Adaptation of Urban Water Supply Infrastructure to Impacts from Climate and Socioeconomic Changes: The Case of Hamilton, New Zealand

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Abstract

While the relations between climate variables and sectoral water demand have been well established in the literature, few studies have attempted to quantify changes in urban water usage with climate change. Concentrating on the city of Hamilton, New Zealand, we investigate possible water use and infrastructure needs for a range of climate and population projections. We find that water demand (at the monthly aggregate level) is largely driven by changes in population, and not significantly affected by changes in climate. However, as population increases, the effect of climate variables on per capita consumption will be magnified. Monthly aggregate changes may further mask potenially significant short-term shortages. In several scenarios, water supply shortages in 2030 occur with a 30-40% probability, suggesting needs for long-term capacity expansion or aggressive demand side management, rather than implementation of short-term management of water demand.

Key Words

Urban water demand, urban water supply, infrastructure, regional climate impact, climate adaptation.

1 Introduction

Urban governments, charged with ensuring adequate future levels of drinking water, face a particular challenge in planning for the impact that climate change can have on water supply systems. Increased temperatures and/or decreasing precipitation can have a double impact: increased evapotranspiration and lowered recharge rates reduce the total water available in the hydrological system while also increasing the total end-user demand. Supply declines while demand increases.

Despite the potential impacts that climate change can have on water demand, treatment and supply systems, little attention has been paid in the literature to the implications of climate change for water use in the larger socioeconomic and particularly an urban context (see, e.g., Frederick 1997, Vörosmarty et al. 2000). Among the few exceptions is a 1979 micro-level analysis of urban household water demand that includes climate variables and finds that "demand is highly responsive to changes in … the level of climatic variables" (Danielson, 1979, 763). More recently, Burian (2006) investigates broader impacts of climate change on urban water cycle dynamics and associated changes in potable water demand and supply. The CLIMB project, which explores climate's long-term impacts on metropolitan Boston (Ruth et al. 2000, Kirshen et al. 2004, 2006) couples a detailed spatial hydrological model of water supply with a fixed projection of annual water demand to produce yearly projections of climate impacts on the ability of metropolitan Boston to meet its water needs. Arnell investigates the impact of climate change on water supply but "assume[s] no effect of climate change on the demand for water" despite observing that "climate change is likely to increase demand for water" (Arnell, 1999, S31). The metropolitan east-coast assessment by Rosenzweig et al. (2000) concentrates on the adequacy of urban water supply infrastructure systems for metropolitan New York under different climate conditions without exploring in detail the potential climate impacts on changes in demand.

Given the lack of region-specific investigations into potential climate impacts on urban water demand in the context of socioeconomic change, we present in this paper a case study of water demand in Hamilton City, New Zealand, under a range of alternative climate scenarios. The purpose of this analysis, which is part of a larger project on Climate's Long-term Impacts on New Zealand Infrastructure (CLINZI), is three-fold (Ruth et al. 2006). First, we wish to develop a methodology to move climate impact analysis from continental and national to the local scales at which investment decisions are made. Second, we wish to quantify climate impacts in conjunction with other socioeconomic changes that occur at the scale of a city. We therefore concentrate on urban impacts and adaptation, rather than larger regional, upstream or downstream issues. Third, we wish to carry out an analysis in a setting that does not present climate impacts that are obvious *a priori*, such as impacts of sea level rise in a coastal zone, or impacts from changes in extreme weather conditions, such as droughts or flash floods. Instead, we have chosen Hamilton because its inland location, relatively moderate climate and lack of intra and inter-annual extremes pose rather subtle challenges to regional infrastructure planning and policy making.

The paper is organized to address each of these topics. First, we lay out the main characteristics of water demand and supply in Hamilton, as well as the city's current and potential future climatic conditions. Next, we discuss the data used in our study, followed by a description of our analysis and findings from a range of socioeconomic and climate scenarios. The paper closes with a brief summary and conclusions.

2 Water Issues in New Zealand

Water issues are of significant concern to New Zealanders. While many parts of the country have sufficient water resources to meet current and anticipated future demand, other parts (principally eastern areas) are likely to experience water shortages. Additionally, water quality is increasingly becoming a concern (Ministry for the Environment, 2001).

2.1 Water Issues in Hamilton City

Hamilton City draws its water supply from the Waikato River, which passes through the city on its way from Lake Taupo to the ocean. Hydro dams upstream of Hamilton, combined with the relatively limitless supply of Lake Taupo, provide the electricity generator, Mighty River Power, with almost complete control over river flow rates near the city. While drastic changes in climate around the lake and along the path of the river could affect water availability in Hamilton, a hydrological model to explore in detail the region's potential surface and groundwater supply is beyond the scope of this study. Additionally, it is possible that Hamilton City may face water-consent restrictions in the future as competition for water use from the Waikato River increases. However, the extent of this is uncertain, and water availability is orders of magnitude above anticipated supply. Thus, for the purposes of this project, we assume climate change will not have an impact on water availability in Hamilton during the next 25 years.[1]

Hamilton still faces potential climate change induced planning issues with respect to treated water demand and costs of water treatment. Hamilton operates a single water treatment facility with a capacity of 85 ML per day. Water is drawn from the Waikato River, filtered and treated for drinking, and stored in one of eight water-storage facilities in the city with a total capacity of 90.2 ML until it is piped to residential, commercial, and industrial end-users. If climate change produces conditions that lead to heightened water usage, then this supply capacity could require extension to keep pace with demand. The models outlined below investigate whether, under projected socioeconomic and climate change scenarios, this is the case. The first is a water usage model that gauges the impact of climate change on total monthly water use. The second has a more refined daily timescale and investigates whether climate change produces any shortfalls in water production on a day-to-day basis.

2.2 Climate and Climate Change in Hamilton City

New Zealand's climate is affected by the surrounding ocean as well as by its diverse topography; its climate varies from subtropical to temperate. Climate changes were recorded in New Zealand during the 20th century, including increasing temperatures (~ 0.7°C), reductions in frost frequency, and rising sea level (~14–17 cm) (Wratt et al. 2003). The decrease in annual frost frequency, by up to 15 days, has occurred mostly in the southeast of the South Island and the central North Island. To date, climate change has brought warmer winters and higher overnight temperatures, resulting in a longer growing season and a pronounced decline in the diurnal temperature range (McGlone 2001).

New Zealand's temperatures are likely to increase 1–4^{o}C. This warming trend will not keep pace with the global estimate due to the slow thermal response of the southern ocean. New Zealand is estimated to undergo a 0.7^{o}C increase for every degree of global warming between 1990 and 2100. Temperatures across the North Island could be 3^{o}C warmer over the next 70–100 years, whereas temperatures in the South Island could increase 2.5^{o}C. As the North Island warms, most regions will become increasingly tropical. Based on general circulation models (GCMs), two major changes are expected:

[1] This assumption is consistent with all discussions with city water planners, Hamilton City Council, and Mighty River Power employees.

30 fewer frost days by 2100 (or half the existing frost days); and more warm days (above 25°C) in the north and east of the North Island (McGlone 2001).

Changes in the precipitation regime will be patchier than those for temperature. In general, precipitation changes 10% for each degree of warming, which would steepen current precipitation gradients across the islands (McGlone 2001), resulting in an increase of annual average rainfall in the west of the country but a decrease in many eastern areas. Heavy rainfall events will become more frequent and the risk of drought will grow in some eastern areas (Wratt et al. 2003). According to the Climate Change Office (2004), flooding could be four times as frequent by 2070 throughout all of New Zealand, though storms might not necessarily become more severe (McGlone 2001).

The city of Hamilton is the regional capital of the Waikato region (Figure 1). Located in the upper half of the North Island, at a latitude of 38°S, it has a relatively mild climate with warm, humid summers and mild winters. High temperatures average 22°C in the summer and 14°C in the winter. The highest temperature on record is 31°C, the lowest -9.9°C. The area receives 108 cm of rain a year, with heavier rainfall in the winter months (30% of annual) and lower rainfall in the summer (22% of annual). Annual sunshine hours range from 2000 to 2100. Although a landlocked city, Hamilton's climate is influenced by the surrounding oceans: mostly by westerlies from the Tasman Sea, but also by southerlies from the Antartic Ocean as well as northerlies from the southern Pacific. Similar to much of New Zealand, athough the weather is not extreme, it is variable and changes over short periods of time.

Figure 1. Location map showing Hamilton in the North Island of New Zealand

3 Data and Limitations

3.1 Water Consumption Data

We obtained water consumption data for this analysis from the Hamilton City Council. It consists of daily total drinking water consumption in the Hamilton reticulation network from 1 January 1996 through to 31 December 2004. Only total system consumption figures are available. Consequently, we are not able to distinguish water use for residential, commercial, and industrial sectors. For the monthly analysis, we aggregated the data into monthly totals, normalizing each total for the length of the month so that all data assume a 30.416-day month. To reflect changes in the local population size, water consumption figures were adjusted to a per capita basis.

We also obtained water abstraction data for the same time period from the same source. However, regression of water abstraction data against water treatment data shows a consistent relationship between the two (a 5.9% loss of water, with an R^2 of .97). This relationship enables us to assume that water abstracted from the river is a constant function of water consumption.

As Figure 2 shows, water consumption generally ranges from 10,000 liters per person per month in the winter months to around 16,000 litres per person per month during the summer (330 – 530 liters per person per day). While the winter months appear fairly consistent across years, there are some years, such as 1998 to 2000, where summer-time consumption figures are well above normal. Not surprisingly, the summer months in 1998 and 1999 were the warmest summers, on average, during the sample period. The higher consumption during the summer of 2000 likely is a result of 1999 being the driest year during the sample period leaving the summer of 2000 with a dry start. On the daily cycle, water use is higher during weekdays than during weekends, reflecting increased industrial and commercial usage during the work week.

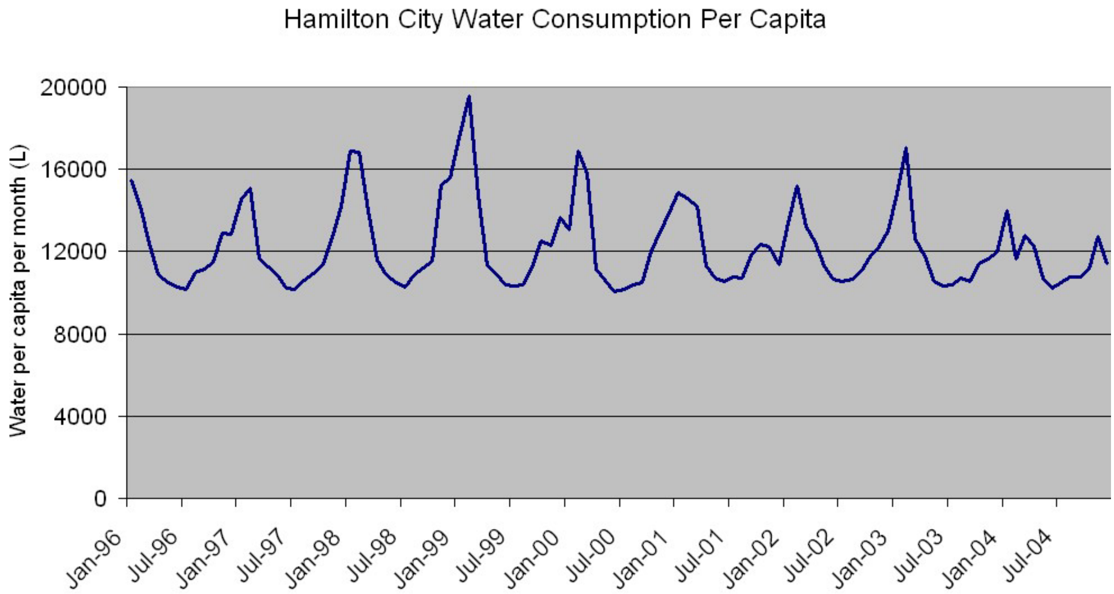

Figure 2: Hamilton City water consumption per capita, 1996–2004

3.2 Historical Climate Data for Hamilton

To develop the climate impacts model, historical data on temperature, precipitation, humidity, wind speed, and gust speed were necessary. Initial data came from four weather stations with varying temporal and climatic variable coverage monitored by the National Institute of Water & Atmospheric Research (NIWA) in the Hamilton area (Penney 2001). For the period 1996–2004, the 2101 and 12616 stations at the Ruakura research facility in Hamilton City provided complete daily rain time series as well as temperature and wind speed information. The 2101 station recorded measurements from January 1996 to March 1997, and the replacement 12616 station (installed at the same location) started recording measurements in October 1996. There was an overlap of roughly five months, from October 1996 to March 1997, between the two stations, where both were recording rainfall and temperature data. For that period, we chose to use the readings from the newer 12616 station for our dataset.

Humidity was excluded as an explanatory variable of water usage for two reasons, even though it may be significant in determining water use. First, humidity data were only available for 25 years (1972–1997), which only allowed for an 18-month overlap with the water use data. Second, there are no projections for how humidity changes under climate change scenarios.

Much like other regional climate impact studies (Ruth 2006), the CLINZI (Climate's Long-term Impacts on New Zealand Infrastructure) project, of which this water infrastructure impacts and adaptation study is a part, simulates climate impacts on a monthly time scale. To match the temporal resolution of CLINZI, the water infrastructure impact assessment required the creation of a dataset of monthly climate variables from the daily data. Most of the variables capture standard attributes such as total rainfall and averages of temperatures over the month. Other variables are intended to capture attributes of extreme weather events (e.g., the number of 3-day streaks above/below extremes, streaks of rainless days) or give a sense of the magnitude of weather events over the month (e.g., cooling degree days or mm rain days). A separate analysis, at daily time intervals, is presented below to explore infrastructure impacts and adaptation strategies that may not be apparent at coarser temporal scales.

3.3 Climate Change Scenarios for Hamilton

New Zealand's National Institute of Water and Atmospheric Research (NIWA) provided specific projections of temperature and precipitation under six different climate change scenarios for selected stations within the Waikato region, expressed as changes from the "current climatology, which can be taken as the 1971 to 2000 normals" (Mullan, *pers. comm.*). Changes are: 1) direct (downscaled) model changes from the 1980s (1970–1999) to the 2030s (2020–2049), without any other adjustment; and 2) scaled changes from the nominal year 1990 to the 2030s, for both a "low" and "high" scaling intended to show regional changes accompanying the full range of the Intergovernmental Panel on Climate Change (IPCC) global temperature change projections (Mullan *pers. comm.*). Changes were provided for each season (summer, autumn, winter, spring) for the Hamilton City area (Mullan et al. 2001, Wratt et al. 2003). Given the limited climate variability over the last century, the presumed "low" and "high" ranges are understood to cover possible future variability in the light of fundamental uncertainties about climate change at global, regional and local scales.

For the purposes of this project, we chose the low and high emissions scenarios from the rescaled CSIRO and Hadley models (Houghton et al. 2001) for a total of four climate change projections (Table 1 and Table 2). The projections selected were made for the same station from which we drew historical climatic data.

Table 1: Modeled Temperature Change (^{o}C) between 1990 and 2030s under four climate change scenarios at Ruakura station (Mullan *pers. comm.*)

Season	S1: CSIRO Low	S2: CSIRO High	S3: Hadley Low	S4: Hadley High
summer	0.38	0.82	0.23	0.49
autumn	0.47	1.03	0.24	0.52
winter	0.35	0.75	0.40	0.87
spring	0.29	0.62	0.30	0.65

Table 2: Modeled Precipitation Change (%) between 1990 and 2030s under four climate change scenarios at Ruakura station (Mullan *pers. comm.*)

Season	S1: CSIRO Low	S2: CSIRO High	S3: Hadley Low	S4: Hadley High
summer	-12.7	-5.8	-2.0	-0.9
autumn	0.7	1.5	-5.8	-2.7
winter	-1.8	-0.8	5.5	12.0
spring	-2.9	-1.4	-12	-5.5

3.4 Population Scenarios For Hamilton City

The 1996 population of Hamilton City was 108,500 people. Statistics New Zealand has produced three projections for future population in Hamilton: a low projection of 150,000 people in 2030, a mid projection of 164,500 people by 2030, and a high projection of 180,000 people in 2030 (Statistics New Zealand 2000). Similar to our assumptions about future climate conditions, the low and high population forecasts are assumed to bound the range of likely population sizes in the city. Those extremes, as well as the midpoint, provide valuable input into planning and policy making. Population estimates were reported in five-year increments, and for purposes of our model, we assumed that population grows linearly between these five-year end points.

4 Analysis

The analysis of relationships between climate and water consumption follows a two-step process. In the first step, on the basis of the data described above, we statistically estimate functional relationships between climate variables and the observed water consumption data. In the second step, we use the regression results to calculate potential future water consumption under alternative climate scenarios.

4.1 Monthly Water Consumption

The monthly water consumption model consists of the log of per capita water consumption regressed against the number of 3-day streaks of 26°C or higher, the maximum rainfall in a 3-day period during the month, the mean daylight temperature of the month, the longest rainless (less than 2mm of rain) streak during the month, and the total number of rainless days. Dummy variables for January–November were included to control for non-climate related intra-annual variation in water usage, such as those associated with growing seasons, and human consumptive needs during above average temperature events.

The log-linear model form was chosen to control for heteroscedasticity in the errors of the linear OLS model, and because scatter plots of water consumption against the dependent variables showed a clear log-linear relationship, as demonstrated for DaysNoRain and MeanLgtTemp (Figure 3).

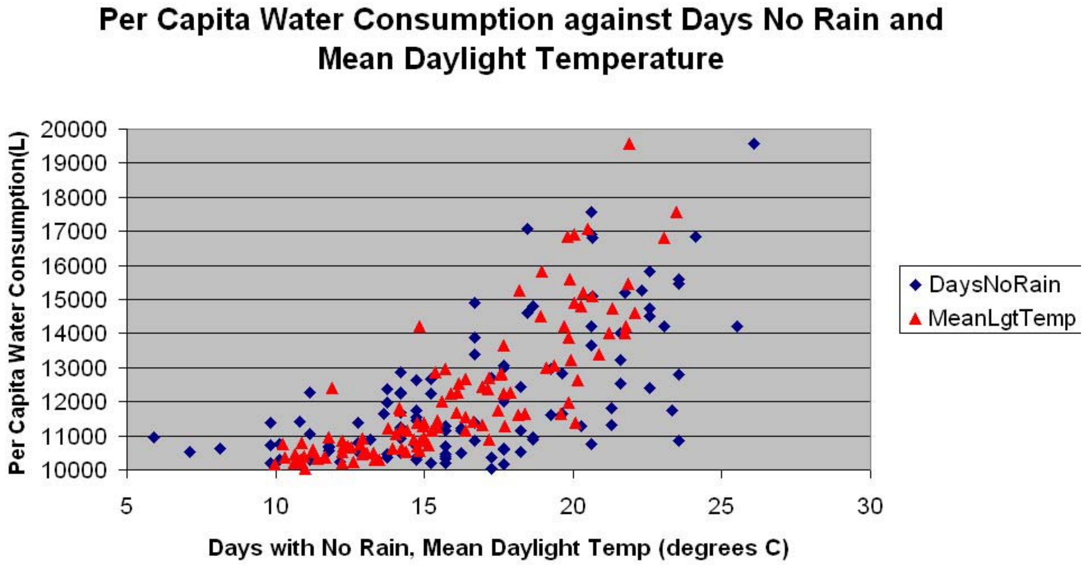

Figure 3: Per capita water consumption against days with no rain and mean daylight temperature

Regression results from the analysis are shown in Table 3. The analysis employed a Prais-Winston estimation to correct for serial autocorrelation (Stata 2005). As would be expected, there is a significant and positive relationship between water consumption and the two temperature variables (MeanLgtTemp and Streaks26_3day) and between water consumption and the two measures of rainlessness (MaxRainlessStreak and DaysNoRain). The rainfall variable, Max3DayRain, exhibits a significant and negative relationship. The month dummies, tested groupwise, are also significant.

Table 3: Regression results for the water consumption model

Dependent Variable:	Log(Monthly Water Consumption Per Capita) in litres				
Prais-Winsten AR(1)					
Observations	108	F(16,91)	437.63	R^2	0.9872
Durbin-Watson (original)	1.313540	Root MSE	.04147	Adjusted R^2	0.9849
Durbin-Watson (trans)	2.002040	Rho	.4220185		

Parameter	Coefficient	Std. Err	t	P>|t|	[95% Conf. Interval]	
Jan	.027	.020	1.31	0.192	-.0137327	.0674616
Feb	.052	.024	2.17	0.033	.0043646	.0987913
Mar	-.024	.022	-1.10	0.273	-.0674249	.0192857
Apr	-.16	.022	-7.10	0.000	-.2041987	-.1149456
May	-.17	.026	-6.60	0.000	-.2251367	-.1210215
Jun	-.13	.032	-4.25	0.000	-.1975199	-.0716417
Jul	-.16	.034	-4.62	0.000	-.2256852	-.0899886
Aug	-.13	.032	-4.07	0.000	-.1916858	-.0658601
Sep	-.13	.027	-4.89	0.000	-.1826185	-.0770603
Oct	-.11	.022	-5.13	0.000	-.1560153	-.0689511
Nov	-.017	.018	-0.95	0.346	-.0517488	.0183305
streaks26_~y	.0026	.00105	2.48	0.015	.001277	.0114784
max3dayrain	-.00082	.00024	-3.41	0.001	-.0013038	-.0003439
meanlgttemp	.011	.0036	3.24	0.002	.0044371	.0185449
maxrainles~k	.00076	.00139	5.46	0.000	.0026223	.0056256
daysnorain	.0075	.0014	5.35	0.000	.0046864	.0102221
_cons	9.11	.078	116.71	0.000	8.952278	9.262295

4.2 Daily Water Consumption

To explore whether any intramonthly weather patterns can create shortages in water supply on a day-to-day basis over the course of a year, we developed a similar model to the monthly model above. The log of per capita daily water usage was regressed against the maximum temperature, rainfall during the current and previous day, the number of rainless days in the previous three days, and the average wind speed. Dummy variables for January to November were included to control for non-climate related intra-annual variation in water usage, such as those associated with growing seasons and human consumptive needs during above average temperature events. An indicator dummy variable that distinguishes weekdays from weekends was used as individual day-of-week dummies did not offer a significant improvement over this approach.

The log-linear model form was chosen to control for heteroscedasticity in the errors of the linear OLS model, and because scatter plots of water consumption against the dependent variables showed a clear log-linear relationship. Minimum temperature, average temperature, and temperature indicator during previous days were all tested but were either insignificant or failed to offer any explanatory value above the daily maximum temperature. Similarly, the counts of rainless days during the previous 2 to 10 days were all tested. The count during the previous three days proved the most significant.

Regression results from the analysis are shown in Table 4. The analysis employed a Prais-Winston estimation to correct for serial autocorrelation. As would be expected, there is a significant and positive relationship between water consumption and the temperature variable. It indicates that for every one degree increase in temperature, water consumption will increase by 1.4%. The two indicators of rainfall exhibit a negative relationship—more rainfall translates into lower watering needs and thus less water usage. Water consumption decreases by 0.22% for every millimeter of rain on the current day and 0.135% for every mm of rain the day prior. Similarly, the more rainless days in the previous three days, the more water is used: 2.7% more water for each day without rain. A negative relationship exists between wind speed and water usage, though the magnitude of the relationship is rather small: a one meter/second increase in average wind speed only decreases consumption by 0.65%. Not surprisingly, the dummies indicate that more water is used in the summer, later spring and early fall months (November to March) and on weekdays than during other months and over weekends. Almost 12% more water is used per day in November than in June, and 3% more water is used on a weekday than an otherwise equivalent weekend.

Table 4: Regression results for the daily water consumption model

Dependent Variable	**Log(Daily Per Capita Water Consumption)**				
Prais-Winsten AR(1)					
Observations	1821	F(17,1803)	420.08	R^2	0.7984
Durbin-Watson (original)	.987418	Root MSE	.008559	Adjusted R^2	0.7965
Durbin-Watson (trans)	2.110625	Rho	.5154		

Parameter	Coefficient	Std. Err	T	P>|t|	[95% Conf. Interval]	
Jan	.0502	.0187	2.69	0.007	.01353	.08683
Feb	.122	.0195	6.26	0.000	.08403	.1606
Mar	-.0506	.0191	2.64	0.008	.013051	.08809
Apr	-.0559	.0194	-2.89	0.004	-.09390	-.01799
May	-.0831	.0195	-4.25	0.000	-.1214	-.04478
Jun	-.0869	.0204	-4.25	0.000	-.1270	-.04679
Jul	-.0631	.0209	-3.02	0.003	-.1041	-.02207
Aug	-.0688	.0205	-3.35	0.001	-.1090	-.02853
Sep	-.0513	.0200	-2.56	0.010	-.09050	-.01203
Oct	-.0144	.0193	-0.75	0.456	-.05231	.02347
Nov	.0249	.0186	1.34	0.182	-.01163	.06139
Weekday	.0298	.00455	6.56	.000	.02092	.03876
MaxTemp	.01407	.00117	12.01	0.000	.0117711	.0163637
Rainfall	-.002224	.000354	-6.28	0.000	-.0029184	-.0015298
Rainfall(n-1)	-.0013501	.000337	-4.01	0.000	-.0020108	-.0006895
RainlessDays3	.02751	.00321	8.57	0.000	.0212115	.0338007
WindSpeed	-.00653	.00254	-2.58	0.010	-.011502	.-.0015565
_cons	-8.163543	.03060	-266.82	0.000	-8.223459	-8.103447

5 Scenarios and Model Results

Using the five climate scenarios discussed above (one base case without climate change, four with different assumptions about changes in temperature and precipitation) and each of three population scenarios from Statistics New Zealand, we ran simulations that projected monthly water consumption figures using the linear model described above. For each of the fifteen climate-population scenarios (five climate scenarios by three population scenarios), we ran 50 simulations, using moving-block bootstrapping (Vogel and Shallcross 1996), and averaged the results to create our projections. The resulting projections thus embed a wide range of possible intra- and interannual variation in climate and population.

For the daily model, we ran only the projections for 2030 under the base case and four climate change scenarios under each of the three population scenarios. We ran 25 tests for each of the 15 scenario combinations, with the base case climate of 2030 in each test equivalent to the climate in one of the years 1980 to 2004 inclusive.

5.1 Monthly Water Usage Projections

Monthly water usage is projected to increase under every scenario due primarily to population growth. However, there is significant difference in water usage depending on the population scenario (Figure 4). By 2030, peak summer usage is 2800 million liters (ML) under a “high” population projection, as compared to 2350 ML under a “low” population projection. The impact of different climate scenarios, however, is much smaller. As Figure 5 shows, the difference between the base case scenario (S0) and one of the more extreme climate scenarios (S2) amounts to less than 1%. Despite the significance of climate variables in water consumption, the small magnitude of the change during the next 25 years results in an equally small magnitude of climate change induced changes in water consumption.

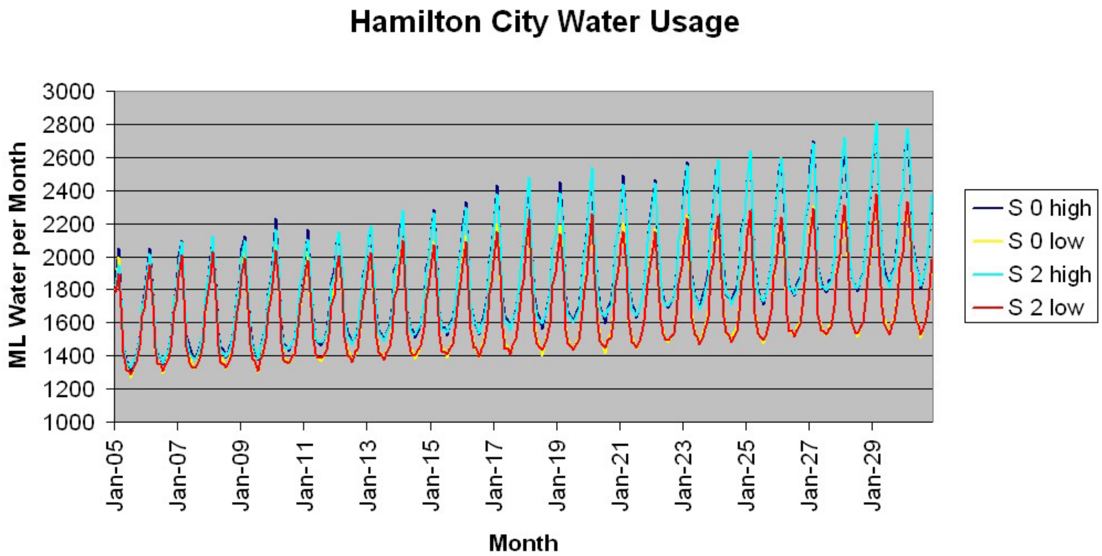

Figure 4: Hamilton City water usage, 2005–2030

5.2 Daily Water Usage Projections

On the daily level, water consumption in 2030 is dominated by population growth. As with the monthly projections, the difference between the base case (no climate change) and the climate change scenarios is miniscule. The maximum 3-day water usage for the city under the high population projection in the base case is 300 ML. Under the scenario with the largest increase in overall water usage, S2, this maximum increases to just 304 ML for a difference of 1.3%. The small magnitude of this change is what we would expect given the assumed magnitude of climate change and the elasticities described above. For example, the largest increase in temperature, 1.04°C during autumn under S2, translates into a 1.4% increase in water consumption. Despite the significance of the climate variables in determining daily water usage, the magnitude of climate change in Hamilton by 2030 is not large enough to translate directly into large shifts in water demand.

This is contrasted by the large impact that the different population scenarios have on total water usage projections. A day with 79 ML of water consumption under the low population projection of 150,000 people increases to 98 ML under the high population projection of 180,000 people; an increase of 20%. Since per capita figures were used, every one percent increase in population directly translates in our model into a one percent increase in total water consumption.

Despite the evidence for a small impact of climate change when the changes are considered as averages, these numbers do raise an interesting point about the future of water consumption and supply in Hamilton City. Currently, the city is equipped to supply 85 ML a day and has a reserve storage capacity of just over 90 ML. According to our model, under a high population scenario, six days in a row without rain and with temperatures above 30°C would be enough to deplete this reserve capacity leaving a deficit between demand and supply of 15 ML on the seventh day. Under a medium population scenario, this shortage could occur with twelve days of hot, dry weather.

In our projections, which include only changes to climate means (and not changes to the number or intensity of droughts or heat waves), a streak that would leave Hamilton City without enough water in a seven-day period occurred 10 times in 25 runs of Scenario 2—an average of a 40% chance of water shortages in any given year after 2030. This represents a significant increase over the 24% annual chance of shortfalls predicted for the base case scenario (see Figure 5). Although increases to means have a marginal impact on daily water consumption, it seems that there are cases where water supply is barely met under high population scenarios such that a small increase in temperature or decrease in rainfall is enough to create a shortfall. If climate change, in addition to changes in means, also increases the number of hot-dry spells, this probability could be pushed even higher.

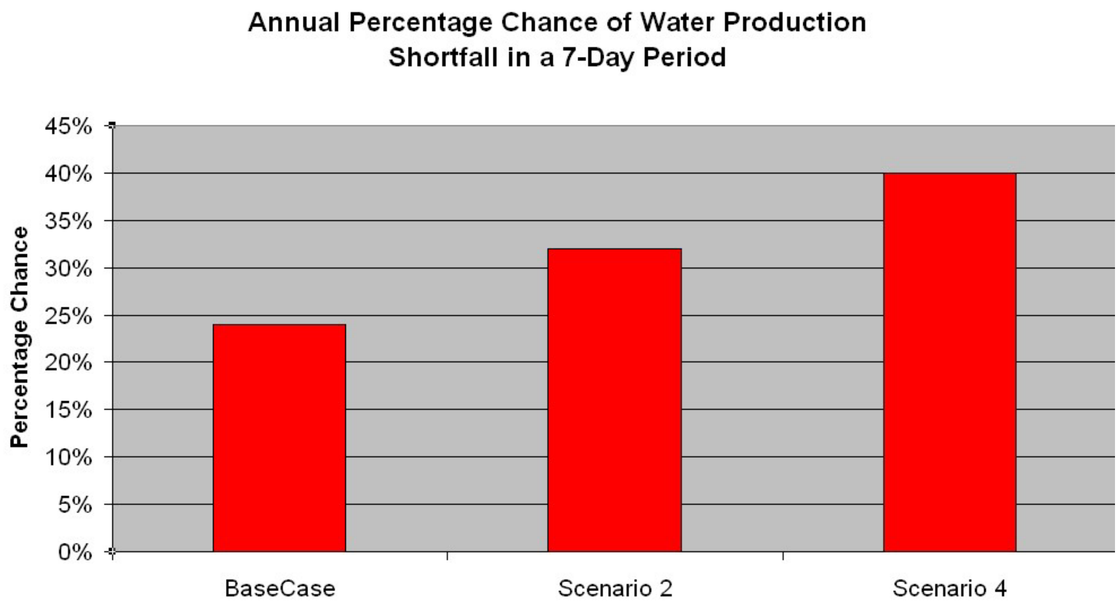

Figure 5: Annual Percentage Chance of Water Production Shortfall Under High Population Projections (see Tables 1 and 2 for scenario definitions)

6 Discussion and Conclusions

This analysis of the impacts of climate change on water consumption and drinking water supply in Hamilton City is limited by a number of constraints. First, the monthly time step (as opposed to daily) does not allow us to see whether climate characteristics that occur within months (which most extreme events are likely to be) will threaten the City's ability to maintain adequate reserves of drinking water. Second, the unavailability of sector-specific data, and the corresponding need to aggregate all end-uses into one number, means we are unable to analyze the different impacts climate change might have on different sectors of the city. Regardless, the analysis does offer a number of key insights into the next 25 years of drinking water supply/demand in Hamilton and possible policy orientations that can address these.

First, changes in water demand (at the monthly aggregate level) are largely driven by changes in population, and not significantly affected by changes in climate. Policy makers would be wise to continue to focus on demographics when planning water system upgrades. These decisions should be sensitive to climate change, but not driven by it (even though it may be fashionable to do so). Indeed, as our results from the daily analysis show, high population growth in Hamilton City may result in an increased sensitivity to climate change allowing small changes in climate to tip demand/supply balances into a shortfall.

However, the apparent lack of water demand sensitivity to climate *change* does not leave Hamilton City free of impact from climate itself. As population increases, the effect of climate variables on per capita consumption is multiplied by an increasing number in determining total water consumption. Thus, a temperature difference (20°C to 30°C) that results in a 8ML increase in consumption today translates into a 14ML increase in 2030 under a high population scenario. Thus, dry warm streaks that do not tax water supply today might, even with only slight climate change, result in increasing drinking water shortages in Hamilton City. If climate change also results in increases in consecutive warm/dry days, this effect could be even more pronounced.

Hamilton City Council is currently considering expanding the water treatment facility to be able to handle 100ML per day of drinking water production (Martin Lynch, *personal communication*). Even under the high population scenarios, this increase in capacity would enable Hamilton City to withstand all but the driest and warmest conditions projected by our models. There is no seven-day streak in the bootstrapped climate change scenarios where more water is consumed than would be covered by 100 ML/day production capacity. Of course, under a 7-day warm/dry spell, we might expect Hamilton to explore other, short-term adaptation strategies. Limits on water usage, such as restricting lawn watering or car washing, would be a cost effective, though short-term, means of dealing with these temporary shortages when they arise. While this might be a prudent stop-gap measure, if such shortages are occurring with a 40% probability in 2030, the more long-term capacity expansion solution will be much more appealing.

Finally, this study highlights a number of data needs if Hamilton, or cities like it, are to best plan for regional climate change. Sectoral-level water consumption data would allow for a more detailed analysis of the sector-specific impacts of weather on water demand. More refined representation of sectoral impacts would also enable more sophisticated conclusions about, and implementation of, options for adaptation to climate change.

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