NIWA
Taihoro Nukurangi

Gisborne District Water Resources Under Climate Change

Prepared for Gisborne District Council

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Executive summary

Gisborne District Council is currently developing a regional plan for freshwater management that will give due regard to climate change, as required by the National Policy Statement for Freshwater Management. Climate change is likely to affect the provision of freshwater resources and values in Gisborne District.

The purpose of this report is to review the existing knowledge of freshwater changes under climate change and to extend this knowledge to include changes in average seasonal river flow and annual low flows. For Gisborne District, the reasonably foreseeable impacts of climate change related to freshwaters this century, and as soon as 2040, are:

- Hydrological conditions that are different from the past;
- Water resources that are more variable and harder to predict;
- Less rainfall in the wetter winter-spring period (due to stronger westerlies), and slightly more rainfall in summer and early autumn (weaker westerlies);
- Higher temperatures throughout the year;
- More time spent in drought;
- Greater crop water requirements;
- A general decline in surface water supply, least pronounced in summer and most pronounced in winter;
- Floods that are more extreme when they do occur;
- Slightly lower average annual low flows, though the decreases are too small to warrant any changes in planning at this stage; and
- Reduced groundwater recharge from land, though river-based recharge is not likely to change.

The most likely changes to river flow for the Waipaoa River at Kanakanaia are reported in Table 1. These are middle-of-the road estimates of future conditions. However, given the uncertainties inherent in climate and hydrological projections of the future, it is possible that river flows turn out to be higher or lower than projected here.

Table 1. Summary of the climate change projections for the Waipaoa River at Kanakanaia and its catchment. Precipitation, P, is the total rainfall and temperature, T, is the average temperature, both near the centre of the catchment. Q is the average river flow. MALF is the 7-day average annual low flow.

Period	1980-1999				2030-2049				2080-2099			
	P (mm)	T (^oC)	Q (m^3/s)	MALF (m^3/s)	P (mm)	T (^oC)	Q (m^3/s)	MALF (m^3/s)	P (mm)	T (^oC)	Q (m^3/s)	MALF (m^3/s)
Summer	215	17	14.2		222	18	13.7		226	20	12.9	
Autumn	298	14	28.4		310	14	27.6		310	16	25.1	
Winter	321	9	51.3		286	9	40.6		279	11	35.0	
Spring	228	12	23.2		208	13	19.2		192	14	15.7	
Annual	1062	13	29.4	2.45	1025	14	25.3	2.36	1007	15	22.3	2.21

Adaptation options available to water stakeholders, users and managers alike, include:

1. More efficient use of water, a reduction in water use, and the development of additional water supplies and water storage;

2. Better use of weekly and seasonal forecasting of water supply and demand; and

3. Water resource planning methods that account for both the uncertainties and the trends associated with climate change. These include adaptive management and scenario planning. In terms of setting limits, results presented in this study suggest:

    a. No change in MALF-based minimum flow setting until more information comes to light (revisit in 5-10 years' time); and

    b. A possible reduction in non-summer water allocation caps.

1 Introduction

In 2011, the Ministry for the Environment gazetted the National Policy Statement for Freshwater Management, which requires regional plans for freshwater to give regard to “the reasonably foreseeable impacts of climate change.” This is an important evolution in policy direction given the potential effects that climate change may have on water availability, water demand, droughts, water quality, aquatic ecology and other water-related values. As the Gisborne District Council (GDC) is currently in the initial stages of preparing a regional plan, this report has been commissioned by the GDC to provide the necessary scientific background on climate change and freshwater resources for their District.

Drawing from existing studies and new analysis, this report will thus provide:

- a review of existing studies relevant to water resources in Gisborne District;
- an empirical modelling assessment of seasonal flow and mean annual low flow (MALF) changes under climate change for the Waipaoa River;
- analysis of potential adaptation options for water resource stakeholders;
- a summary of the reasonably foreseeable impacts of climate change on water resources; and
- recommendations for further analysis.

2 Review of Existing Studies

Several reports have been produced in the last five years with particular bearing on Gisborne District. They include (Savage 2006) and (Savage 2009), which provided overviews of the potential impacts of climate change for the region, (McMillan et al. 2010), which assessed future flooding in one of the district's catchments, and (Clark et al. 2011), which reassessed the effects of climate change on drought nationally.

2.1 Savage (2006): General assessment

(Savage 2006) addressed the potential impacts of climate change on Gisborne District in very broad, and almost entirely qualitative, terms, subject to the knowledge available at the time.

2.1.1 Hydrological changes

As reported by (Savage 2006), precipitation was projected to decrease and temperature to increase for all seasons in 2030 and 2080, based on results from the Intergovernmental Panel on Climate Change's (IPCC) Third Annual Report. Projections of annual precipitation change varied from up to -31% to 4%. Drought risk was expected to increase across the District (discussed in more detail below), while more intense storms would reduce the availability of water. (Savage 2006) stated further that the changes in 2080 precipitation and evaporation would translate to a 10-40% decrease in water entering rivers and lakes, though the source of these numbers is unclear. The implications for aquifers were unknown, though reduced recharge was deemed plausible, as was elevation of coastal water tables due to sea-level rise. Restriction of the Waipaoa River mouth was thought to be possible, due to sea- level rise and coastal sediment processes that could restrict the Waipaoa River mouth, causing water to back up more within the lower reaches of the flood control scheme.

In terms of drought, (Savage 2006) provided substantially more information, which stemmed from a study by (Mullan et al. 2005). This study considered two plausible scenarios of future climate change each for two periods in the future, and quantified drought by using the potential evapotranspiration deficit (PED) accumulated over a growing year. PED is the difference between what could be evaporated under prevailing climatic conditions and what did evaporate.

It was noted in (Mullan et al. 2005) and (Savage 2006) that PED represented the amount of water needed to prevent a loss of production due to water shortage. This needs to be tempered as many crops benefit from slight water stress (e.g., grapes), or require dry conditions in order to mature (e.g., cereal and seed crops). Furthermore, crop productivity relates more closely to the amount of transpiration, which can remain steady if even potential atmospheric evaporative demand for water, and subsequently PED, increase.

Despite this, the general findings of (Mullan et al. 2005) remain informative. Under low-medium climate change in 2080, PED-related droughts that currently occur about once every twenty years in portions of Gisborne District (including the Poverty Bay flats, and the East Coast to approximately Tokomaru Bay) could occur every five or ten years. For the hill country areas, a one-in-twenty-year drought could occur on average every fifteen to twenty years. Under medium-high climate change, current one-in-twenty-year droughts are projected to occur on average between once in every 2.5 years and once in every five years.

2.1.2 Water quality and aquatic ecosystem change

With changes in air temperature, hydrological conditions, and sea-level rise, (Savage 2006) also expected changes for water quality and aquatic ecosystems:

- More intense rainfall is expected to exacerbate soil erosion.
- Ephemeral wetlands will likely be subjected to longer dry periods, with some wetlands drying up and others experiencing higher sedimentation.
- Freshwater ecosystems in general may be disrupted due to reduced stream flows and warmer water temperatures.
- Sea-level rise would increase the salinity of coastal aquifers and tidally influenced rivers.

2.1.3 Agricultural water demand

With higher temperatures and a greater risk of drought, (Savage 2006) found there is expected to be greater demand for water for both stock and irrigation. It was suggested that this may manifest itself in both higher abstraction from existing schemes, or in the development of new schemes. Irrigation may also be extended to stock farming to support grazing crops. Water demand may also increase if the water holding capacity of soils is reduced by the loss of organic matter. With regards to the Makauri aquifer, a key source of water to the Poverty Bay Flats, (Savage 2006) predicted that increased abstraction coupled with reduced groundwater recharge may make its use unsustainable.

(Savage 2006) also stated that, in the medium term (20 to 50 years), there may be a need for increased monitoring and regulation of surface and ground water usage. Individual farmers may decide to consider larger-scale water storage and irrigation systems. Long term, whole-catchment planning would be desirable, with timeframes of 50 to 100 years; much longer than farmers and regional councils currently consider, (Savage 2006) notes.

2.1.4 Effects of afforestation

Among the various options to mitigation climate change addressed by (Savage 2006) was carbon sequestration in the form of afforestation. Planting forests has the additional benefit of reducing soil erosion and conserving water quality (Blaschke et al. 2008). Not mentioned by Savage (2006), however, is that this would also reduce catchment water yield and low flows (Fahey, 1994; Farley et al. 2005); a reduction in low flows may in turn adversely affect water quality. This occurs for several reasons: (1) the greater canopy area intercepts and evaporates more rainfall before it has a chance to reach the ground; (2) the greater leaf area is typically able to transpire more water, depending on the species; (3) the taller and aerodynamically rougher canopy surface accentuates atmospheric transport of moisture; and (4) the deeper rooted plants are typically able to reach and extract more subsurface moisture.

2.1.5 Additional impacts

Several other impacts were identified by (Savage 2006) which have a bearing on freshwaters:

- Low river flows or empty dams would compromise fire fighting efforts.
- Recreational use of water bodies may increase due to warmer temperatures.
- Rural domestic water supplies may come under increased pressure as water supplies and water quality decline.

2.1.6 Water resource management

With the myriad of potential impacts of climate change on water resources, (Savage 2006) stated that the Gisborne District Council will need to take care in allocating water among competing users. More water stored or used by farmers upstream would lead to less available for downstream users or for the replenishment of lowland aquifers. Minimum flows may also need to be set in order to maintain aquatic life.

2.2 Ministry for the Environment (2008): Climate

MfE (2008) is currently the state of the art in terms of guidance for regional authorities regarding the climatic aspects of climate change. It presents results from climate change modelling across the country, for the 2040s and 2090s, based on multiple Global Climate Models (GCMs) and multiple future emissions scenarios.

Changes in seasonal and annual temperature for Gisborne District are presented in Table 2, and in seasonal and annual precipitation for Gisborne township are presented in Table 3. The model results project an average increase in temperature of about 1 °C throughout the year for the 2040s and about 2°C by the 2090s. Mean seasonal rainfall amounts are likely to increase slightly in summer and autumn and to decrease moderately in winter and spring. These changes in rainfall relate to decreased frequency of westerly conditions during summer and autumn and stronger westerlies during the winter and spring.

Table 2. Projected changes in seasonal and annual mean temperature (in °C) for Gisborne District for the 2040s and 2090s. The first value in each square is the average change from the various climate models and emissions scenarios; the values in brackets represent the lower and upper limits.

	Summer	Autumn	Winter	Spring	Annual
2040s	1.0 [0.2, 2.6]	1.0 [0.3, 2.7]	0.9 [0.1, 2.2]	0.8 [0.0, 2.1]	0.9 [0.2, 2.4]
2090s	2.2 [0.8, 6.2]	2.2 [0.6, 5.6]	2.0 [0.5, 5.2]	1.9 [0.3, 5.2]	2.1 [0.6, 5.5]

Table 3. Projected changes in seasonal and annual mean rainfall (in %) for Gisborne township for the 2040s and 2090s. The first value in each square is the average change from the various climate models and emissions scenarios; the values in brackets represent the lower

	Summer	Autumn	Winter	Spring	Annual
2040s	3 [–26, 33]	4 [–18, 46]	–11 [–30, –2]	–9 [–21, 3]	–4 [–15, 14]
2090s	5 [–38, 41]	4 [–25, 27]	–13 [–41, 1]	–16 [–42, 7]	–5 [–22, 8]

2.3 Savage (2009): General assessment

The focus of (Savage 2009) was to provide an update of (Savage 2006) based on advances in the science during the intervening three years. The single most important development during this time was the delivery of the IPCC’s Fourth Assessment Report (AR4) in 2007, with a shift in projection periods to 2030-2049 (the “2040s”) and 2080-2099 (the “2090s”), though this development had limited bearing on the matter of freshwater resources as discussed in the report.

In terms of water supply and demand, (Savage 2009) noted that the slightly higher projected rainfall in summer relative to current conditions (a change from the previous report) would reduce irrigation requirements. However, the lower rainfall in the winter may reduce river flow and groundwater recharge. Given the importance of these changes to the Gisborne District, it was recommended that the risks associated with climate change be incorporated into freshwater management, as well as in the planning of long-lived water resources infrastructure.

As an adaptation option for farmers, it was noted that higher soil organic matter would lead to a number of benefits, including improved soil moisture retention.

2.4 McMillan et al. (2010): Flooding

(McMillan et al. 2010) assessed the potential impacts of climate change on flooding in two catchments in the North Island, one of which was Tolaga Bay's Uawa River. They took climate data generated by a regional climate model for the period 2070-2100 to drive the catchment hydrological model TopNet. The scenarios used to drive the climate modelling were the A2 and B2 scenarios from the IPCC AR4. A2 and B2 refer to emissions scenarios defined in the AR4; A2 is considered a "middle-of-the-road scenario, while B2 is considered more extreme, though still plausible. The results were compared with the contemporary context as defined by the period 1970-2000.

As Figure 1 shows, (McMillan et al. 2010) projected a shortening of the annual high-rainfall period. Instead of extending from May-October, as occurs currently, the period shortens in 2070-2011 under both emissions scenarios to June-September. Furthermore, while the mean daily rainfalls during July and August are expected to be maintained under the B2 scenario, they decline by 10-20% under the A2 scenario. Rainfall extremes are projected to change little for all seasons except summer, when significant increases are expected under both A2 and B2. These events are, however, rare. Spring precipitation is thus likely to decline by the end of the century more than other seasons. As for spatial variability in the hydrological response, differences in precipitation changes are expected even within the same catchment.

In terms of floods with return periods of less than 30 years, flood magnitudes are expected to change, but to different degrees and directions depending on the emissions scenario and the return interval of the flood. Under A2, floods with a return period of about 2 years are expected to reduce in magnitude, those with return periods from about 2-10 years will change little, while less frequent floods are expected to increase in discharge. Under B2, all floods are expected to increase in magnitude.

2.5 Clark et al. (2011): Drought

(Clark et al. 2011) provide an update of the national drought assessment under climate change previously provided by (Mullan et al. 2005), as discussed by Savage (2006). The update differs in several respects, by using newer climate change projections and by assessing drought impacts with a more accurate representation of drought processes.

The climate change projections are drawn from the climate model ensemble used in the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4). Three major global greenhouse gas emissions scenarios are used (B1, A1B and A2), and global climate model output are downscaled to New Zealand locations with improved statistical methods. The 2005 drought study, in contrast, used the Third Assessment Report (TAR) climate models and different downscaling methods. Additionally, the estimates of drought probability were derived from a soil moisture indicator, which is sensitive to moderate to severe intensity droughts greater than one month in duration, rather than PED - in part due to the limitations of PED outlined in Section 2.1.1 above.

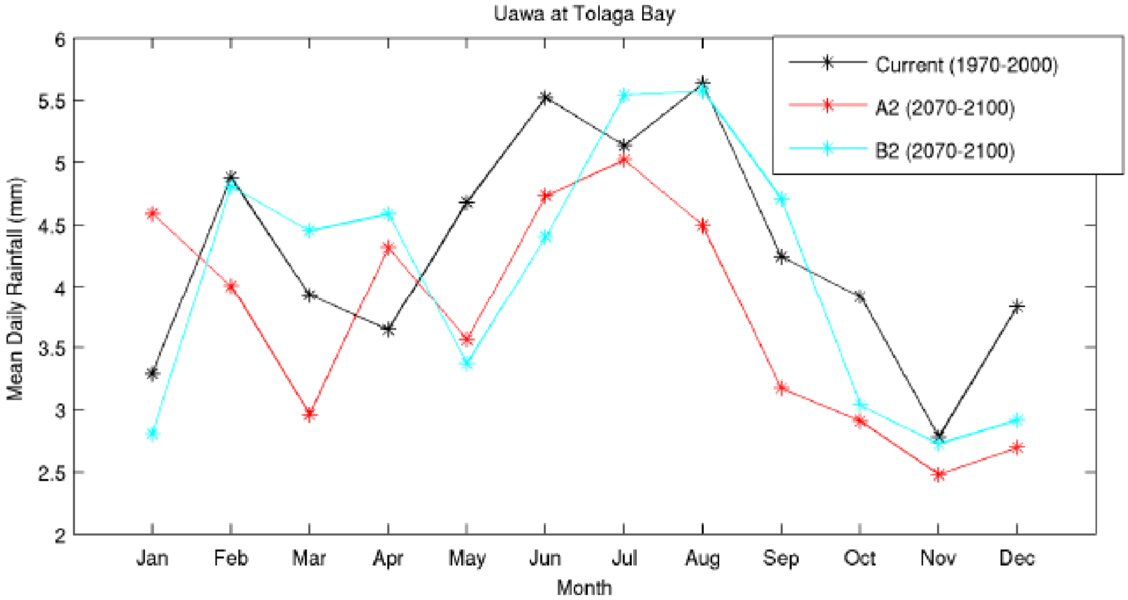

Figure 1. Mean daily rainfall for each month, calculated from the 30-year bias-corrected Regional Climate Model (RCM) output for the Uawa catchment. Figure shows current climate compared with future climate under A2 and B2 IPCC emissions scenarios. From (McMillan et al. 2010).

In general, the results of (Clark et al. 2011) were similar to those of (Mullan et al. 2005). While there were differences among GCMs, a pattern of increased drought duration was identified in Gisborne under climate change. Based on the results of 19 different Global Climate Models (GCMs), the A1B emissions scenario (a “mid-range” scenario), and a downscaling technique based on temperature alone, Figure 2 illustrates national changes in the time spent in drought conditions. The two least likely projections correspond to the two outliers from the 19 GCMs. The most likely outcomes for the Gisborne region District are reported in Table 4.

When radiation is also used to downscale the climate change projections, substantially different results are obtained. The 19 GCMs produce a wider range of projections when radiation is included in the downscaling procedure. In contrast with the non-radiation method, some models project a reduction in time spent under drought for both 2030-2050 and 2070-2090 across all scenarios (B1, A1B and A2). The more likely projections by this method see increases in time spent under drought, though not as large as with the other method. The GCMs with the greatest change are essentially a matter of several percentage points below that without radiation. It must be noted, however, that it is not clear which downscaling method is a better representation of reality. For practical purposes, it would be sufficient at this time to use the results without the influence of radiation, with the proviso that policy interventions be robust to plausible drought outcomes both higher and lower in severity.

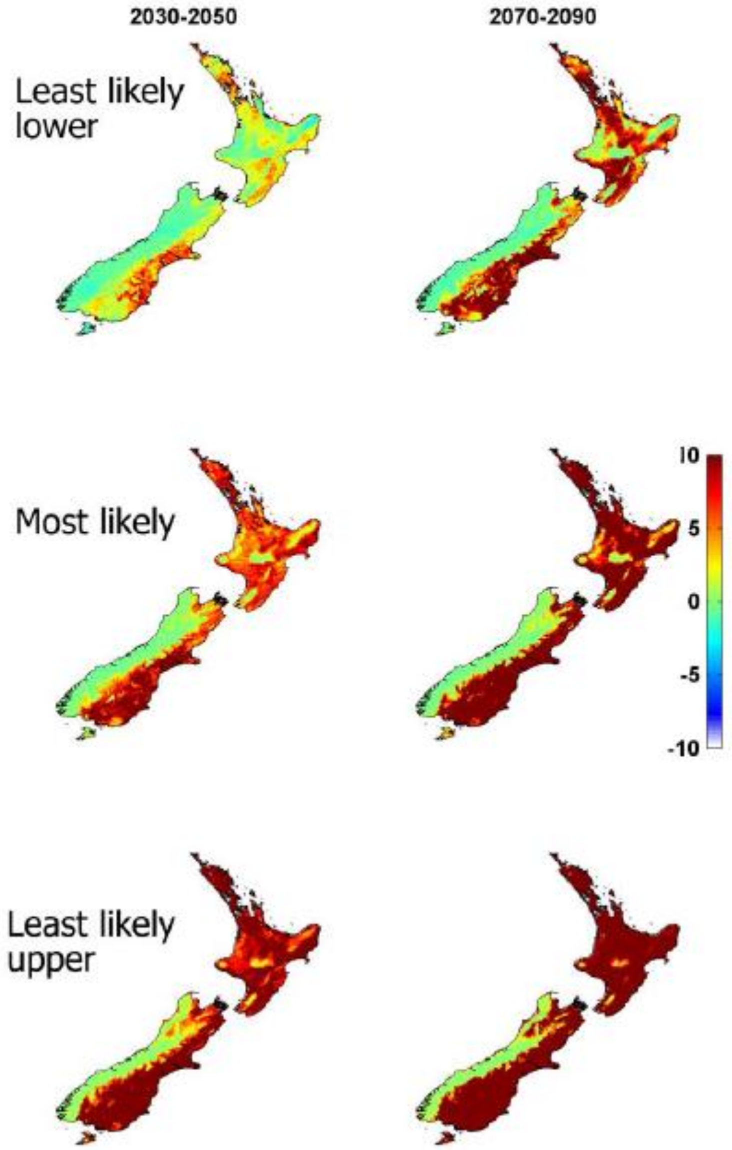

Figure 2. Projected increase in percentage of time spent in drought from 1980-99 levels for the A1B emissions scenario. Results summarise 19 global climate models. From (Clark et al. 2011).

Table 4. Increase in time spent in drought in Gisborne District, based on Clark et al. (2011). Because of the spatial variability, values are approximate.

Elevation	2040	2090
Low	5-10%	10%
High	2%	5-10%

2.6 Gomez et al. (2009): River flow and sediment transport

The focus of (Gomez et al. 2009) was on the effect of climate change on sediment transport and subsequent erosion or aggradation in the Waipaoa River. Two models were used: (1) the daily time-step model HydroTrend was used to simulate river flow and suspended sediment transport along the Waipaoa River; and (2) the Unified Gravel-Sand (TUGS) model was used to simulate the dynamics of gravel and sand transport. To assess the potential impacts of climate change, the models were driven by projections of mean annual temperature and precipitation for the 2030s (2020-2049) and 2080s (2070-2099), as provided by MfE (2004).

Modelling results indicated a reduction in mean annual flow for the Waipaoa River at Matawhero of 13% by the 2030s and 18% by the 2080s. Mean annual suspended sediment was projected to change +/- 1 Mt/y by the 2030s. However, this change may be difficult to detect given contemporary variation in annual suspended sediment yield of 13.4 +/- Mt/y. For the 2080s, suspended sediment discharge may increase by about 1.9 Mt/y or decrease by about 1 Mt/y, depending on the climate change scenario. In terms of bed levels in the lower 27 km of the river, under some climate change scenarios it is possible that the river could aggrade by an average of 0.31 m by the 2030s and by 0.85 m by the 2080s, with significant implications for capacity of the channel and hence for the Waipaoa River flood control scheme.

2.7 Additional Groundwater Interpretation

While the climate change impacts studies that relate specifically to Gisborne District's water resources are limited to those reviewed above, it is possible to make further comments on how the groundwater resource may change in the future, specifically groundwater recharge. Based on two studies (Zemansky et al. 2010; Clark et al. 2011), two qualitative conclusions may be drawn.

On the one hand, where aquifers are fed by the drainage of water from the surface, it is reasonable to expect that the amount of annual recharge would decline. This follows from the increase in soil drought conditions reported by (Clark et al. 2011). In general, only when soil moisture rises above field capacity does drainage from the soil column occur, and hence does the water recharge the underlying aquifer. With longer droughts spilling into autumn and spring, and drier soils, soil drainage would be less likely to occur.

On the other hand, where aquifers are fed by the drainage of water from rivers, as would at least be partially the case for the unconfined Poverty Bay aquifer, it is reasonable to expect negligible changes in recharge, as the slight differences in water level would only have a small effect on infiltration. As the Waipaoa River is not likely to run dry in the future, river-based recharge would not change appreciably. This resembles the results of (Zemansky et al. 2010), where groundwater levels in Waimea Plains aquifer in Tasman remained unchanged even though flows in the Waimea River dropped under climate change.

3 Projections of Climate Change Impacts on the Waipaoa River

While Gisborne-specific research has been conducted on drought and flooding under climate change, no study has specifically considered the freshwater resource itself. To better inform water resource management decisions, it is thus important to develop projections of water resource change in the future. The river chosen for this study is the Waipaoa River, an important river for water resources in Gisborne District, supplying domestic water to Gisborne City, irrigation water for the Poverty Bay Flats, emergency supply of domestic water to Gisborne City, and groundwater recharge for the Poverty Bay Flats aquifer system.

These climate change projections are made with an empirical model that essentially asks: *What were river flows like in the past during seasonal climatic conditions similar to those projected for the future?* The method is an extension to that employed by (Collins 2010) for the Awanui River in Northland. In simple terms, the present method develops relationships between climatic variables and mean seasonal flows and 7-day seasonal low flows, and then uses the seasonal average climate change projections provided by (Ministry for the Environment 2008) to infer hydrological behaviour under an altered climate.

3.1 Existing climate data

Three data sets are required for the empirical analysis: precipitation, temperature and river flow. Locations of the flow and climate sites are depicted in Figure 3.

Daily precipitation and temperature data for the current climate situation are obtained from the Virtual Climate Station Network (VCSN) node near the centroid of the Waipaoa catchment (Agent #30630, 38.425^{o}S 177.775^{o}E) (Figure 4). This data source was chosen over other climate stations in order to gain a continual record for the analysis period and to be as representative as possible of the climatic conditions over most of the catchment. The record ran from 1973-2012 with no data gaps. As VCSN temperature data comprise daily maxima and minima, the two extremes were averaged in order to approximate the mean daily temperature.

Recent river flow data were obtained from the NIWA Waipaoa River flow monitoring site at Kanakanaia (Figure 4). This record was chosen for its longevity and limited number of data errors, while reflecting the hydrological response of a large area without being influenced by tidal variations. The record used ran from 12/11/1972 to 24/1/2012, with 3.01% of the record containing data gaps.

3.2 Model development

Two models of river flow are developed in this section. The first relates seasonal climatic conditions to mean seasonal river flows. The second relates mean seasonal river flow to the same season's 7-day low flow.

3.2.1 Mean seasonal flow

To construct an empirical model of mean river flow as a function of temperature and rainfall, the three time-series are first aggregated to the seasonal time-scale. For summer, data from December, January and February were grouped together; for autumn, March, April and May; and so on for winter and spring. If there were any data gaps at any point in time (only applicable to the flow data), then a gap is retained at the seasonal scale too, regardless of the number of gaps.

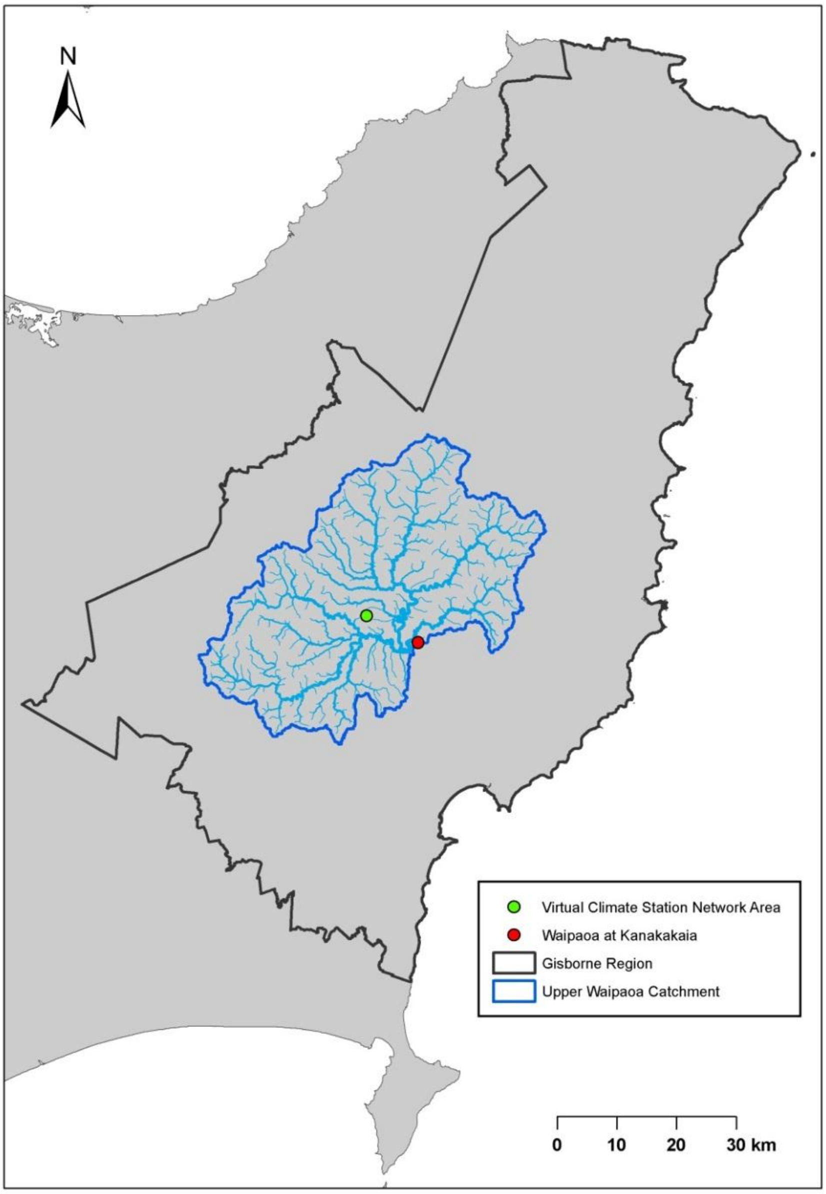

Figure 3. Map of Waipaoa catchment, with VCSN node (green) and flow site (red).

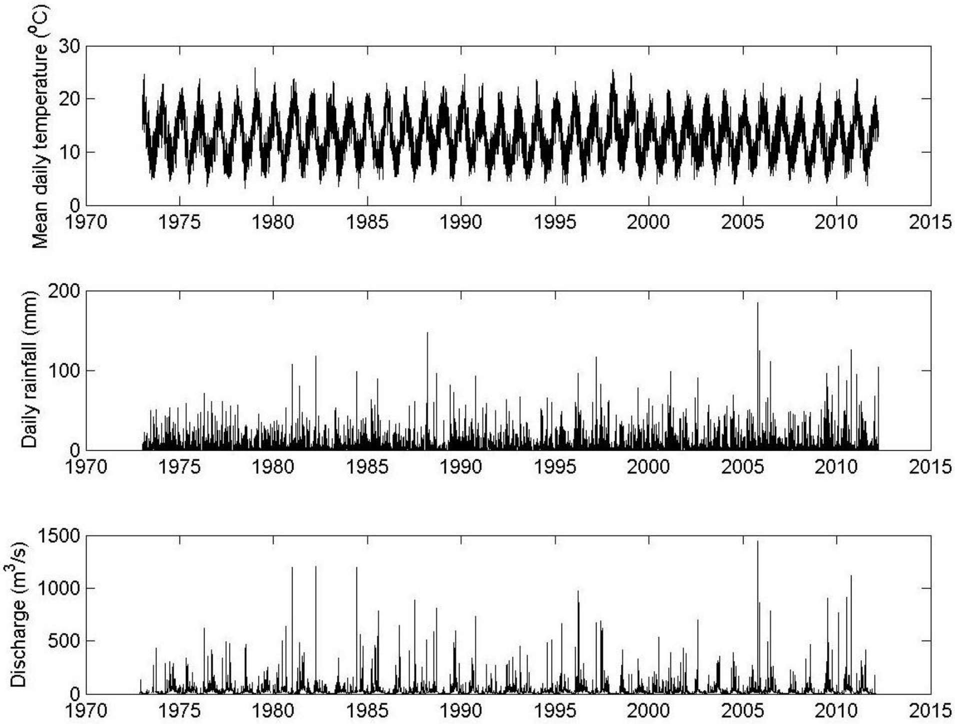

Figure 4. Daily mean temperature and total rainfall at the VCSN site, and mean daily flow at the Waipaoa River at Kanakanaia, illustrating the length and variability of the data used.

An initial comparison of mean seasonal flow and total seasonal rainfall shows a general increasing trend (Figure 5) as expected. Data are clearly clustered according to season, due at least in part to the effects of temperature on evaporation. Considering flow and temperature (Figure 5), the general decreasing trend is apparent, showing that warmer weather is correlated with low flows.

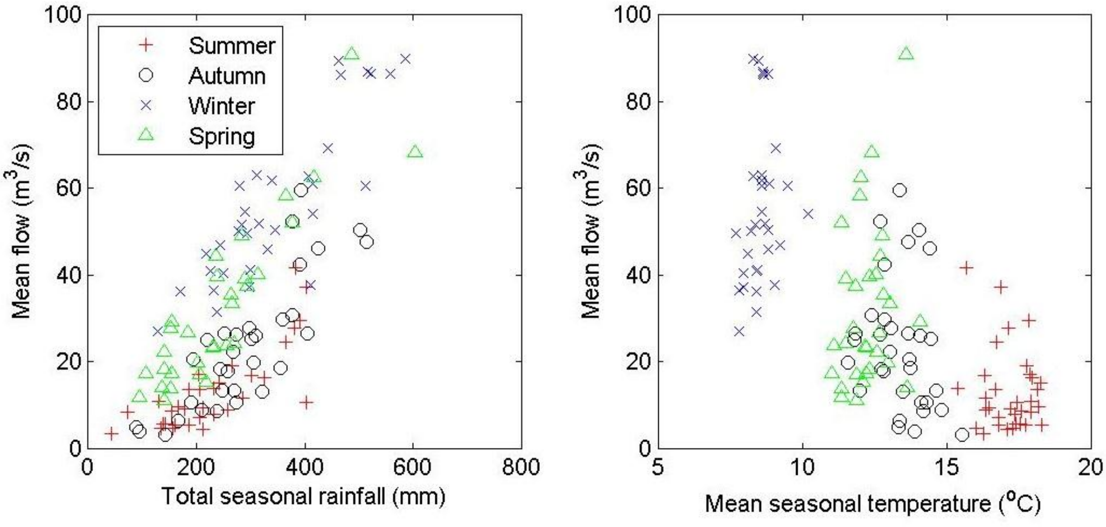

Figure 5. Comparison of mean seasonal flow with total seasonal rainfall and mean seasonal temperature. Data are grouped by season.

Combining both precipitation and temperature into a single expression allows the data to collapse into a more well-defined relationship. The relationship chosen here is:

$$Q = a + b \frac{P}{T}$$

where *a* and *b* are coefficients, *Q* is the mean seasonal flow (m^3/s), *P* is the total seasonal rainfall (mm), and *T* is the mean seasonal temperature (^{o}C). This reflects the general increase of flow with rainfall and a decrease in warmer conditions. Minimising the mean square error of this relationship gives *a* of -4.2 m^3/s and *b* of 1.5 s/^{o}C/mm/m^3, with an R^2 of 0.82 and Root Mean Squared Error (RMSE) of 9.6 m^3/s which are acceptable error statistics for such a model (Figure 6).

3.2.2 7-day seasonal low flow

Developing a model of 7-day seasonal low flow is more difficult than for the mean. This is because low flows depend more on extremes. Despite this constraint, a simple model is developed here that relates mean seasonal flow to the same season's 7-day low flow (Figure 7).

There is a general positive relationship between the two, as expected, with a roughly linear upper bound. However, there is much scatter beneath this bound. This indicates that while minimum flows are higher when mean flows are higher, there is more to the relationship than can be encapsulated by average seasonal conditions. Fitting a linear relationship to the data, and constraining the linear model to pass through the origin provides a modest explanation of the relationship with an R^2 of 0.54. This means that the linear model can be used to explain just over half of the variation of the 7-day seasonal low flows. With such a low R^2 additional caution must be taken in interpreting any results based on this model.

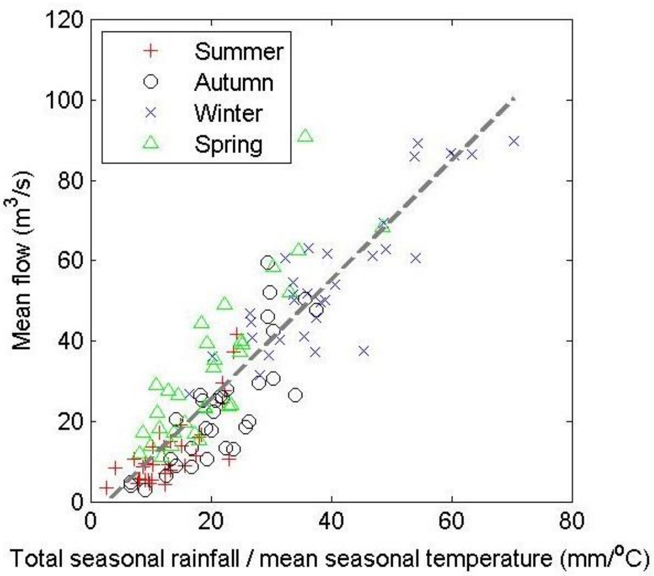

Figure 6. Comparison of mean seasonal flow with the ratio of total seasonal rainfall to mean seasonal temperature. Data are grouped by season. The dashed line represents the best-fit linear regression; R^2 = 0.82, RMSE = 9.6 m^3/s.

This model can be used to infer the 7-day seasonal low flow for any season, provided the mean flow is known. An extension of this is that changes in 7-day seasonal low flows can also be derived from changes in mean flow. This becomes important when climate change projections are made in the following section.

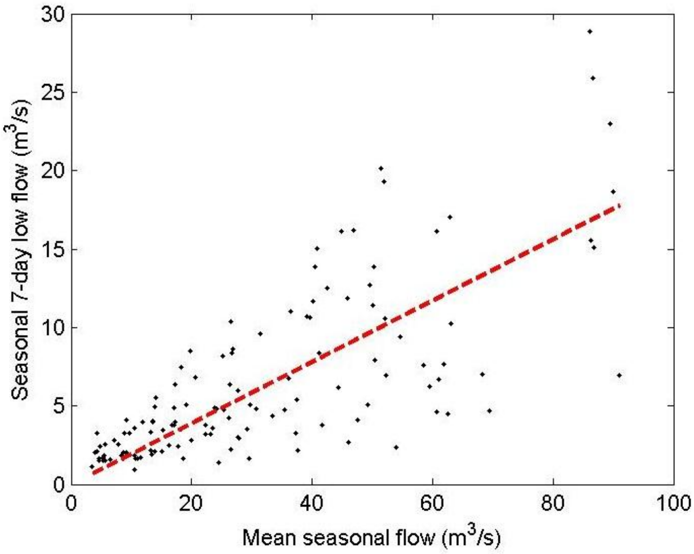

Figure 7. Relationship between mean seasonal flow and seasonal 7-day low flow, for all seasons. Linear regression (Q_{min} = 0.20 x Q_{mean}) has an R^2 of 0.54.

3.3 Climate change projections

3.3.1 Mean seasonal flow

To project the effects of climate change on Waipaoa River flow, the empirical model for mean seasonal flows developed above is used first to infer what the seasonal flow conditions may be under the projected climatic conditions. This is similar to asking the question: What were flow conditions like in the past during climatic conditions similar to those projected under climate change?

Using the VCSN data, total seasonal rainfalls and mean seasonal temperatures were first calculated for the period 1980-1999, referred to in climate change analyses (e.g., MfE 2008) as the “1990s” or the contemporary climate. These values were then modified according to the guidance manual for local government MfE (2008) corresponding to Gisborne (Table 5) for two future periods from 2030-2049 (referred to as the 2040 period) and from 2080-2099 (referred to as the 2090 period). For example, the 215 mm of rain that fell on average during summer from 1980 to 1999 is increased by 3% to approximate the middle-of-the-road projection of precipitation during summer around 2040. Each season is assigned rainfall and temperature changes that are most likely, as well as higher and lower plausible extremes. These extremes represent the uncertainties surrounding the climate change projections.

The rainfall and temperature changes were then combined to determine the corresponding mean seasonal flow, using the model described above. Annual changes were obtained as a weighted average of the seasonal results. For the uncertainty bounds, the wetter and cooler projections were combined together, as were the drier and warmer, in order to represent the worst case range of potential changes. It is likely, however, that the temperature and precipitation changes are correlated, implying that the uncertainty bounds are additionally conservative. The results are reported in Table 6 and in Figure 8.

Table 5. Contemporary conditions and projected changes in rainfall and temperature. Values in square brackets represent the plausible upper and lower uncertainty bounds. Projected changes are from (Ministry for the Environment 2008).

Period	1990		2040		2090	
	Rainfall (mm)	Temperature (°C)	Δ Rainfall (%)	Δ Temperature (°C)	Δ Rainfall (%)	Δ Temperature (°C)
Summer	215	17.4	3 [-26, 33]	1.0 [0.2, 2.6]	5 [-38, 41]	2.2 [0.8, 6.2]
Autumn	298	13.5	4 [-18, 46]	1.0 [0.3, 2.7]	4 [-25, 27]	2.2 [0.6, 5.6]
Winter	321	8.6	-11 [-30, -2]	0.9 [0.1, 2.2]	-13 [-41, 1]	2.0 [0.5, 5.2]
Spring	228	12.4	-9 [-21, 3]	0.8 [0.0, 2.1]	-16 [-42, 7]	1.9 [0.3, 5.2]
Annual	1062	13.0	–4 [–15, 14]	0.9 [0.2, 2.4]	–5 [–22, 8]	2.1 [0.6, 5.5]

Table 6. Contemporary and forecast future mean seasonal and annual flow for the Waipaoa River at Kanakanaia. Values in the square brackets represent plausible upper and lower uncertainty bounds based on regional climate change projections (Ministry for the Environment 2008). The percentage values refer to the change relative to 1990 conditions.

Period	1990	2040		2090	
	m^3/s	m^3/s	% change	m^3/s	% change
Summer	14.2	13.7 [7.6, 20.0]	-3.3 [-46, 41]	12.9 [4.2, 20.6]	-8.7 [-70, 45]
Autumn	28.4	27.6 [18.2, 42. 6]	-3.6 [-36, 49]	25.1 [13.0, 35.7]	-12 [-54, 25]
Winter	51.3	40.6 [26.8, 49.6]	-21 [-48, -3.4]	35.0 [16.2, 48.8]	-32 [-68, -4.9]
Spring	23.2	19.2 [14.3, 24.0]	-17 [-38, 3.5]	15.7 [7.0, 24.4]	-32 [-70, 5.3]
Annual	29.4	25.3 [16.8, 34.1]	-14 [-43,16]	22.3 [10.2, 32.4]	-24 [-65, 10]

The results indicate a decrease in mean seasonal flow for each season; the decrease in summer is small, and the decrease in winter is large. However, the uncertainties around these middle-of-the-road projections can be substantial. For summer, much of the uncertainty bounds include the possibility of an increase in flow, though a decrease is more likely. Autumn exhibits similar results. Spring, on the other hand, appears almost certain to exhibit lower flows, with a projected middle-of-the-road reduction of 33% for 2090 bringing it close to contemporary conditions in the summer. Lastly, all of the projections for winter see a reduction in mean seasonal flow, with middle-of-the-road reductions of 21% and 33% for the 2040s and 2090s respectively.

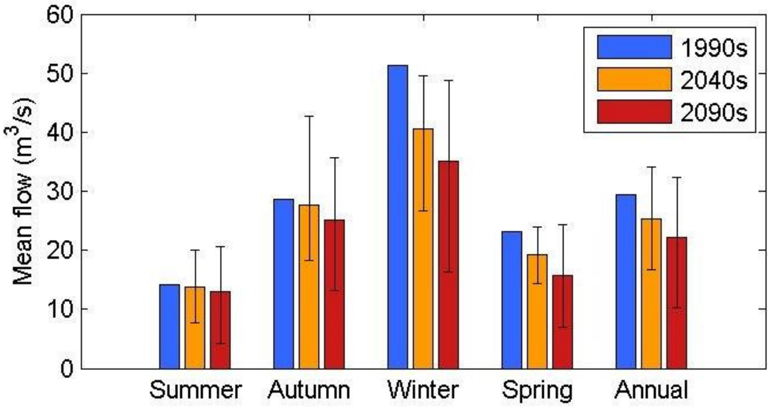

Figure 8. Mean seasonal and annual flow projections for the Waipaoa River at Kanakanaia for 2040 and 2090. The whiskers on the plot show the upper and lower uncertainty bounds, reflecting plausible ranges of future conditions.

3.3.2 Mean annual low flow

To develop projections of mean annual low flow (MALF), the analysis effectively asks: What would MALF have been had the annual low events of the past occurred under climate conditions projected for the future?

To implement this, each annual low flow event for the current period, defined as being from 1980-1999, is first identified. Each of these flows is then scaled by the percent change in mean seasonal flow of the corresponding season, year, and uncertainty bound, as reported in Table 6. For example, the lowest 7-day flow of 1998 was 0.8 m^3/s and occurred in February of that year. Having occurred in summer, this is decreased by 3.3% (see Table 6) to obtain an estimate of the annual low flow in middle-of-the road conditions for 2040. This process is repeated for each year, with the results' average yielding a new MALF for 2040 or 2090, again accounting for uncertainties among the climate simulations. The results are presented in Table 7 and depicted in Figure 9.

These results suggest that MALF is more likely to decrease by 2040, but only slightly. Indeed, the middle-of-the-road projection for MALF in 2040 is still higher than the MALF based on the full flow record (2.25 m^3/s) rather than the 20 years around 1990 (2.45 m^3/s). By 2090, MALF is expected to drop further, but again by a small amount. These changes are on the order of the accuracy of MALF itself. It is also plausible, however, that MALF may increase or decrease substantially. While any increase would bring an increase in water supply, the extreme decreases bring MALF to about a third of what it is now. This would have substantial impacts on the ability to abstract water and nature of the aquatic habitat.

Table 7. Projected effects of climate change on MALF. Changes are relative to the 1980-1999 period and the corresponding mean of the 20 years.

Period	Current	1980-1999	2030-2049		2080-2099	
	m^3/s	m^3/s	m^3/s	% change	m^3/s	% change
MALF	2.25	2.45	2.36 [1.38, 3.50]	-3.4 [-43, 43]	2.21 [0.84, 3.41]	-9.7 [-66, -40]

While these results may paint either a comforting or dire picture of the future, depending on which uncertainty bound is used, it must be stressed that these results are more uncertain than the mean seasonal projections. Indeed, the quantitative advice provided by (Ministry for the Environment 2008) is only made at the seasonal scale, and yet extreme events depend substantially on chance events during the season. Furthermore, the analysis here assumes that the only climatic changes to occur in the future are those that affect average rainfall and temperature. This is unlikely to be the case, with the timing of rainfall events also subject to change.

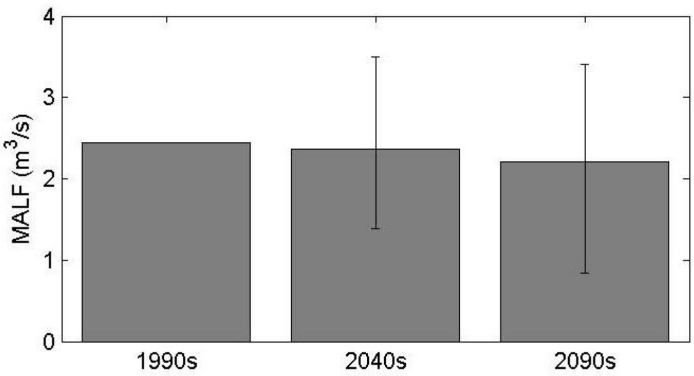

Figure 9. Projections of MALF for the Waipaoa River at Kanakanaia for 2040 and 2090. The whiskers on the plot show the upper and lower uncertainty bounds stemming from GCM model output, reflecting plausible ranges of future conditions.

In light of the projections and the various uncertainties, the best course of action for GDC is to assume no substantial change in MALF, but to review the situation in about 5-10 years once more data have come to light and with more sophisticated models are available, based on improved understanding of the hydrological processes that lead to low flows.

3.4 Discussion

The results reported here point to a likely decline in mean seasonal flows, least so in summer, most in winter, but also critically in spring. MALF is likely to change very little, but could decrease tremendously in the unlikely worst case, or even increase. These results are consistent with the earlier results of (Ministry for the Environment 2008), on which they are based, and (Mullan et al. 2005) and (Clark et al. 2011) with regards to soil moisture drought. The decreases in mean annual flow of 14% by the 2040s and 24% by the 2080s, for the Waipaoa at Kanakania, are also consistent with the results of (Gomez et al. 2009) reported at Matawhero, 40 km downstream: decreases of 13% by the 2030s and 18% by the 2080s.

In order to use these results to best effect, it is important to first appreciate their limitations. The key limitations here are that the models employed are empirical and used only three data sources. The empirical models developed here assume that the hydrological response of the Waipaoa River to seasonal climate patterns will be the same in the future as in the past. This may not be the case, as changing weather systems may alter the timing and intensity of storms. The empirical mean seasonal flow model also represents the hydrological processes in a highly simplified manner. Hence, while the broad hydroclimatic relationships are represented by, a physically based model (e.g., TopNet) would be more accurate. Using more extensive climatic data, either with an empirical or physical model, would also yield more accurate results. Of course, more intensive and extensive modelling would require a greater investment of time, which was outside the scope of the present study.

Much of the uncertainty around the hydrological projections, however, stems not from the hydrological modelling but from the climate modelling and emissions scenarios. Climate models are themselves uncertain, and different climate models can sometimes disagree with one another in terms of the trajectories of climate change. Uncertainty also arises from the emissions scenarios, as we can only have limited knowledge of fossil fuel use, land clearance, and climate change mitigation efforts into the future.

Hence, while the results presented here can give quantitative indications of likely and plausible water resource changes, it is not valid to take any single result (of any model, here or elsewhere) as a precise projection of climate change. Both the central values and their uncertainties must be considered in water resource planning into the future.

It is also import to note that this analysis only considers the supply of surface water. It does not consider groundwater, nor does it consider demand for water (e.g., irrigation, municipal use, industrial use). Climate change is likely to alter groundwater resources, as briefly described earlier in the report, as well as crop irrigation requirements as temperatures increase. It is thus important that climate change impacts on groundwater supply and water demand receive comparable attention as surface water supply. An example of an integrated assessment is given in Aqualinc (2008).

4 Adapting to Changing Water Resources

Having described the potential (projected) implications of climate change for Gisborne District's water resources, it is now important to consider how the various water-related stakeholders may respond, particular the GDC. A range of adaption options are listed below, categorised as being tactical, strategic or transformational, depending on the severity of the anticipated or realised level of climate change.

> **Tactical adaptation** involves modifying existing water resource systems using current practices. They require lower investment and are already well understood, allowing them to be implemented more readily and at shorter notice, however they may not be sufficient to adapt to more than minor climate change.
>
> **Strategic adaptation** involves changes to another known water resource system, or making substantive changes to the current system, where practices and technologies are well known. The cost of strategic adaption is higher than for tactical, but it has a greater ability to respond to a higher level of climate change.
>
> **Transformational adaptation** involves innovation to develop completely new water resources systems. Such adaptation is the least well understood, the highest risk, the most expensive, and the slowest to implement. It may become necessary only under severe climate change.

The specific adaptation options, listed in Table 8, apply variously to all stakeholders, including water resource managers and urban and rural water users.

Of the adaptation options available to regional resource managers, developing policies that reflect the realities and threats of climate change is the most important. Water resource planning will have to accommodate both greater uncertainty and shifting baselines (Kundzewicz et al. 2007), however for long planning horizons it is also very important to distinguish between natural climate variability (e.g., ENSO, IPO) and climate change in order to avoid maladaptation while also accommodating natural extremes.

Several planning methods that may prove useful in this regard are adaptive management, traditional scenario planning, classic decision-making, robust decision-making, and portfolio planning (Bates et al. 2010, Miller et al. 1997, Waage & Kaatz 2011). Adaptive management comprises management activities that change as new data come to light. Traditional scenario planning seeks to identify short-term actions that address a range of plausible future outcomes. Classic decision-making follows a cost-benefit-like process whereby each plausible outcome is assigned a cost and benefit, and the greatest net benefit when integrated over the range of possibilities is deemed the best strategy. Lastly, robust decision-making mixes scenario planning with classic decision-making by developing a suite of options that are robust to uncertainties but are tailored to seek the maximum net benefit. Which method is most suitable will depend on the nature of the risks and the level of certainty associated with the projections – there is no one-size-fits-all method.

In the case of water allocation, managers theoretically have several options available to them, beyond simply doing nothing. Minimum flows and allocation limits may be updated every 10 years (or when important information comes to light), or they may be made more conservative in the anticipation of declining availability. In setting the duration of water take consents, resource managements may carefully consider the timeframe over which water resource changes may occur under climate change and be detected. The 5-year duration granted at present allows ample time for managers and users to adapt in a timely manner.

Table 8. Options to adapt to changing water resources in Gisborne District.

Tactical	Strategic	Transformational
• Identify thresholds for communities, ecosystems and production systems • Shift cropping and grazing calendars • Change crop varieties • Conservation agriculture • Improve soil nutrient management • Increase irrigation and small-scale and large-scale water storage • Irrigation efficiency • Reduce erosion and freshwater contamination • Avoid salinisation of groundwater • Change stock numbers • Review existing infrastructure in terms of climate change projections • More efficient water resource management	• Change crop species • Develop new crop genotypes • Precision agriculture • Develop monitoring and forecasting programmes for water supply and use • Expand and improve access to irrigation • Reduce the extent of taller vegetation in water-short areas • Offset groundwater abstraction with artificial groundwater recharge • Foster collaborative water resource planning and use • Incorporate climate change risks into resource and hazard management • Incorporate climate change risks into new and existing infrastructure • Urban water re-use • Research and development	• Improve crop uptake and conversion efficiency potentials • Move to different land uses • Control urban and industrial expansion • Re-evaluate the societal values behind water allocation • Inter-regional water transfers • Research and development

Should severe adverse climate change occur, in which Gisborne District's water resources become greatly disrupted to the extent that the lower projections in Figure 8 and Figure 9 are realised, it will likely become necessary to re-evaluate the societal drivers behind water allocation decisions (Miller et al. 1997). This may mean a shift away from either water-dependent economic production or from water-dependent environmental and cultural protection.

5 Next steps

In light of the existing knowledge of climate change impacts on Gisborne District's water resources, the various knowledge gaps, and the relative importance of different water resources to the region, this report makes several recommendations to help identify "next steps" in the climate change impact assessment process:

- Assess the potential changes to groundwater recharge for important aquifer systems (e.g., Poverty Bay Flats) under a range of climate change projections;
- Develop plausible scenarios of changes in freshwater demand (e.g., irrigation, domestic use, industrial use) in coming decades;
- Make an integrated assessment of how to manage changes in water demand and changes in supplies of surface water and ground water,
- Conduct more detailed modelling of river flow behaviour under climate change, with an emphasis on low flows;
- Conduct a preliminary assessment of the potential for groundwater salinisation with sea-level rise.

6 Conclusions

For Gisborne District, climate change is likely to have a range of effects on freshwater resources, most likely a reduction in water resources. Furthermore, while knowledge gaps remain, the anticipated changes are large enough to warrant consideration in the drafting of the regional plan for freshwater management.

With regards to the National Policy Statement for Freshwater Management, the reasonably foreseeable impacts of climate change on freshwaters are:

- Hydrological conditions that are different from the past;
- Water resources that are more variable and harder to predict;
- Less rainfall in the wetter winter-spring period (due to stronger westerlies), and slightly more rainfall in summer and early autumn (weaker westerlies);
- Higher temperatures throughout the year;
- More time spent in drought;
- Greater crop water requirements;
- A general decline in surface water supply, least pronounced in summer and most pronounced in winter;
- Floods that are more extreme when they do occur;
- Slightly lower average annual low flows, though the decreases are too small to warrant any changes in planning at this stage; and
- Reduced groundwater recharge from land, though river-based recharge is not likely to change.

Adaptation options available to water stakeholders, users and managers alike, include:

- More efficient use of water;
- Either a reduction in water use and/or an increase in water supplies
- Better use of short- and medium-term forecasting of water supply and demand; and
- Water resource planning methods that account for both the uncertainties and the trends associated with climate change, such as adaptive management and scenario planning. In terms of setting limits, results presented in this study suggest:

    a. No change in MALF-based minimum flow setting until more information comes to light (revisit in 5-10 years' time); and

    b. A possible reduction in non-summer water allocation caps.

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