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Applying the Cumulative Hydrological Effects Simulator (CHES) for managing water allocation

A demonstration of CHES in the Grey catchment, West Coast

Prepared for West Coast Regional Council

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Executive summary

The objective of this report is to demonstrate the capabilities and utility of CHES (NIWA's Cumulative Hydrological Effects Simulator) for facilitating discussions and decision making associated with setting water quantity limits and applying those in the West Coast region.

The Grey River catchment is used as a case study for showcasing some of the key features and capabilities of CHES. The focus is to demonstrate how CHES can be used by WCRC to characterise the current status and consequences of water use in a catchment, explore different water use and limit scenarios, and improve the robustness and transparency of its water allocation planning. For this project six scenarios were defined and applied to the Grey River catchment. In Scenarios 1 to 3 we assume that whenever an abstractor is allowed to take water (based on the rules set in the scenario) that they take the full allowed volume, no matter if they need the water or not. For each scenario we assess the reliability of water supply relative to demand and we consider the effects of water abstraction on physical habitat for two example fish species, adult brown trout and longfin eels.

Scenario 1 simulates the effects of currently consented abstractions. Results show that under current consent conditions, for the 78 abstractions simulated, there are 45 abstractors (58 %) that can take all their allocated water more than 97.5 % of the time, i.e., reliability is greater than 97.5 %. However, there are a relatively large number of takes (42 %) with much lower reliability. Current consent conditions mean that on average across the Grey River catchment there is a 3.6 % reduction in physical habitat availability for adult brown trout compared to natural flows. On average across the catchment, this reduction in physical habitat occurs 38 % of the time. For longfin eels on average there is a 1.2 % reduction in physical habitat availability.

Scenario 2 simulates the effects of applying the allocation rules stipulated under WCRC's Policy 7.3.1 and Policy 7.3.2 (from WCRC's Regional Land and Water Plan 289) across all existing allocations. We show that 597 out of 652 reaches comply with these policies. However, there are 17 reaches where the total water allocation is more than 50 % higher than that allowed under Policy 7.3.1. If WCRC were to split current resource consents into an A and B block where the current allocation exceeds Policy 7.3.1 then both reliability and instream habitat availability would change. For the average abstractor the proportion of the time that they can take their full water allocation would drop by ~4 %. However there would be very little change in the proportion of time that they could take at least some water. In terms of habitat availability, we show that applying Policy 7.3.1 and Policy 7.3.2 consistently across the Grey River catchment would result in an average improvement in habitat availability of 1.5 % for adult brown trout and 1.6 % for longfin eels.

Scenario 3 simulates the effects of applying the rules outlined in the proposed National Environmental Standard on ecological flows and water levels (the proposed NES) across all existing allocations. These rules set limits by way of a minimum flow and set the total allocation of water compared to current abstraction. Results show that under the proposed NES limits the mean reliability would be 92 %. This is an apparent improvement over the previous scenarios but this reliability relates to taking a much smaller volume of water. In terms of habitat availability, on average there is 3.3 % more habitat for adult brown trout and 1.6 % more habitat for longfin eels compared to current water abstraction. The results for Scenarios 1 to 3 demonstrate the consequences of setting different limits, however, the next step is for Councils and their communities to weigh up the various consequences and decide which best meet their objectives.

Scenario 4 is used to demonstrate how adding a dam to an existing example abstraction can improve reliability of water supply, and how CHES can be used to calculate the volume of reservoir that would be required to achieve a given reliability objective.

Scenario 5 is used to demonstrate how CHES can be used to examine the potential effects of a hypothetical proposed new abstraction that would allow a farmer to increase his farm capacity by 500 dairy cows. To do this the farmer will need to abstract enough water to irrigate a sufficient area of pasture and have enough water for drinking and cleaning of dairy sheds. In this scenario we set three objectives relating to reliability, habitat change and implications for downstream abstractors and we use CHES to ascertain how large a storage reservoir would be needed for this new abstraction to meet these objectives.

Scenario 6 simulates the effects of a given climate change scenario (the average of the 12 global climate model scenarios under A1B from the IPCC's third assessment round (IPCC 2001)). Results show that, in general, the south-eastern part of the Grey River catchment will experience a reduction in Mean Annual Low Flow (MALF) and the north-western part of the Grey River catchment will experience an increase in MALF, with a mean change across all reaches in the catchment being an increase in MALF of 51 l/s and an increase in minimum flows (lowest flow in the hydrological time series) of 94 l/s. These increases in low flows result in no change in reliability for a typical abstractor, however, there will be some abstractors with less reliable supply (with the worst case being a 6 % reduction in the proportion of time an abstractor can take their full allocation) and some abstractors will have more reliable supply (with the best case being a 157 % increase). In terms of habitat availability under climate change, on average across all reaches there is a 0.2 % reduction in habitat availability for adult brown trout (compared to current conditions). For longfin eels the results are similar with an average reduction in habitat availability of 0.3 %.

The scenarios presented in this report are by no means an exhaustive summary of all the different capabilities and outputs of CHES, and WCRC may wish to run alternative scenarios or test the effects of these scenarios on alternative species. However, we hope that the results presented provide useful examples and demonstrate the capability of CHES for testing the effects of differing water quantity limits. We also hope that we have demonstrated how CHES can be used to present results in a way that will facilitate discussion with stakeholders and thereby support collaborative decision making.

1 Introduction

1.1 Background

West Coast Regional Council (WCRC) is responsible for managing the status of water resources in the West Coast region. The National Policy Statement for Freshwater Management (NPS-FM; MfE 2014) requires that regional councils set water quantity limits for all freshwater rivers and streams. Water quantity limits describe the amount of water in a freshwater management unit that is required to meet freshwater objectives and must include at least a minimum flow and an allocation limit. WCRC is seeking assistance with defining water quantity limits for the West Coast that effectively balance both in and out-of-stream water uses, while also accounting for spatial variability in the environment. WCRC secured support from the Community Engagement Fund for a project to pilot the use of the Cumulative Hydrological Effects Simulator (CHES), a science-based water allocation decision-support tool developed by NIWA, to support the process of setting robust and transparent water quantity limits in the West Coast region. This report is a key deliverable of this project.

1.2 Purpose

The objective of this report is to demonstrate the capabilities and utility of CHES for facilitating discussions and decision making associated with setting water quantity limits and applying those in the West Coast region. The Grey River catchment is used as a case study for showcasing some of the key features and capabilities of CHES. The focus is to demonstrate how CHES can be used by WCRC to characterise the current status and consequences of water use in a catchment, explore different water use and limit scenarios, and improve the robustness and transparency of its water allocation planning. In addition this report could be used by other councils to see what could be achieved with the CHES tool.

1.3 Scope

The scope of this report is to present results for up to six water use/limit scenarios within CHES and use these scenarios to demonstrate how reliability of water supply can be characterised and how impacts on instream physical habitat availability for two indicator species (adult brown trout and longfin eels (< 30 cm)) can be characterised.

It is intended that this report will provide sufficient information on the capabilities and utility of CHES to allow WCRC to make an informed decision on the value of using CHES to support the planning processes associated with implementing the NPS-FM in the West Coast region.

This report does not include an exhaustive summary of all the different capabilities and outputs of CHES. Permitted takes are not included in the modelling due to a lack of information regarding the location and magnitude of these takes in the catchment. It is also outside the scope of this report to provide a detailed analysis of water resource use in the Grey River catchment or to determine appropriate water quantity limits for the catchment.

2 Water allocation in the West Coast region

Compared with many regions, water is abundant in most areas of the West Coast resulting in relatively limited pressure on water resource availability. However, in certain areas (e.g., the upper Grey River Valley) water availability is coming under increasing pressure during drier seasons due to abstraction for irrigation (WCRC 2015). As a consequence there is a need to ensure appropriate mechanisms are in place to effectively prioritise and manage water use between instream (e.g., physical fish habitat) and out-of-stream (e.g., irrigation, municipal supply) values.

The Regional Land and Water Plan (WCRC 2014) provides the framework for the management of water quantity in the West Coast region. Policies 7.3.1 and 7.3.2 are the primary mechanisms by which limits to the taking of surface water are defined. They state:

- Policy 7.3.1: Takes from rivers where the total volume of water allocated is less than 20 % of the river's mean annual low flow (MALF) will require no minimum flow; and,
- Policy 7.3.2: Where Policy 7.3.1 is being exceeded, a minimum flow based on 75 % of the mean annual low flow will be applied as a consent condition, with no limit on how much can be abstracted.

The absence of a minimum flow (Q_{min}) limit under Policy 7.3.1 means that up to 20 % of MALF can be taken from surface waters at all times (assuming it's available). While this may be considered generous, as it could result in complete drying of rivers, the default allocation limit (ΔQ) set under Policy 7.3.1 is considered to present a low risk of adverse effects due to the small proportion of water being taken (WCRC 2014). For example this ΔQ is lower than that specified in the proposed NES limits. Total allocation is defined under this policy at the point of take, but must take account of the cumulative effects of water takes at other points upstream. In effect this means that any take allowed under this policy must not result in the 20 % allocation limit being exceeded at the point of take or anywhere downstream.

The default minimum flow limit of 75 % of MALF set under Policy 7.3.2 only applies to takes that exceed the default allocation limit set under Policy 7.3.1. The default minimum flow limit is intended to provide for the natural character and life supporting capacity of the aquatic ecosystem (WCRC 2014). The absence of a specified allocation limit beyond that defined in Policy 7.3.1 implies that theoretically all water above 75 % of MALF could be taken for out-of-stream use. However, Policy 7.3.6 does allow for the future capping of overall allocation from a water body.

Policy 7.3.3 of the Plan also allows for individuals to apply for an exception to Policy 7.3.2 whereby a minimum flow < 75 % of MALF can be applied to a take on a site specific basis providing that certain provisions regarding avoiding adverse effects are met.

The NPS-FM requires that WCRC set minimum flow and allocation limits for all freshwater management units in their region. These limits must be set such that over-allocation is avoided and freshwater objectives are met. WCRC considers that the objectives and policies of the Regional Land and Water Plan are well aligned with the requirements of the NPS-FM relating to water quantity (WCRC 2011).

Under the NPS-FM requirements, and as pressure on water resources increases in certain areas of the West Coast, the effectiveness of the current plan policies and rules for ensuring freshwater objectives are met and over-allocation is avoided will need to be monitored. The use of scientific tools, such as CHES, to derive transparent and specific limits that can be linked to objectives (Snelder et al. 2014) can aid in policy monitoring and review.

3 Methods

3.1 The CHES model

CHES is a water allocation decision-support tool that enables users to simulate and compare spatially explicit water management scenarios at a catchment scale. It models the spatially explicit effects of multiple water takes on both out-of-stream (reliability of supply) and instream (physical habitat) values at a daily time-step. This allows the characterisation of trade-offs between environmental state and water resource use under differing water allocation management scenarios.

CHES is an add-in to ArcGIS and was designed as a desktop tool to facilitate the visualisation and analysis of information on water takes and storages in a catchment. It allows a user to characterise the cumulative hydrological impact of water takes (including storages, dams and diversions) on the flow regime of a river catchment at a reach scale. The degree of hydrological alteration can be quantified and translated into consequences for individual takes, in terms of reliability of supply, and for instream values, in terms of changes in physical habitat availability for key fish and invertebrate species.

The underlying basis of CHES is a modelled ~42-year naturalised daily flow time series (5-Jan-1974 to 5-Nov-2015) generated by TopNet for each river reach. This means that for all locations on the river network the hydrological consequences of water use can be characterised at a daily time-step across multiple years. This allows the user to develop an understanding of how natural variations in river flow (e.g., dry vs. normal vs. wet years) affect the availability of water for existing and potential new users, both under current and potential future limit and licencing regimes. Furthermore, it allows the user to understand how the impacts of taking water on instream values might vary as a consequence of natural seasonal and inter-annual variations in river flows across the river network. These outcomes can be compared with freshwater objectives to understand whether the current allocation regime is appropriate and meets the desired outcomes of the NPS-FM and relevant regional policies such as those in the Regional Land and Water Plan.

A key feature of CHES is the ability to simulate the addition of new water takes, storages, dams or diversions in a catchment. Within the CHES interface a user is able to define the characteristics (e.g., location, volume, timing, limits, and storage properties) of a proposed new take. This can be added to the catchment and the impacts on hydrology, reliability of supply for existing users and instream values can be evaluated. Furthermore, CHES can be used to examine whether or not a proposed new take exceeds existing limits (for example on total allocation) or whether it meets freshwater objectives.

CHES can also be used to simulate alternative abstraction scenarios. This includes the option to make different assumptions about how individual users take their water (e.g., they take everything they are consented to take all the time vs. measured water use); the ability to look at the consequences of modifying characteristics of the existing take database (e.g., adding or removing takes, applying different rules to takes); or evaluating the impact of applying different catchment scale minimum flow and allocation limits. Scenario simulations can help the user to understand the spatial and temporal characteristics of water availability and instream impacts resulting from different assumptions about behaviour, or assist with visualising the outcomes of changing allocation rules, for example in order to fulfil different freshwater objectives.

Detailed information on the functionality of CHES is available from the CHES manual (Diettrich 2015). A technical description of the model structure is given in Appendix A of this report.

For this project, the Grey River catchment is used as a case study to demonstrate the capabilities and utility of CHES for facilitating the process of managing water resource use. Details of the model and scenario set-up for the Grey River are described in the following sections.

3.2 CHES set-up for the Grey River catchment

CHES was set-up and calibrated for the Grey River catchment. There are five main steps in this process:

1. Define the catchment boundary and river network.
2. Calibrate the underlying hydrological model.
3. Generate the existing take database.
4. Define and run the reference scenario.
5. Set-up and run alternative allocation scenarios.

Each of these steps are summarised in the following sections. Version 1.0 of CHES was used for this project.

3.2.1 Define the river network

The River Environment Classification version 1 (REC-1) was used as the basis for defining the river network for the Grey River catchment. All river segments upstream of the Grey River mouth (NZREACH 12028002) were included (Figure 3-1). The catchment covers an area of 3,923 km^2 and includes 8,334 river segments. It stretches from the township of Greymouth almost to Reefton in the northeast, and is bounded to the west by the Paparoa and Kaiata Ranges, to the east by the Southern Alps, and to the south by the Hohonu, Alexander and Kaimata Ranges.

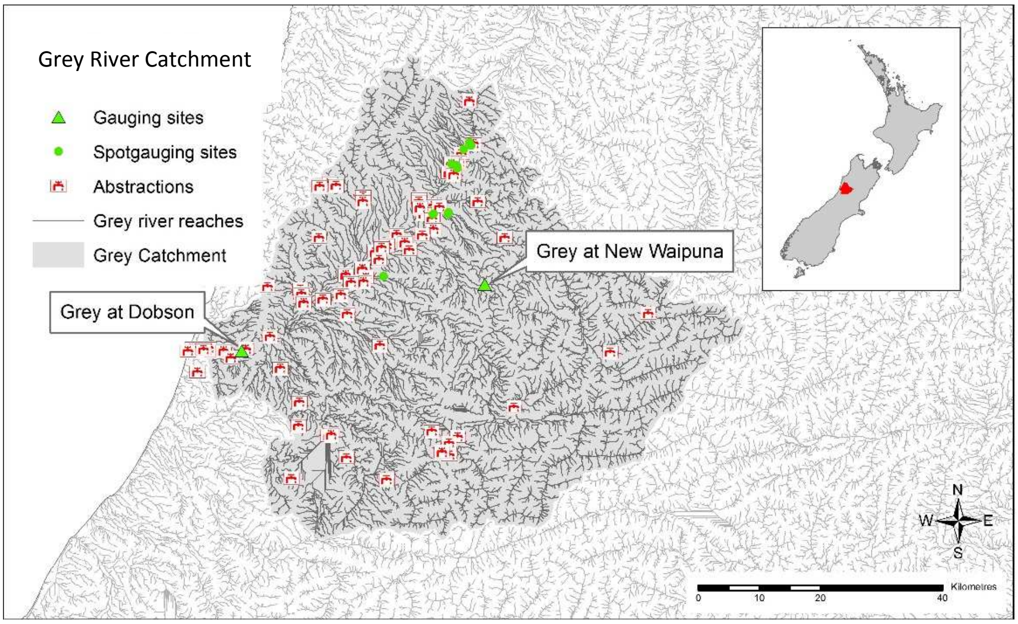


Figure 3-1: The Grey River catchment.

3.2.2 Hydrological calibration

The underlying hydrological time series data for CHES are derived from TopNet. This is a hydrological rainfall-runoff model that uses daily information on rainfall and air temperature in combination with information on catchment topography, soil types and vegetation to generate daily flow time series for each reach in the river network. There are two different versions of TopNet, TopNet-0 and TopNet-GW, and both are used in this project at different stages of the hydrological calibration (Appendix B, Zammit et al. 2016)).

TopNet-0 is calibrated against observed data from flow gauging stations in order to best represent reality. For the Grey River, flows were calibrated against the flow record at New Waipuna (NZREACH 12025991) and Dobson (NZREACH 12028095). Calibration focused on optimising the representation of low flows in the model (using a log-Nash-Sutcliffe optimization function) as this is typically the most critical time for managing water allocation. Full details of the TopNet-0 calibration for the Grey River catchment are described in Appendix B and Zammit et al. (2016).

Part of the Grey River catchment is subject to some groundwater-surface water interactions, however, TopNet-0 ignores these interactions. An adaptation of TopNet-0 was used to represent groundwater-surface water interactions in the hydrological time series. This is the conceptual Ground Water TopNet model, referred to as TopNet-GW. Spot gauging data is needed for the subcatchments where TopNet-GW will be used. This was kindly collated by WCRC staff in the Maimai catchment, which is known for its losing behaviour. This enabled us to run TopNet-GW for the Maimai and Grey at Dobson. Further details on TopNet-GW and the TopNet-GW calibration are provided in Appendix B and Zammit et al. (2016).

Originally, it was intended that ELFMOD (Empirical Longitudinal Flow MODel) would be used to characterise the losses and gains from and to surface water in the Grey River and that this be integrated into the TopNet-0 results. ELFMOD reconstructs longitudinal and temporal flow patterns along river sections using spot measurements of flow magnitude and flow state (flowing or dry) at multiple cross-sections, and time series of river flow and/or proxy variables (e.g., rainfall, groundwater level) from one or more sites along the modelled section (Larned et al. 2010). It was envisaged that physical reach parameters, such as rock porosity, rock age, reach elevation, or reach slope could be correlated to reach gaining or losing properties. If this could be achieved, then the known physical reach parameters could be used to simulate the gaining and losing properties of all reaches in the catchment. Unfortunately, intensive studies did not bring the anticipated correlation and, therefore, we were not able to use the ELFMOD approach to determine gaining and losing reach properties.

3.2.3 Existing take database

The existing take database (Appendix C) forms the basis of the reference scenario and describes the characteristics (e.g., location, allocation limits, minimum flow limits, abstraction type, and instantaneous rate of take) of current consented abstractions in the catchment. Data were supplied by WCRC for all current consented abstractions in the Grey River catchment. These data were converted from an Excel to an XML format for input into CHES.

Table 3-1: A summary of current consented consumptive takes in the Grey River catchment. Based on data supplied by WCRC [4-March-2016, with adjustments made on 8-March-2016 after conversation between Jan Diettrich and Stefan Beaumont].

Take type	Number of takes
Surface water abstraction	47
Groundwater abstraction	39

Originally a data set was supplied by the WCRC containing 172 abstractions. However, 85 of those abstractions were non-consumptive, meaning the overall abstraction amount was 0 l/s. These are abstractions where the water is taken from the river and all of it discharged back into the river within the same reach. Hence the overall change of flow due to the abstraction is 0 l/s and, therefore, those abstractions were removed from the supplied abstraction data set. Abstractions would not have been removed if they were for hydro electricity generation, but none of the abstractions are of this type.

The definition of the catchment boundary used in this project excluded 8 abstractions at the downstream end of the Grey River catchment. Therefore the results presented in this report (see Figure 3-1) relate to 78 abstractions.

3.3 Data analyses

A range of analysis options are available in CHES to summarise and visualise both the instream and out-of-stream consequences of water use at the reach to catchment scale. Key capabilities are the option to map scenario outcomes for a wide range of attributes for all reaches on the river network and the ability to plot time series of attributes for any reach in the river network. Summary statistics can also be derived to characterise the spatial and/or temporal variations in attributes for individual reaches, sub-sets of reaches, or for the whole catchment.

This report is used to demonstrate some of the analysis options currently implemented in CHES to characterise the consequences of water use for attributes that describe instream (physical habitat for fish) and out-of-stream (reliability of supply) values. Furthermore, we provide examples of how CHES can be used to compare and contrast the outcomes of alternative water use/management scenarios. More detail on the range of analysis options available in CHES are provided in the manual (Diettrich 2015) and summarised in Appendix A. Terms introduced below are summarised in the Glossary.

3.3.1 Reliability of supply

Reliability of supply is the primary attribute used in CHES to describe the proportion of time that abstractors are able to take water. We use three different metrics for reliability of supply, all presented as a percentage:

- *R* - the supply of water relative to the demand for water (supply/demand) averaged over time. This is normally used for reliability that is presented as time series.
- *R1* - the proportion of time that the full allocated volume is available. This is equal to the percentage of time that natural flows are greater than the sum of the minimum flow and the abstraction limit. This is normally used for reliability that is presented as histograms.

- *R2* - the proportion of time that at least some water can be taken. This is equal to the percentage of time that natural flows are greater than the minimum flow. This is normally used for reliability that is presented as histograms.

Reliability of supply is only calculated for reaches with a take. Reliability can be summarised for individual takes over time, or spatially across multiple takes.

In this report, examples of catchment wide and site specific evaluations of reliability of supply are provided.

3.3.2 Instream physical habitat

Physical habitat change (for fish and macroinvertebrates) is the main attribute used in CHES to describe the instream impacts of water use. Changing flow can alter the suitability of a physical habitat to support different organisms.

CHES focuses on changes in physical habitat (i.e., water depth and velocity) but doesn't currently incorporate other aspects of habitat such as food availability (despite the fact that this may also be affected by changes in flow). Therefore, throughout the remainder of this report when we refer to 'habitat' it should be understood that we are talking about physical habitat only.

The impact of altered flows on instream habitat can be described in terms of the magnitude (i.e., how much more or less habitat is available), frequency (i.e., how often is habitat changed) and duration of change (i.e., for how long consecutively is habitat changed). Generally speaking, the larger the change, the more frequently it happens and the longer it lasts for, the worse the outcomes for instream values (assuming habitat is reduced).

In CHES habitat is calculated for individual species at a reach scale and is described by a range of habitat indices (integrating different aspects of the magnitude, frequency and duration). Full details of how this is calculated, the range of species for which habitat can be characterised, and the different habitat indices are provided within Appendix A.

For this application to the Grey River, two indicator species (adult brown trout (*Salmo trutta*) and longfin eels (*Anguilla dieffenbachii*)) are used to demonstrate how CHES can be used to characterise the consequences of water use for instream values. These species provide a useful example as they have contrasting habitat preferences, with adult brown trout preferring deeper and faster flowing water than longfin eels.

3.3.3 Scenario comparisons

CHES also has the capability to quantify outcomes with respect to limits or objectives. This can be calculated both within and between scenarios. For example, it is possible to determine what proportion of the allocation limit is currently consented in a given reach (i.e., is it over or under-allocated), or the proportion of time that a particular freshwater objective is met in a given reach. It is also possible to make comparisons between scenarios, assisting users with understanding the relative trade-offs between values under different water use and limit regimes.

In this report a number of different metrics are demonstrated to help illustrate the relative outcomes of different scenarios relative to freshwater objectives and limits. These example scenarios are described in the following section.

3.4 Examining different abstraction scenarios

After consultation with WCRC, six scenarios were defined and applied to the Grey River catchment:

1. Reference scenario (current consented takes)
2. Applying Policies 7.3.1 and 7.3.2
3. Proposed NES limits
4. Adding a water storage reservoir
5. Adding a large new abstraction
6. Climate change.

These scenarios are discussed further below.

Reference scenario – current takes (Scenario 1)

The reference scenario describes the current state of water resource use in the Grey River. The existing take database forms the basis of this scenario, with all abstractors assumed to take all the water they are consented to take (i.e., maximum allocation) all the time, no matter if they need the water or not. This assumption is necessary, as we do not have sufficient data to describe how the actual amount of water taken varies over time. This means that results inevitably overestimate how much water is taken and, therefore, the resulting effects of these water takes represent a 'worst case' scenario. This scenario can be used by WCRC to visualise the current state of water resource use relative to existing limits, and to understand current reliability of supply and impacts on instream habitat for fish. This can help WCRC to identify bottlenecks to current water use and to understand where there is currently capacity for further water use in the catchment.

Applying Policy 7.3.1 and Policy 7.3.2 (Scenario 2)

Policies 7.3.1 and 7.3.2 in the Regional Land and Water Plan (WCRC 2014) provide the framework for the management of water quantity in the West Coast region. However, not all currently consented takes comply with these policies (see Section 4.2.1). In Scenario 2 the limits specified in Policies 7.3.1 and 7.3.2 were applied across all reaches of the Grey River catchment, changing existing allocations so that they are split between an A and B block where necessary, as follows:

- A block (Policy 7.3.1): ΔQ up to 20 % of MALF, Q_{min} = 0 l/s
- B block (Policy 7.3.2): Where demand has outstripped the amount allowed under Policy 7.3.1 (i.e., demand > 20 % of MALF), Q_{min} = 75 % of MALF and ΔQ has no limit.

Under Policy 7.3.1 total allocation is defined at the point of take, but must take account of the cumulative effects of water takes at other points in the catchment. In effect this means that any take allowed under this policy must not result in the 20 % allocation limit being exceeded at the point of take or anywhere downstream. This means that, in the process of splitting current allocations into A and B blocks, the priority order in which takes are considered is important. In this project the takes were sorted by catchment size upstream of each take, such that smallest streams are considered first and therefore water is allocated to the A block from upstream to downstream.

The allocation database required for this scenario was generated outside of CHES (using MATLAB) and then fed back into CHES.

Under this scenario all abstractors are assumed to take the maximum volume of water allowed (such that they comply with Policy 7.3.1 and 7.3.2) all the time, no matter if they need the water or not.

Proposed NES limits (Scenario 3)

The proposed National Environmental Standard for ecological flows and water levels (proposed NES; MfE 2008) made recommendations for default water allocation and minimum flow limits designed to provide a basic level of protection for instream values, while also providing for out-of-stream water use. For river reaches where mean flow is ≥ 5 m^3/s the proposed minimum flow limit was 80 % of MALF and the allocation limit 50 % of MALF. For river reaches where mean flow is < 5 m^3/s, the proposed minimum flow was 90 % of MALF and the allocation limit 30 % of MALF.

In Scenario 3, the proposed NES limits are applied across all reaches of the Grey River catchment. This changes the maximum allocation of each abstraction and, as with the previous two scenarios, all abstractors are assumed to take the maximum volume of water allowed (such that they comply with the NES rules) all the time, no matter if they need the water or not. This scenario provides an example of how CHES can be used to predict the outcomes of applying new limits in terms of reliability of supply for existing abstractors and in terms of habitat change.

Adding a water storage reservoir (Scenario 4)

As the limits applied under Scenario 2 are stricter than those under Scenario 1, if abstractors are required to adjust their takes to comply with Scenario 2 there will be reduced reliability for some abstractors. The objective of Scenario 4 is to demonstrate how CHES can be used to assess the effects of adding a water storage reservoir and what size of reservoir would be required to bring the reliability back to that achieved under Scenario 1, or to an arbitrarily chosen acceptable level.

For this scenario we selected a reach (NZREACH 12030747, located upstream of Lake Haupiri) which currently has a consented abstraction of 40 l/s, resulting in low reliability under Scenario 2 (R = 60 %). We set an arbitrary freshwater objective of achieving the same reliability as is achieved under Scenario 1 (R = 72.5 %). We then use CHES to assess what size of reservoir would be required to achieve this reliability objective. Again, this abstractor is assumed to take the maximum volume of water allowed (such that they comply with Policy 7.3.1 and 7.3.2) all the time, no matter if they need the water or not.

Adding a large new abstraction (Scenario 5)

This scenario is based on a hypothetical situation where a farmer wants to increase his farm capacity by 500 dairy cows. To do this the farmer will need to abstract enough water to irrigate a sufficient area of pasture and have enough water for drinking and cleaning of dairy sheds.

For this scenario we assume that each cow requires 70 l/day for drinking and another 70 l/day for shed cleaning (http://www.therural.co.nz/livestock/how-much-water-does-your-livestock-need). We assume that the area of pasture required is 166 hectares (Morris 2012) and that there will be an irrigation efficiency of 70 %, a crop factor of 1 and a soil trigger of 75 mm (these are variables required by CHES to calculate the water required for irrigation). The demand of water for drinking and cleaning is a constant requirement, but the demand of water for irrigation varies over time and is calculated using the Rapid Assessment Tool (RAT module (see Appendix A)) in CHES. The RAT module uses evaporation and rain data to simulate soil moisture over time and the need for irrigation is 'triggered' when the soil moisture falls below the defined soil trigger level. As this is a hypothetical new abstraction we can provide the metadata required to calculate how the demand for water varies over time (which was not possible for the previous scenarios). Therefore, in this scenario the abstractor is assumed to take the water that they need, rather than the maximum allocation all of the time.

In running this hypothetical scenario we selected a reach (NZREACH 12024235, which is south of Ikamatua) that already has a high level of water demand, with A Block already fully allocated. We set three hypothetical objectives under this scenario. We wish to ascertain how large a storage unit is needed for a new abstraction to be consented in the reach such that 1) the farmer has an overall reliability of > 95 %, 2) the downstream abstractors shall not be affected (i.e., no change from reference Scenario 1), and 3) the habitat for adult brown trout shall not degraded by more than 1 %. Further details are provided in Section 4.6.

Climate change (Scenario 6)

This scenario is included to demonstrate how CHES can be used to explore the potential effects of climate change on reliability of water supply and habitat availability. This analysis is based on a single climate change scenario (average of the 12 global climate model scenarios under A1B from the IPCC's third assessment round (IPCC 2001)). This is not the most recent climate scenario, and is purely illustrative. Under this climate change scenario, predicted changes in temperature and rainfall are used to generate flow data in TopNet. For this approach, only 18 years of flow data are available. Allocations are assumed to be the same as defined under Scenario 1 and all abstractors are assumed to take their maximum allocation all of the time. Reliability and habitat change under this climate change scenario are then compared with reliability and habitat change under the current climate (using the same 18 year period of data from Scenario 2).

D R A F T

4 Results

4.1 Understanding the catchment

Before we present the results of the different abstraction scenarios, we will first use CHES to provide some background understanding of the Grey River catchment, including information on the natural flows in the catchment and where the current takes are located.

4.1.1 Flows in the Grey River catchment

CHES can be used to present flow data for a catchment in various ways. We can look at flows at a given site (reach), or look at parts or all of a catchment. We can examine flow variability over differing time periods and we can examine different flow statistics (such as mean flow, minimum flow or MALF) over varying periods. In the following section we provide some examples of these types of analysis that may be of particular interest in the Grey River catchment. Note that these flow data are all based on mean daily flow data over an almost 42 year period as generated by TopNet (see Section 3.2.2).

Flow variability for Grey at Dobson

Figure 4-1 shows the 'natural' (no abstractions) annual mean flows over approximately 42 years for the Grey at Dobson. This data shows us that the annual means have varied between 295 m^3/s and 511 m^3/s, with an overall mean flow of 373 m^3/s. We can also see that the degree of variability in mean annual flow has changed over time. From 1979-1999 the mean flow was 388 +/- 65 m^3/s, whereas from 2000-present the mean flow was 363 +/- 33 m^3/s. This variability may reflect IPO phases (Interdecadal Pacific Oscillation (see Glossary of abbreviations and terms)).

Figure 4-2 presents the 'natural' weekly mean flows for the Grey at Dobson based on the nearly 42 year dataset. This figure shows us that the driest period in the Grey River catchment is mid-February to mid-March and the wettest period is in October.

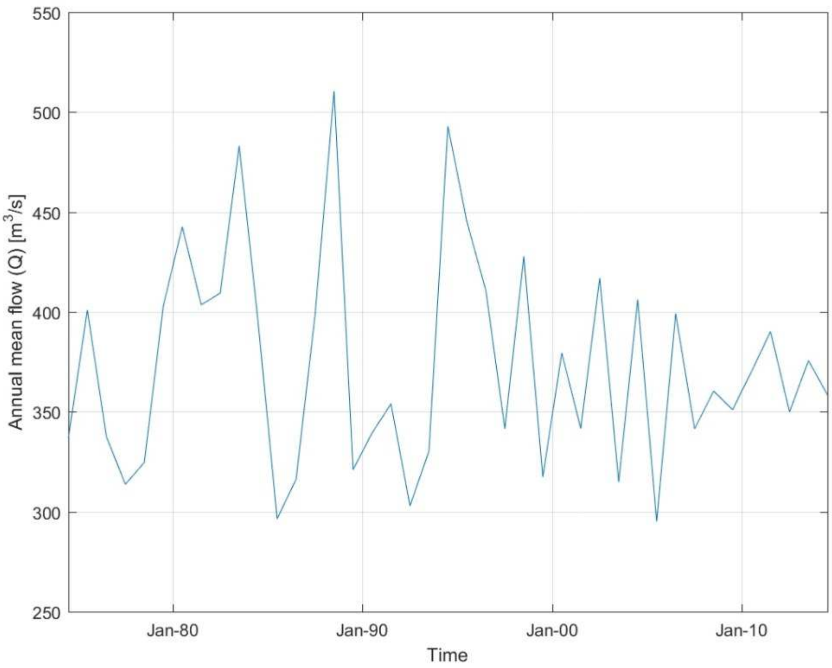


Figure 4-1: Annual mean flows (Q) over approximately 42 years for Grey at Dobson. The key statistics for the data presented here are mean = 373.3 m^3/s, median = 360.4 m^3/s, min = 295.2 m^3/s, max = 510.5 m^3/s, and standard deviation = 52.8 m^3/s.

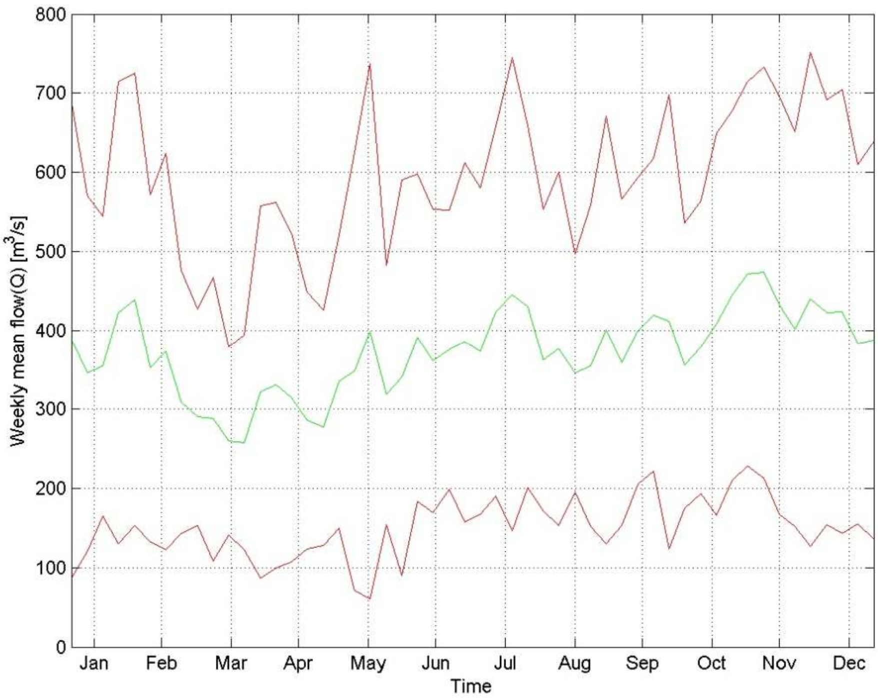
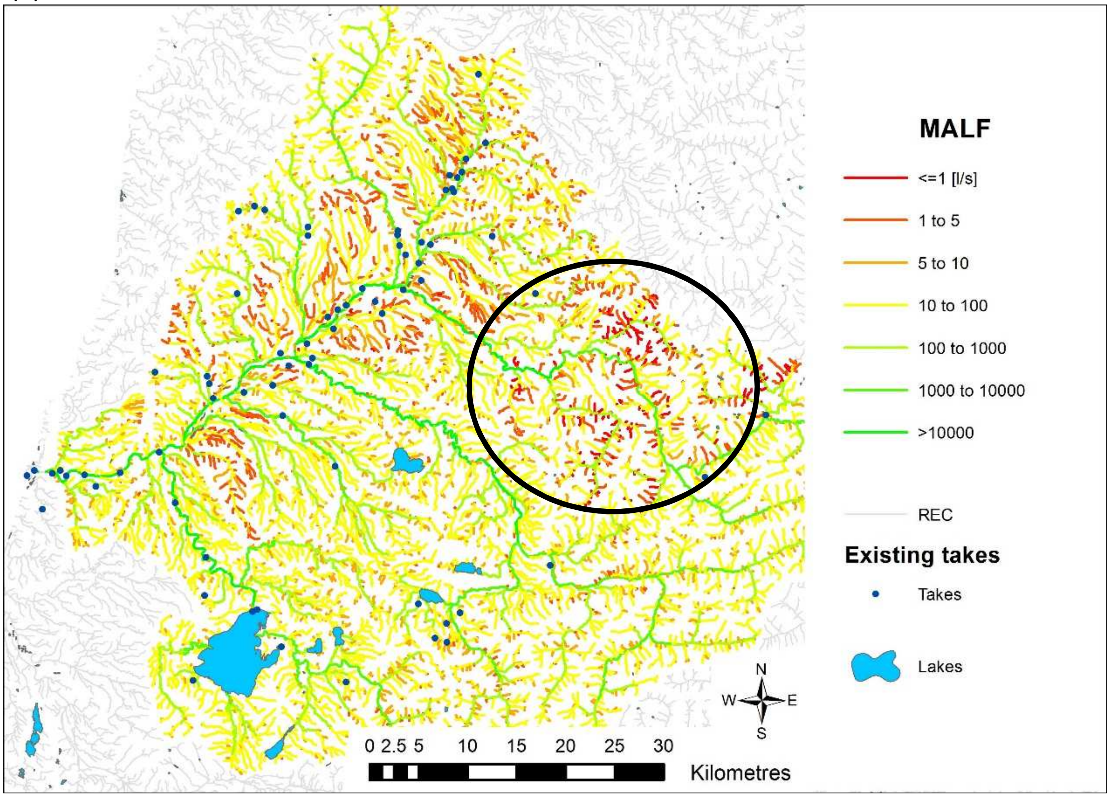


Figure 4-2: Weekly ensemble mean flows (Q) over approximately 42 years for Grey at Dobson. The central green line represents the weekly mean flow, whereas the red lines show the corresponding standard deviation band. The key statistics for the weekly data presented here are mean = 373.3 m^3/s, median = 285.1 m^3/s, min = 259.5 m^3/s, max = 509.5 m^3/s, and standard deviation = 58.6 m^3/s.

MALF in the Grey River catchment

Figure 4-3 (a) presents a map of 'natural' MALF across the whole of the Grey River catchment. This provides a means of qualitatively assessing variability across the catchment, identifying particular regions that have naturally higher or lower flows. For example, the Upper Grey River and Clarke River (the region circled in Figure 4-3 (a)) comprises a large number of reaches with a MALF of < 1 l/s. Note that this figure also shows the location of all the current water takes in the Grey River catchment (blue dots). However, the MALF data is calculated with no water abstraction.

(a)



(b)

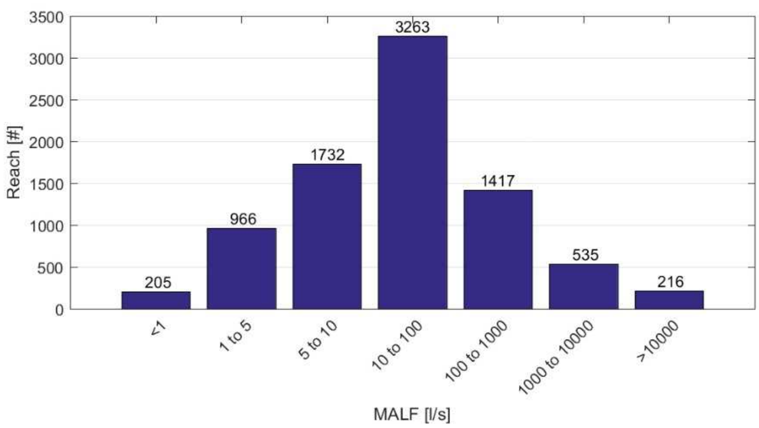


Figure 4-3: (a) Map showing variability in MALF in the Grey River catchment, (b) histogram quantifying the variability in MALF in the Grey River catchment. Note that the region circled has a high number of reaches with low MALF relative to the rest of the catchment. The key statistics for the data presented here are mean = 1,030.8 l/s, median = 18.8 l/s, min = 0 l/s, max = 117,042 l/s, and standard deviation = 5,926.9 l/s.

Figure 4-3 (b) presents a histogram of the Grey River catchment MALF data. This shows us that most reaches have a MALF of 10-100 l/s, however, MALF ranges from 0 l/s to 117,042 l/s, with a mean MALF of 1,031 l/s.

Reaches affected by current takes

Figure 4-4 shows the locations of all the reaches in the Grey River catchment that are affected (touched) by the 86 current water takes i.e., every reach with a take plus all reaches downstream of each abstraction. Water abstraction affects 651 of the total 8,334 reaches in the Grey River catchment. The definition of the catchment used in this project excluded 8 abstractions at the downstream end of the Grey River catchment. Therefore the results presented in following sections relate to 78 abstractions and the 651 reaches affected by these.

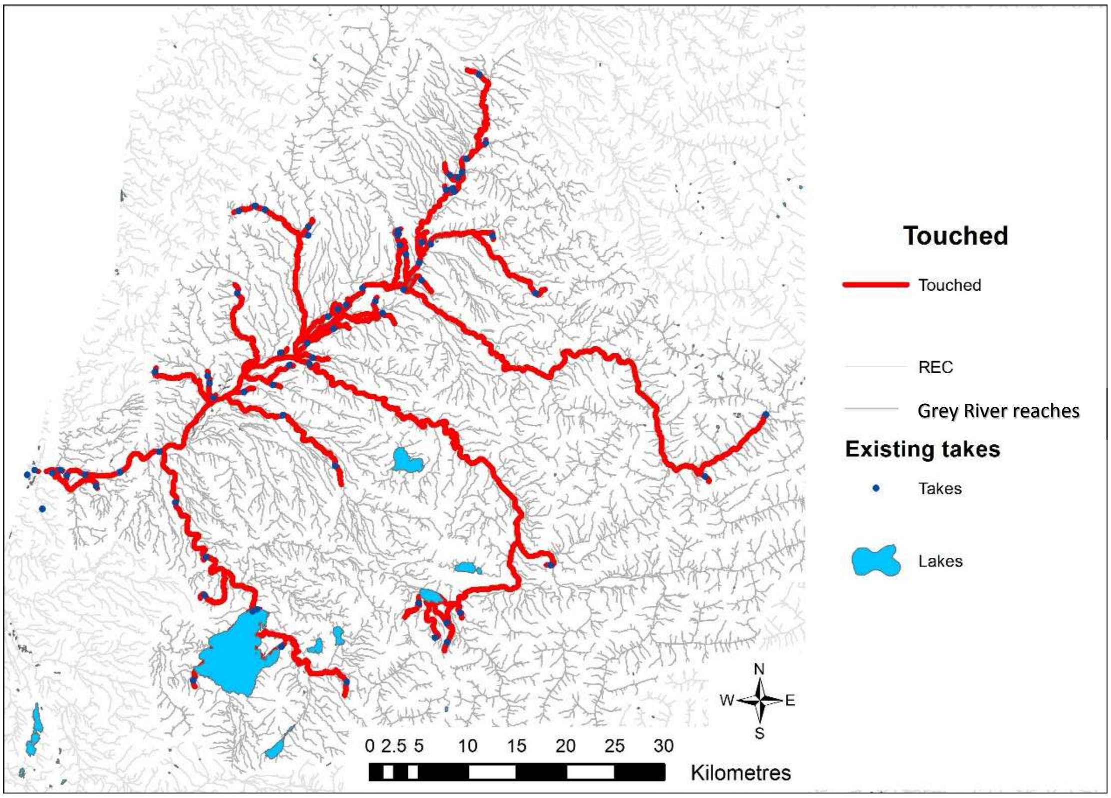


Figure 4-4: Map of reaches affected (touched) by current water abstraction in the Grey River catchment.

4.2 Reference scenario – current takes (Scenario 1)

The aim of this reference scenario is to present results relating to current water allocation in the Grey River catchment. We present the effect of these takes on the reliability of supply and the effect on instream habitat for fish. We also present results demonstrating how these takes relate to the existing water allocation limits (WCRC 2014). The abstraction database supplied by WCRC is provided in Appendix C.

4.2.1 Reliability of abstraction

Figure 4-5 shows the reliability of current water allocation in the Grey River catchment. The reliability presented (*R1*) is the proportion of the time that all consented water can be taken. This figure shows that there are 45 takes that have *R1* greater than 97.5 %. However, there are 23 abstractors which have a reliability of less than 50 %.

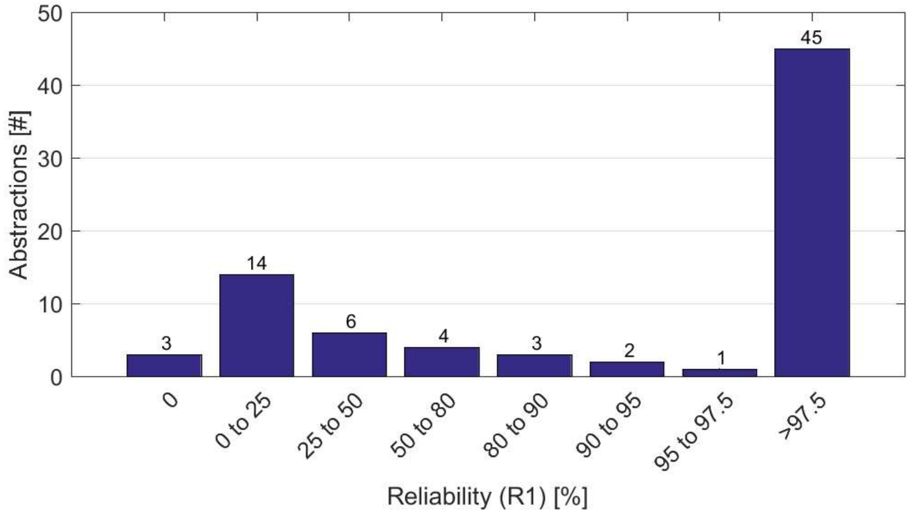


Figure 4-5: Histogram of the reliability (*R1*) of current abstraction in the Grey River catchment. The key statistics for the data presented here are mean = 71.8 %, median = 100 %, min = 0 %, max = 100 %, and standard deviation = 39.7 %.

There are a number of reasons why some abstractions have low reliability:

A. Where there are several abstractions on the same reach CHES prioritises water availability (based on the order the abstractions are entered in the abstraction data base). Therefore, even if two abstractions on the same reach have the same ΔQ, one may have a higher reliability (supply/demand) than the other.
e.g., NZREACH 12023286 has two abstractions, both with a ΔQ = 15 l/s, (Figure 4-6, Table 4-1) the first with a mean *R* of 71 % and the second with a mean *R* of 34 %.
B. If ΔQ for a reach is much larger than the MALF or mean flow of that reach then reliability will be low.
e.g., NZREACH 12021164: ΔQ = 55 l/s, (*R* = 16.7 %); but this reach has natural mean flow of 9.3 l/s and Q_{max} = 129.6 l/s.
C. In some reaches there are multiple abstractions as well as abstraction being greater than MALF (i.e., A and B above).
e.g., NZREACH 12024553 has two abstractors, $\Delta Q1$ = 300 l/s, $\Delta Q2$ = 300 l/s, and the reach has MALF of 75 l/s.
D. Some water allocations have a weekly or annual cap and the interplay of consented daily ΔQ and maximum weekly/annual limit results in a low overall reliability.

CHES can be used to investigate the various reasons for low reliability evident on a map of reliability across the catchment by focusing on reaches with low reliability and investigating which of the above causes is responsible. For example, in the Grey River catchment, for abstractions with a mean *R* < 90%, there are 12 abstractions that fall into in Group A and 18 abstractions that fall into Group B above.

We note that the assumption that abstractors want to take all the water that has been consented to them might not be correct and this could skew the simulated reliability. In reality, the less rain that has fallen, the lower the flow will be in the river, and it’s likely that this is when demand will actually be greatest.

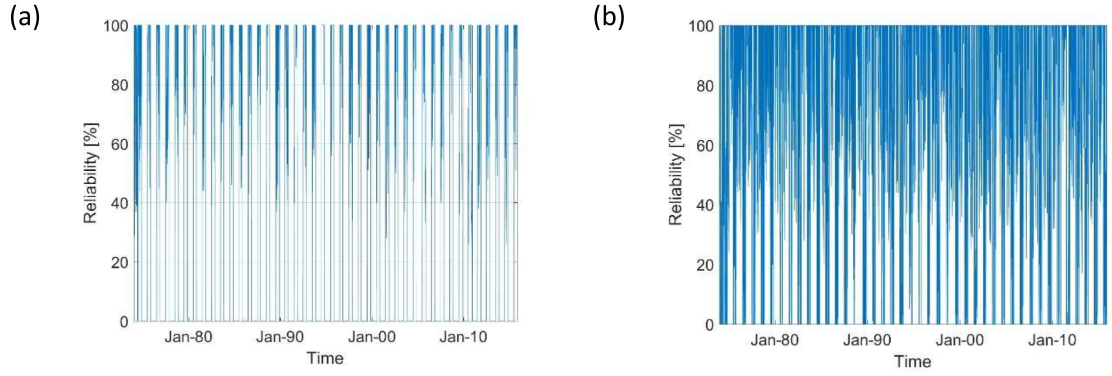


Figure 4-6: An example where there are two abstractions on the same reach with the same *ΔQ* but with varying reliability. Abstraction 1 (a) has a mean *R* of 71 %, whereas abstraction 2 (b) has a mean *R* of 34 %. The key statistics are summarised in Table 4-1.

Table 4-1: Statistical properties of reliability *R* for Abstraction 1 and Abstraction 2 in the same reach.

	Mean	Median	Min	Max	STD
Abstraction 1 *R* [%]	71.0	96	0	100	36.8
Abstraction 2 *R* [%]	34.2	0	0	100	45

4.2.2 Habitat change due to abstraction

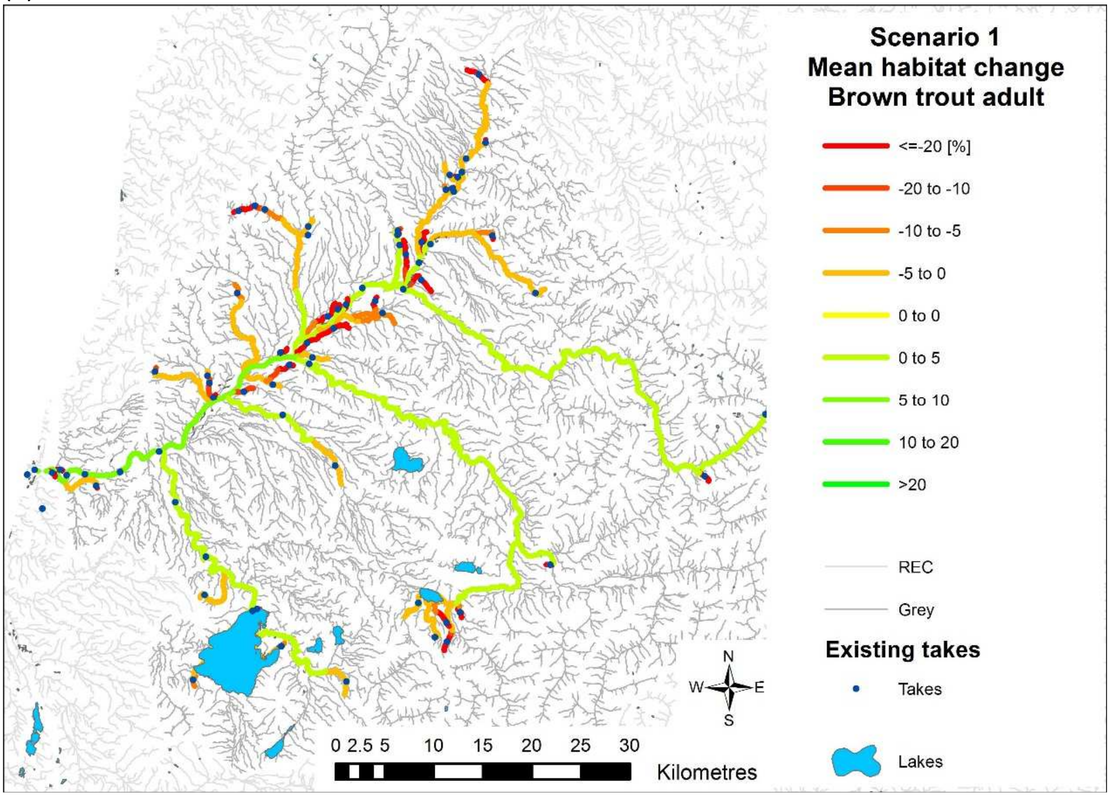
CHES can examine the degree of habitat change for any given species (for which there is habitat preference information, Table A-1). CHES produces a habitat change time series for each reach and can then calculate various statistics from each of these time series (e.g., mean, median, minimum or maximum). The distribution across the catchment of any one of these statistical metrics can then be presented on a map or as a histogram. As well as describing 'magnitude of habitat change' (*ΔH*), CHES can also produce results in terms of frequency of change (by which we mean the proportion of time that habitat is decreased, or alternatively increased), or we can examine the maximum consecutive duration of change in habitat (measured in days).

In this section we examine change in habitat resulting from current water abstraction using several of the metrics described above. We present example results for adult brown trout, as they are a species of particular interest to WCRC. We then compare these results to those of longfin eels, as they have quite different habitat requirements and would be expected to be affected quite differently.

Magnitude of habitat change

To examine habitat change, CHES calculates a timeseries of habitat change for every reach. It can then take a given statistic of each timeseries (such as mean habitat change) and examine how that statistic varies across all reaches in the catchment. This information is presented on a map or as a histogram. The method used to calculate habitat change is described in detail in Appendix A. Figure 4-7 presents the mean magnitude of habitat change for adult brown trout due to current abstraction. Figure 4-7 shows that there are more reaches that have an increase in habitat due to current abstraction (391) than reaches that have a reduction in habitat (260). However, due to the distribution of habitat changes shown in the histogram, the net degree of habitat reduction is greater than the net degree of habitat gain. This results in a mean habitat change of - 3.6 % (reduced habitat) averaged across all reaches.

(a)



(b)

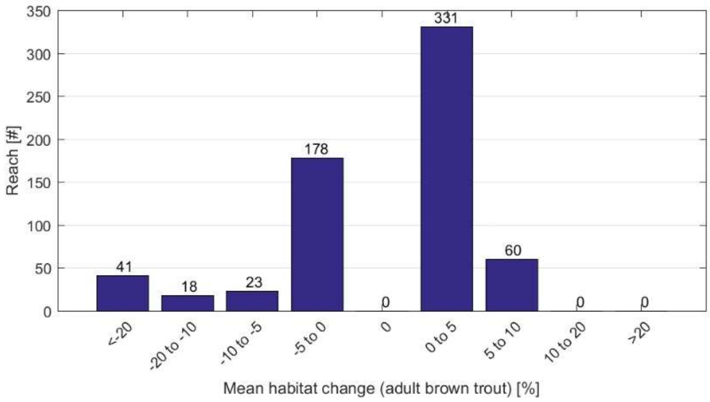


Figure 4-7: Mean habitat change for adult brown trout as a result of current abstraction presented as (a) a map and (b) an histogram. The key statistics for the data presented here are mean = -3.6 %, median = 0.1 %, min = -100 %, max = 7.6 %, and standard deviation = 16 %.

The results in Figure 4-7 are those relating to mean habitat change, however, we could also examine the median, minimum or maximum habitat change calculated from the timeseries generated for each reach. We present the histograms for each of these statistical metrics in Figure 4-8. The distribution of each histogram can also be described using key statistics. These are presented for each histogram in Table 4-2. Table 4-2 shows that there is very little difference between the mean and median habitat change across the catchment (i.e. the statistics of the distributions are very similar). This may not always be the case, however, for the remaining scenarios presented in this report we will only present habitat change results in terms of mean habitat change. Minimum and maximum habitat change results describe the extremes of habitat change, which may appear to be important. However these results generally describe a degree of change that happens very infrequently and therefore these results are generally not particularly useful. The following section presents results relating to the frequency of habitat change, which is more meaningful.

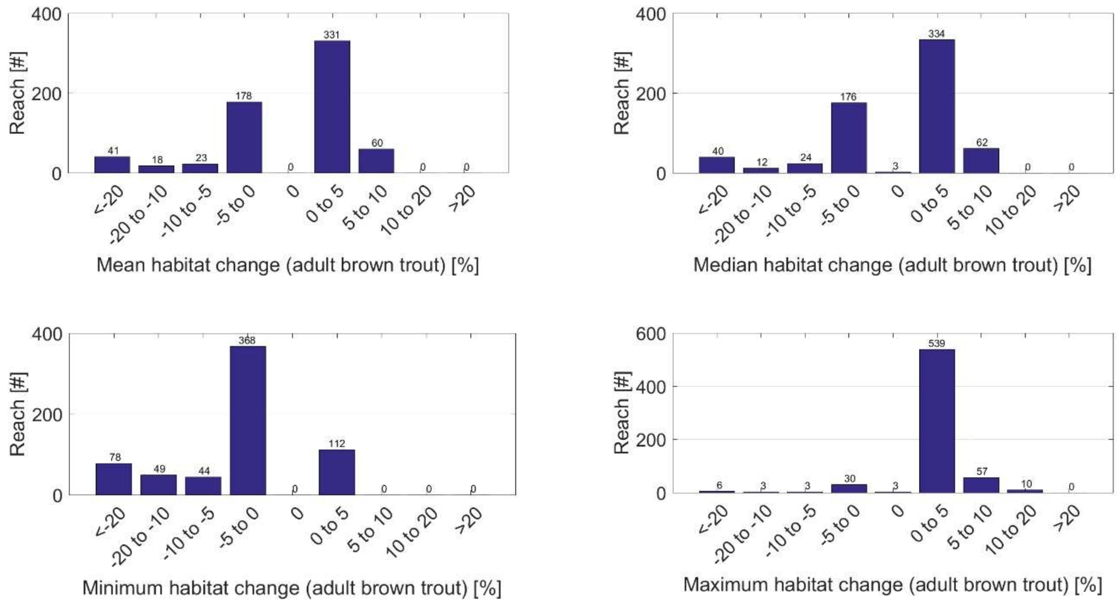


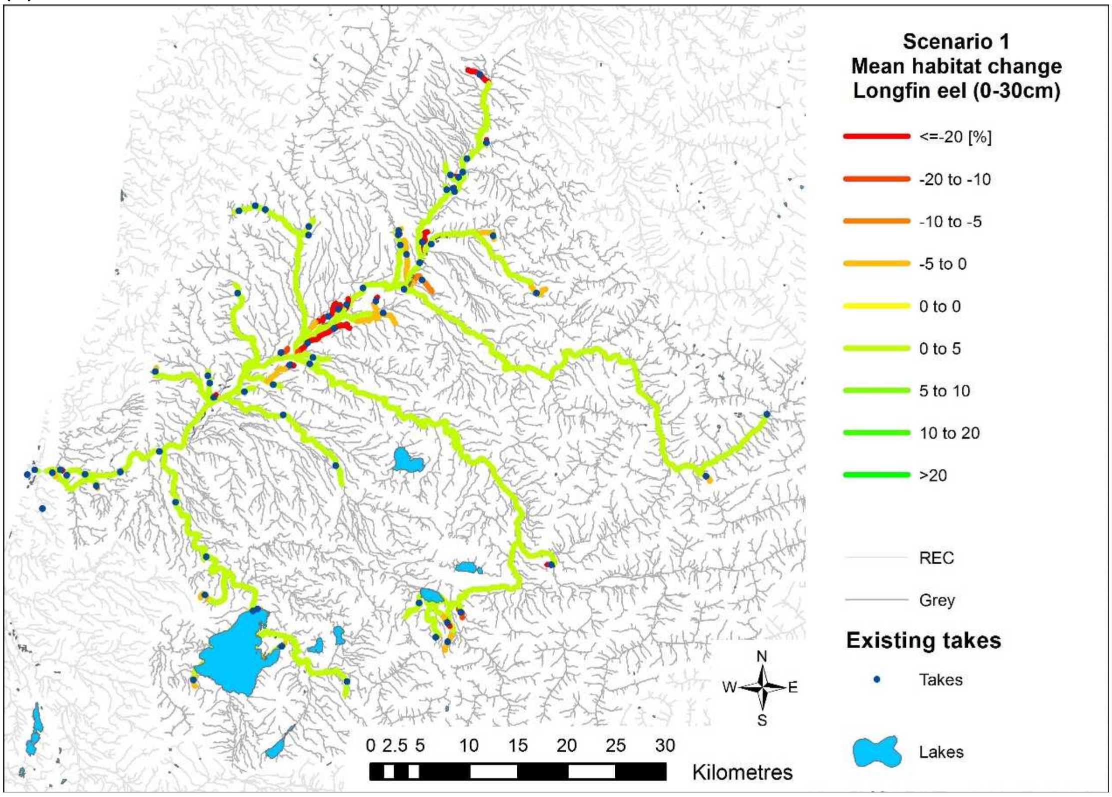
Figure 4-8: Histograms of mean, median, minimum and maximum habitat change for adult brown trout under current abstraction (Scenario 2). Corresponding statistical values for each plot can be found in Table 4-2.

Table 4-2: Statistical properties of the different methods of simulating habitat change for brown trout adult. Note that a negative value means a reduction in habitat availability.

	Mean	Median	Min	Max	STD
Mean habitat change [%]	-3.6	0.1	-100	7.6	16
Median habitat change [%]	-3.5	0.1	-100	7.5	16.6
Maximum habitat change [%]	0.9	0.3	-97.8	13.9	6.3
Minimum habitat change [%]	-9.4	-0.5	-100	4.6	23.5

Figure 4-9 presents the mean magnitude of habitat change for longfin eels due to current abstraction. Figure 4-9 shows that the vast majority of reaches (591 out of 652) have an increase in habitat due to current abstractions. However, as with adult brown trout, mean habitat change is negative (- 1.2 %), which is a mean reduction in habitat. Again, this is due to the distribution of habitat change across the catchment, with the reaches that have very large reductions in habitat skewing the mean. The location of these reaches can be seen in the map in Figure 4-9.

(a)



(b)

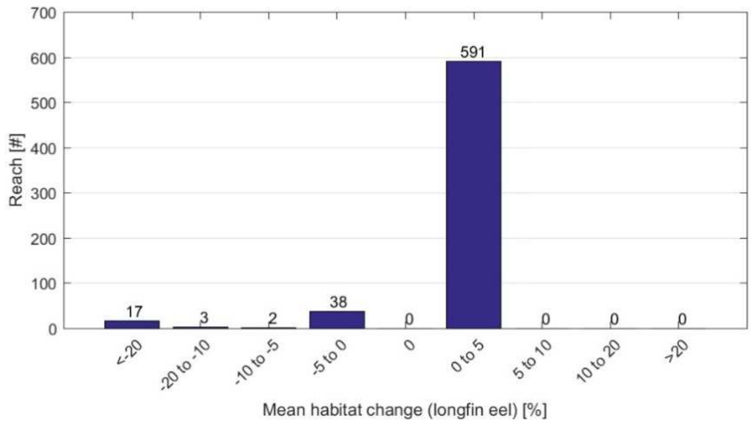
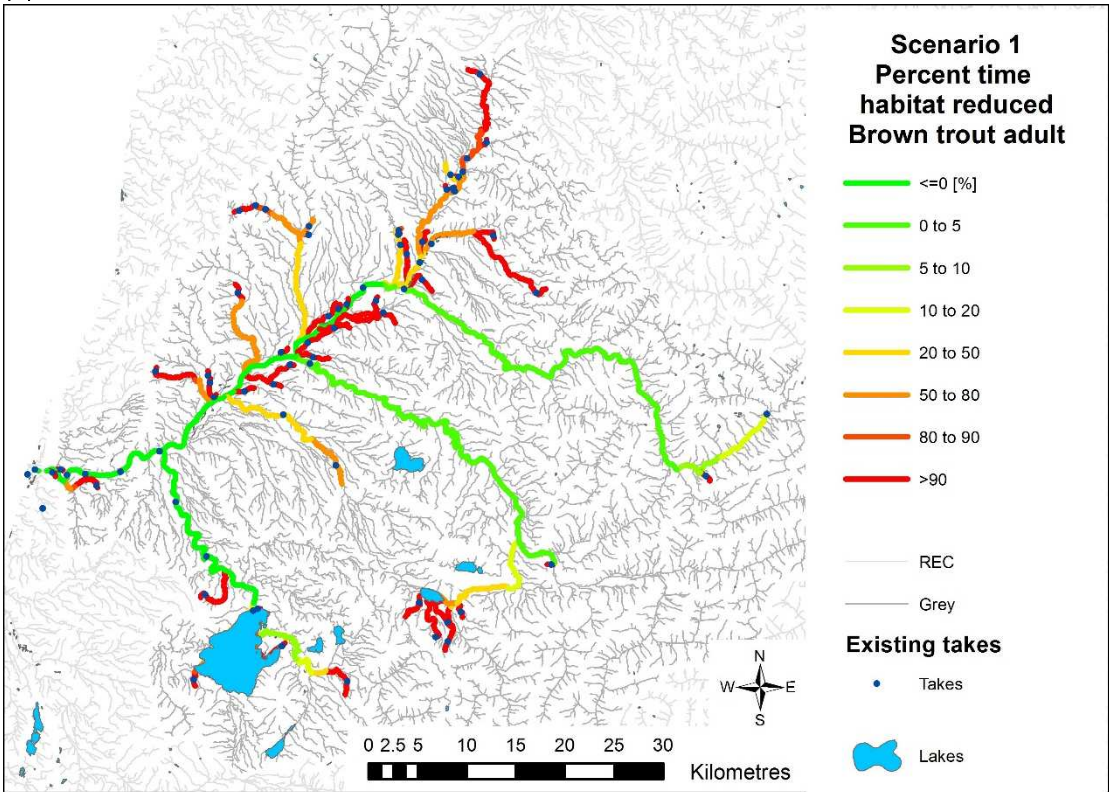


Figure 4-9: Mean habitat change for longfin eels as a result of current abstraction. The key statistics for the data presented here are mean = -1.2 %, median = 0.2 %, min = -100 %, max = 3.9 %, and standard deviation = 11.8 %.

Frequency of habitat change

There are several ways that the frequency of habitat change may be examined. We are perhaps most interested in how often each reach experiences a reduction in habitat. These data are presented in Figure 4-10. Figure 4-10 (a) indicates that the smaller the stream, the more often habitat is reduced. Figure 4-10(b) shows that 112 reaches never have reduced habitat (0 %), and 151 reaches have reduced habitat more than 90 % of the time. On average the reaches affected by water abstraction have a reduction in habitat 38 % of the time.

(a)



(b)

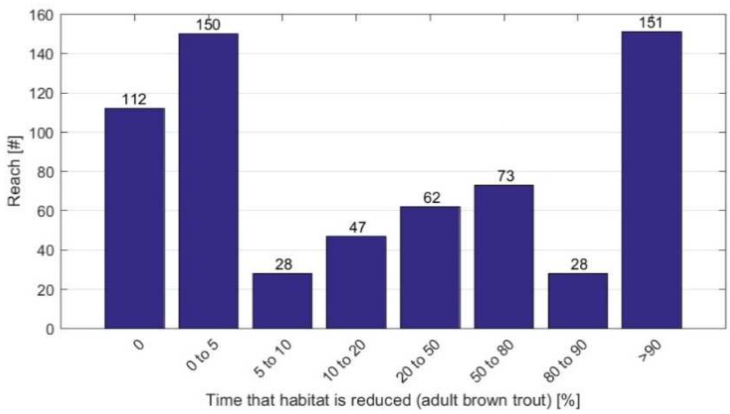
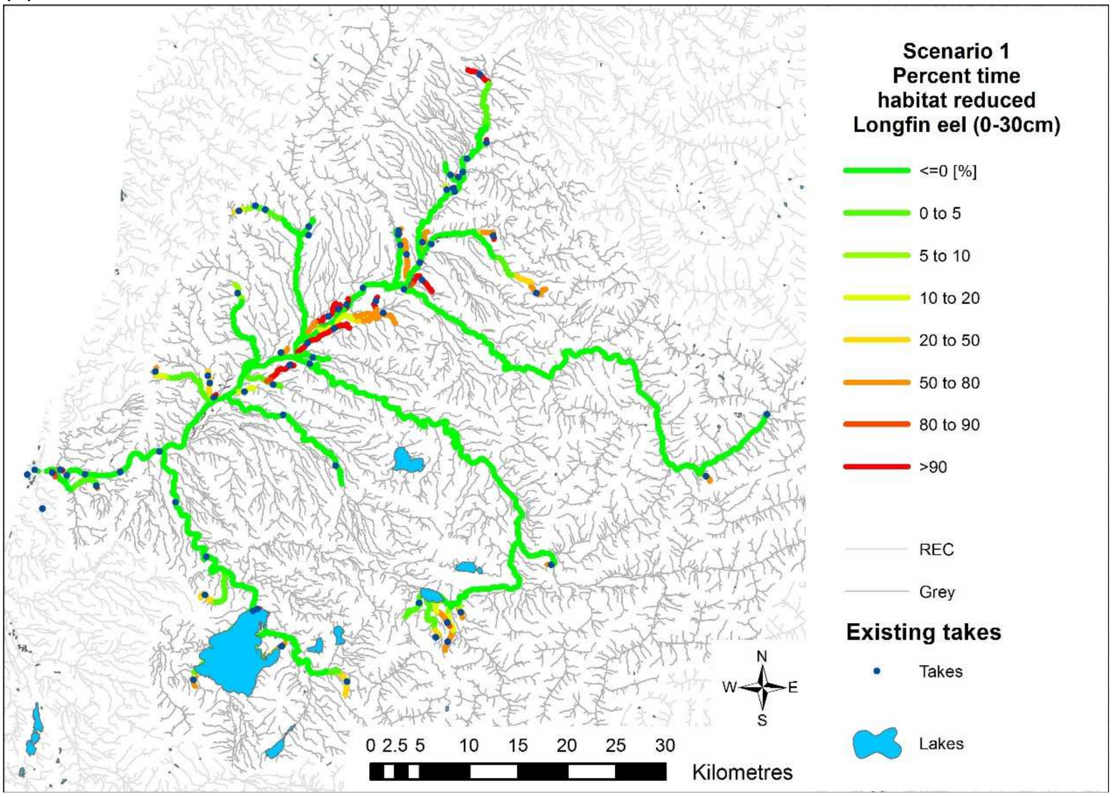


Figure 4-10: Percentage of time that adult brown trout habitat is reduced in the Grey River catchment due to current water abstraction. The key statistics for the data presented here are mean = 38.1 %, median = 15.5 %, min = 0 %, max = 100 %, and standard deviation = 40.7 %.

The map of frequency of habitat reduction for longfin eels (Figure 4-11) highlights the same reaches with a reduction in habitat shown in Figure 4-9. Examining the histogram, Figure 4-11 tell us that 21 reaches have a reduction in habitat more than 90 % of the time and on average habitat is reduced 9 % of the time.

(a)



(b)

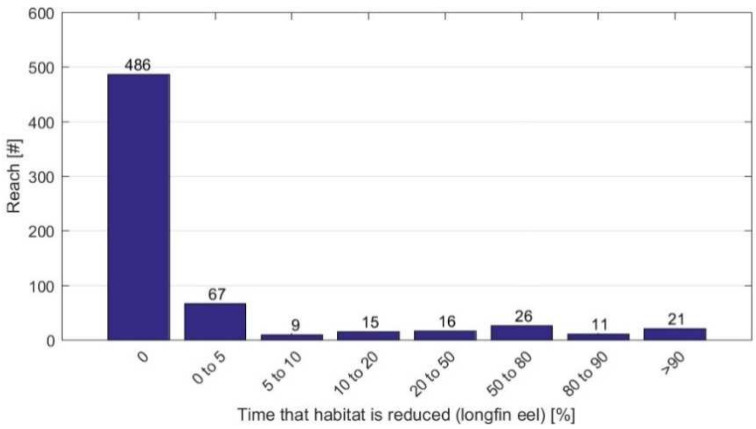


Figure 4-11: Percentage of time that longfin eels habitat is reduced in the Grey River catchment due to current water abstraction. The key statistics for the data presented here are mean = 8.4 %, median = 0 %, min = 0 %, max = 100 %, and standard deviation = 23.4 %.

Max duration that habitat is reduced

As with frequency of habitat change, there are several ways that duration of habitat change can be analysed. We assume that what might be particularly meaningful for instream biota is the maximum consecutive period of time that habitat is reduced. These data are presented in Figure 4-12, again showing that 112 reaches never have reduced habitat for adult brown trout, but 120 reaches have a reduction of habitat for more than 400 days consecutively (out of approximately 42 years). Looking at the statistics describing the distribution of these data, we can see that the median value across the catchment for the maximum consecutive period of habitat loss is 63 days, however, the mean is a much higher 1,322 days. This is due to the fact that some reaches have a very large consecutive period of habitat loss (maximum 15,280 days) which skews the distribution. Note that such long consecutive periods of habitat loss are influenced by the assumption that all consented water is being abstracted all of the time, regardless of actual need. In reality, a single abstractor is unlikely to take their full allocation consecutively for more than 400 days. If further information was available from the abstractors, describing how much water was actually taken over time, then CHES could use this information and this metric would provide more realistic results.

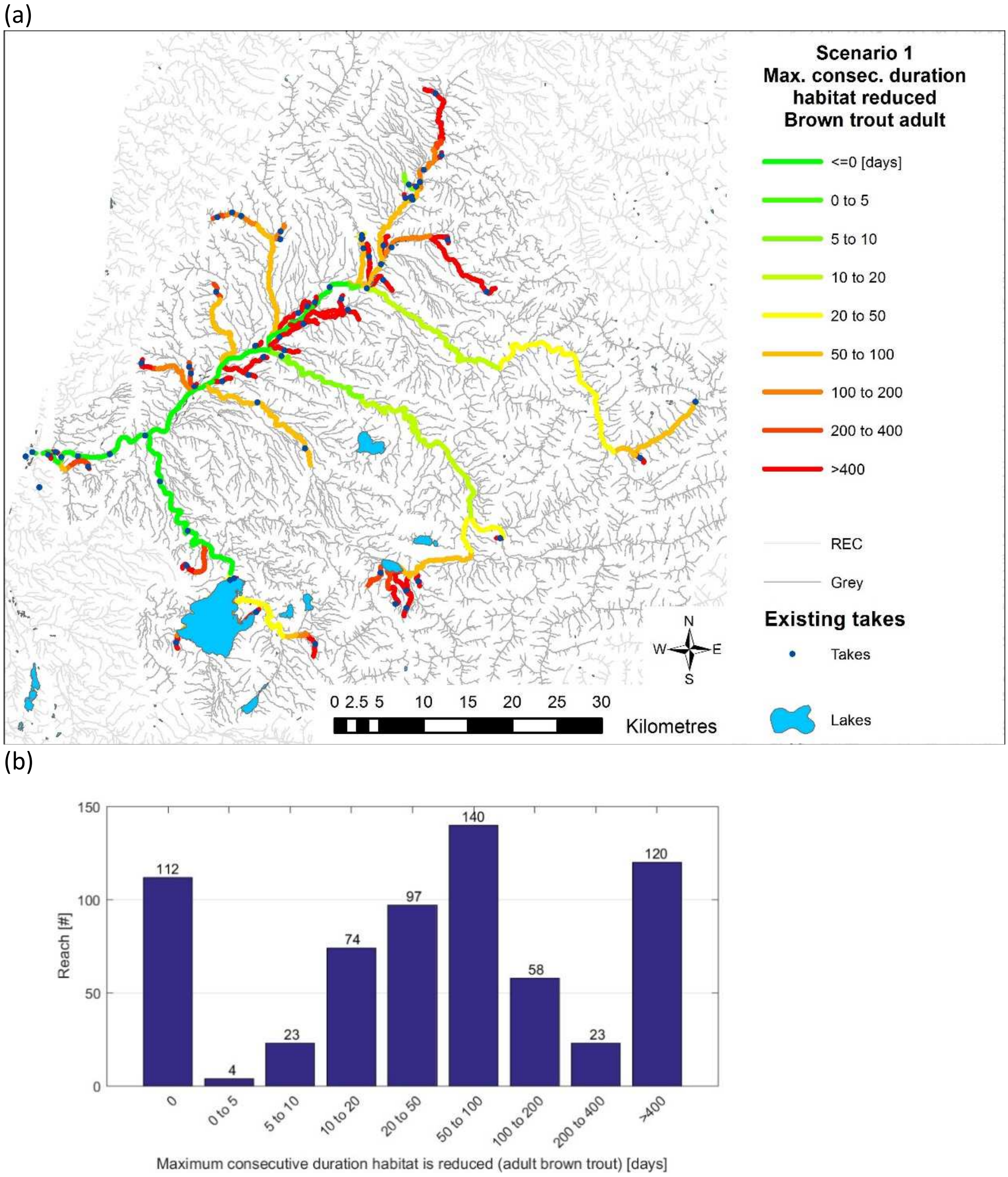
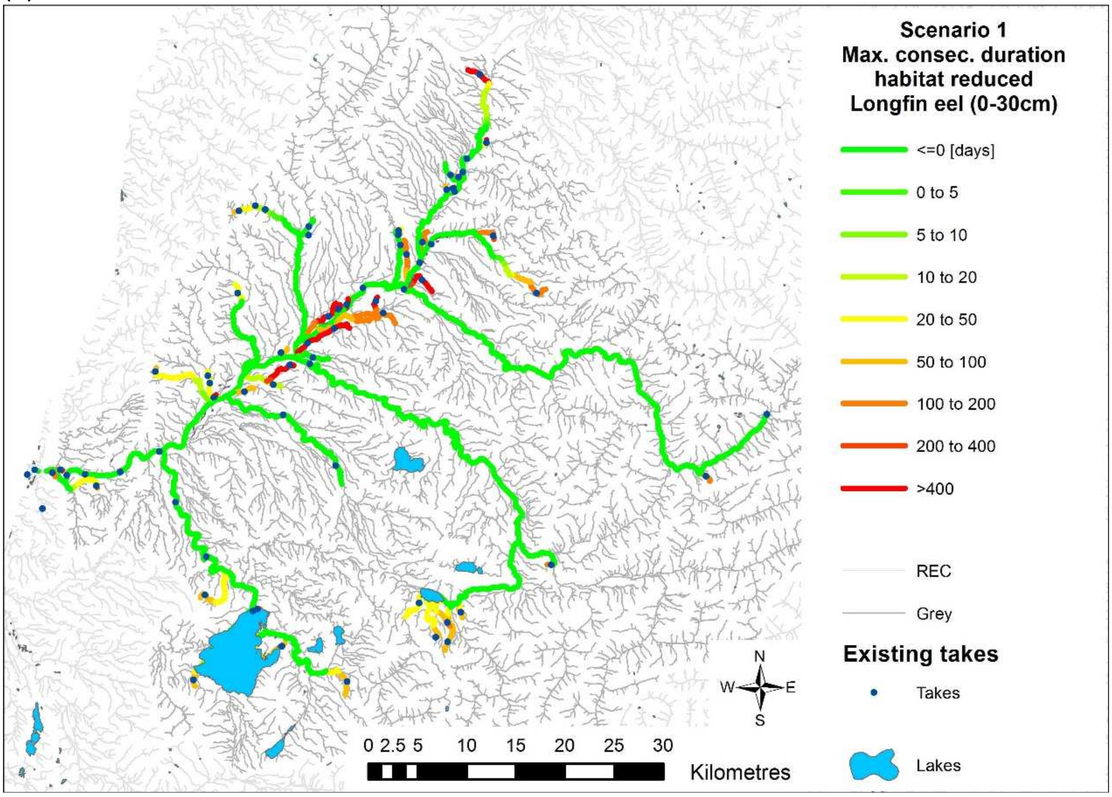


Figure 4-12: Maximum consecutive duration that adult brown trout habitat is reduced in the Grey River catchment due to current water abstraction. The key statistics for the data presented here are mean = 1,322.5 days, median = 63 days, min = 0 days, max = 15,280 days, and standard deviation = 3,910.8 days.

The map of the maximum consecutive duration of habitat reduction for longfin eels (Figure 4-13) again highlights the same reaches with a reduction in habitat shown in Figure 4-9. Examining the histogram, Figure 4-13 tell us that 19 reaches have a reduction of habitat for more than 400 consecutive days over the ~42 year flow record and the average reach has a maximum consecutive duration of habitat loss of 92 days.

(a)



(b)

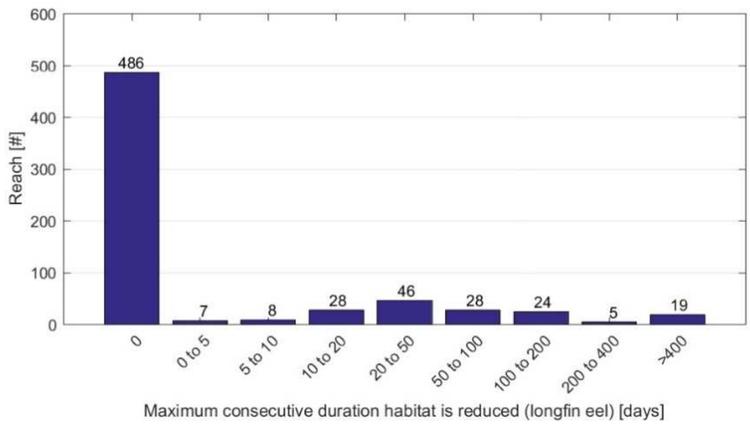


Figure 4-13: Maximum consecutive duration that longfin eels habitat is reduced in the Grey River catchment due to current water abstraction. The key statistics for the data presented here are mean = 92.1 days, median = 0 days, min = 0 days, max = 15,280 days, and standard deviation = 891.2 days.

4.2.1 Compliance with Policies 7.3.1 and 7.3.2

Policies 7.3.1 and 7.3.2 have been written with the intention that cumulative abstractions allow for the natural character and life supporting capacity of the aquatic ecosystem (WCRC 2014). However, Section 4.2.2 has highlighted that current abstraction is having a large negative impact on habitat for adult brown trout and longfin eels in a number of reaches. Many of the consents for water abstraction will pre-date Policies 7.3.1 and 7.3.2 and therefore may not comply with these policies.

We can use CHES to examine the difference (change) between *ΔQ* under current abstraction relative to *ΔQ* under Policy 7.3.1, therefore highlighting which reaches do not comply with Policy 7.3.1 and by how much. ‘How much’ an abstraction exceeds Policy 7.3.1 is calculated as the amount that the current *ΔQ* exceeds that allocated under Policy 7.3.1, and is expressed as ‘% greater’. We can explain how this is calculated using the following example: Consider a reach with a MALF of 10 l/s and a consented abstraction of 5 l/s. Under Policy 7.3.1 only 20 % of MALF can be abstracted in the A block, which for this reach is 2 l/s. However, the abstractor has a consent is for 5 l/s, and this would result in the reach being over allocated by 150 % ((5-2)/2*100 = 150 %).

Figure 4-14 highlights the reaches which exceed Policy 7.3.1 under current abstraction. This figure also shows that while the vast majority of reaches comply (589 out of 651) there are 17 reaches where *ΔQ* is > 50 % more than that allowed under Policy 7.3.1.

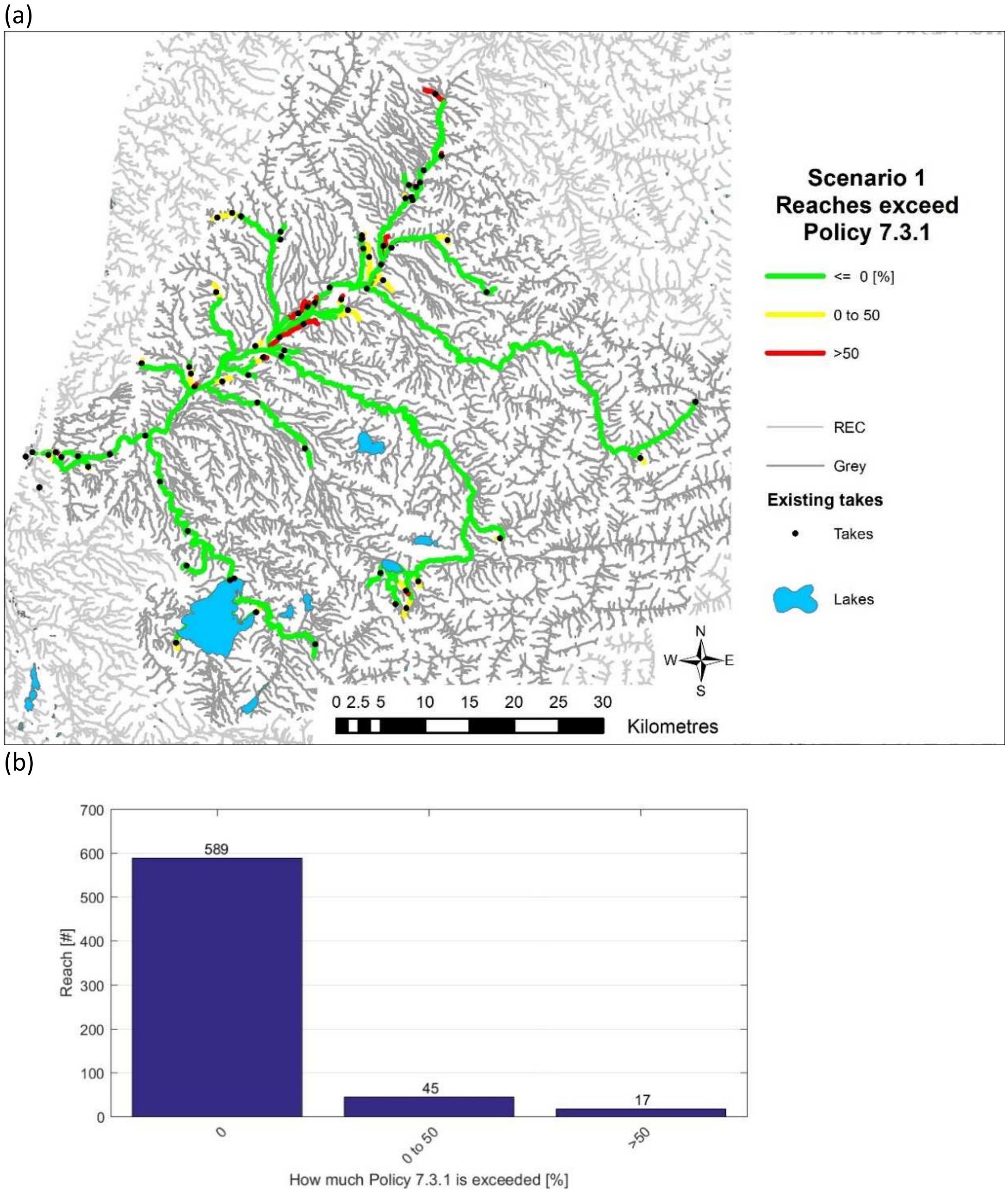


Figure 4-14: Reaches which exceed Policy 7.3.1 under current abstraction. The key statistics for the data presented here are mean = 2.9 %, median = 0 %, min = 0 %, max = 100 %, and standard deviation = 14.1 %.

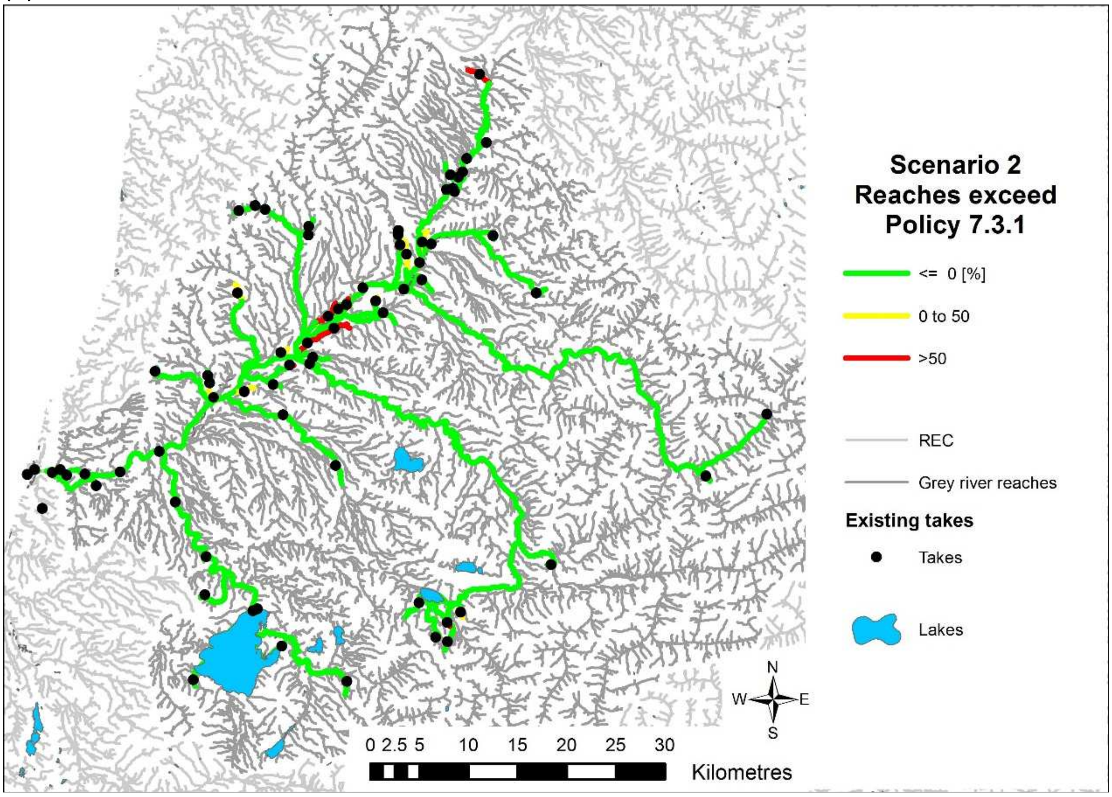
4.3 Applying Policy 7.3.1 and Policy 7.3.2 (Scenario 2)

One option that WCRC could hypothetically consider is to split current resource consents into an A and B block where the current allocation exceeds Policy 7.3.1. If the cumulative currently allocated ΔQ is less than 20 % of MALF then no B block is required, but if the cumulative currently allocated ΔQ exceeds 20 % of MALF then the remainder becomes B block. This adjustment would need to be applied at all the reaches indicated as exceeding Policy 7.3.1 in Figure 4-14. In Scenario 2 we make these adjustments to the current consented abstractions to reflect Policy 7.3.1 and Policy 7.3.2.

In this section we present reliability and habitat change results under Scenario 2. However, we first note that even when we split current allocations into A and B blocks in accordance with Policies 7.3.1 and 7.3.2, we still end up with some reaches exceeding Policy 7.3.1 (Figure 4-15). This might appear to be an error, but there are two reasons why this can happen:

1. **Groundwater abstraction**: This involves a time lag, and therefore this can lead to continued water depletion after abstraction has been turned off on a day-to-day simulation.
2. **Different management reach**: When water is taken from a reach that is different to the management reach (the reach at which limits are set) then flow in the management reach will comply with Policies 7.3.1 and 7.3.2, but flow in the abstraction reach might not.

(a)



(b)

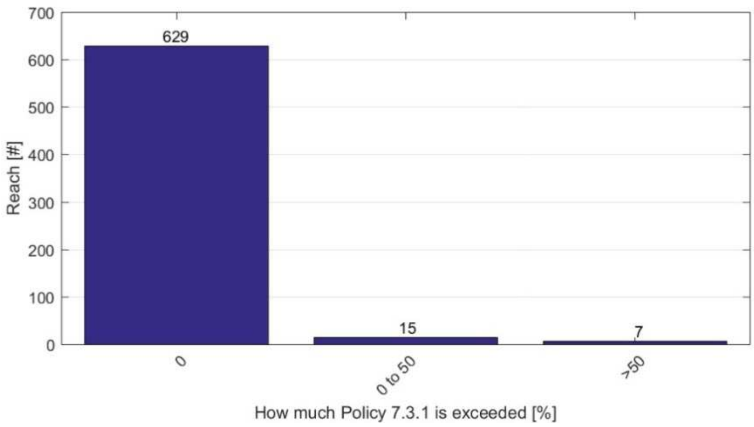


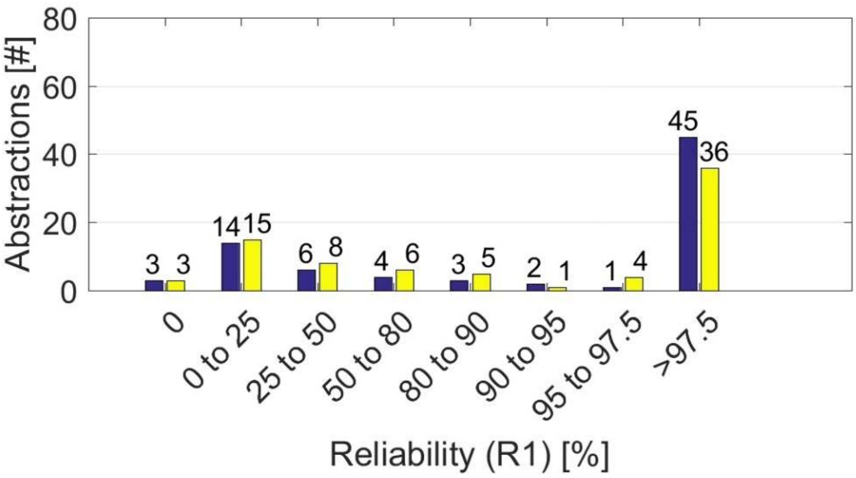
Figure 4-15: Reaches which exceed Policy 7.3.1 under Scenario 2. The key statistics for the data presented here are mean = 1.1 %, median = 0 %, min = 0 %, max = 97.8 %, and standard deviation = 7.7 %.

4.3.1 Reliability of abstraction - comparing Scenario 1 and Scenario 2

As Scenario 2 applies slightly stricter limits on abstraction from those currently consented (Scenario 1) then we would expect the reliability of abstraction to reduce. In this section we use CHES to directly compare these two scenarios. We present two measures of reliability: *R1*, the proportion of time that the full allocated volume is available, and *R2*, the proportion of time that at least some water can be taken. The results comparing Scenario 1 and Scenario 2 for reliabilities *R1* and *R2* are presented in Figure 4-16 (a) and (b) respectively. These results are presented in terms of the number of abstractions achieving different levels of reliability. The statistics behind the reliability results are presented in Table 4-3.

Figure 4-16 (a) shows that for most abstractors there is a reduction in the proportion of the time that the full allocation can be abstracted, with the number of reaches with an *R1* > 97.5 % dropping from 45 to 36. However, there is little change in the proportion of the time that at least some water can be taken, with the number of reaches with an *R2* > 97.5 % only dropping from 67 to 65. (Figure 4-16 (b)).

(a)



(b)

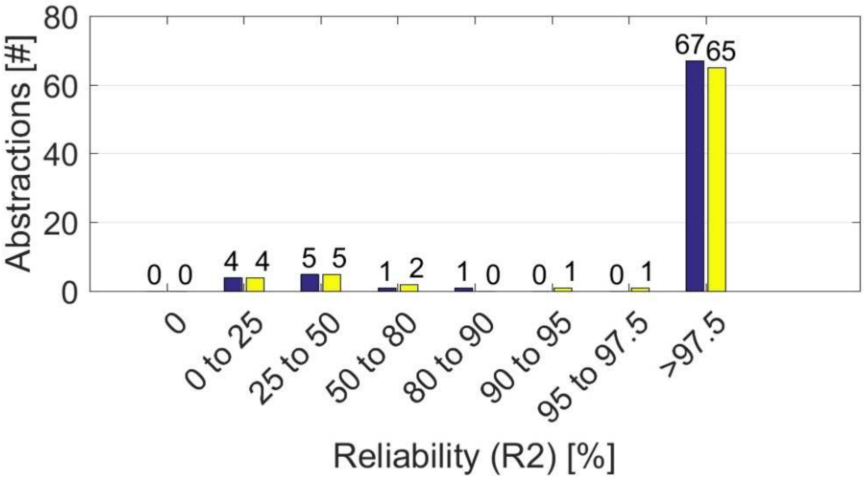


Figure 4-16: (a) Reliability *R1* for Scenario 1 (blue) and Scenario 2 (yellow), and (b) Reliability *R2* for Scenario 1 (blue) and Scenario 2 (yellow). Statistics for these histograms are provided in Table 4-3.

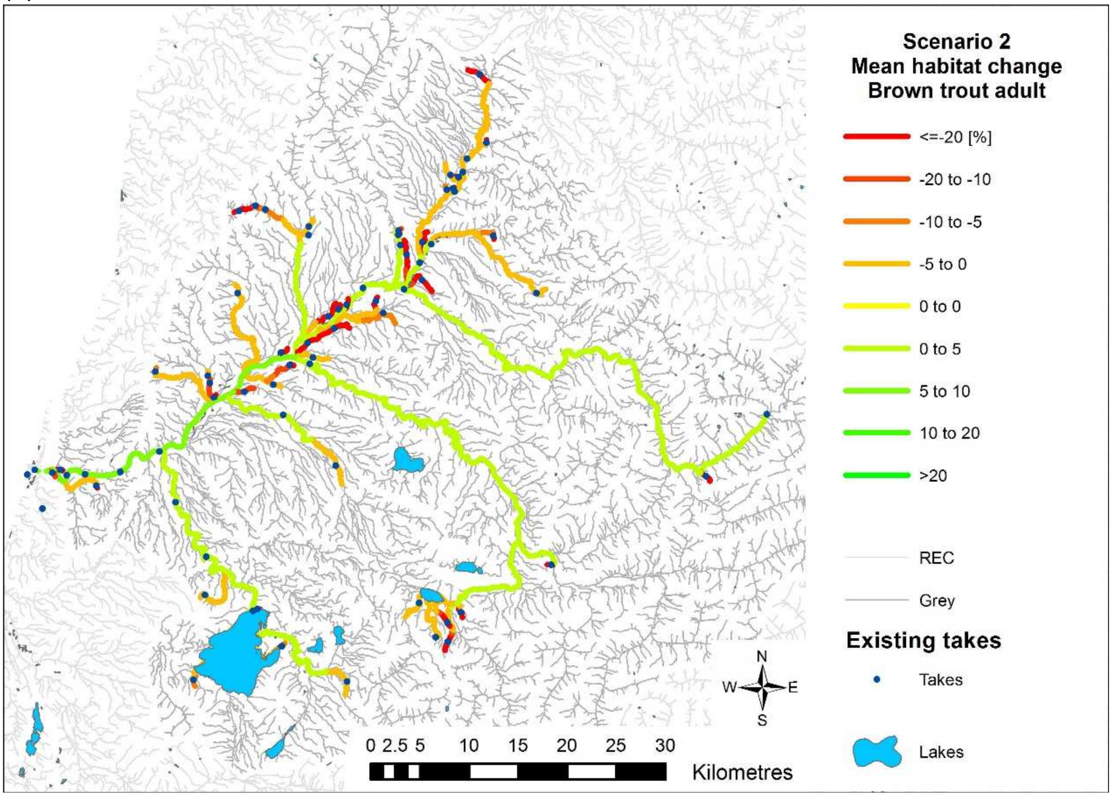
Table 4-3: Statistical properties of reliabilities R1 and R2 for Scenario 1 and Scenario 2.

	Mean	Median	Min	Max	STD
Scenario 1 *R1* [%]	71.8	100	0	100	39.7
Scenario 2 *R1* [%]	68	95.9	0	100	39.4
Scenario 1 *R2* [%]	90.6	100	0.1	100	25.1
Scenario 2 *R2* [%]	90.3	100	0.1	100	25.1

4.3.2 Habitat change under Scenario 2

Figure 4-17 and Figure 4-18 show the mean change in habitat under Scenario 2 for adult brown trout and longfin eels respectively. These figures show that the reaches that are negatively impacted by water abstraction in the Grey River catchment are largely the same under Scenario 1 and Scenario 2, however the degree to which those reaches are impacted alters slightly. Under Scenario 2 the mean change in habitat for adult brown trout is a reduction of 2.5 % (an improvement of 1.1 % compared to Scenario 1). The mean change in habitat for longfin eels is an increase of 0.4 %, compared to a 1.2 % reduction in habitat under Scenario 1 (i.e. a 1.6 % improvement).

(a)



(b)

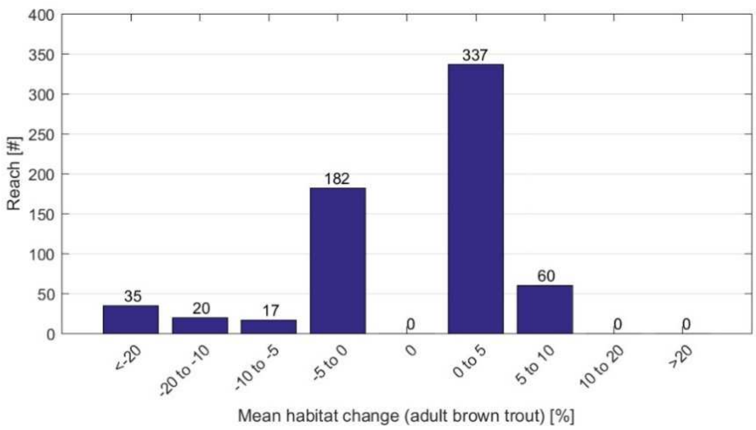
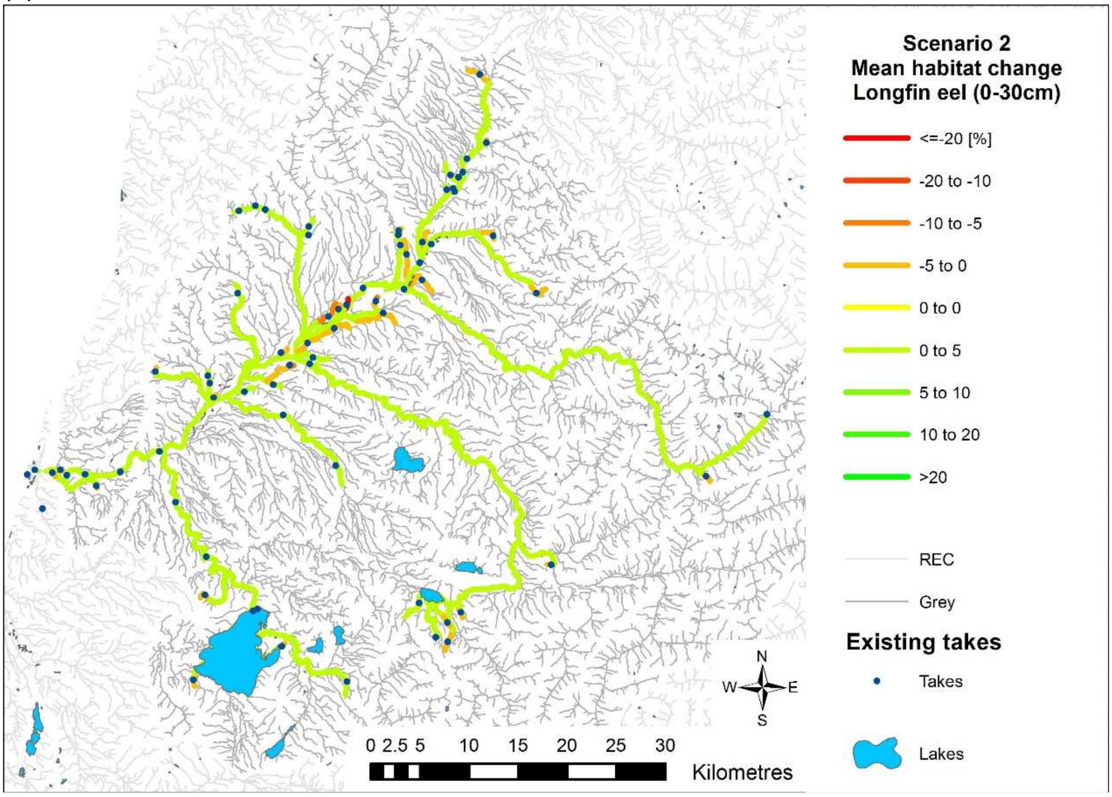


Figure 4-17: Mean habitat change for adult brown trout under Scenario 2. The key statistics for the data presented here are mean = -2.5 %, median = 0.1 %, min = -98.7 %, max = 7.2 %, and standard deviation = 11.3 %.

(a)



(b)

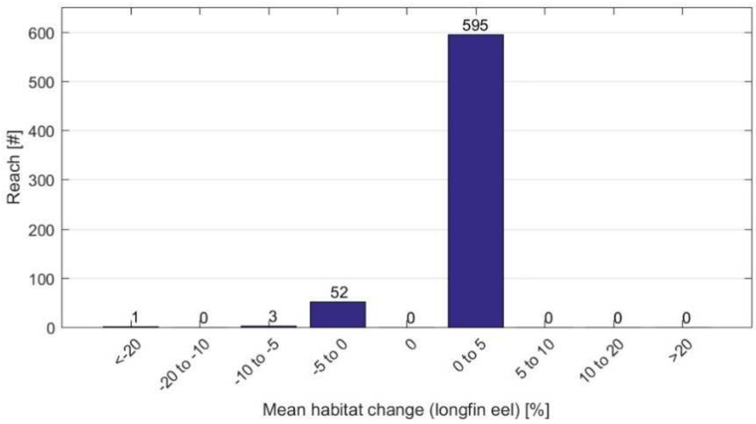


Figure 4-18: Mean habitat change for longfin eels under Scenario 2. The key statistics for the data presented here are mean = 0.4 %, median = 0.2 %, min = -97.4 %, max = 3.7 %, and standard deviation = 4.1 %.

4.4 Proposed NES limits (Scenario 3)

The proposed NES limits stipulate that:

- for river reaches where mean flow is ≥ 5 m^3/s
  - Q_{min} = 80 % of MALF and
  - ΔQ = 50 % of MALF, and
- for river reaches where mean flow is < 5 m^3/s
  - Q_{min} = 90 % of MALF and
  - ΔQ = 30 % of MALF.

These proposed NES limits are more limiting than either Scenario 1 or Scenario 2, both in terms of minimum flow and in terms of the total amount of water that can be taken. Therefore, whilst differences between Scenarios 1 and 2 were relatively small in terms of reliability and habitat change, we would expect the results under Scenario 3 (the proposed NES limits) to paint a different picture.

4.4.1 Reliability of abstraction under proposed NES limits

Under the proposed NES limits we again consider two measures of reliability, *R1* and *R2*. These results are presented in Figure 4-19 (a) and (b) respectively, with the statistics relating to these histograms presented in Table 4-4. The results show that under the proposed NES limits we get a mean *R1* of 92 % and a mean *R2* of 95 %. These reliability values are higher than under Scenario 1 or Scenario 2, however this is because the reliability is based on taking less water. Comparison of the amount of water taken under these three scenarios is discussed in the following section.

(a)

(b)

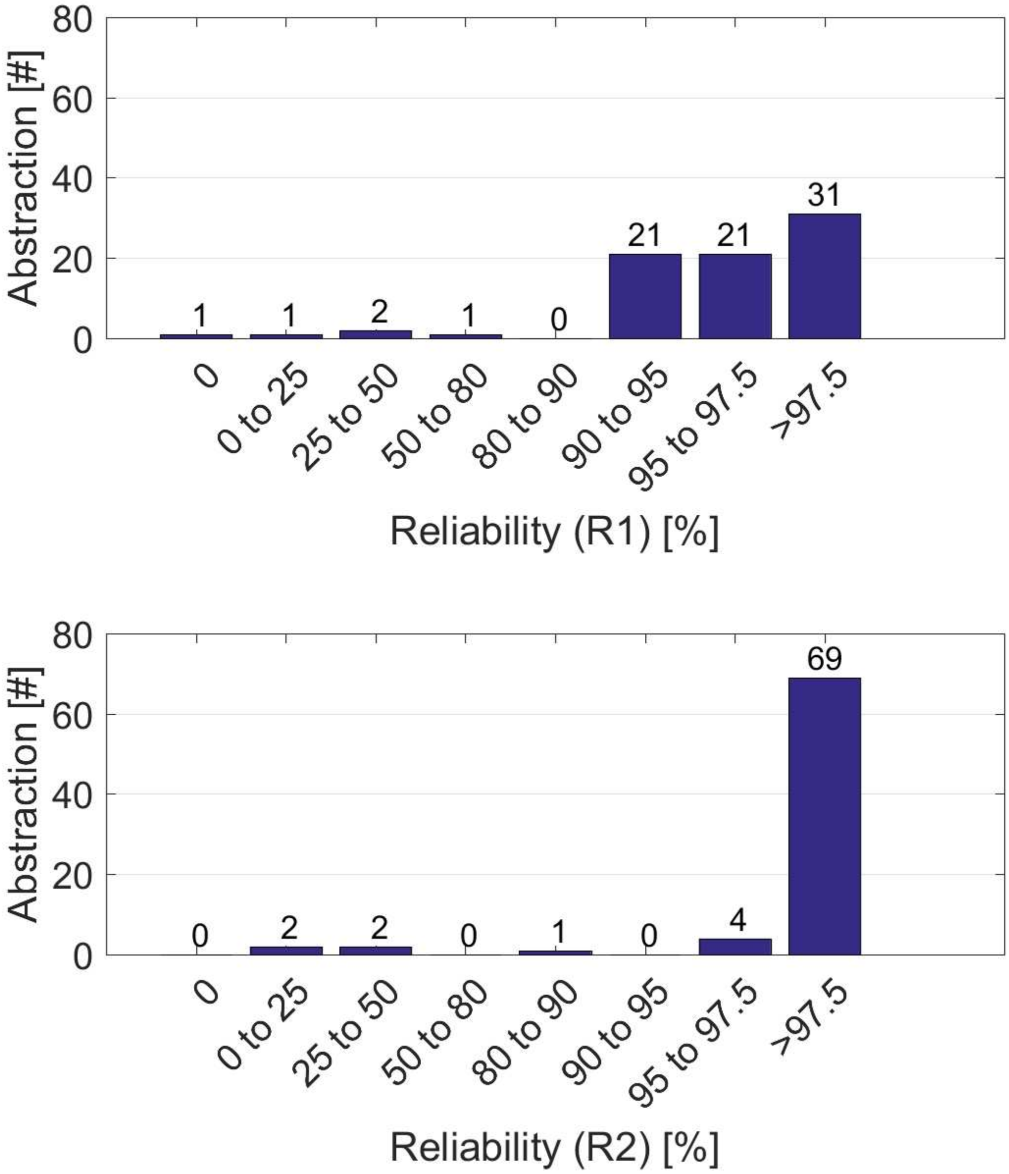


Figure 4-19: (a) Reliability *R1* under proposed NES limits and (b) Reliability *R2* under proposed NES limits. Statistics are provided in Table 4-4.

Table 4-4: Statistical properties of reliabilities *R1* and *R2* for Scenario 3.

	Mean	Median	Min	Max	STD
R1 [%]	92.3	96	0	99.8	17.7
R2 [%]	94.9	98.7	8.4	99.8	16

4.4.2 Water taken over time – comparing scenarios

One way of considering the effect of different abstraction scenarios on a catchment is to examine the total cumulative amount of water taken (ΔQ) upstream of the downstream end of the catchment or another key point of interest, for example the Grey at Dobson site (NZREACH 12028047). Results for the Grey at Dobson site are presented in Table 4-5. These results can also be plotted as water abstraction hydrographs (Figure 4-20). By plotting these results as a hydrograph we get an appreciation of how water availability and abstraction varies over a year. Figure 4-20 presents mean weekly abstraction across a year, and shows that most water could be taken in October and the least amount in February. When comparing these results with natural flows over the year (Figure 4-2), we see this seasonal variability reflects natural flow availability. In reality, the demand for water may be highest in February.

Table 4-5: Total water taken daily upstream of Grey at Dobson under Scenario 1, Scenario 2 and Scenario 3. Note: The statistics in this table are based on daily data. Mean natural flow at Grey at Dobson is 383,505 l/s.

	Mean daily *ΔQ*	Standard Deviation *ΔQ*	Minimum *ΔQ*	Maximum *ΔQ*
Scenario 1 [l/s]	2,525	332	1,663	4,309
Scenario 2 [l/s]	2,400	399	1,455	4,305
Scenario 3 [l/s]	1,554	110	178	1,621

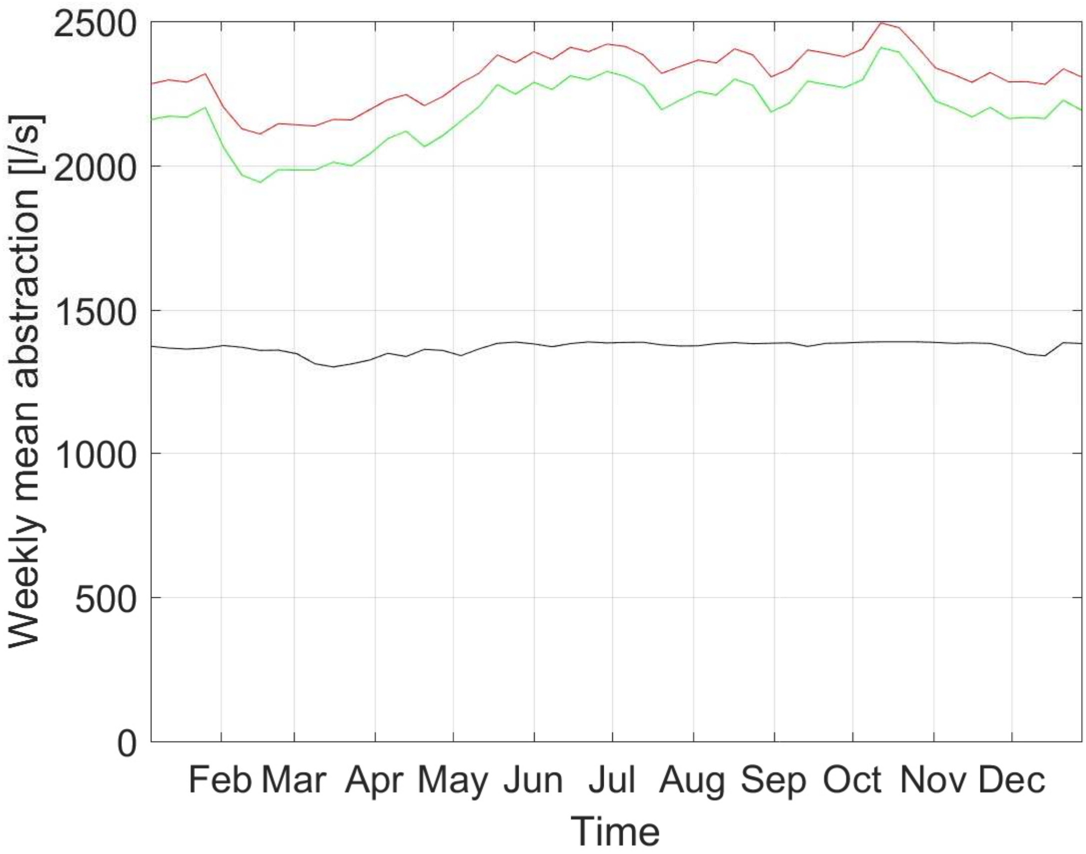


Figure 4-20: Mean weekly abstraction hydrographs showing total water taken upstream of Grey at Dobson under Scenario 1 (red), Scenario 2 (green) and Scenario 3 (black). Statistics are provided in Table 4-6.

Table 4-6: Statistical properties of mean weekly abstraction upstream of Grey at Dobson under Scenario 1, Scenario 2 and Scenario 3.

	Mean *ΔQ*	Median *ΔQ*	Min *ΔQ*	Max *ΔQ*	STD *ΔQ*
Scenario 1 [l/s]	2,310.2	2,319.3	2,108.8	2,494.1	92.8
Scenario 2 [l/s]	2,189.6	2,201.4	1,941.1	2,408.4	112.2
Scenario 3 [l/s]	1,369	1,377.8	1,301.3	1,388.5	21.6

If we are particularly interested in water availability for a given abstractor, we can plot daily water supply over a ~42 year period for that abstractor. We present results in this way for an example abstractor (#12019562) under Scenario 1, Scenario 2 and Scenario 3 in Figure 4-21 (with statistics presented in Table 4-7). For comparison, the statistical properties of the natural flow time series are given in Table 4-8. This example shows that under the proposed NES rules total allocation for this abstractor would be limited to 4.2 l/s, but under Scenario 1 and Scenario 2 total allocation could be up to 60 l/s. However, the frequency with which the full 60 l/s can be taken is low and on the average day they could take 38.5 l/s under Scenario 1. Reliabilities for Scenario 1 and Scenario 2 are 64.2% and 49.7 % respectively, whereas due to the small amount being abstracted under Scenario 3 reliability is large at 96.5 %.

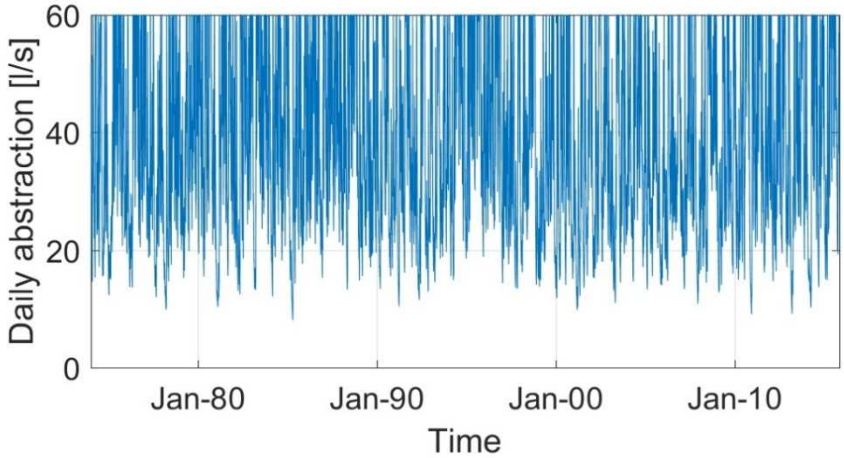
Table 4-7: Statistical values of water supply over time for Scenario 1, Scenario 2, and Scenario 3.

	Mean *ΔQ* [l/s]	Median *ΔQ* [l/s]	Min *ΔQ* [l/s]	Max *ΔQ* [l/s]	STD *ΔQ* [l/s]	Mean R [%]
Scenario 1	38.5	36.2	8.1	60	15.4	64.2
Scenario 2	29.8	25.7	2.8	60	18.1	49.7
Scenario 3	4.1	4.2	0	4.2	0.7	96.5

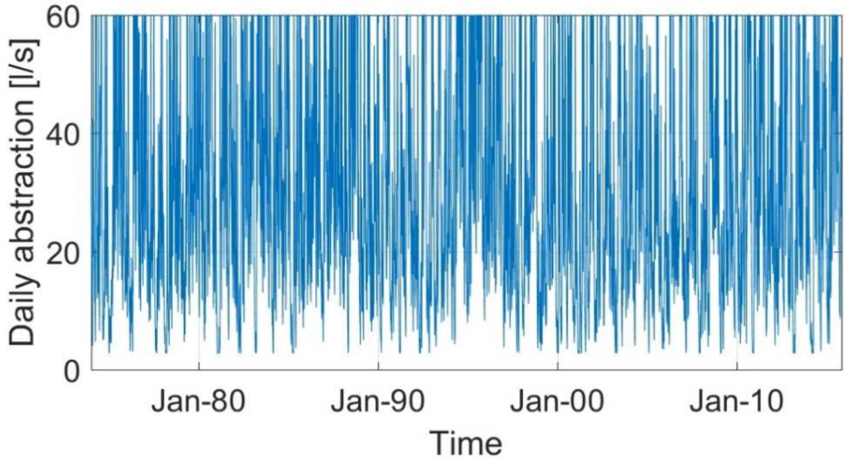
Table 4-8: Statistical properties of the natural flow time series for reach 12019562.

Min Q [l/s]	MALF [l/s]	Mean Q [l/s]	Median Q [l/s]	Max Q [l/s]	STD Q [l/s]
8.1	14.1	46.1	36.2	726.9	34.2

(a)



(b)



(c)

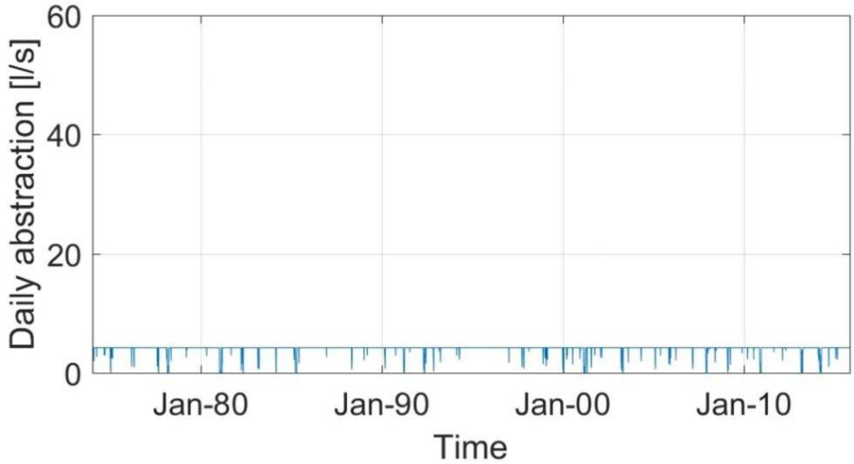


Figure 4-21: Water supply (availability) over time for an example abstractor (#12019562) under Scenario 1 (a), Scenario 2 (b), and Scenario 3 (c). Statistics for these histograms are provided in Table 4-7.

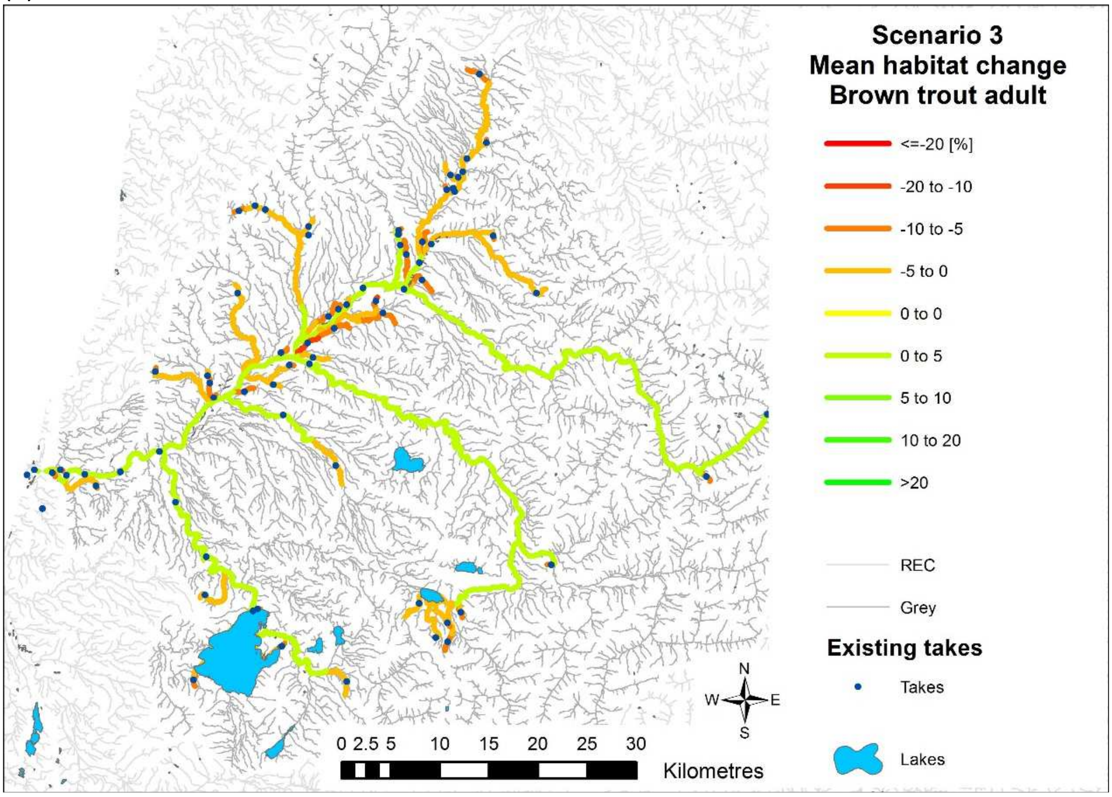
D
R
A
F
T

4.4.3 Habitat change due to abstraction

Figure 4-22 presents the results for the mean change in habitat availability for adult brown trout under Scenario 3. This figure tells us that under the proposed NES rules the mean change in habitat for adult brown trout is a reduction of 0.3 %. We can compare this result (or other alternative statistics) with Scenario 2 (which cause a reduction in habitat of 2.5 %) and Scenario 1 (a reduction in habitat of 3.6 %), by examining the equivalent plots (Figure 4-17 and Figure 4-7 respectively).

Alternatively, we can plot the absolute difference between two given scenarios. When doing this it is important to be clear which scenario is subtracted from which so that there is no confusion as to whether a negative result represents an increase or decrease in habitat availability. Taking a hypothetical example, if under Scenario 3 a given reach has a habitat decrease of 2 % and under Scenario 1 it has a habitat decrease of 4 % and we calculate Scenario 3 – Scenario 1, then the calculation would be: -2 minus -4 = +2, with a positive result representing an improvement in habitat availability under Scenario 3 relative to Scenario 1 (but both scenarios represent a reduction in habitat compared to the natural flows).

(a)



(b)

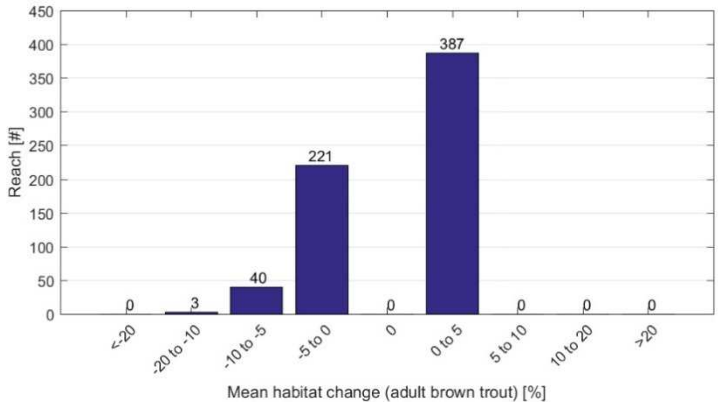
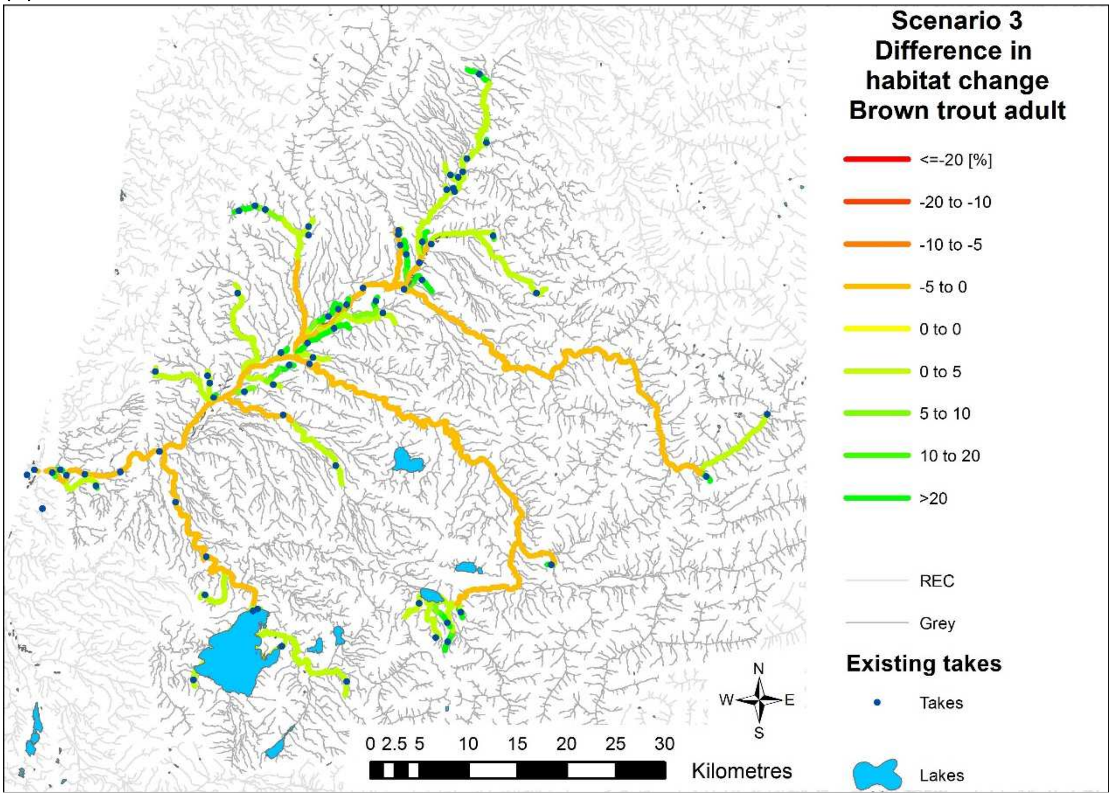


Figure 4-22: Mean habitat change for adult brown trout under Scenario 3. The key statistics for the data presented here are mean = -0.3 %, median = 0 %, min = -13.6 %, max = 4.6 %, and standard deviation = 2.6 %.

We present such an example (Scenario 3 – Scenario 1) in Figure 4-23. This shows that in 325 reaches habitat availability is greater under Scenario 1 than under Scenario 3 (negative difference in habitat change) but on average across all reaches the difference is positive (3.3 %) meaning that overall there is greater habitat availability under Scenario 3 relative to Scenario 1. The equivalent results for longfin eels are presented in Figure 4-24 showing that on average there is a 1.6 % improvement in habitat availability under proposed NES rules compared to current rules.

(a)



(b)

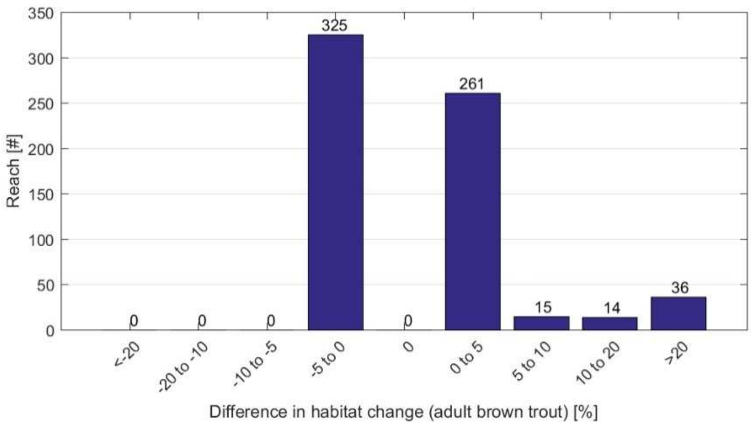
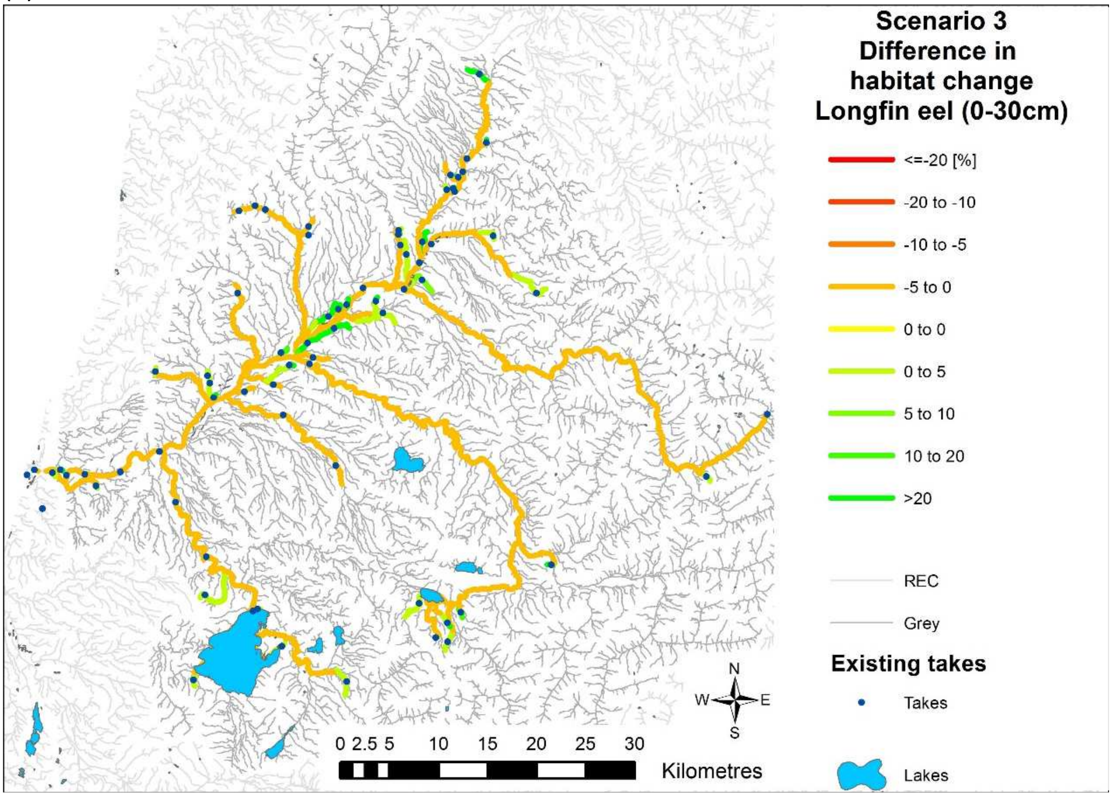


Figure 4-23: The difference in mean habitat change between Scenario 3 and Scenario 1 for adult brown trout. Note calculation is Scenario 3 – Scenario 1, therefore positive numbers (green colour) indicate that habitat availability is greater under Scenario 3 relative to Scenario 1. The key statistics for the data presented here are mean = 3.3 %, median = 0 %, min = -3 %, max = 94.1 %, and standard deviation = 14 %.

(a)



(b)

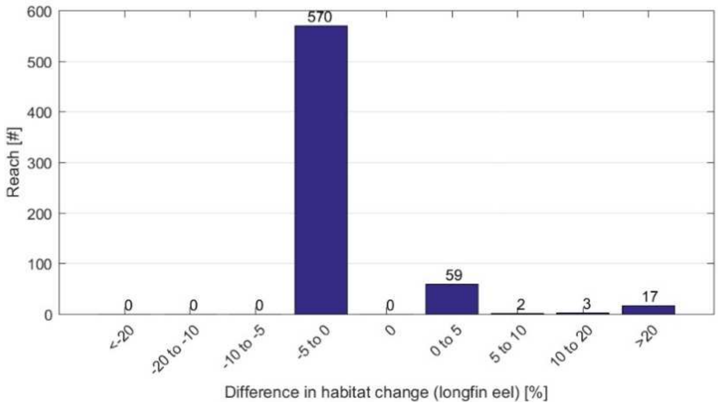
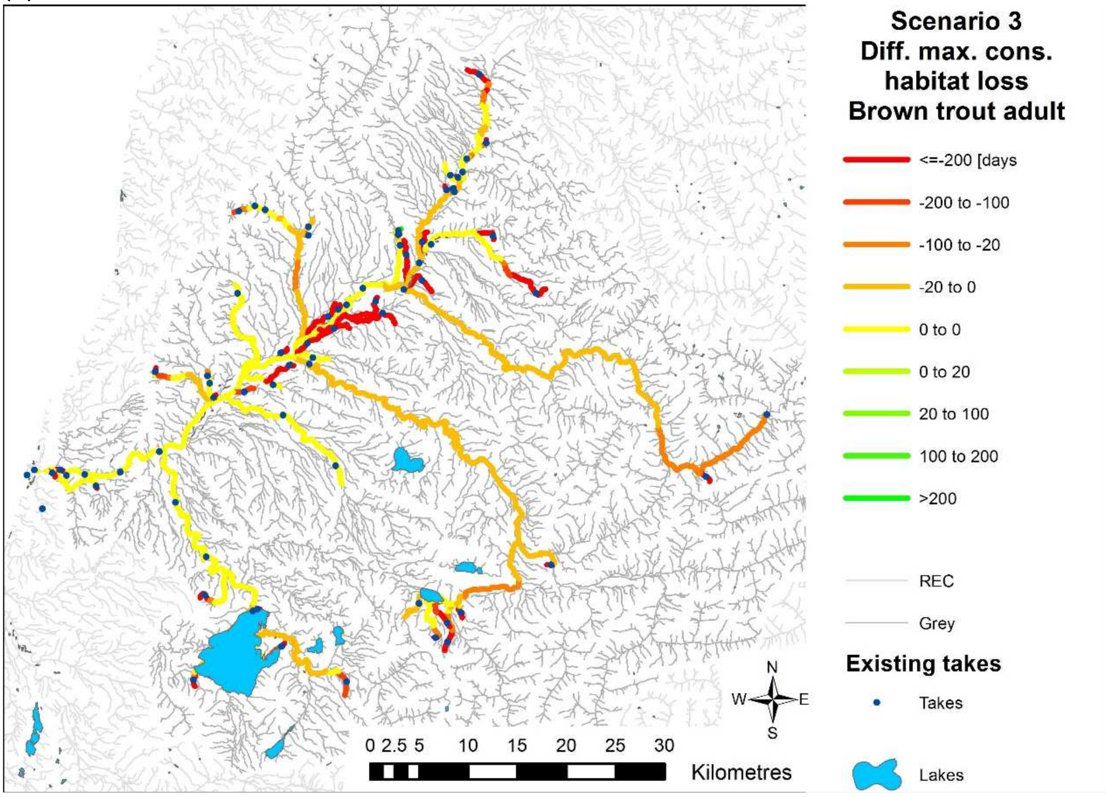


Figure 4-24: The difference in mean habitat change between Scenario 3 and Scenario 1 for longfin eels. Note calculation is Scenario 3 – Scenario 1, therefore positive numbers (green colour) indicate that habitat availability is greater under Scenario 3 relative to Scenario 1. The key statistics for the data presented here are mean = 1.6 %, median = -0.1 %, min = -2.5 %, max = 99.5 %, and standard deviation = 11.6 %.

We can also plot the absolute difference between two given scenarios in terms of maximum consecutive duration of habitat loss. This is essentially the same as subtracting the results presented in Figure 4-12 from the equivalent results under Scenario 3. As the consecutive durations of habitat loss under both scenarios are positive numbers, when we difference the results (Scenario 3 – Scenario 1), a negative result implies that the consecutive period of habitat loss is shorter under Scenario 3 than it is under Scenario 1. These results are presented in Figure 4-25 for adult brown trout and in Figure 4-26 for longfin eels.

(a)



(b)

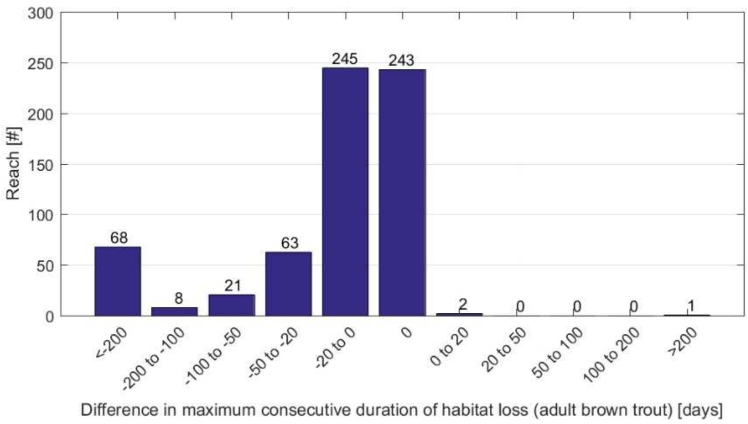
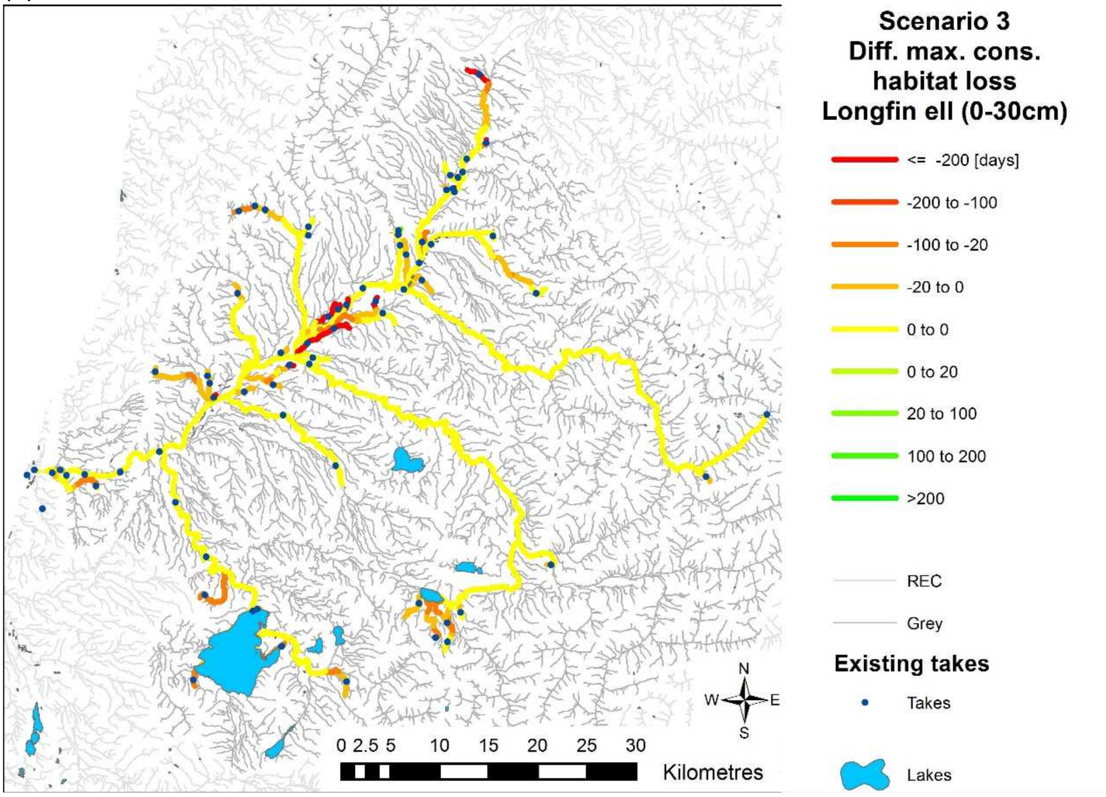


Figure 4-25: The difference in the maximum consecutive duration of habitat loss for adult brown trout between Scenario 3 and Scenario 1. Note calculation is Scenario 3 – Scenario 1, so a negative result (orange-red colour) implies the consecutive period of habitat loss is shorter under Scenario 3 that it is under Scenario 1. The key statistics for the data presented here are mean = -984.3 days, median = -9 days, min = -13.754 days, max = 1,707 days, and standard deviation = 3,217.6 days.

(a)



(b)

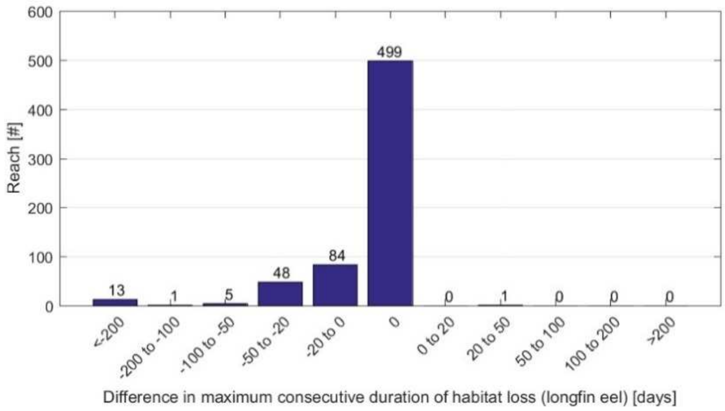


Figure 4-26: The difference in the maximum consecutive duration of habitat loss for longfin eels between Scenario 3 and Scenario 1. Note calculation is Scenario 3 – Scenario 1, so a negative result (orange-red colour) implies the consecutive period of habitat loss is shorter under Scenario 3 that it is under Scenario 1. The key statistics for the data presented here are mean = -68.7 days, median = 0 days, min = -14,174 days, max = 44 days, and standard deviation = 815.6 days.

During this study we also used CHES to examine the differences between Scenario 3 and Scenario 2, and found the results to be very similar to those presented in Figure 4-23 to Figure 4-26. This is because the difference in habitat availability (for adult brown trout and longfin eels) between Scenario 1 and 2 is relatively small (+/- 5 %).

4.5 Adding water storage (Scenario 4)

The aim of Scenario 4 is to demonstrate how CHES can be used to assess the effects of adding a water storage reservoir, in particular how a water storage reservoir can be used to offset the effects of stricter water allocation rules and provide improved reliability.

As an example we selected a reach (NZREACH 12030747) which has a natural mean flow of 42.3 l/s and a MALF of 9.7 l/s (Figure 4-27). This reach has an abstractor who has a consent to take ΔQ = 40 l/s, which has an R of 72.5 % under Scenario 1 (Figure 4-28 (a), Table 4-9). However, if this abstraction was to comply with Policies 7.3.1 and 7.3.2 this consent would need to be split into an A and B block as follows:

- A block: ΔQ = 20 % of MALF = 1.9 l/s, Q_{min} = 0 l/s
- B block ΔQ = 40 l/s - 1.9 l/s = 38.1 l/s, Q_{min} = 7.3 l/s

If these rules were applied then the mean reliability (R) for this abstractor to take the full 40 l/s (A block and B block combined) would be reduced to 59.9 % (Figure 4-28 (b), Table 4-9).

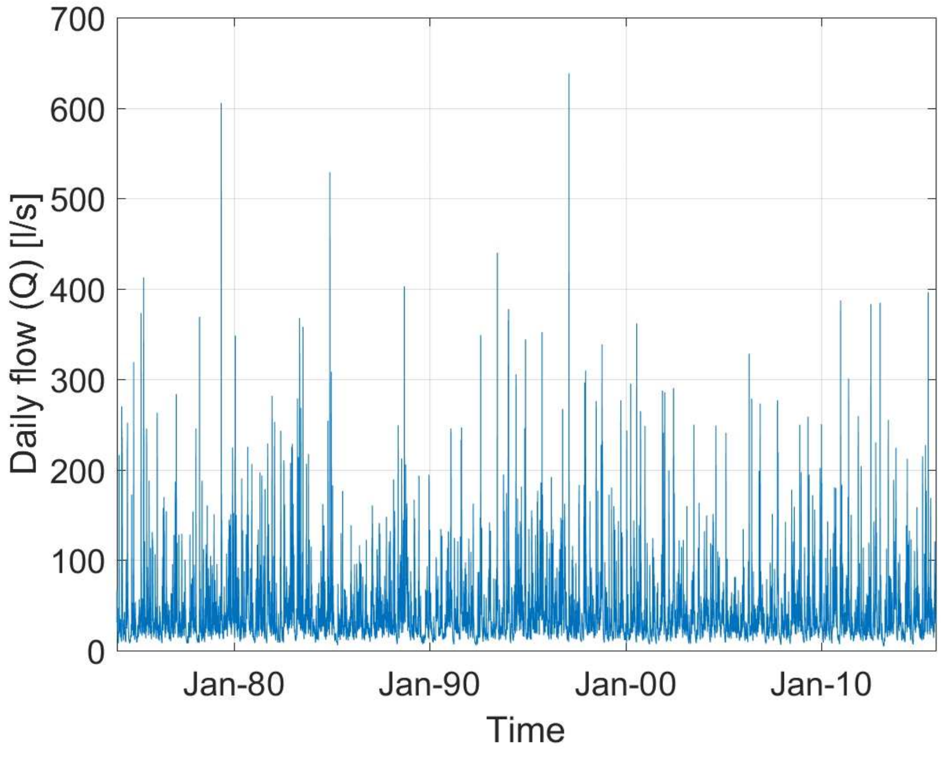
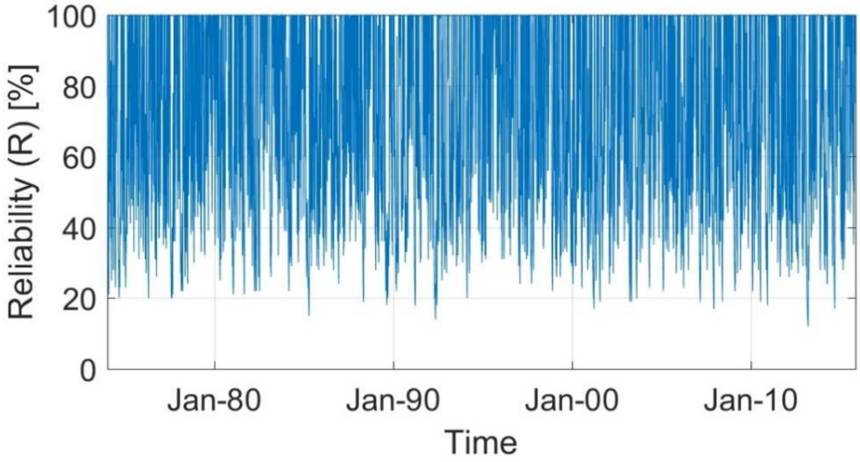


Figure 4-27: Natural flows in the example reach (NZREACH 12030747) used in Scenario 4. The key statistics for the data presented here are mean = 42.3 l/s, median = 30.1 l/s, MALF = 9.7 l/s, min = 4.7 l/s, max = 638.4 l/s, and standard deviation = 39.5 l/s.

(a)



(b)

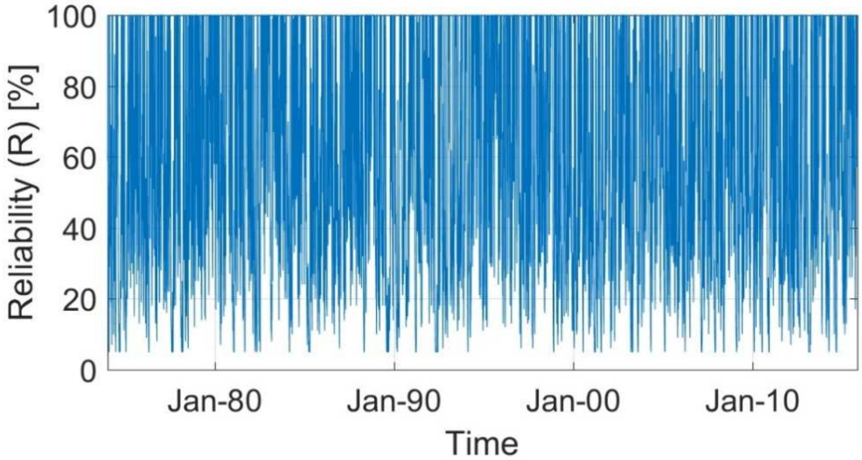


Figure 4-28: Reliability (*R*) over time under (a) Scenario 1 and (b) Scenario 2 for the example reach (NZREACH 12030747) used in Scenario 4. Key statistics for the data presented are provided in Table 4-9.

Table 4-9: Statistical properties of reliability *R* for Scenario 1 and Scenario 2.

	Mean *R*	Median *R*	Min *R*	Max *R*	STD *R*
Scenario 1 [%]	72.5	75	12	100	26.1
Scenario 2 [%]	59.9	57	5	100	32.3

As an example, we can use CHES to examine what size reservoir would be required for this abstractor to meet the hypothetical objective of regaining the reliability under Scenario 1, whilst following Scenario 2 rules. This is an iterative process as CHES doesn't directly calculate the optimum size of reservoir. We need to choose a storage capacity for the reservoir, which will provide additional supply when river flows are low. We also need to choose an increased ΔQ. This is because the existing ΔQ is needed to meet existing water requirements (e.g. irrigation) and the abstractor needs to be able to take more than this when river flows are high in order to fill the reservoir. The ΔQ chosen essentially sets how quickly the dam can be filled.

If we start by assuming we need a storage capacity of 10 x daily demand (34560 m^3) and we keep other conditions the same (ΔQ = 38.1 l/s, Q_{min} = 7.3 l/s), then we achieve no increase in reliability (mean *R* = 59.9 %). However, if we increase ΔQ to 640 l/s (this is arbitrary but we chose this as it is the maximum flow for this reach; Figure 4-27) then mean *R* increases to 73.7 % (Figure 4-29), thereby exceeding our objective under this scenario. Further iterations with CHES show that we can achieve the reliability of Scenario 1 if we have a reservoir storage volume of 8.4 x daily demand.

If the objective was instead for this abstractor to achieve maximum reliability, this would require a storage volume of 163 x demand. With a dam of this volume reliability (*R*) increases to 87.3 % (Figure 4-30). Even though a larger dam could be simulated, there is not enough water in the river to utilise the extra storage volume of the dam.

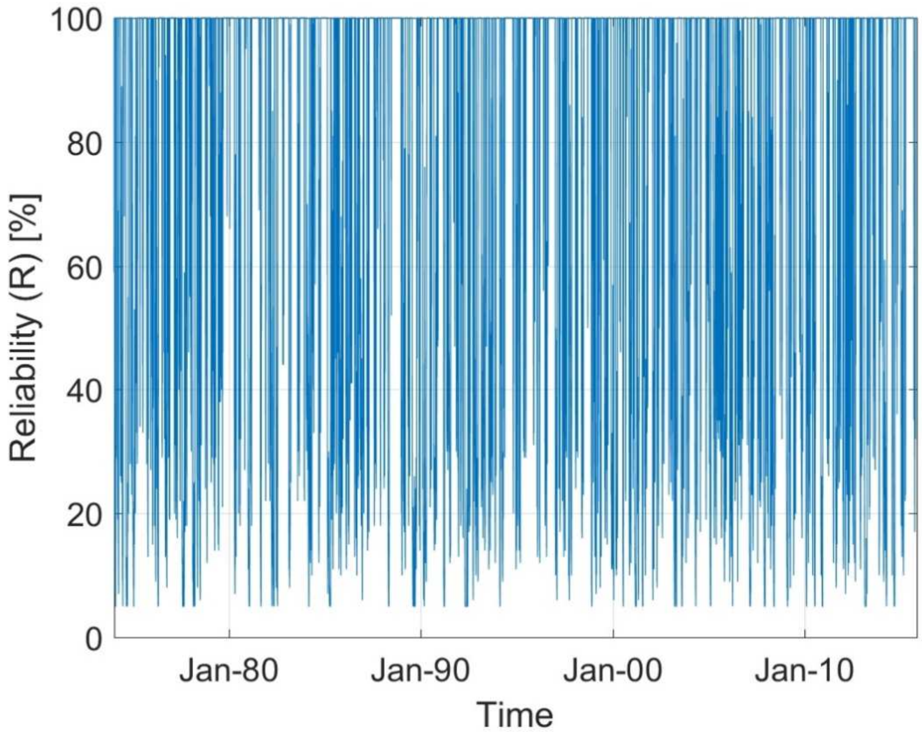


Figure 4-29: Reliability (*R*) for example abstractor with ΔQ = 640 l/s, Q_{min} = 7.3 l/s and dam volume = 10 x demand. Note this assumes the dam is empty at the start. The key statistics for the data presented here are mean = 73.7 %, median = 100 %, min = 5 %, max = 100 %, and standard deviation = 34.7 %.

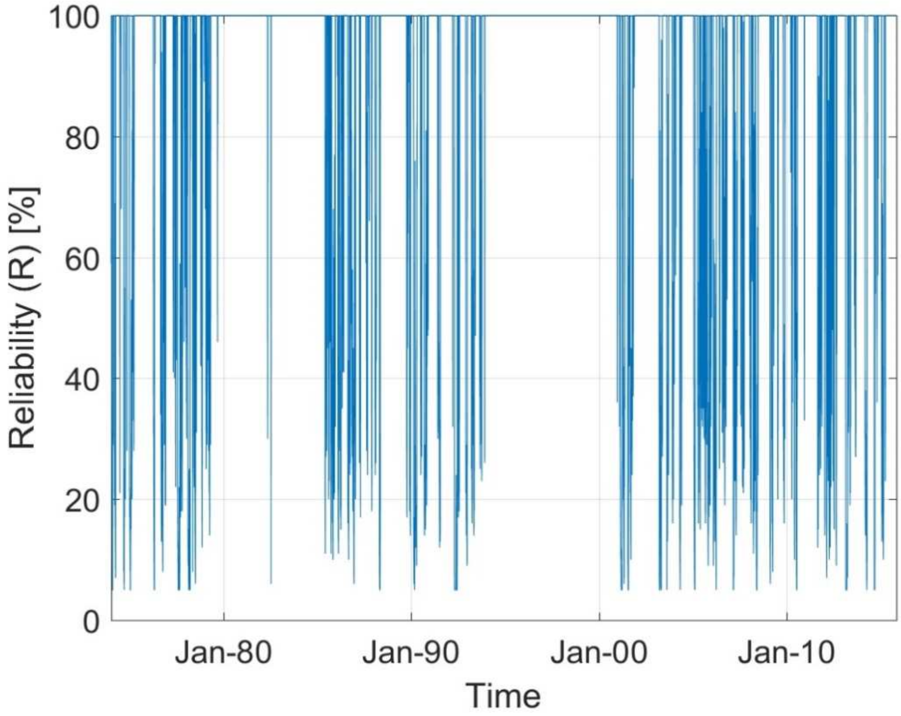


Figure 4-30: Reliability (*R*) for example abstractor with *ΔQ* = 640 l/s, Q_{min} = 7.3 l/s and dam volume = 163 x demand. Note this assumes the dam is empty at the start. The key statistics for the data presented here are mean = 87.3 %, median = 100 %, min = 5 %, max = 100 %, and standard deviation = 27.4 %.

In this scenario we did not consider how the increased maximum allocation required to fill the dam could affect the reliability of downstream abstractions or how it could change habitat availability. However, these questions could easily be answered.

4.6 Adding a large new abstraction (Scenario 5)

This scenario is based on a hypothetical situation where a farmer wishes to increase his farm capacity by 500 dairy cows. To do this the farmer will need to abstract enough water to irrigate a sufficient area of pasture and have enough water for drinking and cleaning of dairy sheds. Our aim under this scenario is to ascertain how large a storage reservoir is needed for a new abstraction to be consented in the reach such that we comply with Policies 7.3.1 and 7.3.2 and meet three hypothetical objectives:

- A mean *R* of > 95 %, and
- The habitat for adult brown trout shall not degraded by more than 1 % (compared to Scenario 1), and
- The downstream abstractors shall not be affected (i.e. no change in reliability compared to reference Scenario 1).

As outlined in the methods (Section 3.4), we assume that each cow requires 70 l/day for drinking and another 70 l/day for shed cleaning (The Rural). This gives a total drinking and cleaning demand of 70 m^3/day for all 500 cows. In addition, we assume that the area of pasture required is 166 hectares (Morris 2012) and that there will be an irrigation efficiency of 70 %, a crop factor of 1 and a soil trigger of 75 mm (these are variables required by CHES to calculate the water required for irrigation).

The supply of water for drinking and cleaning is a constant requirement. However, the supply of water for irrigation varies over time and is calculated using the Rapid Assessment Tool (RAT module) (Woods et al. 2012) in CHES. The RAT module uses evaporation and rain data to simulate soil moisture over time and the need for irrigation is 'triggered' when the soil moisture falls below the defined soil trigger level. For a more in depth description of the RAT tool please see Appendix A or the CHES manual (Diettrich 2012).

The example reach (NZREACH 12024235, located south of Ikamatua) has a natural mean flow of 69.6 l/s and MALF = 20.3 l/s. This reach already has a high level of water demand, with A block fully allocated. Therefore, for this proposed abstraction, only B block is available (i.e. we follow Policy 7.3.2).

If we assume, based on compliance with Policy 7.3.2, that the new abstraction can be up to ΔQ = 825.4 l/s (the maximum flow for this reach) and Q_{min} = 15.2 l/s (75 % of MALF) with no means of water storage (i.e. no dam) then the mean reliability (*R*) will be 88.3 % (Figure 4-31). Whilst a reliability of 88.3 % might be acceptable for irrigating pasture, the water required for drinking and cleaning is a constant demand that requires 100% reliability. The fact that A block is fully allocated means that a dam will be required to provide 100 % reliability for the drinking and cleaning water. Note that the total water demand for the proposed new abstraction varies over time due to irrigation needs. Therefore, when we calculate reliability in this section it is calculated based on a varying demand as well as the usual varying supply (i.e. in most scenarios we assume the demand to be constant but in this scenario the irrigation demand is not and CHES can account for this).

Assuming a maximum abstraction of ΔQ = 825.4 l/s, and following several iterations with CHES, we find that if we add a dam with a reservoir volume of 86,400 m^3 then *R* increases to 95.8 % (Figure 4-32), which would meet our first hypothetical objective. It should be noted that reliability will inevitably be low when a dam is first added as it will start empty and there are very low flows during the first month of simulated flows, when some irrigation would be needed but the water could not be supplied from the still empty dam. It is important that we also meet the requirement of 100% reliability for the constant demand for drinking and cleaning water. If we run CHES for ΔQ = 70 m^3/day (the total demand for cleaning and drinking water only) with the same Q_{min} we find that we can achieve a reliability of 100 % with a smaller reservoir volume of 4,665 m^3 (e.g. reservoir dimensions of 30 m x 31 m x 5 m). In summary, to meet our reliability objectives for this hypothetical new abstraction would require a reservoir volume of 86,400 m^3 which could be provided by reservoir dimensions of 131 m x 132 m x 5 m.

We also found that we can achieve a maximum *R* of 100 % for cleaning, drinking <u>and</u> irrigation water if we increased the reservoir volume to 607,392 m^3. However, this would likely be considered excessively large, equating to a reservoir of size 348 m x 348 m x 5 m.

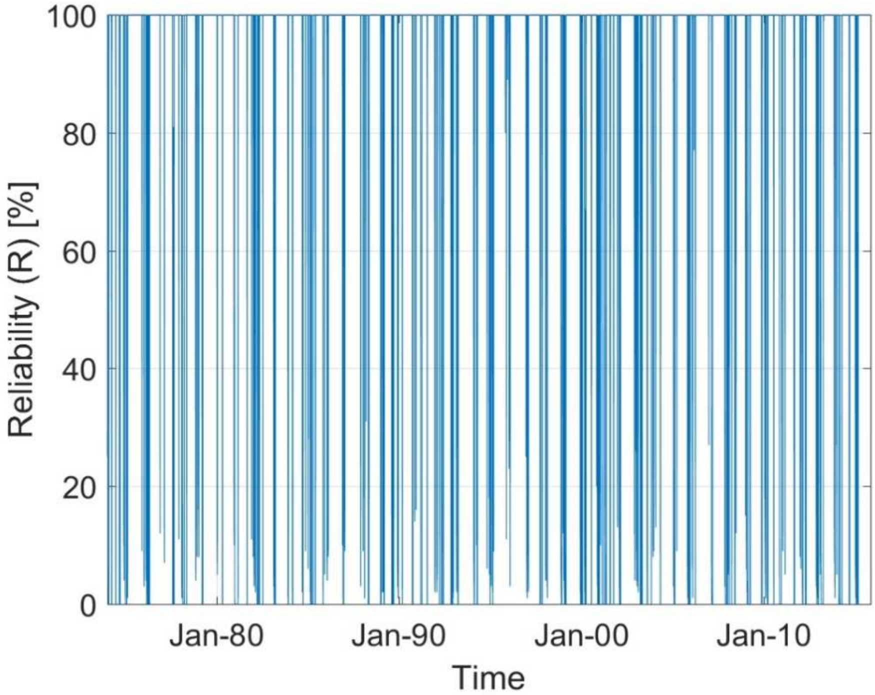


Figure 4-31: Reliability (*R*) for a hypothetical large new abstraction of ΔQ = 825 l/s, Q_{min} = 15.2 l/s with no dam on NZREACH 12024235. The key statistics for the data presented here are mean = 88.3 %, median = 100 %, min = 0 %, max = 100 %, and standard deviation = 32.1 %.

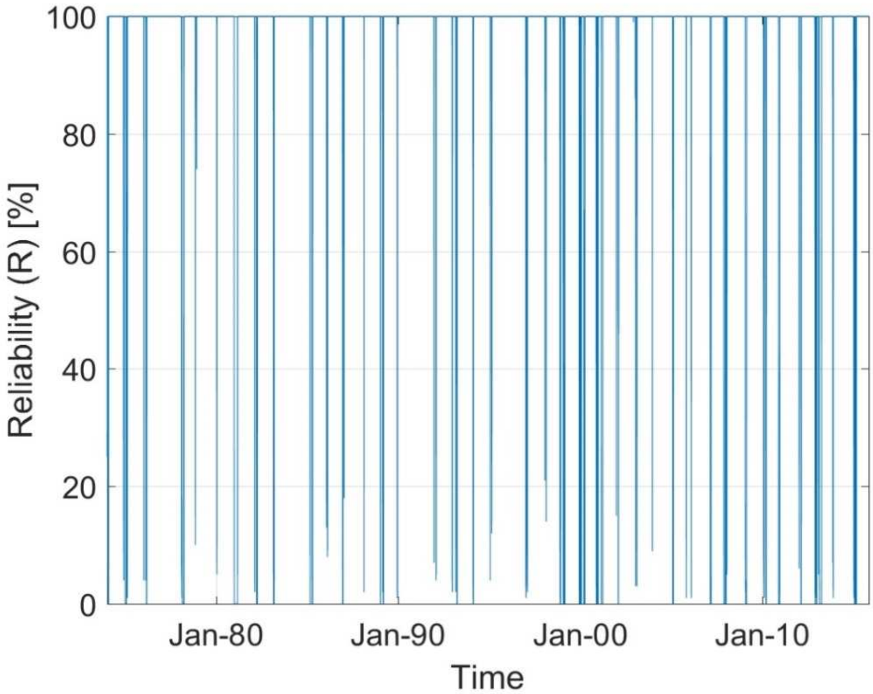
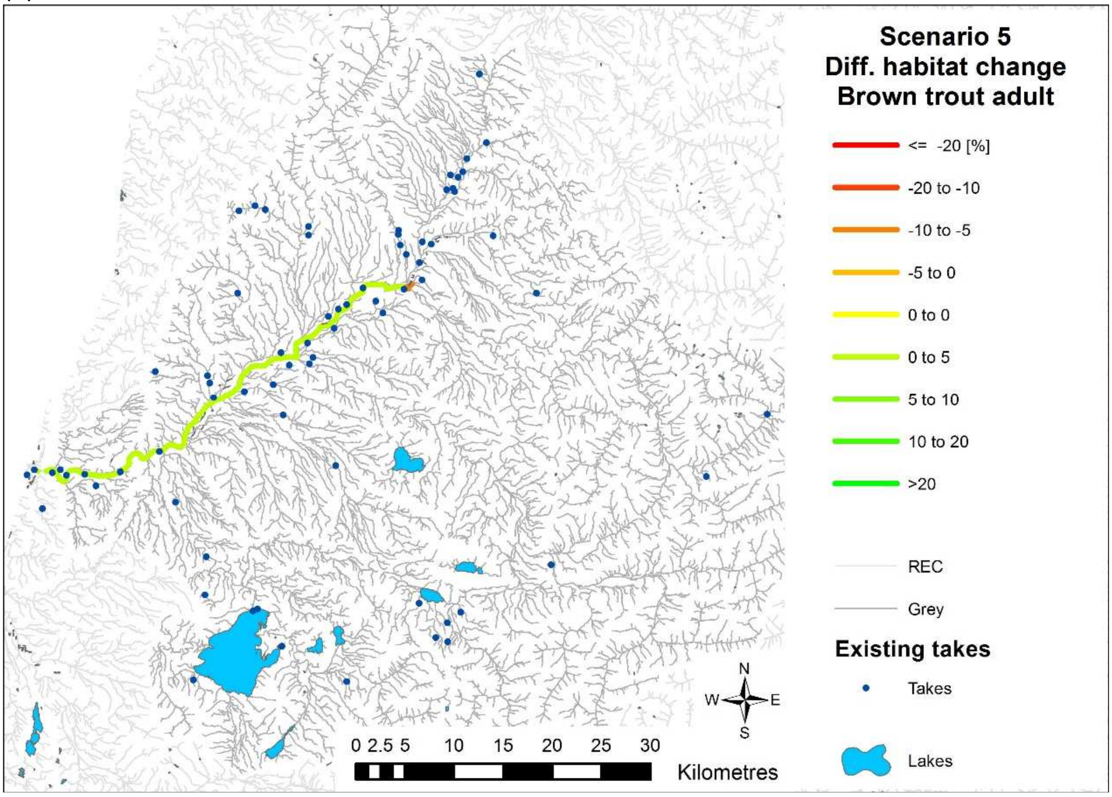


Figure 4-32: Reliability (*R*) for a hypothetical large new abstraction of ΔQ = 825 l/s, Q_{min} = 15.2 l/s with a reservoir volume of 86,400 m^3 on NZREACH 12024235. Note that the dam starts empty. The key statistics for the data presented here are mean = 95.8 %, median = 100 %, min = 0 %, max = 100 %, and standard deviation = 19.8 %.

Our second hypothetical objective was that the habitat for adult brown trout shall not be degraded by more than 1 % compared to the current scenario. We test this by plotting the difference between the mean habitat change (for adult brown trout) under this new scenario (Scenario 5) minus the mean habitat change under Scenario 1. Figure 4-33 shows that there is one reach which has a greater reduction in habitat under Scenario 5 and the greatest reduction in habitat (minimum difference in habitat change) is 3.2 %, which is greater than our 1 % objective. However, this reduction is only located in the reach where the new abstraction is occurring. In all other reaches, habitat change is positive due to the abstraction. This is due to the fact that all other reaches are on the main stem of the river, which have large natural flows, and any reduction in flow will lead to more preferencial conditions for adult brown trout. However, the improvement in physical habitat in those reaches is less than 0.1 %, which is negligible.

(a)



(b)

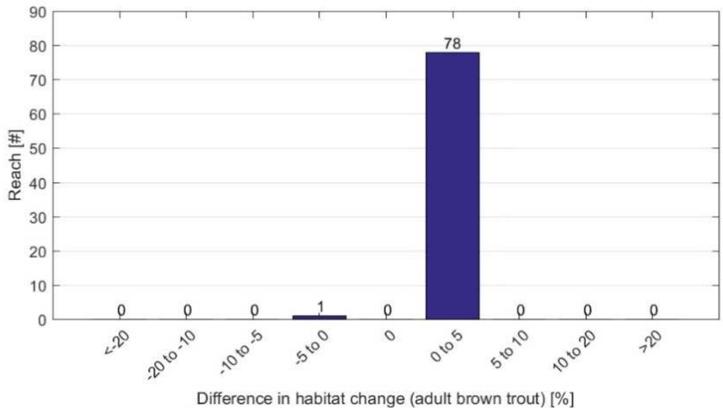


Figure 4-33: The difference between the mean habitat change for adult brown trout under Scenario 5 minus the mean habitat change under Scenario 1. The key statistics for the data presented here are mean = -0.1 l%, median = 0.0 %, min = -7.3 l%, max = 0.0 %, and standard deviation = 0.8 %.

Our third hypothetical objective was that the downstream abstractors shall not be affected (i.e. no change in reliability from reference Scenario 1). This was tested and we found there was no change in reliability, as the abstractors downstream of the dam all retain a reliability of 100 %.

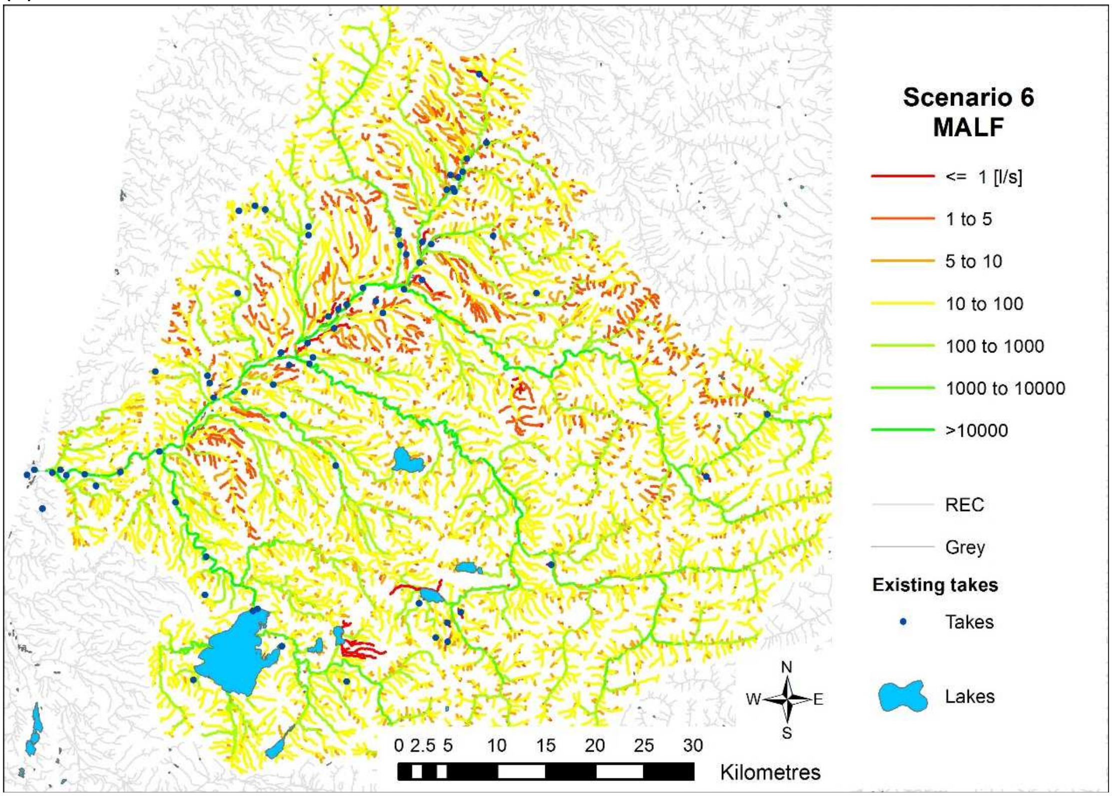
4.7 Climate change (Scenario 6)

In this scenario we use CHES to explore the potential effects of climate change on river flows, reliability of water supply and habitat availability.

4.7.1 Change in flow statistics

Firstly, we explore how natural flows (with no abstraction) change in the Grey River catchment under this climate change scenario. Figure 4-34 shows the distribution of MALF across the Grey River catchment under the example climate change scenario. This shows the mean MALF across the catchment is 1,146 l/s compared to 1,031 l/s under the current climate (Figure 4-3). This indicates that on average the Grey River catchment will have higher low flows. However, if we want to get an appreciation of how a change in climate will affect different parts of the catchment we can plot the difference in MALF between the climate change scenario and the current climate (Figure 4-35). Note that for the climate change scenario there is a shorter record of flow data available (18 years) and, therefore, the same period for the current climate is used when differencing the results. Figure 4-35 shows that, in general, the south-eastern part of the Grey River catchment will experience a reduction in MALF and the north-western part of the Grey River catchment will experience an increase in MALF. In particular, this figure highlights an area (the Upper Grey River and Clarke River) that will experience a large percentage reduction in MALF.

(a)



(b)

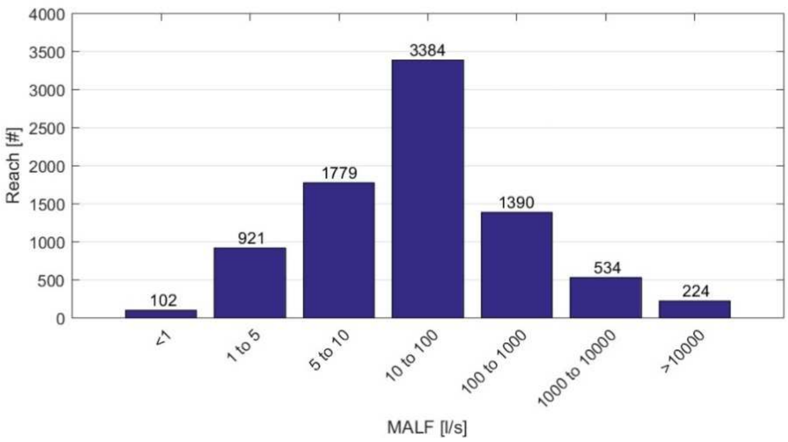
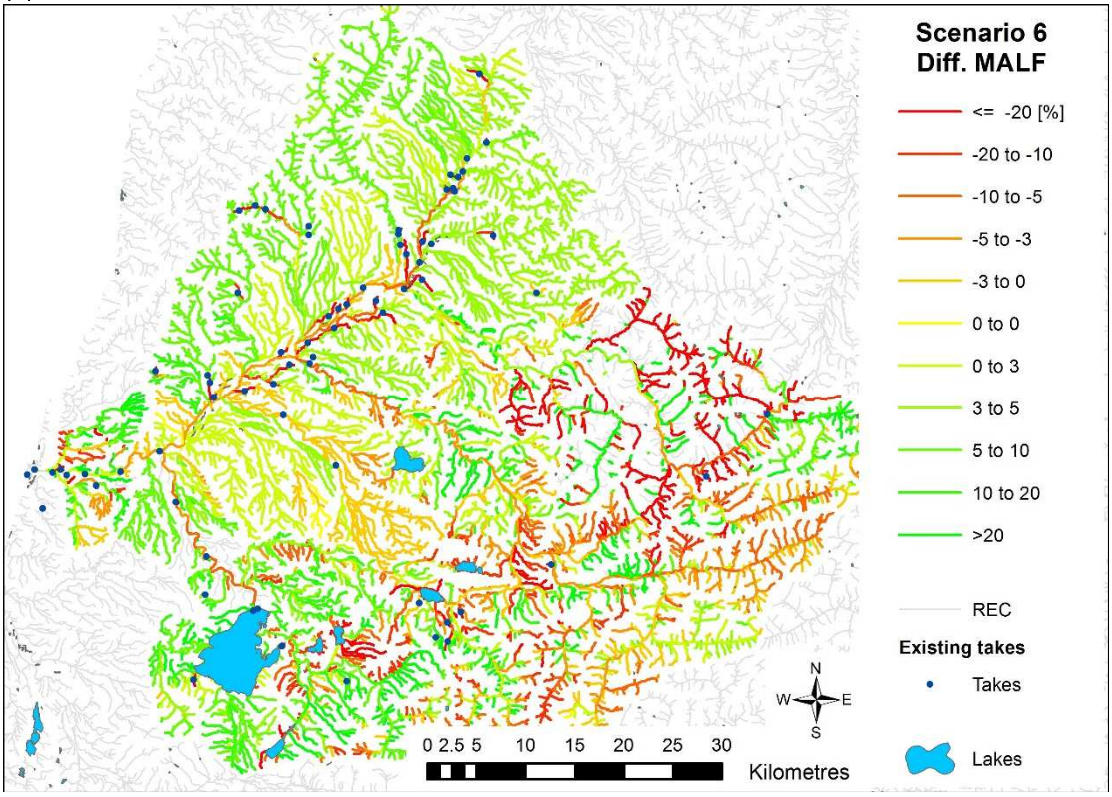


Figure 4-34: MALF in the Grey River catchment under an example climate change scenario. The key statistics for the data presented here are mean = 1,146 l/s, median = 19.2 l/s, min = 0 l/s, max = 126,759 l/s, and standard deviation = 7,169.3 l/s.

D R A F T

(a)



(b)

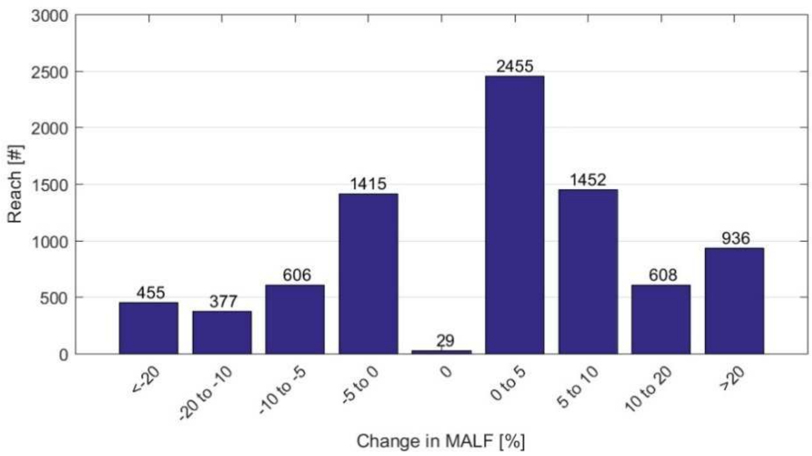


Figure 4-35: The difference in MALF between the climate change scenario and the current climate as a percentage change. The key statistics for the data presented here are mean = 51.3 %, median = 2.3 %, min = -100 %, max = 7,640 %, and standard deviation = 387 %.

4.7.2 Change in reliability

Figure 4-36 and Table 4-10 present the reliability of water supply *(R1* and *R2*) of current abstractions in the Grey River catchment under the example climate change scenario. There is a mean *R1* reliability of 72.5 % under Scenario 6 compared to 71.8 % under Scenario 1 (Figure 4-5).

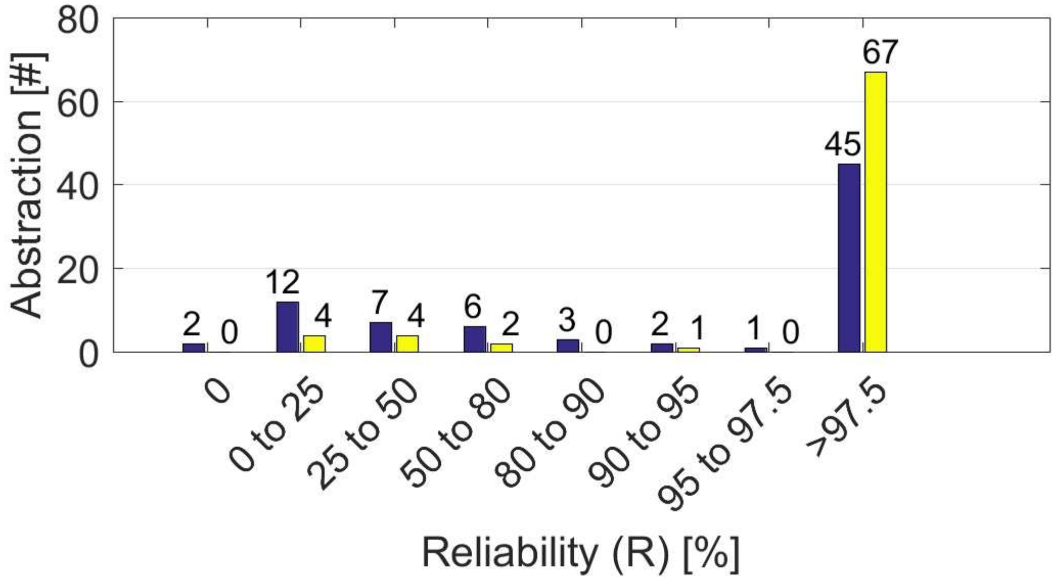


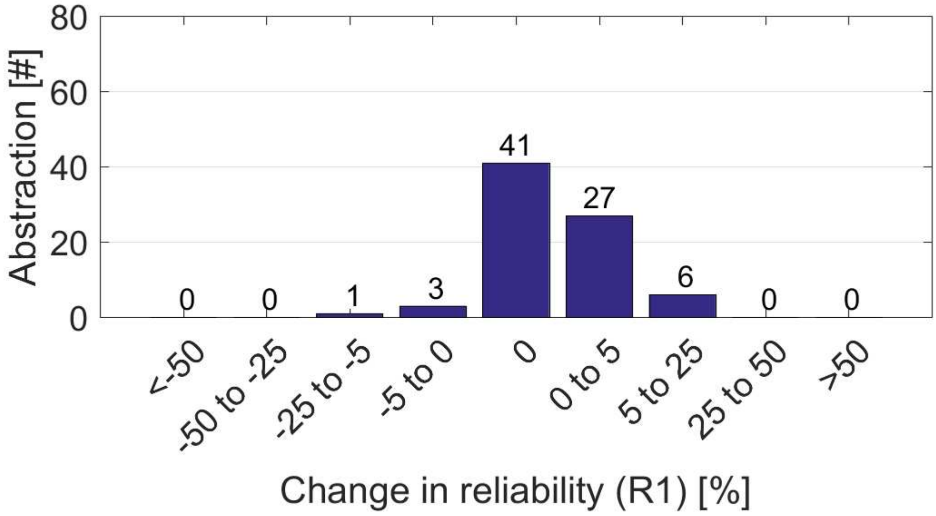
Figure 4-36: Reliability (*R1* (blue) and *R2* (yellow)) of current abstractions in the Grey River catchment (assuming current consent rules) under the example climate change scenario. Key statistics are summarised in Table 4-10.

Table 4-10: Statistical properties of *R1* and *R2* of current abstraction in the Grey River catchment under the example climate change scenario.

	Mean	Median	Min	Max	STD
R1 [%]	72.5	100	0.0	100	39.2
R2 [%]	90.7	100	0.2	100	25.0

The key question we may be interested in with respect to reliability is how much will reliability change as a result of climate change. We present these results for *R1* and *R2* reliability in Figure 4-37 (with statistics in Table 4-11). Note these results are based on Scenario 6 minus Scenario 1. These results show us that the median abstractor will experience no change in either *R1* or *R2* reliability under climate change, however there will be some abstractors with less reliable supply (with the worst case being a 6 % reduction in *R1*) and some abstractors with more reliable supply (with the best case being a 157 % increase in *R2*).

(a)



(b)

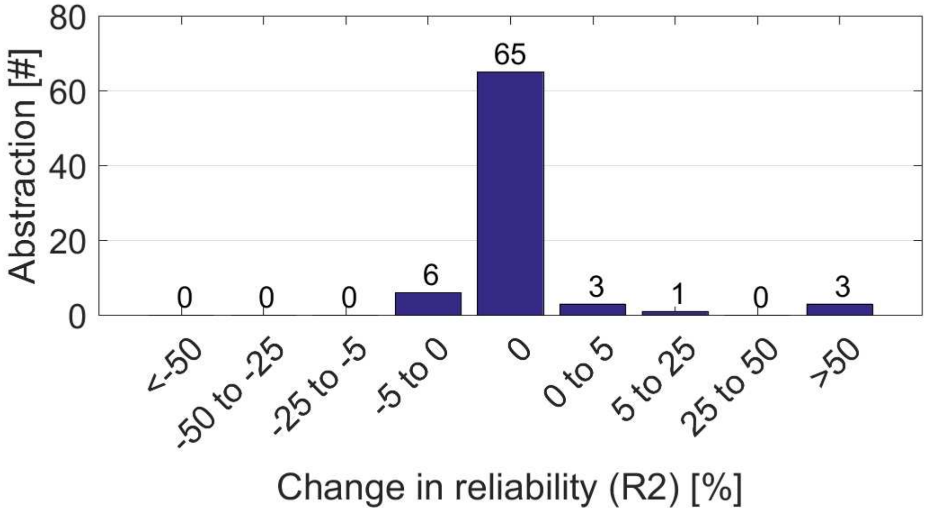


Figure 4-37: Change in reliability of current abstractions in the Grey River catchment as a result of climate change (a) *R1*, (b) *R2*. Note these assume current consent rules (Scenario 1).

Table 4-11: Statistical properties of change in *R1* and *R2* of current abstraction in the Grey River catchment under as a result of climate change.

	Mean	Median	Min	Max	STD
R1 [%]	0.74	0.0	-6.0	10.5	2.2
R2 [%]	4.8	0.0	-0.9	157.0	23.3

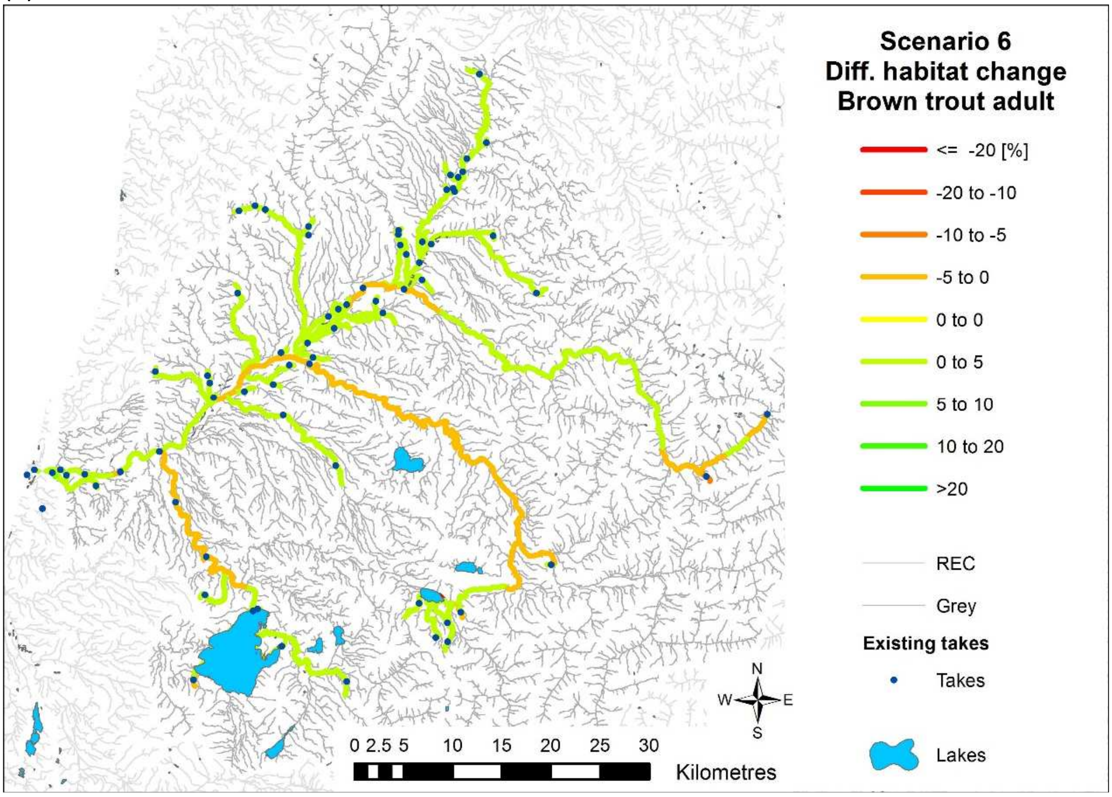
4.7.3 Change in habitat availability

In this section we use the same habitat change examples as those used when considering the effect of applying the proposed NES rules to abstraction (Section 4.4.3). We first consider the difference in mean habitat change for adult brown trout and longfin eels (Figure 4-38 and Figure 4-39 respectively), and then consider the difference in the maximum consecutive period of habitat loss for adult brown trout and longfin eels (Figure 4-40 and Figure 4-41 respectively). In each of these figures the calculation is based on Scenario 6 minus Scenario 1. This means that in the difference in habitat change figures a positive result equates to an improvement in habitat availability under climate change relative to the current climate, and in the duration of habitat loss figures a negative result equates to a reduction in the maximum consecutive period of habitat loss (an improved situation).

Figure 4-38 shows that 463 reaches show an improvement in habitat availability for adult brown trout relative to the current climate. However, on average across all reaches there is a 0.2 % reduction in habitat availability. For longfin eels the results are relatively similar with an average reduction in habitat availability of 0.3 % across the catchment (Figure 4-39).

Figure 4-40 shows that for adult brown trout on average the maximum consecutive period of habitat loss reduces by 44 days under climate change. For longfin eels the maximum consecutive period of habitat loss increases by 11 days under climate change (Figure 4-41).

(a)



(b)

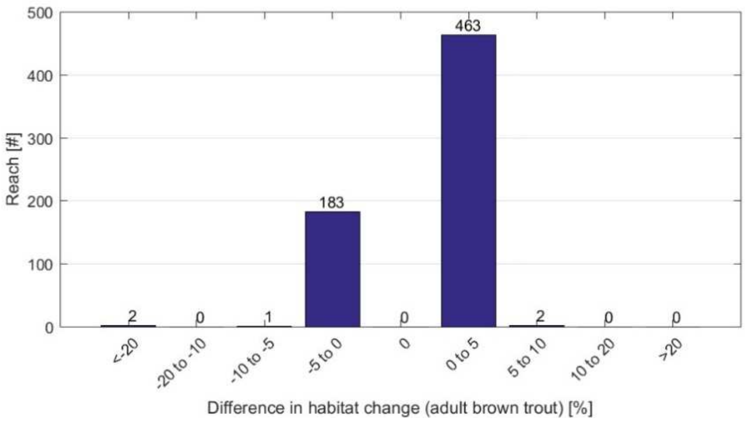
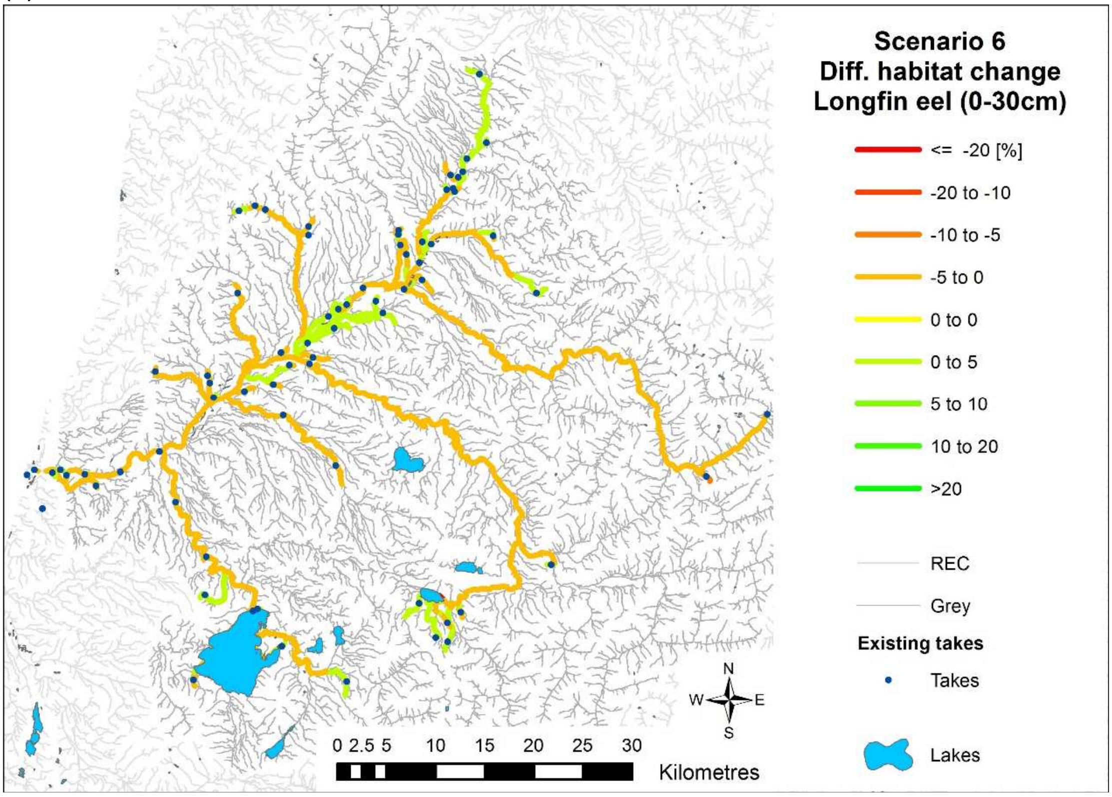


Figure 4-38: The difference in mean habitat change between Scenario 6 and Scenario 1 for adult brown trout. The key statistics for the data presented here are mean = -0.2 %, median = 0 %, min = -100 %, max = 8.2 %, and standard deviation = 5.6 %.

(a)



(b)

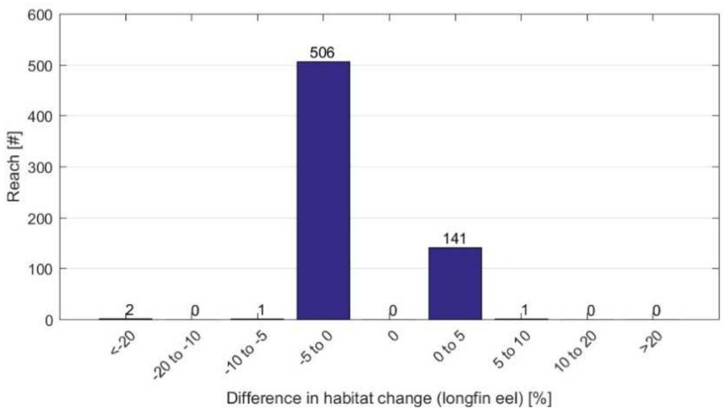
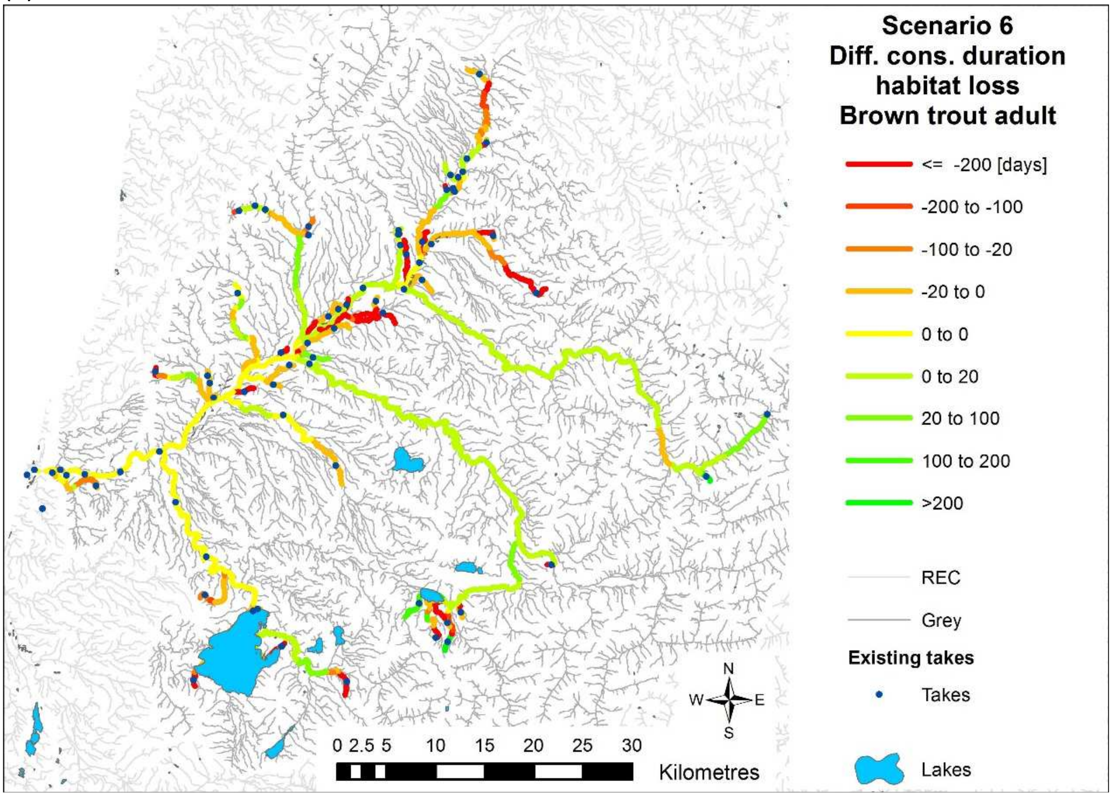


Figure 4-39: The difference in mean habitat change between Scenario 6 and Scenario 1 for longfin eels. The key statistics for the data presented here are mean = -0.3 %, median = 0 %, min = -100 %, max = 6.8 %, and standard deviation = 5.6 %.

(a)



(b)

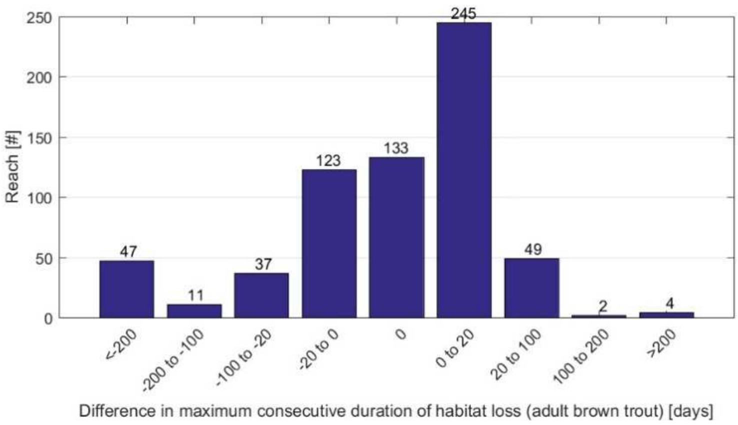
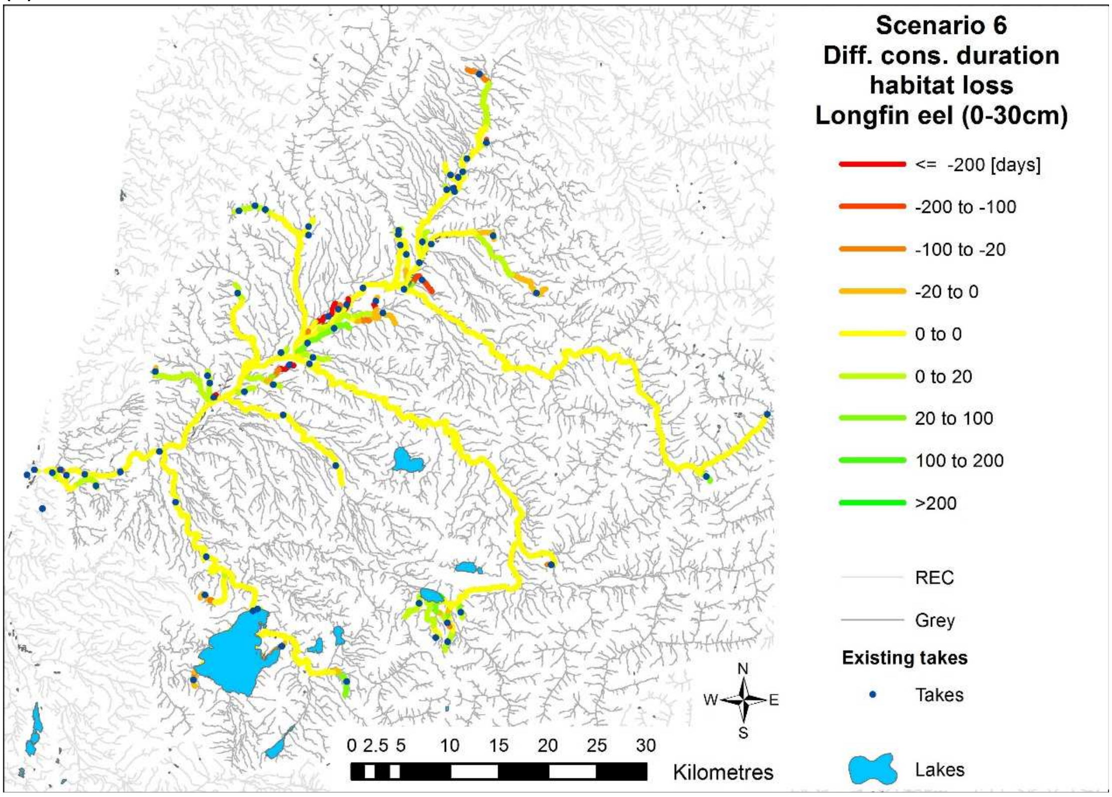


Figure 4-40: The difference in consecutive duration of habitat loss between Scenario 6 and Scenario 1 for adult brown trout. The key statistics for the data presented here are mean = -44 days, median = 0 days, min = -3,187 days, max = 6,465 days, and standard deviation = 496.9 days.

(a)



(b)

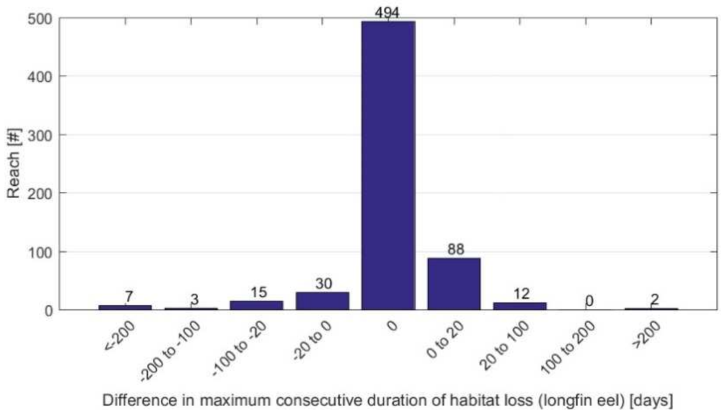


Figure 4-41: The difference in consecutive duration of habitat loss between Scenario 6 and Scenario 1 for longfin eels. The key statistics for the data presented here are mean = 10.5 days, median = 0 days, min = -3,234 days, max = 6,565 days, and standard deviation = 388.6 days.

5 Discussion

The main objective of this report was to demonstrate how CHES can be used to facilitate decision making associated with setting different water quantity limits in the West Coast region. By comparing the results of Scenario 1 and Scenario 2, we can summarise that bringing current abstraction into line with Policies 7.3.1 and 7.3.2 would bring a slight improvement in habitat for adult brown trout (on average 1.1 %) and longfin eels (on average 1.6 %), and a slight reduction (~4 %) in reliability. All abstractors would keep their current total allocation but, for some, part of this allocation would be available less frequently (B block). In contrast, if the proposed NES rules were applied the total allocation would, in most cases, be significantly reduced. Reliability may be increased as this lower flow would be available more of the time, however the available flow may not be sufficient to meet the abstractor's needs. The flipside of these stricter rules would be that habitat availability for adult brown trout and longfin eels would be greater under the proposed NES rules. Depending on the freshwater objectives set in the Grey River catchment, WCRC may find that one of these scenarios is more desirable than the others. Alternatively, WCRC may wish to develop additional scenarios testing different water quantity limits.

In setting future water allocation limits, WCRC may wish to consider the effects of climate change on instream and out-of-stream objectives, as required by the NPS-FM. In this report we have presented results for one illustrative climate change scenario, which indicated that low flows (minimum flows and MALF) are projected to increase in future. However, WCRC may wish to test the effect of alternative (e.g. more extreme) scenarios and examine how the results differ.

WCRC may also wish to test the effects of the scenarios presented in this report, or alternative scenarios, on the habitat of species other than adult brown and longfin eel. The species for which CHES can currently be run are listed in Table A-1. In future CHES may also be able to simulate results for different types of attributes, for example cultural or recreational attributes. The architecture exists in CHES to do this, but to add new attributes into CHES we need reliable relationships between flow and these new attributes.

In this report we also provided an example scenario testing the effects of adding offline water storage as a means of increasing reliability of supply for a given abstractor, and another example to test the effects of adding a hypothetical large new abstraction in a reach where abstraction is already high. These are just examples of how CHES can be used to test whether a given abstraction meets specified objectives for a given abstractor, in a given reach or in the catchment downstream. We hope that these examples are useful in demonstrating what is possible, but these examples are by no means an exhaustive summary of all the different capabilities and outputs of CHES. For example, CHES could also be used to assess the effects of a water diversion, or adding an online storage dam (i.e. blocking the river). We anticipate that WCRC may wish to run many alternative scenarios to those presented here.

5.1 Limitations, assumptions and uncertainty in results

The hydrographs used by CHES are generated for each river reach using the TopNet model. These flows are simulated, not measured, and will therefore differ from measured flows where these are available. This is unavoidable as measured flows are simply not available for every reach in the catchment. While simulated flows are not perfect, this is the best method of assessing effects for unmeasured reaches. The effort that has gone into developing TopNet is such that the simulated flows are the best available estimates of actual flows at all reaches in the catchment.

Each scenario simulated within CHES for this project uses the same simulated flow data. This means that fair comparison can be made between scenarios, providing useful information for WCRC and external stake holders. Also, when simulating instream and out-of-stream attributes that rely on the MALF value, CHES uses TopNet calculated MALF values generated from the simulated hydrographs. These MALF values are not necessarily the most accurate estimate of MALF in absolute terms. However, using TopNet MALF in combination with TopNet hydrographs results in better representation of likely reliability and habitat change (assuming low flow calibration of TopNet is good).

Non-consumptive abstractions were removed from the CHES simulation. The reason for this is that they do not change the overall flow downstream of the abstraction. Also, there were no data on the consented allocation for most of the non-consumptive abstractions. It should not be assumed that these abstractions will all have a reliability of 100 %. If WCRC wish to understand the reliability of these abstractions, we recommend that they collect this missing information and rerun and reprocess the scenarios with the amended abstraction data base.

There are also permitted takes throughout the catchment, but these have unknown location and permitted allocation and could therefore not be included in this project. Excluding these takes from the simulations underestimates water use and, therefore, overestimates reliability and underestimates impacts on instream habitat under each reference scenario. If information on permitted takes becomes available in future, it could be incorporated within CHES to provide much improved simulations.

Some of the abstractions in the catchment are ground water abstractions. The ideal approach for these abstractions would be for the simulation to take water from the ground water aquifer and for this to result in an increased water flow from the surface water body to the ground water aquifer and/or to a reduced water flow from the ground water back to the surface water body. Unfortunately, this capability has not yet been implemented in CHES and TopNet. Instead, CHES currently uses a 'stream depletion approach' (Jenkins 1977). This is simplification, which we accept is a compromise.

Overall, the largest individual limitation on simulated results will be that the actual volume of water taken on a day to day basis from each abstractor is unknown. Some metered abstraction data were supplied by WCRC to NIWA. Unfortunately, the data available were deemed to be inadequate. This was because the data were only available for a handful of abstractors, and only for a couple of years. For this information to give meaningful results in CHES it would be needed for at least the majority of abstractors and ideally over the entire simulation time period. The lack of this information meant that during this project we assumed that each abstractor takes the maximum volume of water that they are allowed to take (under the given scenario rules) all of the time. This assumption resulted in unrealistic results for some measured effects (for example, the maximum consecutive period of habitat loss). In reality, at times of the year when there is more rainfall and flows in the river are higher, many abstractors may take little or nothing from the river. This means that reliability with which abstractors can take the water they actually need would be higher than those simulated and the habitat change would be less that that simulated. In other words, the results presented might be considered to be a 'worst case' scenario. In future, if people are required to monitor the volume of water abstracted, this information will be able to be incorporated within CHES and more accurate results could be simulated. We demonstrate this capability in Scenario 5 when we specify a crop factor, irrigation efficiency and soil trigger level which enables us to simulate a new hypothetical abstraction timeseries using the RAT module. Therefore, we 'know' how much water will be used in this scenario.

A number of key assumptions are made within CHES regarding how water is routed through the river network and how water use is managed. In summary:

- The effects of water travel time between reaches is not modelled. If water is abstracted from a location on any given day that volume of water will also be removed from all downstream reaches on that same day.
- Upstream users are given priority when determining allocation between water takes. Flow is routed from the top to the bottom of the catchment in CHES. Consequently, flow is reduced by abstraction at each point of take sequentially down the catchment. This means that if cumulative upstream abstraction results in flow being depleted to the minimum flow limit before all takes are accounted for, downstream takes may be restricted. This may be different to real-world situations where priority may, for example, be determined on a first-come-first-served basis, or on the basis of importance (e.g. public water supply high priority versus watering lawns low priority).
- It is assumed that when natural flows are below the management flow (minimum flow + allocation limit) and above the minimum flow that partial restrictions on water use are implemented. That is, water users can take water at a rate lower than their maximum allocation volume, but greater than zero (i.e. complete shut-off). In reality this may not be practical due to constraints around infrastructure and the ability to vary instantaneous rates of take from pumps with fixed volumes.
- Perfect, real-time knowledge of river flows and water use is assumed in CHES in order to govern the operation of water abstractions.
- Instream habitat is defined only by water depth and velocity. In reality, habitat availability and use may also be determined by factors such as water quality, migration, food availability, competition, shade, woody debris etc.

We acknowledge that there is inevitably a degree of uncertainty in the results presented, both with respect to flow and the attributes that have been derived from the flow. This includes uncertainty in the simulated reliability and uncertainty in the degree of habitat change. To quantify the uncertainty of these attributes would first require quantification of the uncertainty of the hydrographs that have been simulated by TopNet (and used as inputs to CHES). Unfortunately, this type of analysis exceeded the scope of this project. In addition, it is currently not possible to propagate errors within CHES, but this will be addressed in a future version of CHES.

6 Conclusion

In this report we have applied CHES to the Grey River catchment and have run six different water abstraction scenarios. We use these scenarios to demonstrate how reliability of water supply can be characterised and how impacts on instream physical habitat availability for two indicator species (adult brown trout and longfin eels (< 30 cm)) can be characterised.

The first scenario is used to characterise the current status and consequences of water use in Grey River catchment. The second scenario examines the effects of minor changes in current allocation rules to bring current allocated abstraction into line with WCRC policies. The third scenario examines how instream and out-of-stream attributes would change if water allocation limits followed the proposed NES rules. The fourth scenario examines how reliability for a given abstractor could be improved by adding off stream water storage. The fifth scenario is used to show how CHES can test the effects of a hypothetical large new abstraction in a reach that already has a high level of water allocation. Finally, scenario six is used to examine how reliability of supply and habitat availability may change as a result of an example climate change scenario.

This report does not include an exhaustive summary of all the different capabilities and outputs of CHES. It is also outside the scope of this report to provide a detailed analysis of water resource use in the Grey River catchment or to determine appropriate water quantity limits for the catchment. However, we hope that this report provides useful examples and sufficient demonstration the capabilities and utility of CHES to allow WCRC to make an informed decision on the value of using CHES to support the planning processes associated with implementing the NPS-FM in the West Coast region.

We also hope that the Grey River catchment case study is useful to other regional councils, showcasing some of the key features and capabilities of CHES.

7 Acknowledgements

The development of CHES was funded by NIWA's Freshwater and Estuaries Centre under the Sustainable Water Allocation Programme (NIWA SCI 2015-16). Thank you to Stefan Beaumont, Emma Reeves and Mike Meehan of West Coast Regional Council for their support in getting this project off the ground and for their timely input into the development of the CHES scenarios and advice on how to make this report most useful.

WCRC have significantly contributed to the project with the following:

- WCRC staff carrying out spot gaugings in the Maimai (~12 visits at 10 sites)
- Supplying NIWA with meta data (e.g. flow, abstraction data)
- Supplying WCRC equipment to carry out additional spot gaugings (e.g. transport).

8 Glossary of abbreviations and terms

CHES	Cumulative Hydrological Effects Simulator
ELFMOD	Empirical Longitudinal Flow MODel
MALF	Mean Annual Low Flow
NES	National Environmental Standard for ecological flows and water levels, proposed by MfE (2008)
NPS-FM	National Policy Statement for Freshwater Management
NZREACH	REC reach number
IPO	Interdecadal Pacific Oscillation – a natural climate fluctuation affecting the Pacific region and resulting in long periods of higher or lower mean annual rainfall
ΔQ	Water allocation limit – the maximum volume of water per day that can be abstracted in a given reach.
Q_{min}	Minimum flow limit - a limit on water abstraction whereby water cannot be abstracted when flow in the given reach drops to Q_{min}.
RAT	Rapid Assessment Tool, a module of CHES that calculates water demand for irrigation based on irrigated area, crop grown, evaporation rate, rainfall and soil moisture trigger level.
R	Reliability of water supply calculated as the supply of water divided by the demand for water (supply/demand) averaged over time.
R1	Reliability of water supply calculated as the proportion of time that the full allocated volume is available. This is equal to the percentage of time that natural flows are greater than the sum of the minimum flow and the abstraction limit.
R2	Reliability of water supply calculated as the proportion of time that at least some of the allocated water can be taken. This is equal to the percentage of time that natural flows are greater than the minimum flow.
REC-1	River Environment Classification version 1 (released in 2003)
REC-2	River Environment Classification version 2 (improved version released January 2015)
Strahler Order	Stream order, with smallest tributaries having an order of 1, with increasing order as tributaries join larger streams.
TopNet-0	Hydrological model
TopNet-GW	Hydrological model v2, including a conceptual GW module.
WCRC	West Coast Regional Council

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Appendix A CHES model description

The CHES model framework integrates a hydrological model built on a spatial representation of the river network with generalised statistical models of instream attributes. The following sections provide a technical description of the underlying modelling framework, model parameters and model attributes of CHES.

Spatial framework

The spatial framework for CHES is the River Environment Classification (REC; Snelder and Biggs 2002), which is a digital representation of the New Zealand river network. Each segment/reach is associated with several attributes including the total catchment area, stream order, as well as the climatic, topographic, geological, and land-cover characteristics of the upstream catchment. The REC classifies all river and stream segments into classes at several levels of detail (Snelder and Biggs 2002). Both REC-1 and REC-2 (see glossary) are implemented in CHES.

Hydrological data

The hydrological time series data underlying CHES are generated using TopNet, a rainfall-runoff model. It tracks the day-to-day movement of water through the hydrological cycle using daily information on rainfall and air temperature to "drive" the model from the atmosphere, and information on topography, soil type, and vegetation type to calculate the movement of water near, on, and just below the ground. The model uses the REC as its spatial framework and for each reach it calculates each hour how much water is being added as rain and inflow from upstream reaches, how much water leaves as evapotranspiration, how much leaves as river flow, and by how much the storage of water in the soil and shallow groundwater changes. This approach to water balance modelling is internationally accepted, and widely used in situations where insufficient measured flow and storage data are available (Beven and Freer 2001). The original version of TopNet, TopNet-0, does not currently model any losses or gains from reaches to deep ground water storages.

A newer version of TopNet, TopNet-GW, includes a conceptual ground water to surface water interaction. With the help of spot gauging data, water exchange between the surface water body and a deep ground water storage can be simulated. In addition, modelling the movement of water in deep ground water storage to further downstream deep ground water storage is also possible. A more in depth description of the TopNet calibrations are given in Appendix B and in Zammit et al. (2016).

CHES utilises estimates of the 7-day mean annual low flow (MALF) for indexing minimum flow and allocation limits, and for deriving descriptors of the instream habitat attribute. For analyses of reliability of supply and habitat change in CHES, estimates of MALF derived from the TopNet hydrological time series are utilised to ensure consistency in the relative magnitude of MALF and the flow record in the hydrological time series used in the model to evaluate outcomes.

Generalised physical habitat vs. flow relationships

CHES utilizes coupled generalised models of mean wetted width versus flow, and habitat versus reach-averaged specific discharge (width/flow) to describe the relationship between instream habitat availability and flow at any site.

Estimating wetted width

Booker (2010) defined a power-law relationship between discharge, Q [m^3 s^{-1}], and mean wetted width, W [m], for each river reach:

$$\log(W) = d_0 + d_1 \log(Q) \quad (1)$$

$$d_0 = a_0 + a_1 \log(A) \quad (a)$$

$$d_1 = b_0 + b_1 \log(A) \quad (b)$$

A is catchment area [km^2] and *a*, and *b* are values dependent on REC classes. All logs are to the base 10. The resulting d_0 and d_1 values have been derived for each reach using the method of Booker (2010). This is implemented in CHES to estimate width-flow relationships for all river segments (NZREACH) in the REC network on a daily basis.

Estimating instream physical habitat

Conventional instream habitat models link hydraulic model predictions with microhabitat-suitability criteria to predict the availability of suitable habitat at various discharge rates (e.g., RHYHABSIM; Jowett 1996; Clausen et al. 2004; Jowett and Biggs 2006). The availability of suitable habitat is commonly expressed as Weighted Usable Area (WUA) in units of m^2 per 1000 m of river channel (with two examples given in Figure A-1). WUA is an aggregate measure of habitat quality and quantity, and is specific to each reach, specific to a particular discharge, and specific to taxa/life stage. Instream habitat models can be used to assess WUA over a range of flows and therefore can be used to make predictions on how habitat changes in response to changes in flow.

Criticisms of instream habitat models include lack of biological realism (Orth 1987) and failure of microhabitat-suitability criteria to reflect the detailed mechanisms that lead to density–environment associations (Mathur et al. 1985; Booker et al. 2004; Lancaster and Downes 2010; Davey et al. 2011). However, many microhabitat suitability models have a high degree of transferability between rivers and are therefore useful bases for the management of stream catchments (Lamouroux et al. 2010). The models have been applied throughout New Zealand (Lamouroux and Jowett 2005) and the world (Dunbar and Acreman 2001), primarily to assess impacts of abstraction. PHABSIM in particular has become a legal requirement for many impact studies in the USA (Reiser et al. 1989) and RHYHABSIM (the New Zealand equivalent) a standard tool employed to define minimum flows in New Zealand (e.g., MfE 2008).

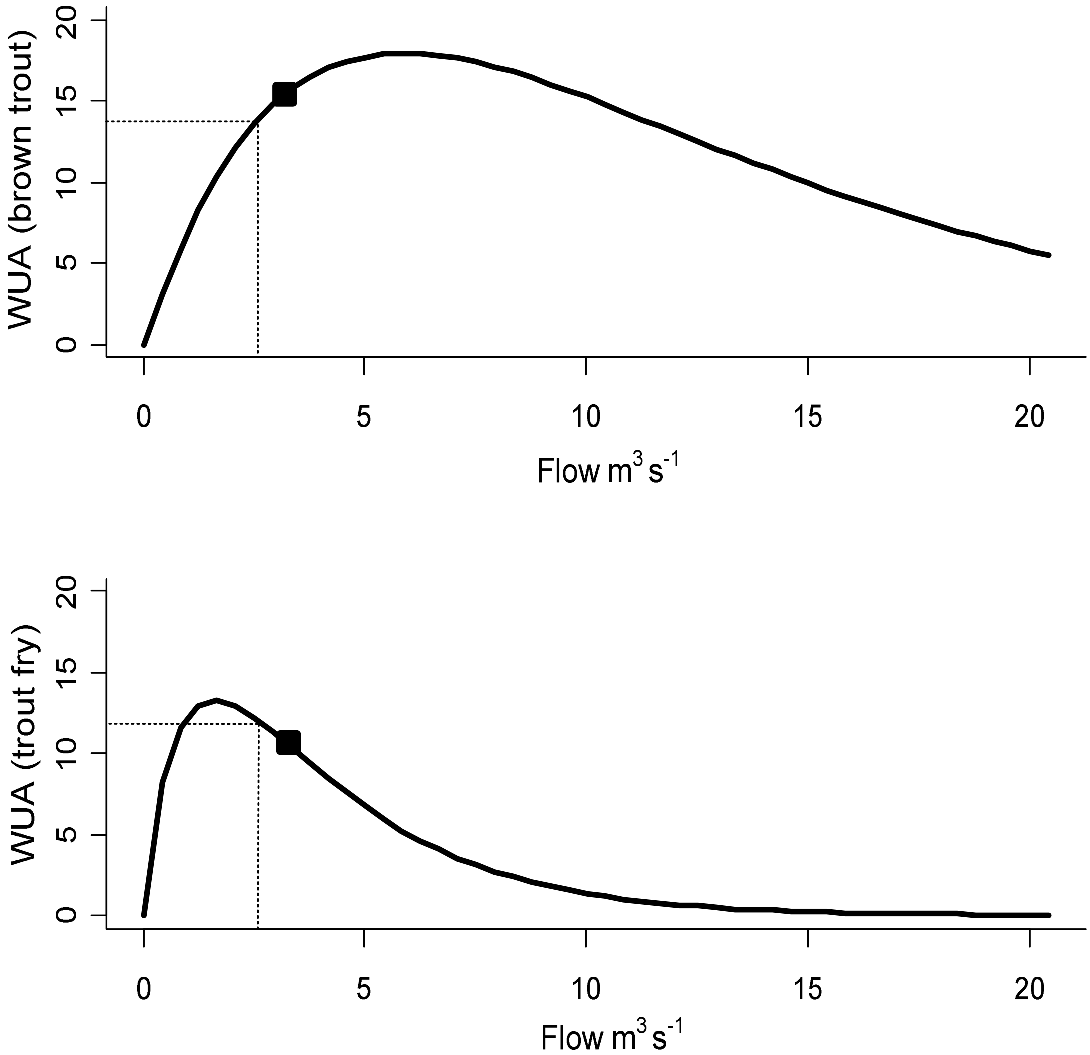

Figure A-1: WUA versus flow curves for adult brown trout and brown trout fry for a network segment (mean flow = 20 m^3/s). These curves are defined by combining equations A-1 and A-2. MALF for the segment (3.3 m^3 s^{-1}) is shown by the black square on the curve. WUA at the proposed NES minimum flow of 80% MALF are shown by the dashed lines. Note that WUA decreases between MALF and the minimum flow for adult brown trout (*Salmo trutta*), but increases for brown trout fry.

Generalised instream habitat models (Lamouroux and Jowett 2005) have been developed from the results of many individual habitat studies conducted throughout New Zealand. These models generalise the relationship between flow and habitat in natural stream reaches based on simple reach-average hydraulic characteristics (Lamouroux and Jowett 2005). Therefore, when linked with hydraulic geometry models (i.e., empirical models relating hydraulic parameters such as width, depth, and velocity to discharge), generalised habitat models make it possible to simulate the relationship between flow and habitat over whole river networks (see examples in Jowett 1998; Lamouroux and Capra 2002; Lamouroux 2008; Snelder et al. 2011). The generalised instream habitat models provided by Jowett et al. (2008) are used to estimate WUA as a function of reach-averaged specific discharge (width/flow). The flow-habitat relationships describe a unimodal shape that depends on two coefficients, *j* and *k* that are specific to a taxa and *i*, which is specific to a reach:

$$WUA = i\left(\frac{Q}{W}\right)^{j} e^{-k\left(\frac{Q}{W}\right)} \quad (2)$$

The ratio of WUA at two discharges depends only on discharge and the width-discharge relationship, but not on the reach coefficient *i*. Consequently, the width-flow relationship (**Error! Reference source not found.**) can be combined with **Error! Reference source not found.** to estimate relative changes in habitat with changes in flow over a whole river network (Lamouroux and Souchon 2002).

Hence here we use habitat change (*ΔH*) as a surrogate for a relative change in weighted usable area for two different flows at the same location:

$$\Delta H = \frac{WUA_N - WUA_p}{WUA_N} * 100 \quad (3)$$

Here the subscript *N* stands for natural flow (flow without any abstraction) and *P* stands for proposed flow (flow including all abstractions). The habitat change is a value ranging from negative 100 % to positive infinity %, representing a measure of fish/taxa specific change.

Generalised habitat models are currently only available for a restricted number of species and life stages in New Zealand (Table A-1). The values for the model coefficients were derived by Jowett et al. (2008) from a dataset of 99 stream reaches in New Zealand. The ‘flow demand’ (in terms of optimal discharge per unit width) for some species is logical based on our understanding of the traits of the individual species, e.g., torrent fish (*Cheimarrichthys fosteri*) (which prefer fast flowing riffle habitats) having the highest demand of the native fish species. However, the optimal discharges defined by the Jowett et al. (2008) models are less intuitively logical for other species, e.g., common bully (*Gobiomorphus cotidianus*) (which have very flexible habitat requirements, but relatively high flow demand). It is possible that this is symptomatic of a sampling bias in the data used to derive the models towards daytime habitats in wadeable gravel rivers.

New generalised habitat models have recently been derived for a sub-set of New Zealand fish species (Doug Booker, NIWA, unpublished data). The uncertainty in these models is better characterised allowing recommendations as to the preferred generalised habitat method for each set of habitat suitability criteria. There was strong evidence that generalised habitat methods were able to characterise between-site differences in habitat-flow relationships for the majority of species for which the new models were derived. At present, these new models are not implemented in CHES. However, it is expected that when they are finalised they will be made available in CHES.

Table A-1: Species for which generalised physical habitat models are available in New Zealand. The model parameters *c* and *k* are displayed and optimum discharge per unit width provides an indication of relative flow demand (Source: Jowett et al. (2008)).

Species	*c*	*k*	Optimum discharge per unit width ($m^2 s^{-1}$)
Inanga	0.19	19.74	0.01
Shortjaw kokopu	0.19	16.35	0.01
Upland bully	0.11	8.63	0.01
Cran's bully	0.09	6.84	0.01
Banded kokopu (juvenile)	0.19	13.3	0.01
Canterbury galaxias	0.03	2.29	0.01
Roundhead galaxias	0.31	10.64	0.03
Flathead galaxias	0.28	9.11	0.03
Longfin eel (<30 cm)	0.07	2.07	0.03
Lowland longjaw galaxias	0.33	9.35	0.04
Redfin bully	0.26	7.39	0.04
Shortfin eel (<30 cm)	0.13	2.32	0.05
Common bully	0.39	6.51	0.06
Brown trout fry	0.86	10.21	0.08
Brown trout yearling	0.40	4.18	0.09
Nesameletus	0.26	2.62	0.10
Brown trout spawning	1.24	9.89	0.13
Bluegill bully	1.01	6.13	0.16
Rainbow trout spawning	1.49	8.78	0.17
Deleatidium	0.33	1.92	0.17
Torrentfish	0.88	4.05	0.22
Brown trout adult	1.17	4.35	0.27
Food producing habitat	1.19	4.25	0.28
Rainbow trout feeding (30-40 cm)	0.93	2.89	0.32
Coloburiscus humeralis	1.35	4.17	0.32
Aoteapsyche	1.44	3.17	0.45
Zelandoperla	1.71	3.40	0.50

Model parameters

The existing take database is a fundamental model input that is required for setting up scenarios. The existing take database describes the location and rules governing water use for all consented abstractions in the target catchment. There are four types of abstraction that can be represented in CHES: takes, diversions, storages and dams. A summary of the main model parameters used to describe each of these abstraction types is provided below.

Take

A 'Take' is a standard run-of-river surface water abstraction. The primary parameters used to describe a take are: location, allocation limit (ΔQ) and minimum flow limit (Q_{min}).

- Location describes where on the river network the Take is positioned.
- Allocation limit defines how much water can be taken.
- Minimum flow limit defines the flow in the river at which abstraction will be restricted. This can apply at the point of take, or an alternative flow management site (e.g., a flow gauging station).

It is also possible to specify rules regarding the time of year (on a monthly basis) that the allocation and minimum flow limits apply.

Diversion

A 'Diversion' can be used to represent situations where water is abstracted from one location and returned elsewhere on the river network. The return location cannot be upstream of the location that water is taken. In CHES, any abstraction type can be converted into a diversion. Additional information is needed to define the location where water is returned to the river network. Diversions are non-consumptive, i.e., all water that is abstracted is diverted to the new location on the river network.

Storage

A 'Storage' is an off-line (i.e., not directly connected to the river) storage pond. In addition to the parameters required to describe a take, information is also required on the dimensions and operational properties of the storage unit.

- The dimensions of the storage unit are defined in terms of its length, width and height.
- The operational properties of the storage unit include the minimum and maximum water levels in the storage, and the rules regarding when and how much water is taken from the storage.

Water taken from a storage can be treated as consumptive (i.e., it never returns to the river) or it can be returned to the river network at a downstream location.

Dam

A 'Dam' is an online storage (i.e., it blocks the river). The user is required to specify the location and physical dimensions of the dam, plus define its operational properties. Based on the user supplied information on the height and location of the dam, and the underlying digital elevation model, CHES will automatically generate a dam rating curve (water level versus water volume behind the dam).

- The dimensions of the dam are defined in terms of the dam crest height. Further information can be supplied on the spillway design.
- The operational properties of the dam include the minimum and maximum water levels in the dam and the rules regarding when and how much water is to be taken from the dam.
- A minimum flow limit for downstream of the dam can also be defined.

Water taken from a dam can again be treated as consumptive (i.e., it never returns to the river) or it can be returned to the river network at a downstream location.

Allocation types

While a water user may hold a consent to take a particular volume of water, they may not fully exercise that right to take water all of the time. The difference between consented allocation volumes and actual water use can be significant in some cases. In CHES the user is able to specify an assumption as to how allocations will be utilised.

The worst case scenario would occur if all users took all water they are consented to take all of the time. This is termed Maximum Allocation. In reality water users will frequently only use a proportion of their total allocated volume. A CHES user can investigate the consequences of this by defining an assumption that only a certain percentage of Maximum Allocation is utilised. This approach could also be used to investigate the impacts of increasing caps on allocation volumes by defining a percentage of Maximum Allocation that is >100%.

Where information on actual water use is available (i.e., a water use time series), it is possible to supply this as a user input to the model. There is also an option to use estimates of water use based on predictions of irrigation requirements associated with different land use types and crop/stock requirements.

Model attributes

Attributes are used to represent the outcomes for different instream and out-of-stream values in CHES. The primary attribute for out-of-stream values currently implemented in CHES is reliability of supply. The main attribute for instream values is currently instream habitat. A brief summary of these attributes is provided below, along with an explanation of the attribute descriptors used to characterise changes in the attributes resulting from water use.

Reliability of supply

Understanding how reliably a water user is going to be able to abstract and therefore make use of the water they are allocated is valuable information for water resource managers and water users. For a given water abstraction, by combining information about how that abstraction is managed (i.e., allocation limit and minimum flow) with the underlying hydrological flow time series, CHES is able to determine the proportion of time for which an allocation volume can be fully or partially utilised (i.e., natural flows are greater than the minimum flow), and also the proportion of time when the abstraction would be fully restricted (i.e., no water can be taken because the natural flow is less than the minimum flow).

In CHES reliability of supply is represented by two descriptors:

- *R1* is the proportion of time that the full allocated volume of water for a given take can be abstracted. This is equivalent to the percentage of time when the natural flow is greater than the sum of the minimum flow and cumulative upstream abstraction.
- *R2* is the proportion of time that an abstraction is not fully restricted, i.e., some or all of the allocated volume of water for a given take is available to be abstracted. This is equivalent to the percentage of time that natural flows are greater than the minimum flow limit. The proportion of time that full restrictions would apply for a given take can be derived by subtracting R_2 from 100.

Reliability of supply is determined for all abstractions in CHES. Information on reliability is therefore available for each individual abstraction and can be summarised spatially across multiple abstractions in a catchment. Summary statistics for *R1* and *R2* can be determined across a range of temporal scales (e.g., weekly, monthly, yearly).

Instream physical habitat

There is a long history in New Zealand of using instream habitat availability to evaluate the potential instream impacts of water use. Its use is based on the assumption that natural low flows act as a habitat bottleneck for aquatic species. Consequently, if the magnitude of low flows is decreased, and/or the frequency and/or duration of low flows is increased, the constraints on instream habitat availability are greater and hence the potential for negative impacts on aquatic species increases.

In CHES, the predicted changes in instream habitat availability that result from water use are referenced against habitat availability at the natural flow (**Error! Reference source not found.**). This is being estimated using the daily flow time series, for the natural and the modified hydrographs. This results in a daily habitat change time series, which is being used as the basis for the descriptors below. A range of descriptors are used to characterise the changes in instream habitat availability, reflecting the different dimensions of magnitude and duration.

- Mean daily physical habitat change

  This describes the mean daily difference in habitat availability between two scenarios. It is a measure of the magnitude of change in habitat availability and is described by **Error! Reference source not found.**.

  $$Mean\ daily\ habitat\ change = \sum \Delta H_t / N \quad (4)$$

  where ΔH_t is the difference in habitat between the two scenarios on day *t*, and *N* is the number of days in the time series over which the comparison is being made. ΔH_t will be negative if habitat is reduced, and positive if habitat is greater. This is calculated at a reach scale, but can also be summarised as a catchment average.

- Mean daily physical habitat reduction

  This describes the mean daily difference in habitat availability between two scenarios only for days when habitat change is negative. It is a measure of the magnitude of change in habitat availability and is described by **Error! Reference source not found.**.

$Mean\ daily\ habitat\ reduction = \sum \Delta H_t / N_R \quad \text{for: } t \in \Delta H_t < 0 \quad (5)$

where N_R is the number of days in the time series over which the comparison is being made where habitat is reduced. This descriptor takes account of the fact that in the calculation of mean daily habitat change, multiple days of habitat reduction may be 'cancelled out' by multiple days of habitat increase, therefore giving a false sense of the overall consequences of water use for instream values.

- Mean daily physical habitat increase

This describes the mean daily difference in habitat availability between two scenarios only for days when habitat change is positive. It is a measure of the magnitude of change in habitat availability and is described by **Error! Reference source not found.**.

$Mean\ daily\ habitat\ reduction = \sum \Delta H_t / N_I \quad \text{for: } t \in \Delta H_t > 0 \quad (6)$

where N_I is the number of days in the time series over which the comparison is being made where habitat is increased. This descriptor takes account of the fact that in the calculation of mean daily habitat change, multiple days of habitat increase may be 'cancelled out' by multiple days of habitat decrease, therefore giving a false sense of the overall consequences of water use for instream values.

- Proportion of time physical habitat is decreased

This is a measure of the duration of habitat change. It describes the proportion of days in the time series over which a comparison is being made where the difference in habitat between two scenarios is negative (i.e., habitat is reduced). It is described in **Error! Reference source not found.**.

$Time\ habitat\ is\ decreased = N_R / N * 100 \quad (7)$

Proportion of time physical habitat is increased

This is a measure of the duration of habitat change. It describes the proportion of days in the time series over which a comparison is being made where the difference in habitat between two scenarios is positive (i.e., habitat is increased). It is described in **Error! Reference source not found.**.

$Time\ habitat\ is\ increased = N_I / N * 100 \quad (8)$

Maximum duration of continuous physical habitat reduction

This describes the maximum number of consecutive days that habitat is reduced compared to the reference scenario. This is another measure of the duration of habitat change and is an indicator of prolonged stress due to reduced flows. It is not weighted to reflect the magnitude of habitat change.

- **Maximum duration of continuous physical habitat increase**

This describes the maximum number of consecutive days that habitat is increased compared to the reference scenario. This is another measure of the duration of habitat change. It is not weighted to reflect the magnitude of habitat change.

Rapid Assessment Tool (RAT)

The RAT module is a supply-demand simulation, accounting for how much water falls as rain and how much water evaporates, or should evaporate if a sufficient water source is available. This simulation is based on the crop, and area to be irrigated (Woods et al. 2012). The evaporation time series is part of the TopNet simulation and depends on input temperature and sunshine, as well as the crop being grown, as different crops are associated with different rates of evaporation. The rain time series is the other input, also originating as part of the TopNet input. In addition, the user can specify a soil trigger level below which an irrigation shall be turned on to keep the soil moisture above this trigger level. This irrigation water stems from the river take. The following equation is calculated on a daily basis:

Irrigation (from river) = evaporation – rain (9)

In summary, this module determines how much water is needed for irrigation and when to irrigate in order to keep the soil water level above a trigger level.

Appendix B TopNet calibration of the Grey River catchment

TopNet was used as the hydrological model to deliver the hydrographs needed for the CHES tool. This Appendix provides a brief summary of TopNet and the calibration process followed in order to run CHES for this project. A more detailed description of the TopNet component of this project is provided in a separate report (Zammit et al. 2016)

Introduction

TopNet is a rainfall-runoff model. There are currently two versions of the model, TopNet-0 and TopNet-GW.

- TopNet-0: This is the TopNet model which ignores surface water – deep ground water interactions. This TopNet model should only be used for catchments/parts of the catchment where there is no groundwater surface water interaction, or where only a small subsurface water storage exists in each reach, as any larger ground water aquifers will be ignored.
- TopNet-GW: This is the TopNet model that includes a conceptual ground water aquifer, allowing for water exchange between deep ground water and surface water bodies. To run TopNet-GW further catchment information is required. This includes reach gaining and losing properties, which can be derived from spot gauging data. A TopNet-GW simulation is more appropriate for reaches with surface-water ground water interaction but this TopNet model takes longer to run than a TopNet-0 calibration.

Each of these TopNet models generates hydrographs based on the selected Strahler Order. For example, if we select:

- Strahler order 1: then TopNet will simulate hydrographs for the catchment, using reaches of order 1, 2, 3, 4,….
- Strahler order 2: then TopNet will simulate hydrographs for the catchment, using reaches of order 2, 3, 4,…
- Strahler order 3: then TopNet will simulate hydrographs for the catchment, using reaches of order 3, 4,…

The higher the Strahler Order that TopNet uses in the simulation, the faster a TopNet calibration can be carried out. However, a drawback is that when higher Strahler order numbers are selected then there could be greater uncertainty in the hydrographs generated for all reaches. We ran TopNet for Strahler order 3. This meant that we needed to generate hydrographs for reaches with Strahler order 2 and 1 outside of TopNet. We did this using catchment area ratios. We then tested whether this approach gave similar results to generating these hydrographs in TopNet and found that it did.

TopNet Calibration for the Grey River catchment

For this project the following calibrations were carried out:

- TopNet-0 at New Waipuna (Strahler Order 3) using the flow recorder at New Waipuna. It was assumed that upstream of New Waipuna no surface water to deep ground water interaction exists. This generates the TopNet parameters for all reaches upstream of New Waipuna (Zammit et al. (2016)).
- TopNet-0 at Grey at Dobson (Strahler Order 3) using the flow recorder at Grey at Dobson. This used the information from the New Waipuna calibration, keeping those constant and only changing the TopNet parameter for the rest of the catchment upstream of the Grey at Dobson (Zammit et al. (2016)).
- TopNet-GW for Maimai (Strahler Order 3) not modifying the TopNet-0 parameter set but modifying the TopNet ground water parameter only. For this the spot gauging data supplied from WCRC was used and measured spot gauging data was compared with simulated flow data (Zammit et al. (2016)).
- TopNet-GW for Grey at Dobson (Strahler Order 3). Here the TopNet parameter from New Waipuna, and the Maimai were used, and the remaining catchment was calibrated using the TopNet-GW model, by comparing measured and simulated flows (Zammit et al. (2016)).

Additional information supplied by WCRC

For the calibration of TopNet-GW at Maimai, spot gauging data was supplied from the following locations:

Site Name	NZReach
Mawheraiti Rv @ SH7 Maimai (G4)	12021060
Slab Hut Ck @ u/s Mawheraiti Confl (G5)	12021288
Casolis Ck @ SH7 (G6)	12021358
Mawheraiti Rv @ u/s Stoney confl	12022155
Stony Ck @ vehicle crossing (G17)	12022101
Unnamed Ck @ u/s Mawheraiti-Stony confl	12022042
Mossy Ck @ u/s Mossy Ck Br No1	12023678
Snowy Rv @ u/s Mossy Ck confl	12023673
Snowy Rv @ u/s Mawheraiti confl	12023688
Mawheraiti Rv @ u/s Snowy Rv confl	12023703
Orwell Ck @ Carters Rd	12025694

For each of these spot gauging locations, spot gaugings were carried out on the following dates:

- 28-May-2015
- 4-June-2015
- 17-June-2015
- 14-July-2015
- 22-July-2015
- 9-Sep-2015
- 22-Sep-2015
- 24-Sep-2015
- 29-Oct-2015

These data was essential in running the TopNet-GW calibration for the Maimai.

WCRC also supplied daily abstraction volumes for two abstractors. However, they abstracted on an irregular basis, and data spanned only ~2 years. Therefore this information could not be used.

In addition, groundwater bore data were available for two groundwater abstractions spanning several years, but not over all 42 years of CHES simulation period. It was not possible to include those in the TopNet-GW calibration, as it was felt that they were not representative of the simulated deep ground water aquifer and as they did not cover the required 42 year time period.

Simulation of the Grey River catchment hydrographs for each reach

Using the above TopNet calibration, the TopNet Grey river catchment simulation was carried out so that each of the 8399 reaches upstream of the river mouth would have a hydrograph. This was completed in several steps:

- Simulation of all Strahler Order 3 reaches upstream of Grey at Dobson
- Simulation of all Strahler Order 1 reaches for the Little Grey River upstream of the Blackwater River confluence (upstream of 12023703)
- Simulation of all Strahler Order 1 reaches for the Grey River upstream of the SH7 bridge (upstream of 12024303)
- Simulation of all Strahler Order 1 reaches for the Big River (upstream of 12025319)
- Simulation of all Strahler Order 1 reaches for the Ahaura River (upstream of 12025750)
- Simulation of all Strahler Order 1 reaches for the Arnold River (upstream of 12027654)
- Simulation of all Strahler Order 1 reaches between the Grey River mouth and Grey at Dobson.

For all other reaches, that were only simulated as Strahler Order 3, the hydrographs for the upstream reaches of Strahler Order 2 and Strahler Order 1 were generated using the ratio of catchment areas.

D R A F T

Appendix C Abstraction database

Table C-1: Grey River catchment abstraction database. Supplied by WCRC. ConsId (consent ID), Reach number (NZReach relating to abstraction), abstraction type ("GW" is ground water abstraction, "SW" is surface water abstraction), ΔQ (total allocation), and Q_{min} (minimum flow).

ConsID	Reach number	Abstraction type	ΔQ [l/s]	Q_{min} [l/s]
AUTH-RC06064/4	12019562	GW	60	0
AUTH-RC06064/3	12021164	SW	55	0
AUTH-RC11129/1	12021583	SW	34	0
AUTH-RC13078/1	12021852	SW	90	0
AUTH-RC01125/1	12022042	SW	28	0
AUTH-RC01271/1	12022101	SW	45	370
AUTH-RC02192/1	12022238	SW	30	0
AUTH-RC-2015-0166-L1	12022274	GW	35	0
AUTH-RC09079/1	12022295	SW	60	0
AUTH-RC02020/2	12022664	SW	2	50
AUTH-RC98021/2	12022753	SW	250	50
AUTH-RC06168/1	12022756	SW	2	0
AUTH-RC06250/1	12022981	SW	1	0
AUTH-RC01172/1	12023165	GW	10	0
AUTH-RC07173/5	12023230	GW	55	0
AUTH-RC11145/3	12023259	SW	4.9	0
AUTH-RCN99017/1	12023286	SW	15	0
AUTH-RCN99017/2	12023286	GW	15	0
AUTH-RC06253/1	12023334	GW	0.6	0
AUTH-RC01319/1	12023458	GW	19	0
AUTH-RC-2014-0039-01	12023489	GW	180	300
AUTH-RC11137/1	12023533	SW	70	10
AUTH-RC11005/1	12023827	SW	200	0
AUTH-RC98021/33	12024096	SW	10	0
AUTH-RC00084/2	12024248	SW	20	0
AUTH-RC00084/3	12024248	GW	20	0
AUTH-RC-2014-0061-01	12024249	SW	70	0
AUTH-RCN99017/1	12024303	SW	15	0
AUTH-RC02176/3	12024342	SW	1.2	0
AUTH-RC00407/2	12024531	SW	60	0
AUTH-RC00407/1	12024531	GW	60	0
AUTH-RC-2014-0061-02	12024531	GW	200	0
AUTH-RC13102/1	12024553	SW	300	11565

ConsID	Reach number	Abstraction type	ΔQ [l/s]	Q_{min} [l/s]
AUTH-RC13102-V1	12024553	SW	300	156
AUTH-RC01310/1	12024633	GW	130	0
AUTH-RC-2014-0112-01	12024661	SW	145	0
AUTH-RCN97044/1	12024877	SW	10	0
AUTH-RC13063/1	12025063	GW	100	0
AUTH-RC08091/1	12025348	GW	100	0
AUTH-RC13067/1	12025547	GW	70	0
AUTH-RC05086/1	12025649	GW	0.5	0
AUTH-RC01174/1	12025649	GW	8	0
AUTH-RC12190/1	12025915	GW	200	0
AUTH-RC11102/1	12025944	GW	145	0
AUTH-RC03105/5	12025984	SW	8	0
AUTH-RC01180/3	12026056	SW	6	0
AUTH-RC07200/2	12026241	SW	50	0
AUTH-RC13051/1	12026299	SW	50	100
AUTH-RC-2014-0077-01	12026467	GW	55	0
AUTH-RC02259/9	12026575	SW	602	0
AUTH-RC00208/1	12026962	SW	25	0
AUTH-RC93039/1	12026980	SW	11.5	0
AUTH-RC12107/1	12026980	GW	5	0
AUTH-RCN94482/1	12027654	GW	2.1	0
AUTH-RC07054/2	12027684	SW	25	0
AUTH-RC06193/6	12027956	SW	676	0
AUTH-RC06193/7	12027956	GW	50	0
AUTH-RC01162/1	12028017	GW	1	0
AUTH-RC01180/2	12028027	GW	18	0
AUTH-RC10157/1	12028028	GW	13.9	0
AUTH-RC01180/1	12028048	SW	10	0
AUTH-RC01337/1	12028048	SW	1	0
AUTH-RC09148/1	12028082	SW	20	0
AUTH-RC02274/1	12028103	GW	5	0
AUTH-RC01092/3	12028104	GW	177	0
AUTH-RC07025/1	12028254	GW	13.5	0
AUTH-RC02178/1	12028515	SW	100	0
AUTH-RC06038/1	12028515	GW	100	0
AUTH-RCN95420/1	12028695	SW	5	0
AUTH-RC01173/1	12028695	SW	2	0
AUTH-RC97020/5	12029607	GW	0.03	0
AUTH-RC13175/1	12029730	SW	30	0

ConsID	Reach number	Abstraction type	ΔQ [l/s]	Q_{min} [l/s]
AUTH-RC13119/1	12030305	SW	3	0
AUTH-RC00333/4	12030344	GW	7	0
AUTH-RC01060/1	12030493	SW	0.5	0
AUTH-RC13040/2	12030549	GW	25	0
AUTH-RC04142/1	12030593	GW	3	0
AUTH-RC13040/1	12030747	GW	40	0
AUTH-RC10025/1	12030985	SW	8.89	0
AUTH-RC91044/1	12031032	SW	2	0
AUTH-RC03308/1	12031167	GW	5	0
AUTH-RC01178/1	12031631	SW	2	0
AUTH-RC01059/1	12031675	SW	5	0