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Assessing the effects of climate change on water resources: the Waimea Plains

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Abstract

Climate change has the potential to cause a variety of effects on water resources. It is necessary to assess the potential effects of climate change on hydrologic systems to provide the information needed to develop rational management strategies to cope with such change. This paper reports on a case study of the Waimea Plains catchment located in the Tasman region, South Island, New Zealand. Two methods were used to assess the effects of climate change: (1) trend analysis of historic climate and hydrologic data from routine monitoring systems using the Mann-Kendall method; and (2) modelling of projected effects as a result of standard greenhouse gas emissions scenarios. Trend analysis results were mixed. Statistically significant trends were noted for some climate and hydrologic variables but not others. Modelling started with regionally downscaled climate projections based on the IPCC A1B and A2 emissions scenarios. Modelling projections focused on downstream Waimea River flow and groundwater levels for the critical dry period of a record drought year. Both mechanistic computer modelling (MODFLOW) and artificial intelligence modelling were used. Key inputs for this model, such as rainfall recharge, were obtained from artificial intelligence modelling. Artificial intelligence modelling was also applied directly to project stream flow and groundwater levels. Modelling results were similar for both mechanistic and artificial intelligence models. Water usage increased but the decrease in rainfall recharge of groundwater was largely made up by increased stream recharge. The net result was substantial impact on stream flow but only minor effects on groundwater levels. Recommendations from this study include improved routine monitoring of hydrologic variables and expanded modelling efforts in other catchments under a wide variety of hydrologic and climate change conditions.

Keywords

Climate change, assessment, hydrologic systems, trend analysis, Mann-Kendall, groundwater modelling, artificial intelligence modelling

Introduction

Climate change is affecting and will increasingly affect both the quantity and quality of the world's water resources in a variety of ways. On a global basis, warming climate is expected to result in increased evapotranspiration and atmospheric water vapour, producing increased rainfall, surface runoff, stream flow, groundwater recharge, and rising groundwater levels. However, rainfall may decrease in some areas, meaning less stream flow and, coupled with evapotranspiration, declines in groundwater recharge and levels. Climate change is also expected to increase the number and intensity of extreme climate events, with related hydrologic changes. Water quality is described by a number of variables. Some of these are directly impacted by climate change. For example, increased atmospheric concentrations of CO_2, believed to be a major factor in recent global warming, also produce increased concentrations of CO_2 dissolved in water. This has manifold consequences, including decreased ocean pH and alkalinity (Intergovernmental Panel on Climate Change (IPCC)), 2007; Bates *et al.*, 2008). However, studies of seasonally oscillating subsurface processes at a research site in Kansas indicate that increases in the levels of groundwater dissolved CO_2 there are 'partially accommodated by net weathering of limestone'. The resultant 'alkalinity and associated cations from mineral dissolution' may 'persist in groundwater, which is discharged to streams and to deeper aquifers,' corroborating 'increasing alkalinity in the Mississippi River,' as reported by Raymond and Cole (2003) (Macpherson *et al.*, 2008).

Current climate variability can produce floods and droughts which affectwater resources management. Climate change will produce changes in hydrologic characteristics that can be expected to alter the reliability of water management systems and related infrastructure to a greater degree in the future than in the past, requiring adaptation if we are going to be able to cope with these changes. This demands improved assessment of relevant observational data and modelling of the impact of climate change on hydrologic systems at scales relevant to decision making (Bates *et al.*, 2008).

'Estimating the possible impacts of climate change on water resources represents one of the most difficult challenges faced by water managers' and has led to much recent study and several publications on the topic. However, 'most of these studies focus on surface water and generally oversimplify or even neglect groundwater' (Goderniaux *et al.*, 2009). Earman and Dettinger (2011) also indicate that there are 'few available predictions of the impact of climate change on groundwater systems.' Similarly, despite the importance of groundwater in New Zealand, there has been little study of the potential effects of climate change on groundwater systems in this country. Of the consents issued by regional councils to take water for consumptive purposes (i.e., not including hydro power), 68% are for groundwater, about 34% of the consumptive volume allocated (Rajanayaka *et al.*, 2010). Nevertheless, it was concluded in a recent review of climate change implications for New Zealand hydrology that with respect to this topic 'groundwater is severely understudied' (Collins *et al.*, 2011).

This paper reports on research conducted to assess the potential effects of climate change on hydrologic systems in the Waimea Plains catchment in New Zealand, with emphasis on the groundwater system. Projected impacts of climate change on water resources in New Zealand in general, as delineated by Mullan *et al.* (2008), are summarized in Table 1.

Two general approaches were used in this assessment: (1) analysis of historic monitoring data to determine existing trends; and (2) hydrologic modelling to explore future scenarios. Information on the study area will be presented first, followed by a description of methods used, presentation of results, and

Table 1 – Potential effects of climate change on New Zealand water resources[1]

Resource	Potential Effect
Rivers	River flows likely to increase in west and decrease in east. More intense precipitation events likely to increase flooding (by 2070 could be up to a fourfold increase in the frequency of heavy rainfall events). Less water for irrigation in northern and eastern areas. Increased problems with water quality.
Lakes	Lake levels likely to increase in western and central parts of New Zealand and decrease in some eastern areas. Higher temperatures and changes in rainfall could result in a range of effects, including: 1. Increased eutrophication; 2. Alteration of lake margin habitat; 3. Negative impacts on aquatic macrophytes; 4. Decrease in range of trout; and 5. Increase in range of pest species.
Wetlands	Coastal and inland wetlands likely to be adversely affected by increases in temperature, increases/decreases in rainfall, and sea level rise.
Groundwater	Little change to groundwater recharge is expected in eastern New Zealand, where increased demand for water is likely. Some localised aquifers in northern and eastern regions could experience reduced recharge.
Water Quality	Reduced rainfall and increased temperatures could have significant impacts on the quality of surface water resources in northern and eastern New Zealand. Lower stream flows or lake levels would increase nutrient loading and lead to increased eutrophication.

[1] From: Mullan *et al.* (2008).

finally a summary of results, conclusions, and recommendations.

Waimea Plains catchment study area

The Waimea Plains (Fig. 1) is located on the northern tip of the South Island of New Zealand near the communities of Nelson and Richmond. Climate change projections indicate this catchment is likely to experience only relatively minor changes in temperature and rainfall. Based on the average of 12 global circulation models (GCMs) using the "middle of the road" A1B emissions scenario for the nominally 50 and 100 year periods beyond 1990, projections indicate approximate temperature increases of 0.9 and 2.1°C and precipitation increases in the ranges of 0 to 2.5% and 2.5 to 5%, respectively (Wratt and Mullan, 2008). These projected changes are among the lowest for any region in New Zealand. Major factors in selecting this catchment for study were the existence of both relevant data and a functional groundwater-river interaction model. Furthermore, if effects were found to be likely in this case, they would be even more likely in other regions where projected climate changes are greater.

Two rivers flow into the Waimea Plains: the Wairoa River from the mountains to the east and the smaller Wai-iti River from the south. These two rivers combine to form the Waimea River. The flow of the Wai-iti River is much less than that of the Wairoa River and during warm weather the Wai-iti River frequently becomes dry. For example,

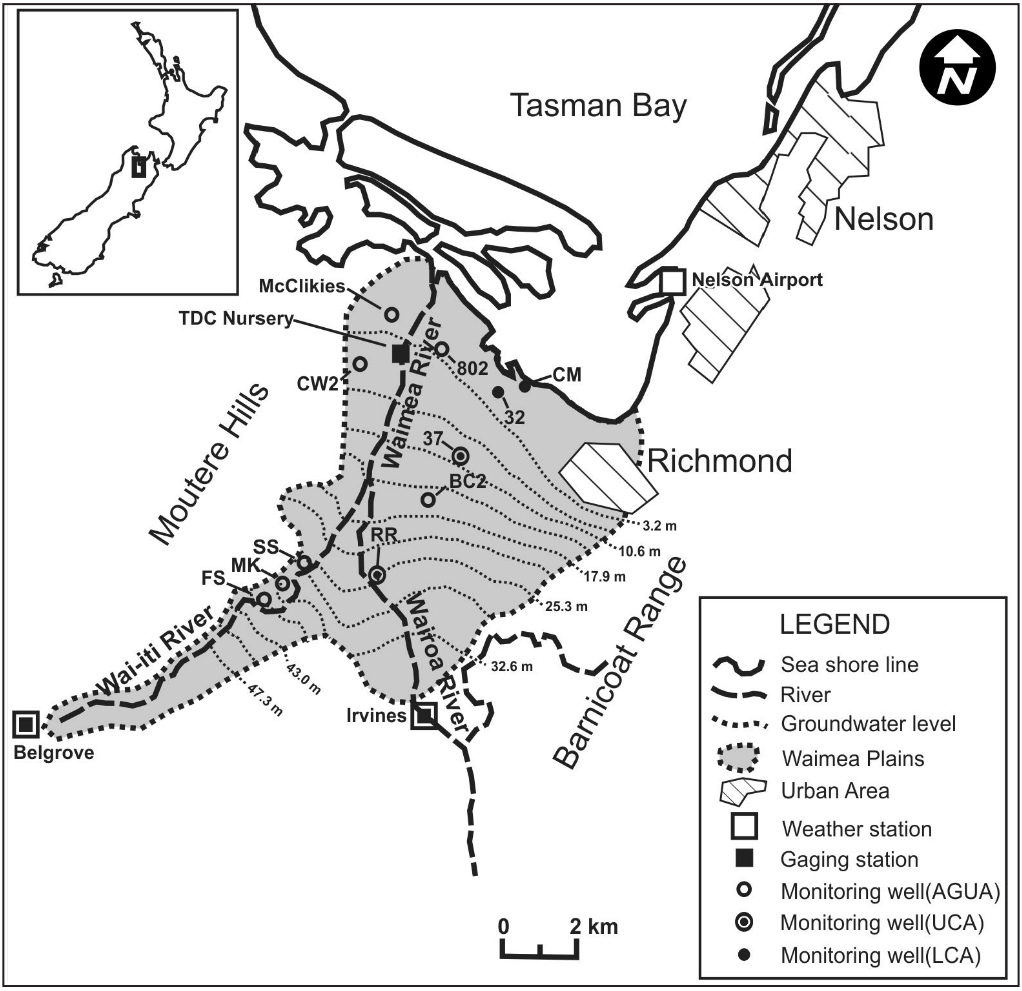

Figure 1 – Waimea Plains study area

during the record drought of 2001 it was dry at Livingston (immediately prior to joining the Wairoa River) from 8 February through to 5 May 2001 (M. Doyle, Tasman DC, pers. comm.). With respect to groundwater, there are three identified aquifers underlying the Waimea Plains. These are the shallow Appleby Gravel unconfined aquifer (AGUA), an upper confined aquifer (UCA), and an underlying lower confined aquifer (LCA). The locations of these aquifers are progressively displaced to the east with depth (Dicker *et al.*, 1992).

Methods

Trend analysis of historic data

Historic data were assessed through compilation of long-term climate and hydrologic monitoring data from existing databases and analysis using the non-parametric Mann-Kendall method with Sen's slope indicator.

Detection of climate change effects requires relevant long-term data. It is important that such data be routinely collected and of high quality. A survey was conducted in late-2009 to identify all historic and current climate and hydrologic monitoring programs and relevant databases available from them within New Zealand. This survey included national institutes, notably the National Institute for Water and Atmospheric Research (NIWA) and the Institute of Geological and Nuclear Sciences (GNS Science), and all 16 regional authorities in New Zealand. The variables being monitored and the number of stations involved at the time of the survey are listed in Table 2.

The numbers for national and regional stations in Table 2 are mutually exclusive. Therefore, for example, the national total would be 645 stream flow gaging stations and 1,130 groundwater wells being sampled for water quality. These numbers are continually changing and Table 2 can be viewed only as snapshot in time. In general, the numbers of surface water stations and groundwater wells involved in these monitoring programs have been increasing over the last 20 years.

There are other hydrologic databases relevant to climate change not listed in Table 2 because they were not pertinent to the circumstances of the Waimea Plains study

Table 2 – Number of climate and hydrologic monitoring stations in New Zealand[1]

			Waimea Plains[5]	
Type Monitoring	**National[3]**	**Regional[4]**	**National[3]**	**District[5]**
Climate[2]				
Rainfall	>140	647	3	7
Other meteorological variables	>140	88	3	0
Surface Water				
Streamflow	130	515	0	4
Stream stage only	0	318	0	0
Lake level	0	16	0	0
Spring flow	0	7	0	0
Stream water qualitiy	77	782	0	4
Groundwater				
Groundwater levels	0	1740	0	9
Groundwater quality	110	1020	3	0
Soil moisture	60	54	0	0
Rainfall recharge lysimeter	0	7	0	0

1 Information obtained from survey of all 16 regional authorities in New Zealand.
2 National climate database maintained by NIWA (http://cliflo.co.nz). Contains historic and current data for over 6,500 stations operated for various periods of time since 1850 at locations throughout New Zealand. The New Zealand national weather service (MetService) makes hourly weather publicly available from over 40 stations around the country (Met Service, 2011). NIWA has hourly climate data for over 140 stations and daily climate data for over 500 stations (J. Schmidt, NIWA, pers. comm.).
3 'National' means from databases maintained by Met Service and NIWA (climate), NIWA (surface water), and GNS Science (groundwater).
4 Combined number of stations for all 16 regional authorities (including district councils with unitary authority such as TDC).
5 Stations located within the Waimea Plains study area. Note that there are no 'national' stations for surface water monitoring (only those maintained and operated by TDC) and that the only sampling for groundwater quality is through the GNS Science NGMP programme. The Livingston stream flow case and water quality sampling station, and the Redwood Lane monitoring well are not shown in Figure 1. Groundwater levels are not routinely reported for three NGMP wells shown in Figure 1 (32, 37 and 802).

area (e.g., monitoring the extent and volume of glaciers and open coast monitoring of sea level). There was once a national lakes database maintained by NIWA; however, it was discontinued in the mid-1990s as an economy measure (J. Schmidt, pers. comm., 2010). Variables monitored in water samples from surface waters (a small set of contaminant-related variables) are much more limited than from groundwaters and there is little overlap. Only three of the 16 regional councils analyse surface water samples for major ions. This essentially precludes comparisons between surface waters and groundwaters and handicaps evaluation of surface water quality data for potential climate change effects.

Climate and hydrologic data tend to have considerable natural variability. It is also evident that the data stored in these databases are of uneven quality. The authors are most familiar with groundwater level and quality databases in New Zealand. In general, there have not been national guidelines requiring data quality assurance programs for these and the various regional authorities making field measurements and taking samples have been left to their own devices. Efforts have been made to remedy this situation. Notably, a national protocol for groundwater sampling was developed in 2006 (Daughney *et al.*, 2006). However, when rigorous evaluations of these databases are conducted, anomalies indicating either errors in field procedures and/or laboratory analysis or data entry errors are often encountered. Additionally, unexplained data gaps are also seen. All of these circumstances reduce the ability to determine with confidence what trends are actually occurring.

The numbers of national and district databases for stations within the Waimea Plains are listed in Table 2. Data for these stations were obtained from GNS Science, NIWA, and Tasman District Council (TDC) and analysed for trend using the non-parametric Mann-Kendall method with Sen's slope estimator. This non-parametric approach is well-suited for analysis of time series climate and hydrologic data and is widely used for that purpose because such data are frequently skewed, have outliers, and may not be normally distributed (Helsel and Hirsch, 2002; Roxana, 2010). Nevertheless, the direction of the trend and its slope are frequently consistent with results obtained using parametric linear regression. Because the Mann-Kendall method is intended to detect monotonic trends, prudent evaluation of the nature of time series data is necessary before trying to apply it, as the Mann-Kendall method is not suitable for data that are not monotonic in nature (Helsel and Hirsch, 2002; Roxana, 2010).

Projecting future hydrologic effects of climate change

Computer modelling provides the ability to simulate climate change scenarios and their effects on hydrologic systems. The predictive ability of such modelling is, of course, restricted by the limitations of computer modelling in general (Bader *et al.*, 2008; Praveena*et al.*, 2010; Nilsson *et al.*, 2006). We don't fully understand all of the processes we attempt to model either in general or for the specific area involved. We also don't have comprehensive or perfect data and are forced to model under a level of substantial uncertainty. However, computer modelling currently provides the best and most rational way to comprehensively evaluate all of the information we have and to better understand system relationships.

Goderniaux *et al.* (2009) have pointed out, with regard to climate change modelling of surface and subsurface hydrologic systems, that 'a reliable estimate of groundwater recharge is needed because it represents the connection between atmospheric and surface-subsurface processes and is therefore a key element in the context of the impacts of climate change on groundwater'. Rainfall recharge was modelled using two different approaches in this study.

Computer modelling was conducted for the Waimea Plains area by sequentially using a variety of models.

NIWA provided regionally downscaled modelling results for two emissions scenarios (A1B and A2). The American GFDL CM2 and Japanese Miroc 3.2 GCM, respectively, were used for these two scenarios (J. Schmidt, NIWA, pers. comm. and climate change emission scenario projections, 2010). These results were provided as daily temperature and rainfall.

Data-driven artificial intelligence (AI) modelling was used to develop relationships from historic data and then to provide projected results for the following variables under climate change conditions:

- Water usage – a multi-layer perceptron (MLP) trained neural network with an extended Kalman filtering (EKF) learning algorithm was applied;
- Groundwater rainfall recharge – genetic programming (GP) was applied to each of the three classifications of soils (based on water holding capacity) identified in the Waimea Plains (i.e., soil textures with 38, 78, and 130 mm plant-available water) using the same model developed by Hong et al. (2005) for similar soils in the Christchurch area;
- Wairoa River flow at Irvines (the main upstream flow of the Wairoa River which also provides recharge to Waimea Plains groundwater) – a dynamic neuro-fuzzy local modelling system (DNFLMS) was applied in the same manner as shown by Hong and White (2009). Wai-iti River flow was considered negligible and was not included in the model;
- Waimea River flow at the TDC Nursery location (downstream flow from the Waimea Plains, Fig. 1) – DNFLMS was applied; and
- Groundwater level at the McCliskies well (shallow downstream well in the Waimea Plains, Figure 1) – DNFLMS was applied.

The soil water balance model SOILMOD was also used to predict groundwater recharge. These results were compared to results from the GP model noted above. SOILMOD has been found to be consistent with actual lysimeter data in the past (Thorpe and Scott, 1999), but more recent work has found that GP modelling provides more reliable estimates of rainfall recharge than soil water balance models (White *et al.*, 2003; Hong *et al.*, 2005).

The mechanistic U.S. Geological Survey (USGS) MODFLOW groundwater flow model (Hong and Zemansky, 2009) was used to simulate groundwater-surface water interactions, with the primary outputs being Waimea River flow at the TDC Nursery location and groundwater levels at the McCliskies well (both on the down-gradient end of the Waimea catchment). The model was run in a one-year transient mode with a daily time step. A finite difference groundwater flow model was first produced for the Waimea Plains in the 1980s using a USGS code that predated MODFLOW (Fenemor, 1989). GNS Science updated this model to MODFLOW in the late 1990s (White and Murray, 1998) and further improved and updated it on several occasions over the following 10 years. After updating, it was recalibrated to reproduce downstream Waimea River flow and groundwater levels at two monitoring well points (Hong and Zemansky, 2009). AI modelling results for water usage, groundwater rainfall recharge, and Wairoa River flow at Irvines were used as inputs to the MODFLOW model. MODFLOW model results for Waimea River flow at the TDC Nursery location and groundwater levels at the McCliskies well were compared to results from DNFLMS modelling.

NIWA provided a historic data set (1972-2009) and projections for each of two emissions scenarios over two climate change time frames nominally centred on 2040 and 2090 (50 and 100 years, respectively, beyond 1990). The emissions scenarios were the "middle of the road" A1B scenario and the "divided world" A2 scenario (projecting greater greenhouse gas emissions and resultant temperature rise). For each scenario, 37 years of projected daily rainfall and minimum and maximum temperatures were provided (2030-2066 and 2080-2116). It was determined through review of these projections that the July 2058-June 2059 year was equivalent to the July 2000-June 2001 year, the drought year of record for the Waimea Plains, with the only difference being the impact produced by climate change. Therefore, modelling focussed on arriving at projections for the July 2058-June 2059 year and comparing them with actual data for the historic July 2000-June 2001 year. In most cases, the comparison was made for the critical warm and dry period of the year of 21 February-21 April. Project time and budget constraints precluded additional modelling.

Table 3a – Trend analysis results – trend indication (# of stations)

	Trend Analysis Result				
			Trend[5]		Earliest
Type Monitoring	**National[3]**	**TDC[4]**	**INCR**	**DECR**	**Data**
Climate					
Temperature (mean annual)	3	0	3	0	1944
Rainfall (annual total)	3	7	3	6	1941
Evaporation[1] (annual total)	2	0	5	0	1949
Solar radiation[2] (main daily/yr)	3	0	–	–	1969
Sunshine hours (annual total)	1	0	1	0	1949
Relative humidity (mean daily/yr)	4	0	3	1	1962
Cloud cover (mean daily/yr)	2	0	0	1	1940
Surface Water[6]					
Streamflow (annual total from daily measurements)	0	4	0	2	1958
Stream water quality (monthly samples)	0	4	6	2	1999
Groundwater[7]					
Well water level measurements (monthly)	0	10	4	6	1975
Well water quality samples (quarterly)	3	0	1	1	1975

1 Evaporation data of four types exists: (1) raised pan; (2) Penman; (3) Priestley-taylor PET; and Penman open water.
2 'Yr' means year. No trend is indicated for solar radiation because the plot was not monotonic (see Figure 3).
3 'National' means from database maintained by NIWA (climate and surface water) or GNS Science (groundwater).
4 TDC means from databases maintained by Tasman District Council (as regional council authority).
5 Trend as determined by Mann-Kendall method. "INCR" and "DECR" means indication of increasing or decreasing trend whether the trend is statistically significant or not. For some variables there were fewer trends than stations because of insufficient data for analysis (e.g., rainfall at the TDC Nursery station) or because no trend was found (e.g., cloud cover). For other variables, there were more trends than stations because the variable was measured or reported more than one way at the same station (e.g., evaporation).
6 Trend results for surface water quality are the number of variables for which there was a trend (see Table 3b for additional detail).
7 Trend results for groundwater quality are the number of wells having trends (see Table 3b for additional detail).

Results

Trend analysis of historic data

Results of trend analysis for historic climate and hydrologic data for the Waimea Plains catchment are summarized in Table 3 (parts a and b).

A trend was considered statistically significant at or below the 5% level and weakly significant in the greater than 5% to less than or equal to 10% range. For the most part, results were either statistically significant or not and there were few weakly significant

Table 3b – Trend analysis results - trend indication

Type Monitoring	Slope	Trend Units	Stat Sig[3]	Remarks
Climate				
Temperature (mean annual)	0.02-0.03	oC/Yr	3 of 3	Slopes for longest two records.
Rainfall (annual total)	-12.37	mm/Yr	1 of 9	Slope for only station with statistically significant results.
Evaporation[1] (annual total)	1.5-7.0	mm/Yr	4 of 5	4 different measures at 1 station with 5-18 years missing data.
Solar radiation[2] (main daily/yr)	–	–	–	DECR to 1989, INCR thereafter (mixed data from 2 stations at same airport).
Sunshine hours (annual total)	3.0	hours/Yr	–	Overall INCR but similar to solar radiation data with DECR to 1989 and INCR thereafter.
Relative humidity (mean daily/yr)	0.17-0.47	%/Yr	2 of 4	INCR statistically significant, DECR not statistically significant.
Cloud cover (mean daily/yr)	-0.17	oktas/Yr	1 of 2	No trend at station with longest record.
Surface Water				
Streamflow (annual total from daily measurements)	-0.02 to -0.06	m3/sec per Yr	2 of 2	No trend for Wairoa River (longest record), record too short for Waimea River at TDC Nursery
Stream water quality (monthly samples)	–	–	–	Wairo River (INCR NO3-N and DRP), Wai-iti River (INCR pH and T with DECR flow adjusted conductivity), Waimea River (INCR flow adjusted conductivity and NO^3-N, DECR DRP).[4]
Groundwater				
Well water level measurements (monthly)	-43 - 17	mm/Yr	6 of 10	Shallow wells: 4 INCR and 4 DECR; Deep wells 2 DECR (no change for UCA wells).5
Well water quality samples (quarterly)	–	–	–	No change for shallow wells, DECR levels for UCA, INCR levels for LCA.[5]

1 Evaporation data of four types exists: (1) raised pan; (2) Penman; (3) Priestley-Taylor PET; and Penman open water.
2 'Yr' means year. No trend is indicated for solar radiation because the plot was not monotonic (see Figure 3).
3 Trend statistically significant or not ('Stat Sig') at 95% confidence level (P=0.05).
4 Variables listed are: (1) dissolved reactive phosphorus ('DRP'); (2) nitrate-nitrogen ('NO^3-N'); (3) pH; and (4) temperature (T).
5 'UCA' and 'LCA" mean upper and lower confined aquifer, respectively

ones. The clearest statistically significant trends found from the historic data were as follows:

1. Climate:

a. Increasing temperature;
b. Increasing evaporation;
c. Increasing sunshine hours;
d. Increasing relative humidity; and
e. Decreasing cloud cover.

2. Surface water:

a. Decreasing flow at two stations on the Wai-iti River (no trend was found for Wairoa River flow and there were insufficient annual data to analyse for Waimea River flow trends);
b. Increasing flow-adjusted NO_3-N and DRP levels in the Wairoa River;
c. Decreasing flow-adjusted conductivity at one station in the Wai-iti River; and
d. Increasing flow-adjusted conductivity and decreasing flow-adjusted DRP levels in the Waimea River.

3. Groundwater:

a) A split for shallow wells with water levels increasing in two and decreasing in two of a total of eight wells in the Appleby Gravel unconfined aquifer (AGUA).There were no statistically significant trends for the other four shallow wells.
b) Water levels decreasing in all deep wells;
c) Decreases in levels for 10 of 21 water quality variables (including conductivity, pH, NO_3-N, and most major ions) in the mid-depth well but no trend for other variables;
d) Increases in levels for seven of 21 water quality variables (ammonia-nitrogen, conductivity, and most major ions) in the deepest well but no trend for other variables; and
e) No water quality trends for the shallow well except a weakly significant increase in conductivity).

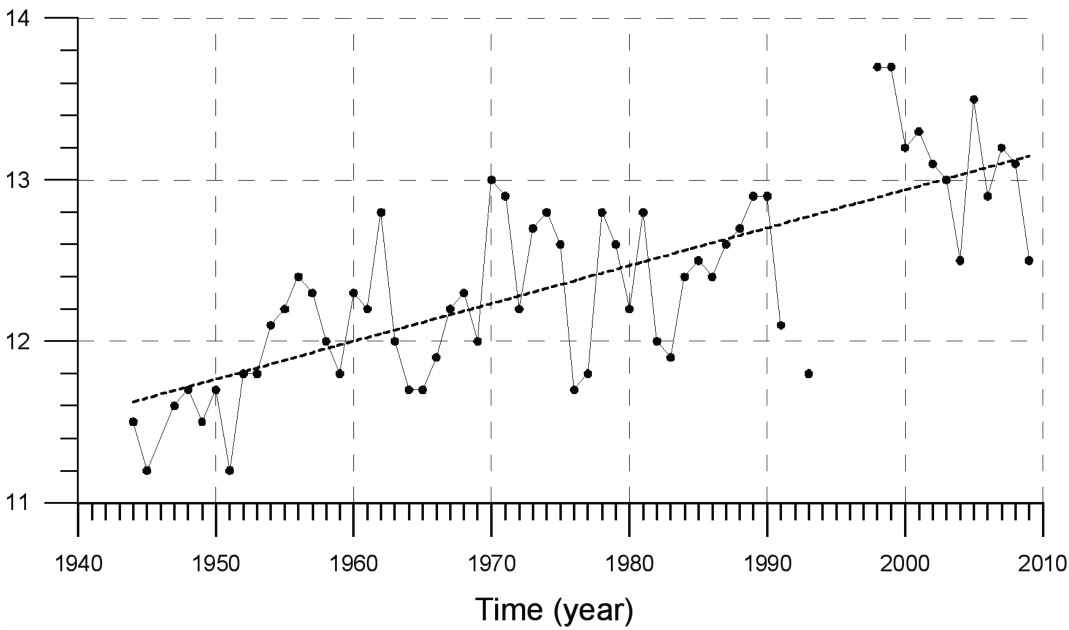

Figure 2 – Time series plot and trend – air temperature at Nelson Airport

A time series plot of mean annual air temperature data at Nelson airport (see Fig. 1, upper right) with a linear regression line showing the increasing trend confirmed by Mann-Kendall analysis is presented in Figure 2. This plot also illustrates the existence of data gaps in the record. Data is incomplete for five years in the 1990s of the 65-year record starting in 1944. It should be noted that slopes for the trend line determined by linear regression and by the Sen's slope estimator in combination with the Mann-Kendall method were very similar (0.0234 and 0.0239°C/year, respectively).

A time series plot of mean annual daily solar radiation data at Nelson airport is shown in Figure 3. This plot illustrates the need to use caution in evaluating trends. Analysis of all of the data for the 41-year period of record (starting in 1969, with data missing for two years in the mid-1980s) would indicate a small, but not statistically significant,

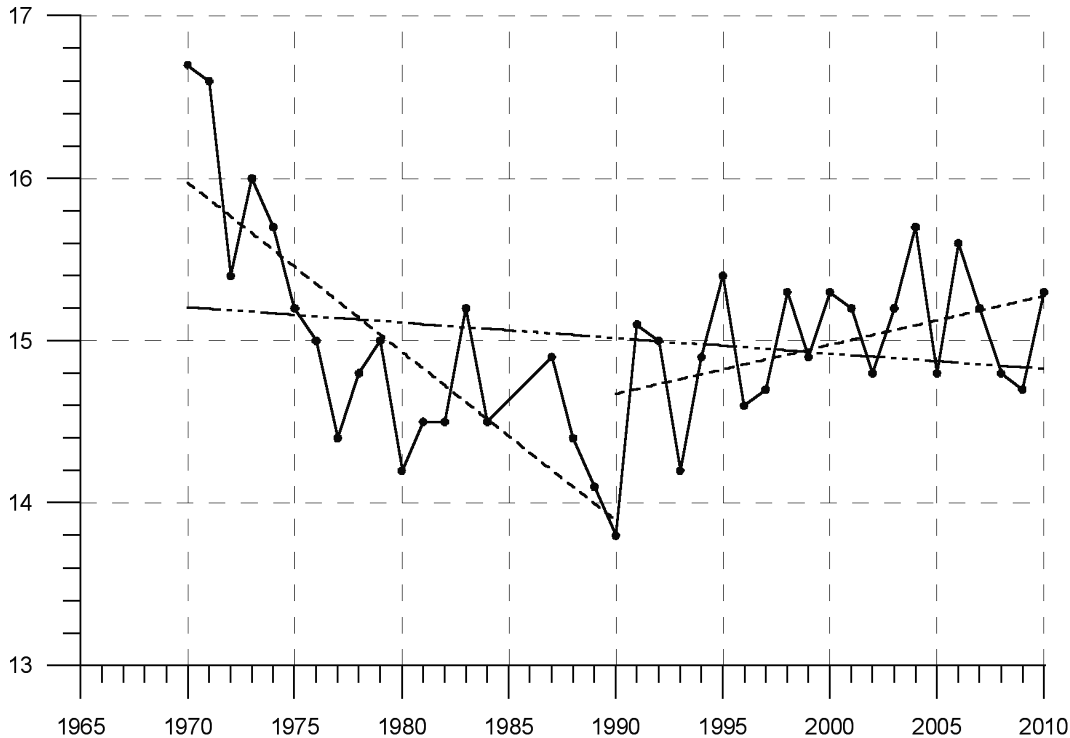

Figure 3 – Time series plot and trends – solar radiation at Nelson Airport.

decreasing trend. However, visual inspection of the data indicates they are not monotonic in nature. The decreasing trend is only for the early period ending with 1989. When these data (i.e., 1969-1989) were analysed separately, this decreasing trend was found to be statistically significant. Thereafter, there appears to be an increasing trend, although it was not statistically significant. This pattern is consistent with the trend generally seen elsewhere in the world (Wild *et al.*, 2005; Trenberth *et al.*, 2007; Science Daily, 2009).

A time series plot of the mean monthly groundwater level for the shallow AGUA McCliskies well near the coast of the Waimea Plains is shown in Figure 4. This plot shows

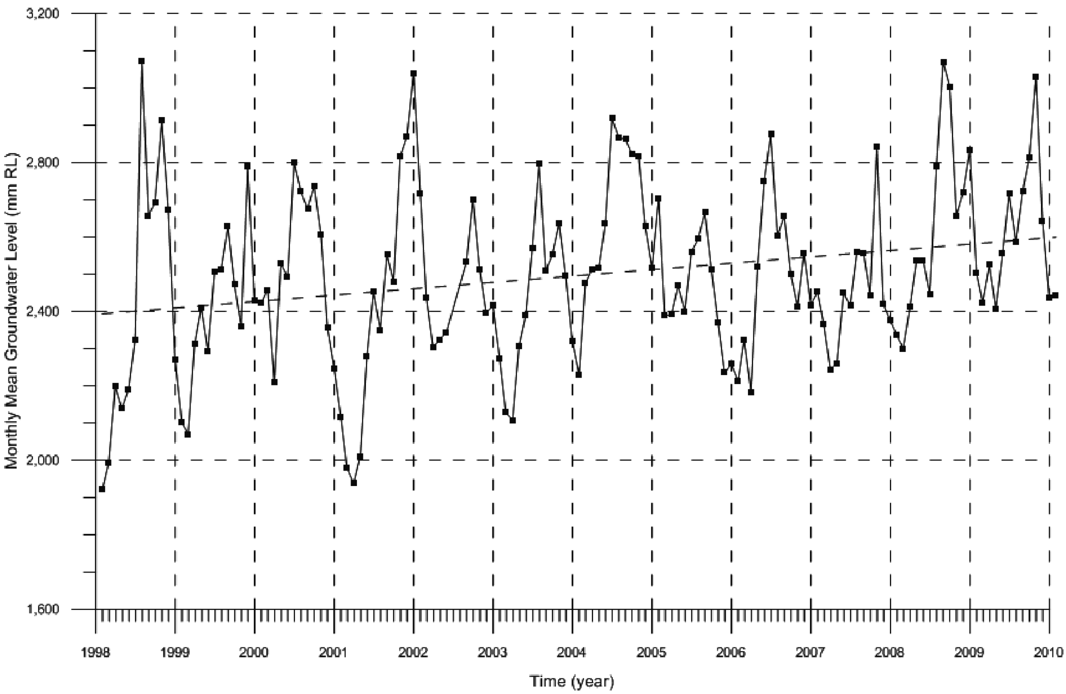

Figure 4 – Time series plot and trend – groundwater level at a shallow Appleby Gravel unconfined aquifer (AGUA) well near the coast

the typical seasonal pattern of groundwater levels for many parts of New Zealand, with higher winter and lower summer levels. It also shows an overall rising trend on the order of 17 mm/year. This well could be influenced by sea level change. This direction of change is consistent with that possibility, but is at a much higher rate than the roughly 2 mm/year expected for current sea level rise from climate change (Mullan*et al.*, 2008).

Projecting future hydrologic effects of climate change

Key modelling results for the July 2058-June 2059 year were compared with the historic July 2000-June 2001 drought year. The outcome of this comparison is summarised in Table 4 (parts a and b) and as follows:

1) Water usage – there was a projected increase in water usage during the critical 21 February-21 April period of drought in 2059 compared to what it was in 2001. Projected increases were 13% and 18% for the A1B and A2 emissions scenarios, respectively.
2) Groundwater rainfall recharge – there was a projected decrease in groundwater rainfall recharge for the entire 1 July 2058-30 June 2059 year compared with the historic 1 July 2000-30 June 2001 year. Projected decreases by GP modelling were 10% and 18% for the A1B and A2 emissions scenarios, respectively. SOILMOD also projected decreases in groundwater rainfall recharge; however, it projected much larger decreases of 14 and 30%, respectively.
3) Wairoa River flow at Irvines – there were only minor changes calculated in meanWairoa River flow at Irvines during the critical 21 February-21 April period of drought projected for 2059 compared to what it had been in 2001 and these changes were in opposite directions.

Table 4a – Modelling results – annual basis

Water Year Period of July-June Rainfall Recharge (mm)					
Year	**Emissions Scenario**	**GP**	**%DECR**	**SOILMOD**	**%DECR**
2000-2001	Historic	400	–	619	-
2058-2059	A1B	361	10	530	14
2058-2059	A2	327	18	434	30

Waimea River at TDC Nursery[1] Low Flow (<100 L/sec)			
Year	**Emissions Scenario**	**Days**	**%DIFF**
2000-2001	Historic	18	-
2058-2059	A1B	27	50
2058-2059	A2	30	67

1 Days with flow less than 100 L/sec during water year.

Table 4b – Modelling results – driest part of the year (21 February-21 April)

Critical Dry Period of 21 February-21 April					
		Wairoa River - Irvines Mean Flow (L/sec)		**Mean Water Usage L/sec**	
Year	**Emissions Scenario**	**DNFLMS**	**%DIFF**	**%DIFF**	**%DIFF**
2000-2001	Historic	2,061	-	715	-
2058-2059	A1B	1,950	-5	810	13
2058-2059	A2	2,093	2	844	18

Year	**Emissions Scenario**	**Mean Waimea River Flow (L/sec) - TDC Nursery**			
		DNFLMS	**%DECR**	**MODFLOW**	**% DECR**
2000-2001	Historic	433	-	433	-
2058-2059	A1B	335	-23	342	-21
2058-2059	A2	318	-27	316	-27

		Mean GW Level McCliskies Well (mm)	
Year	**Scenario Emissions**	**DNFLMS**	**MODFLOW**
2000-2001	Historic	1,962	1,962
2058-2059	A1B	1,962	1,964
2058-2059	A2	1,964	1,963

They were a decrease of 5% for the A1B emissions scenario and an increase of 2% for the A2 scenario.

4) Waimea River flow at TDC Nursery – there was a calculated decrease in mean Waimea River flow at TDC Nursery

during the critical 21 February-21 April drought projected for 2059 compared to mean flow in 2001. Projected decreases by DNFLMS modelling were 23% and 27% for the A1B and A2 emissions scenarios, respectively. MODFLOW projected similar decreases of 21% and 27%, respectively, for these two emission scenarios. Finally, DNFLMS shows substantial increases in low flow events (days with flows less than 100 L/sec) for the Waimea River at the TDC Nursery location, with increases of 50% and 67%, respectively, for the A1B and A2 emissions scenarios.

5) Groundwater levels –only minor impacts on groundwater levels at the McCliskies well for either emissions scenario by both DNFLMS modelling and MODFLOW.

Summary, conclusions, and recommendations

Summary and conclusions

Non-parametric trend analysis of climate and hydrologic data using the Mann-Kendall method with Sen's slope estimator produced clear indications of trends in climate variables consistent with climate change. In particular, there were statistically significant increases in atmospheric temperature, evaporation, sunshine hours, and relative humidity. The rate of temperature increase observed was consistent with climate change effects that have been documented elsewhere (IPCC, 2007). There is also an indication of decreased rainfall, but this was only statistically significant for one of the six out of nine stations indicating a possible decrease. The other three indicated increases which were not statistically significant. Although the increase in sunshine hours was statistically significant, the overall pattern was similar to the bifurcated plot for solar radiation, with a decreasing trend for early time data and an increasing trend for late time data.

There were no strong indications of climate change impacts to surface waters. The statistically significant decrease in flow found for the Wai-iti River is possibly an indication and is consistent with the decreasing, but not statistically significant, trend in rainfall for the Belgrove station in that part of the catchment. However, there was no trend for the larger Wairoa River and there were insufficient annual flow data to support trend analysis for the Waimea River. Similarly, with respect to water quality, the increasing trend in temperature for the Wai-iti River is consistent with climate change expectations, but not the increasing pH. Changes in nitrate-nitrogen (increasing in the Wairoa and Waimea Rivers) and dissolved reactive phosphorus levels (increasing in the Waimea River but decreasing in the Wairoa River) would most likely be related to agricultural practices rather than climate change, per se. However, they could be indirectly related if climate change causes agricultural practices to change.

Similarly, there were no clear indications of climate change impacts to groundwaters. This may have been, in part, due to the influence of both rainfall and stream recharge on the groundwater system. Although increased evapotranspiration from climate change reduced rainfall recharge, this was moderated by stream recharge. Climate change impacts would be expected to manifest themselves in the shallow unconfined aquifer first, but trends for water levels in that aquifer were split between increasing and decreasing and there were no trends in this aquifer for any of the water quality variables except a weakly increasing conductivity trend (which could be considered consistent with expectations as a result of climate change). The different lengths of available data for groundwater levels in monitoring wells may also have been a factor, as there appears to be an indication of increasing trends during the latter 10 to 15 years, while wells with longer records have an overall decreasing trend. The statistically significant increasing trend for water level in the well closest to the coast (McCliskies well) is also suggestive of a possible connection to increasing sea level produced by climate change. However, the rate of increase is relatively high compared to the current sea level trend. In contrast, trends for water levels in the deeper two confined aquifers were all decreasing. With respect to water quality in the deeper aquifers, there were multiple water quality variables with significant decreasing trends in the upper confined aquifer and increasing trends in the lower confined aquifer. None of these opposing trends in the two confined aquifers are considered likely to be related to climate change.

Projections from both artificial intelligence modelling and mechanistic surface water-groundwater interaction modelling (MODLFOW with artificial intelligence modelling inputs) indicate that climate change may cause substantial reduction in flow for the Waimea River at the downstream TDC Nursery location during the critical warm weather period (21 February-21 April) of an extreme drought (up to a 27% decrease for the A2 emissions scenario) and increase the number of low flow days during such a year from 18 to 30 (a 67% increase). Since Wairoa River flow at Irvines for the two climate change emissions scenarios is roughly comparable to historic flow, the downstream flow decrease for the Waimea River at TDC Nursery appears to be a result of extra losses/depletion in the Waimea Plains as a result of climate change.

From a management standpoint, the practical implication of this conclusion is that future droughts under climate change in the Tasman District may become more severe than they have been in the past, and thus management alternatives for dealing with them will likely have to be augmented (e.g., provision of additional storage capacity, rationing, or other methods for reduction of water demand).

Trend analysis of historic monitoring data using the Mann-Kendall method, as performed in this study, provides an effective way of assessing trends that have occurred. When the trends are clear cut and there is a long record, as with atmospheric temperature, unambiguous results are possible. However, the inherent variability of hydrologic data may complicate identification of trends, particularly with shorter records and data gaps.

The computer modelling methods employed in this study provide a rational way to assess possible scenarios. However, much work is left to be done to determine optimum assessment methods and there is considerable uncertainty in these projections, starting with the regional downscaling of climate projections produced by NIWA. For example, NIWA projects a mean annual temperature increase (based on output from 12 GCMs for the A1B emissions scenario) for the Tasman region of 0.9°C by 2040 in comparison to 1990. However, the range of temperature increases produced by different models is 0.4 to 1.4°C (Wratt and Mullan, 2008). Furthermore, world efforts to control greenhouse gas emissions have been less than effective to date and recent observations indicate that actual emissions may exceed the worst-case IPCC scenario (Le Quere, 2011). If this situation continues, climate change impacts may far exceed A1B and A2 emissions scenario projections.

Recommendations

These methods may be applied to any catchment where there are sufficient data for analysis and to support modelling. However, they are data-dependent and the development and maintenance of high-quality, long-term databases is necessary. In New Zealand, it is recommended that standard protocols be developed and used for field measurements, field sampling, and laboratory analysis and that data quality programs be developed and instituted. There is considerable room for improvement in these areas. Additionally, what is being monitored should be reviewed and carefully considered. At the present time, surface water quality monitoring is narrowly focused on only a few contaminant-related variables, while a much larger suite of variables is routinely monitored in groundwater (including major ions). The ability to consider changes in surface water quality that may result from climate change and quality relationships between surface water and interconnected groundwater is handicapped by this uneven water quality monitoring. Monitoring efforts to assess climate change require a long-term commitment to routine data collection and an effort to minimize data gaps.

Results from this project provide, for the first time, information by which to consider the potential effects of climate change on a groundwater system in New Zealand. This work should be continued in other areas of New Zealand with varying hydrologic conditions and climate change projections. Particular effort should be invested in approaches to the quantification of rainfall recharge of groundwater.

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