationships are represented by just two parameters (as described in section 3). Whilst a greater representation of dam operating conditions could be made, this is currently not implemented in the national model. Existing TopNet simulations therefore are unable to represent real operationally induced changes in downstream flow conditions even over the medium to long-term.

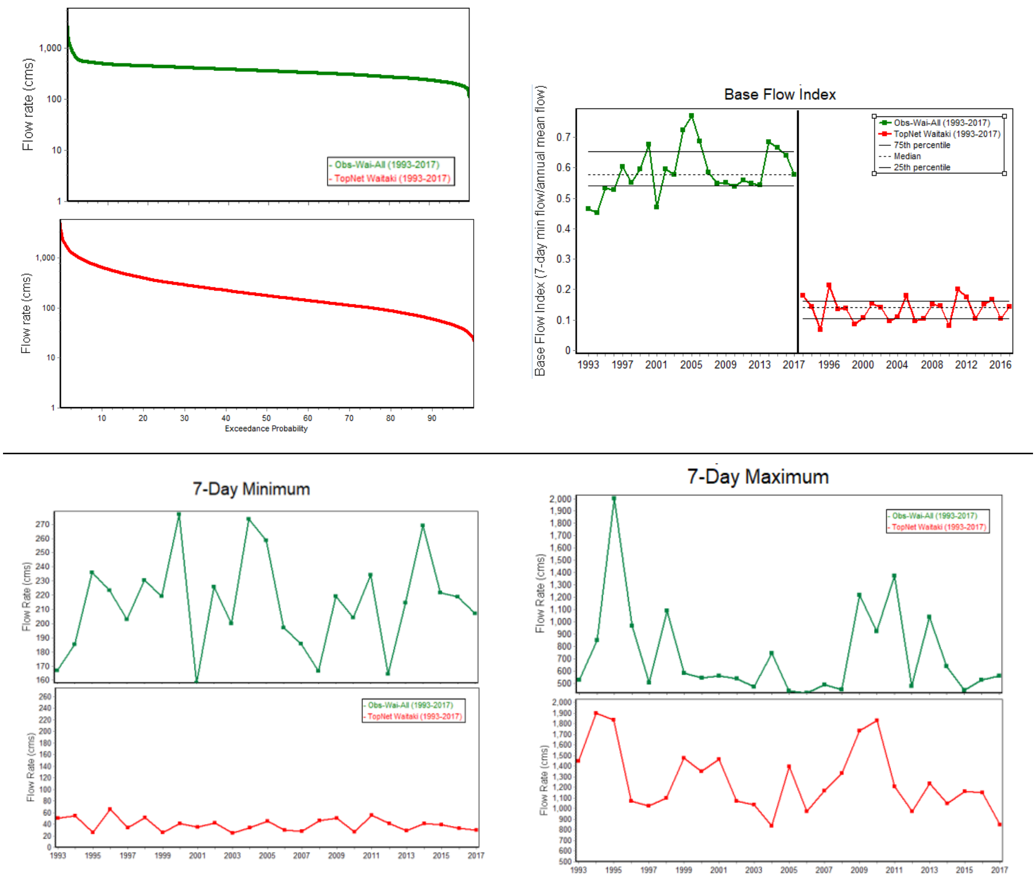

Figure 4.10: Observed flow (green) and TopNet modelled flow (red) for the Waitaki from 1993 to 2017.

A more complex example in which simulated and observed flow data cannot be so easily compared is shown in Figure 4.11. In this case, the TopNet model has been used to simulate flows downstream of the Ohau Weir (mean flow 54.2 m^3/s). However, in addition to a natural channel linking drainage from the Ohau Weir to Lake Ruataniwha (mean flow 12.6 m^3/s), a canal carries over 80% of the total flow between the two lakes (i.e. estimated mean flow 66.34 m^3/s).

Whilst flow data from the natural channel between the lakes was available, canal flow was not available. Total outflows from the lake (estimated by Henderson et al. (2014)) over a 10-year period (representing combined river and canal flow) are shown in Figure 4.11. The TopNet model is approximately 30% lower than the estimated total outflows from the lake. This discrepancy represents the combined errors within both the TopNet model and the outflow estimates. The variability of estimated observed flow is less than that predicted by the TopNet model in which flows are influenced by the amount of storage within the lake (represented by the area-volume lake level relationship described in section 3). It is likely, however, that actual flow releases from the lake via the canal are even more variable than this and managed on a daily operational basis determined by electricity supply and demand.

The uncertainty related to the representation of managed flows has implications when TopNet simulations are used in assessment of flow and water availability downstream of non-consumptive structures, which whilst not significantly reducing the total annual water availability, will change seasonal, monthly and even daily water availability downstream. For this reason, we suggest that the current national TopNet model simulations are not appropriate to be used to represent the "altered flow scenario" at locations downstream of dams as they do not currently reflect the variability introduced by dam operations. Similarly, the national TopNet model simulations would have difficulty in representing natural flows, because they include a simplified representation of engineered structures (albeit based on empirical formula). By recourse then, it is suggested that long time-series that include pre- and post-dam periods be used to assess downstream impacts unless simulations can be developed to represent the statistical behaviours of operational conditions, or naturalised flows can be reconstructed from observed reservoir inflow time-series.

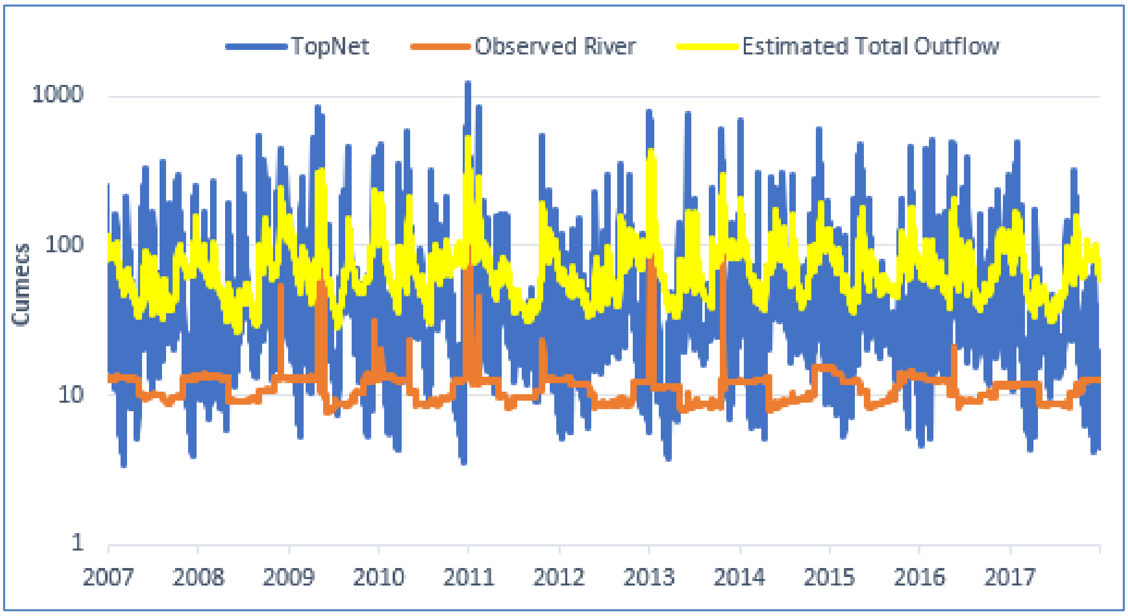

Figure 4.11: Flow time-series for Ohau Weir for 2017 showing estimated canal, observed river and TopNet modelled total outflows.

5 Discussion

Dams and reservoir management can exert major impacts on river hydrology, particularly with respect to low flows, peak flows and inter-annual variability. Most studies indicate that the frequency, duration and magnitude of low flows are increased after dam construction, and that the frequency, duration and magnitude of peak flows are decreased (Magilligan and Nislow, 2005). These trends were largely evident in the changes between pre- and post-impacted flows identified in the Waitaki River flow time-series (downstream of the Waitaki Dam).

Takes from lakes and rivers are often set at high rates during periods of high flow so that available storage can be used to capture and then release water at times when it is most needed to meet demand. The power station consents for water use in the Waitaki basin for example, are generally greater than available flow. These relatively high consent rates allow power stations to use high river-flows, typically within time scales of less than one week. Figure 5.1 shows the differences between the natural upstream flow to the dam, and downstream (recorded) flow releases (from upstream storage). For this to happen, upstream inflows to the catchment in spring/summer are stored in Lakes Pukaki and Tekapo until March to cater for the winter electricity demand at that time. This is similar to the long-term analysis shown in Figure 4.7.

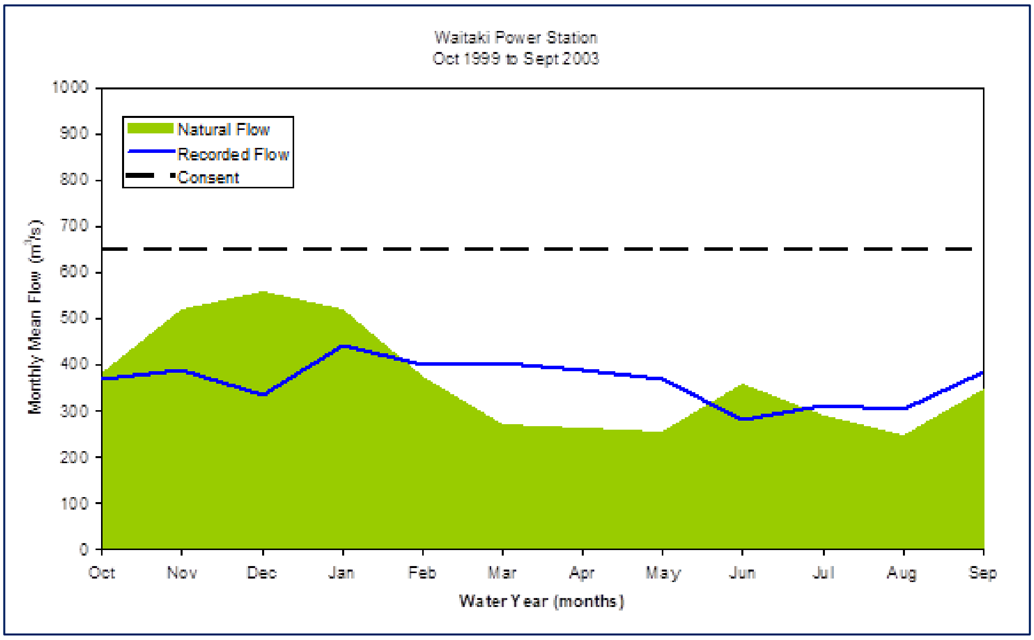

Figure 5.1: Mean monthly flows at Waitaki Dam for the water years 2000-2003. Blue is recorded total flow as monthly averages over the four years. Green is simulated naturalised flows (after Henderson et al.,2004).

Whilst statistical measures of the change in hydrological characteristics of a river can be used to represent the impacts of dams, the extent of such changes will also depend on the initial catchment characteristics, the climatic regime of the location, dam storage capacity and the operational regime of the dam. Ideally, a comparison of pre- and post-dam flows (as provided in Section 4.3) would be made to assess such impacts. Where possible comparison of pre- and post-dam flows should be accompanied by comparison of pre- and post-dam climatological conditions. This would provide an assurance that any differences in hydrological patterns were purely driven by dam operations rather than climatological factors. This analysis is not always possible due to lack of pre- and post-dam flows or consistent long-term climatological data. In the absence of pre-impact data, an alternative approach may be to naturalise observed lake outflow data (using upstream observed reservoir inflows), or to simulate both natural and altered states using hydrological models.

Regarding simulation using hydrological models, the following sources of uncertainty may be of concern:

- uncertainty produced within flow simulations (with/without dams);
- accurate representation of dam management (general operating rules that do not include the influence of market pricing and competition); and
- assumptions made to compensate for the uncertainties described above, and likely impact.

In this work we compared altered and naturalised flow regimes as per the methods suggested by Richter et al (1996; 1997). Recently it has been suggested that natural flow regime may not necessarily be the most appropriate baseline against which to compare altered flow regimes (Stewardson et al., 2017). This is particularly the case where a river has a long history of flow alteration (Acreman et al., 2014). In these situations, it may be more appropriate to design environmental flows to achieve specific ecosystem functions irrespective of the natural flow regime. However, this approach requires that strong relationships between flow regime components and in-stream values are established, and that mechanisms for effective adaptive management are in place. See Gregory et al. (2006), Poff et al. (2010) and Booker (2018) for further details. One example of linking flow regime components and in-stream values is provided by Macnaughton et al. (2017) who developed a method which represented biotic alteration of fish communities resulting from hydrological alteration.

It should be noted that whilst the IHA indices were selected to represent ecologically-relevant aspects of the flow regime, the IHA-RVA method provides a purely hydrological analysis. This method provides an objective basis for quantifying hydrological alteration. However, to be used for environmental flow setting, the method should be placed within a larger sequence of steps following the ELOHA framework or similar approach. This framework would start with developing hypotheses which relate in-stream values to hydrological characteristics, followed by monitoring of ecological state and the potential for long-term adaptive management of flow regimes.

In New Zealand the conflicting demands for natural resources are assessed within an “effects-based” resource governance framework; the Resource Management Act (RMA). The RMA has driven the framework for environmental flow setting described by the Ministry for the Environment (Figure 5.2; MfE, 1998; MfE, 2008) and influenced the need to set water resource use limits in the NPS-FM (MfE, 2015). The RMA’s values-based framework and MfE’s guidelines for assessing environmental impacts are ideally fulfilled through a comparison of flow management scenarios and their consequences for both in-stream values (e.g., ecosystems) and out-of-stream values (e.g., reliability of supply or electricity production).

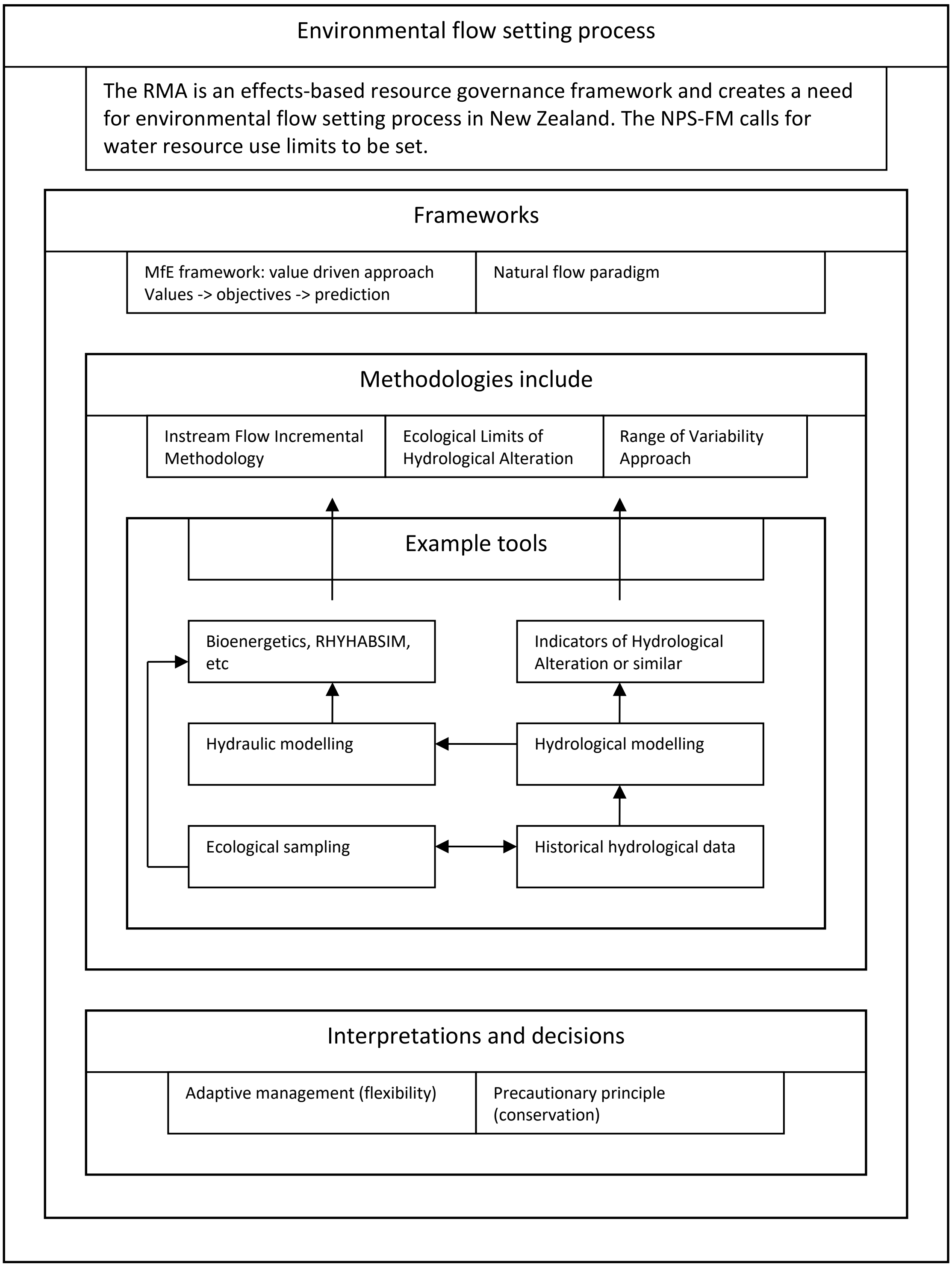

Figure 5.2: Conceptualisation of the environmental flow setting process in New Zealand.

Application of the RVA through comparison of a suite of IHA indices calculated from two flow scenarios revealed that this method does provide a useful framework for quantifying proposed or historical changes to natural flow regimes. The method provides potentially useful information on several aspects of the flow regime including: seasonal patterns; floods, droughts, and rates of change (flashiness). However, there are several technical considerations that need careful consideration when applying this method. These considerations relate to several issues:

- a relatively long hydrological record is required;
- ideally historical flow data would be available from pre- and post-alteration periods, or a simulated natural flow record could be generated;
- the record should be checked for trends and repeating patterns using regression techniques because the effects of long-term climate change, cyclical climatic variations, land use changes and abstractions may be present in the hydrological record; and
- results are only valid for the gauged location.

Furthermore, there are some methodological issues which should be considered when applying the method within the New Zealand legislative context (i.e. for the requirements of the RMA and NPS-FM):

- IHA parameters derived from naturalised or pre-alteration flows cannot be used to recommend water resource use limits as minimum flows and total allocation (as required by the NPS-FM), but the method could be used to generate and compare altered flow scenarios;
- there are currently no pre-defined rules as to acceptable levels of change to the distribution of each parameter, but these levels could be altered according to the likely risks to, and importance of, the values being considered;
- there is currently no pre-determined method for ranking the importance of each parameter, but logical links could be made between parameters and ecological functions, and redundancy analysis can be used to reduce the number of parameters required;

The method assumes that as there is greater departure from natural hydrological conditions there is greater risk of potential environmental change.

6 Conclusions

In this work we explored methodologies to quantify the influence of dams and reservoir management on downstream flows with an emphasis on their influence on in-stream environmental values. Methods used to accomplish this task use inputs of natural and altered river flow time-series. We compared three contrasting methods for obtaining these river flow time-series for a catchment heavily influenced by hydropower operations (the Waitaki catchment) including: 1) observed flow time-series data for periods before and after dam construction; 2) reconstruction of naturalised lake outflows from lake inflows for comparison with observed lake outflows; and 3) flow time-series calculated from hydrological models representing natural and altered scenarios.

In the case of the Waitaki time-series data, we concluded that the appropriate output from hydrological models is not currently available because the default national TopNet model is neither an adequate representation of the natural situation, nor the altered (current) situation. Reconstructed naturalised lake outflows from lake inflows were available for comparison with observed lake outflows. However, historical pre-upstream storage management data were also available. In the case of the Waitaki, we concluded that historical pre- and post-altered time-series represent an appropriate data source to assess impacts on downstream flows when applying the RVA methodology to characterise overall flow regime effects. Use of pre- and post-altered flow time-series assumed that any climatological differences in hydrological patterns between the two periods is overridden by human alteration to catchment hydrology. When considering schemes other than the Waitaki, use of pre- and post-altered time-series would also be appropriate where hydrological alteration is high, and long lengths of high-quality pre- and post-dam construction flow time-series are available. However, these data are not always available (e.g., when a dam is proposed at an ungauged location). Naturalised flows are required for comparison with observed altered flows where sufficient quality or length of pre-scheme data are not available. It should also be noted that observed altered flows may have been influenced by historical changes in operating procedures or infrastructure such that the entire time-series does not represent the current operating regime.

The RVA methodology characterises effects of dams on the overall flow regime rather than effects on extreme events such as extreme floods or droughts (e.g. the 1 in 20-year low flow). We note that an analysis of effects on hydrological extremes would have more stringent data requirements than the standard RVA methodology requires.

We applied the Nature Conservancy's Indicators of Hydrologic Alteration software to calculate 33 hydrologic indices under pre- and post- alteration. These hydrologic indices represent intra- and inter-annual variability, and magnitude, duration, frequency, timing and rate of change of river flows. This method has been widely used in the international literature to represent human-induced changes in the flow regime. However, the method does not provide a single quantification of hydrological impact or pressure that can be mapped because various aspects of the flow regime are being considered within the analysis. This is in contrast with the water allocation pressure maps provided by Booker (2018). We therefore conclude that the Indicators of Hydrologic Alteration provide a transparent and objective method for quantifying the influence of non-consumptive water use (including hydropower schemes). The method does compliment previous work on quantifying pressure from consents on water resources (e.g., Booker 2018), but cannot be directly translated into pressure maps. We noted that either pre- and post-scheme or observed and naturalised flow time-series must be available to apply this method.

7 Acknowledgements

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8 References

Bandaragoda, C., Tarboton, D. and Woods, R., 2004. Application of TopNet in the distributed model intercomparison project. Journal of Hydrology, 298(1-4), 178-201.

Biggs, B.J.F., 2000. Eutrophication of streams and rivers: dissolved nutrient chlorophyll relationships for benthic algae. Journal of the North American Benthological Society 19, 17-31.

Booker, D.J., 2018. Quantifying the Hydrological Effect of Permitted Water Abstractions across Spatial Scales. Environmental Management, DOI:10.1007/s00267-018-1040-7.

Booker, D. J., Snelder, T. H., Greenwood, M. J., and Crow, S. K., 2015. Relationships between invertebrate communities and both hydrological regime and other environmental factors across New Zealand's rivers. Ecohydrology, 8(1), 13-32. https://doi.org/10.1002/eco.1481

Booker, D.J., Henderson, R.D., Whitehead, A.L. 2016a. National water allocation statistics for environmental reporting. NIWA client report for Ministry for the Environment, 2017065CH, 21pp

Booker, D., Whitehead, A., Henderson, R. and Yang, J. 2016b. Nationally consistent methods for calculating water allocation indicators, NIWA Client Report (2016023CH).

Booker, D.J. and Woods, R.A., 2014. Comparing and combining physically-based and empirically-based approaches for estimating the hydrology of ungauged catchments. Journal of Hydrology, 508, 227-239.

Bunn, S.E. and Arthington, A.H., 2002. Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. Environmental Management, 30, 492-507.

Cheng, J., Xu, L., Wang, X., Jiang, J. and You, H., 2018. Assessment of hydrologic alteration induced by the Three Gorges Dam in Dongting Lake, China. River Research and Applications, 34(7), 686-696.

Colwell, R.K., 1974. Predictability, constancy, and contingency of periodic phenomena. Ecology, 55, 1148-1153.

Crow, S.K., Booker, D.J., Snelder, T.H. (2012) Contrasting influence of flow regime on freshwater fishes displaying diadromous and non-diadromous life-histories. Ecology of Freshwater Fish, 22, 82-94.

Eum, H.I., Dibike, Y. and Prowse, T., 2017. Climate-induced alteration of hydrologic indicators in the Athabasca River Basin, Alberta, Canada. Journal of Hydrology, 544, 327-342.

Graf, W. L., 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. Water resources research, 35(4), 1305-1311.

Gregory, R., Ohlson, D. and Arvai, J., 2006. Deconstructing adaptive management: criteria for applications to environmental management. Ecological applications, 16(6), 2411-2425.

Grill, G., Lehner, B., Lumsdon, A.E., MacDonald, G.K., Zarfl, C. and Liermann, C.R., 2015. An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. Environmental Research Letters, 10(1), 015001.

Hecht, J.S., Lacombe, G., Arias, M.E., Dang, T.D. and Piman, T., 2018. Hydropower dams of the Mekong River basin: a review of their hydrological impacts. Journal of Hydrology, 568, 285-300.

Henderson, R., Woods, R. and McKerchar, A., 2004. Water audit of the Waitaki catchment above Waitaki Dam, NIWA Client Report: CHC2004-049, Prepared for Meridian Energy Limited.

Horne, A.C., O'Donnell, E.L., Webb, J.A., Stewardson, M.J., Acreman, M. and Richter, B., 2017. The environmental water management cycle. In Water for the Environment (pp. 3-16).

Jardine, T.D., Bond, N.R., Burford, M.A., Kennard, M.J., Ward, D.P., Bayliss, P., Davies, P.M., Douglas, M.M., Hamilton, S.K., Melack, J.M. and Naiman, R.J., 2015. Does flood rhythm drive ecosystem responses in tropical riverscapes? Ecology, 96(3), 684-692.

Li, D., Long, D., Zhao, J., Lu, H. and Hong, Y., 2017. Observed changes in flow regimes in the Mekong River basin. Journal of Hydrology, 551, 217-232.

Lu, W., Lei, H., Yang, D., Tang, L. and Miao, Q., 2018. Quantifying the impacts of small dam construction on hydrological alterations in the Jiulong River Basin of Southeast China. Journal of Hydrology. 567, 382-392.

Mackay, S.J., Arthington, A.H. and James, C.S., 2014. Classification and comparison of natural and altered flow regimes to support an Australian trial of the ecological limits of hydrologic alteration framework. Ecohydrology, 7(6), 1485-1507.

Macnaughton, C.J., McLaughlin, F., Bourque, G., Senay, C., Lanthier, G., Harvey-Lavoie, S., Legendre, P., Lapointe, M. and Boisclair, D., 2017. The effects of regional hydrologic alteration on fish community structure in regulated rivers. River Research and Applications, 33(2), 249-257.

Magilligan, F.J., Nislow, K.H., 2005. Changes in hydrologic regime by dams. Geomorphology 71 (1-2), 61-78.

Mailhot, A., Talbot, G., Ricard, S., Turcotte, R. and Guinard, K., 2018. Assessing the potential impacts of dam operation on daily flow at ungauged river reaches. Journal of Hydrology: Regional Studies, 18, 156-167.

Mathews, R. and Richter, B.D., 2007. Application of the Indicators of hydrologic alteration software in environmental flow setting 1. JAWRA Journal of the American Water Resources Association, 43(6), 1400-1413.

Matteau, M., Assani, A.A. and Mesfioui, M., (2009). Application of multivariate statistical analysis methods to the dam hydrologic impact studies. J. Hydrol. 371, 120-128.

McMillan, H., Freer, J., Pappenberger, F., Krueger, T. and Clark, M., (2010). Impacts of uncertain river flow data on rainfall-runoff model calibration and discharge predictions. Hydrological Processes: An International Journal, 24(10), 1270-1284.

McMillan, H.K., Booker, D.J. and Cattoën, C., (2016). Validation of a national hydrological model. Journal of Hydrology, 541, 800-815.

Mei, X.F., Van Gelder, P.H.A.J.M., Dai, Z.J. and Tang, Z.H., (2017). Impact of dams on flood occurrence of selected rivers in the United States. Frontiers Earth Science, 11 (2), 268-282.

Ministry for the Environment, (1998). Flow guidelines for instream values, Ref. ME270 (Volume A) and ME271 (Volume B). 146 and 215 p.

Ministry for the Environment, (2008). Proposed national Environmental standard on ecological flows and water levels, Discussion document. Wellington: Ministry for the Environment, ME 868. 61 p.

Ministry for the Environment, (2015). A guide to the national policy statement for freshwater management 2014. Ministry for the Environment, Wellington, New Zealand, 96pp

Moreira, M., Hayes, D.S., Boavida, I., Schletterer, M., Schmutz, S. and Pinheiro, A., (2018). Ecologically-based criteria for hydropeaking mitigation: A review. Science of The Total Environment, 657, 1508-1522.

Ngor, P.B., Legendre, P., Oberdorff, T. and Lek, S., (2018). Flow alterations by dams shaped fish assemblage dynamics in the complex Mekong-3S river system. Ecological Indicators, 88, 103-114.

Olden, J.D. and Poff, N.L., (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research & Applications 19, 101-121.

Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacobson, R.B., Kennen, J.G., Merritt, D.M., O'Keefe, J.H., Olden, J.D., Rogers, K., Tharme, R.E. and Warner, A. (2010). The Ecological Limits of Hydrologic Alteration (ELOHA): A new framework for developing regional environmental flow standards. Freshwater Biology, 55, 147-170.

Radinger, J., Alcaraz-Hernández, J.D. and García-Berthou, E., (2018). Environmental and spatial correlates of hydrologic alteration in a large Mediterranean river catchment. Science of The Total Environment, 639, 1138-1147.

Richter, B.D., Baumgartner, J.V., Powell, J. and Braun, D.P., (1996). A method for assessing hydrologic alteration within ecosystems. Conservation Biology, 10, 1163-1174.

Richter, B.D., Baumgartner, J.V. Wigington, R. and Braun, D.P., (1997). How much water does a river need? Freshwater Biology, 37, 231-249.

Schmidt, J.C. and Wilcock, P.R., (2008). Metrics for assessing the downstream effects of dams. Water Resources Research, 44(4). doi.org/10.1029/2006WR005092.

Singh, S.K., Ibbitt, R., Srinivasan, M.S. and Shankar, U., (2017). Inter-comparison of experimental catchment data and hydrological modelling. Journal of Hydrology, 550, 1-11.

Stewardson, M.J., Acreman, M., Costelloe, J.F., Fletcher, T.D., Fowler, K.J., Horne, A.C., Liu, G., McClain, M.E. and Peel, M.C., (2017). Understanding hydrological alteration. In Water for the Environment (pp. 37-64).

The Nature Conservancy, (2009). Indicators of Hydrologic Alteration Version 7.1 User's Manual.

TNC, (2016)Environmental flows concepts website (online). The Nature Conservancy. https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/Concepts/Pages/environmental-flows-conce.aspx (accessed December 2018).

TNC, (2018). IHA software download. The Nature Conservancy. https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/IndicatorsofHydrologicAlteration/Pages/IHA-Software-Download.aspx (accessed December 2018).

Tonkin, J.D., Bogan, M.T., Bonada, N., Rios-Touma, B. and Lytle, D.A., (2017). Seasonality and predictability shape temporal species diversity. Ecology, 98(5), 1201-1216.

White, M.A., Schmidt, J.C. and Topping, D.J., (2005). Application of wavelet analysis for monitoring the hydrologic effects of dam operation: Glen Canyon Dam and the Colorado River at Lees Ferry, Arizona. River Research and Applications, 21 (5), 551-565.

Yang, J., McMillan, H. and Zammit, C., (2017). Modeling surface water-groundwater interaction in New Zealand: Model development and application. Hydrological Processes, 31(4), 925-934.

Zimmerman, J.K.H., Letcher, B.H., Nislow, K.H., Lutz, K.A. and Magilligan, F.J., (2010). Determining the effects of dams on subdaily variation in river flows at a whole-basin scale. River Res. App. 26 (10), 1246-1260.

Appendix A Indicators of Hydrologic Alteration (IHA)

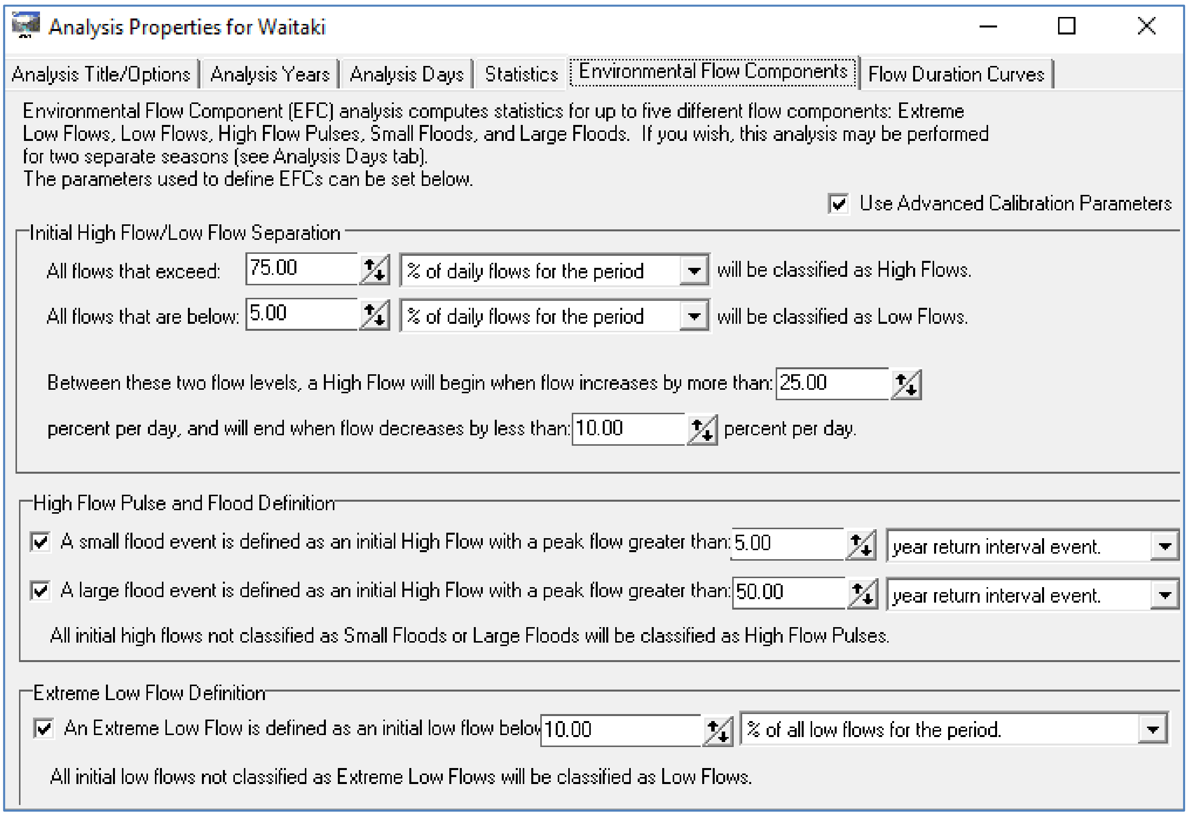
Table A-1: Summary of Indicators of Hydrologic Alteration and ecosystem influences (from The Nature Conservancy, 2009).

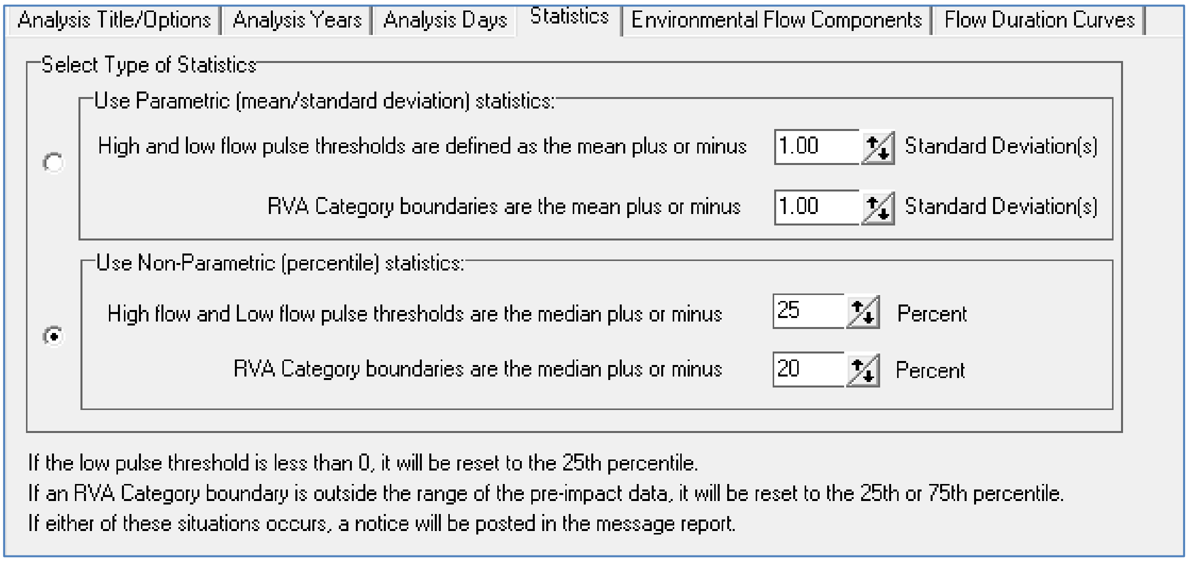
IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
1. Magnitude of monthly water conditions	Mean or median value for each calendar month *Subtotal 12 parameters*	• Habitat availability for aquatic organisms • Soil moisture availability for plants • Availability of water for terrestrial animals • Availability of food/cover for fur-bearing mammals • Reliability of water supplies for terrestrial animals • Access by predators to nesting sites • Influences water temperature, oxygen levels, photosynthesis in water column
2. Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means Number of zero-flow days Base flow index: 7-day minimum flow/mean flow for year *Subtotal 12 parameters*	• Balance of competitive, ruderal, and stress- tolerant organisms • Creation of sites for plant colonization • Structuring of aquatic ecosystems by abiotic vs. biotic factors • Structuring of river channel morphology and physical habitat conditions • Soil moisture stress in plants • Dehydration in animals • Anaerobic stress in plants • Volume of nutrient exchanges between rivers and floodplains • Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments • Distribution of plant communities in lakes, ponds, floodplains • Duration of high flows for waste disposal, aeration of spawning beds in channel sediments

3. Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum ——————————— *Subtotal 2 parameters*	• Compatibility with life cycles of organisms • Predictability/avoidability of stress for organisms • Access to special habitats during reproduction or to avoid predation • Spawning cues for migratory fish • Evolution of life history strategies, behavioral mechanisms
4. Frequency and duration of high and low pulses	Number of low pulses within each water year Mean or median duration of low pulses (days) Number of high pulses within each water year Mean or median duration of high pulses (days) ——————————— *Subtotal 4 parameters*	• Frequency and magnitude of soil moisture stress for plants • Frequency and duration of anaerobic stress for plants • Availability of floodplain habitats for aquatic organisms • Nutrient and organic matter exchanges between river and floodplain • Soil mineral availability • Access for waterbirds to feeding, resting, reproduction sites • Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
5. Rate and frequency of water condition changes	Rise rates: Mean or median of all positive differences between consecutive daily values Fall rates: Mean or median of all negative differences between consecutive daily values Number of hydrologic reversals ——————————— *Subtotal 3 parameters* ——————————— **Grand total 33 parameters**	• Drought stress on plants (falling levels) • Entrapment of organisms on islands, floodplains (rising levels) • Desiccation stress on low-mobility streamedge (varial zone) organisms

Appendix B Parameter settings

Figure B-1: Parameter settings used to describe Environmental flow component analysis. (extreme flows and pulses).





Appendix C Pre- and Post-Impact IHA's for the Waitaki Catchment

Table C-1: Pre- and post-impact Indices of Hydrologic alteration (IHA for the Waitaki catchment).

	Medians			Coefficient of dispersion		
	Pre- (1928-48)	Post- (1993-2017)	TopNet (1993-2017)	Pre- (1928-48)	Post (1993-2017)	TopNet (1993-2017)
January	438.3	397.1	163.3	0.5266	0.3309	0.7517
February	462.3	417.6	88.3	0.4665	0.2371	0.7947
March	389.7	400.4	126	0.3192	0.1722	1.047
April	365.4	360.6	126.7	0.7736	0.3743	1.359
May	254.7	328.9	215.2	0.6814	0.306	0.6331
June	211.4	317	229.4	0.4902	0.3097	0.7312
July	171.7	327.6	160.6	0.364	0.2776	0.641
August	167.6	343.5	179.8	0.5874	0.2686	0.6187
September	188	353.2	251.4	0.6544	0.3312	0.722
October	332.9	314.2	186.9	0.579	0.239	1.094
November	396.1	334.3	174.7	0.3856	0.2835	0.9701
December	457.7	323.9	167.6	0.1587	0.1811	0.719
1-day minimum	91.6	175.5	30.7	0.4394	0.2148	0.3795
3-day minimum	115.1	190.6	31.77	0.3878	0.2228	0.4061
7-day minimum	122.1	219	39.1	0.2955	0.1875	0.4916
30-day minimum	136.9	267.5	91.78	0.2995	0.2034	0.3347
90-day minimum	168.2	296.5	169.4	0.3405	0.1648	0.29
1-day maximum	1034	620.6	3147	0.8692	0.9745	0.3672
3-day maximum	992.2	584.8	1859	0.7741	0.9679	0.3287
7-day maximum	844.9	558.6	1167	0.6977	0.8241	0.354
30-day maximum	717.9	496.8	639.4	0.3161	0.3671	0.4381
90-day maximum	553.7	440.3	421.6	0.2532	0.2837	0.2564
Number of zero days	0	0	0	0	0	0
Base flow index	0.3591	0.5767	0.1399	0.2745	0.1963	0.4099
Date of minimum	226	296	50	0.1639	0.4754	0.2268
Date of maximum	22	24	311	0.2186	0.3019	0.4781
Low pulse count	4	3	20	2.125	1.833	0.375
Low pulse duration	5	1.25	3	4.55	0.8	0.3333
High pulse count	7	19	31	0.5	0.5263	0.1935
High pulse duration	11	2	2	0.8636	0.375	0
Low Pulse Threshold	194		100			
High Pulse Threshold	446.5		330.4			
Rise rate	15.3	30.65	130.2	0.5882	0.1884	0.4155
Fall rate	-11.8	-30.2	-30.05	-0.75	-0.2492	-0.5233
Number of reversals	123	169	129	0.7358	0.09467	0.07364

Appendix D Summary statistics for pre- and post-impacted flows

Table D-1: Summary statistics for periods of analysis for pre and post impacted flows on the Waitaki River.

	Pre-impact observed: 1928-1948 (21 years)	Post-impact observed: 1993-2017 (25 years)	Post-impact modelled: 1993-2017 (25 years)
Normalization Factor	1	1	1
Mean annual flow	355.4	366.6	295.6
Non-Normalized Mean Flow	355.4	366.6	295.6
Annual C. V.	0.61	0.37	1.27
Flow predictability	0.65	0.7	0.39
Constancy/predictability	0.76	0.95	0.8
% of floods in 60d period	0.31	0.27	0.18
Flood-free season	34	2	1