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Journal of Environmental Management 83 (2007) 460–477

Journal of Environmental Management

www.elsevier.com/locate/jenvman

# The climate's long-term impact on New Zealand infrastructure (CLINZI) project—A case study of Hamilton City, New Zealand

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Received 3 October 2005; received in revised form 15 May 2006; accepted 27 September 2006

## Abstract

Infrastructure systems and services (ISS) are vulnerable to changes in climate. This paper reports on a study of the impact of gradual climate changes on ISS in Hamilton City, New Zealand. This study is also the first of its kind to be applied to New Zealand ISS. In the future, the CLINZI project will extend to other areas of New Zealand.

Using historical climate data and four climate change scenarios, we modelled the impact of climate change on aspects of water supply and quality, transport, energy demand, public health and air quality. Our analysis reveals that many of Hamilton City's infrastructure systems demonstrated greater responsiveness to population changes than to gradual climate change.

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*Keywords:* Climate change; Infrastructure; Integrated assessment; Adaptation

## 1. Introduction

The Earth's climate is changing at unprecedented rates. As a result of higher greenhouse gas concentrations, global average surface temperature has increased by about 0.6 °C over the 20th century with the 1990s probably the warmest decade in instrumental record (Intergovernmental Panel on Climate Change, 2001). This average global change masks regional variations. For example, higher latitudes in the northern hemisphere have warmed more than the equatorial regions (Office of Science and Technology, 1997). Recent climate change in the Southern Hemisphere is marked by a strengthening of the circumpolar westerlies in both the stratosphere and the troposphere (Gillet and Thompson, 2003).

Climate changes of these proportions may affect human structures and activity. Of particular importance are the effects of climate change on infrastructure systems and services (ISS) such as flood control, water supply and energy distribution. The real value of these services lies in their contribution to economic development and quality of life.

ISS are very sensitive to climate. While several North American and European studies have shown that the possible damages to ISS as a result of climate change are the same or larger than damages to agriculture (see for example, Cohen, 1996, 1997; Huang et al., 1998; Koteen, 2001 #914; see for example, Bloomfield et al., 1999; Rosenzweig et al., 2000; Ruth et al., 2006; Schmandt and Clarkson, 2005), there have been surprisingly few integrated assessments of the impact of climate change on ISS in New Zealand.

The primary purpose of this paper is to explore and quantify potential impacts of gradual climate change on the ISS in Hamilton City, New Zealand. This Hamilton City study is the first of a series of case studies to be conducted on New Zealand ISS as part of the ongoing CLINZI (Climate's Long-term Impact on New Zealand Infrastructure) project.

## 2. Research background

In common parlance, the term 'infrastructure' often refers to public utilities such as water, electricity, gas,

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0301-4797/$ - see front matter © 2006 Published by Elsevier Ltd.
doi:10.1016/j.jenvman.2006.09.022

sewage and telephone services. However, we define ISS more broadly. Infrastructure systems and services are defined here as the interrelated built, institutional and environmental systems and services that provide modern society with the ability to function. This broad definition includes both human-made infrastructure (dams, roads, supply pipelines, etc) as well as ecosystem infrastructure (such as the ecosystem's ability to provide water, clean air, etc). We also extend the notion of ISS to include the institutional and policy structures that define the operating environment for the physical services.

ISS deserve special attention in the climate-change debate. To date, most of the work on the impacts of climate change has focussed on individual sectors of an economy, with particular attention given to the impacts of climate change on agriculture (Bloomfield et al., 1999; Ruth, 2006). However, the number of studies conducted on regional impacts of climate change, including impacts on urban areas, is increasing (e.g., the National Institute of Water and Atmosphere's (NIWA) "Adaptation to Climate Variability and Change" programme[1]). Most of these studies are ISS specific, concentrating, for example, on implications of climate change for water supply or electricity generation. Few studies integrate impacts across ISS to capture possible ripple effects and interdependencies. Table 1 lists the main studies and compares the areas on which they focus and the extents to which they address interdependencies.

### 2.1. *The need for regional/local focus in climate change studies*

The general issue of infrastructure sensitivity to climate and climate change is of interest to all communities. However, we argue that studies of climate change impacts on ISS should be performed at the local or regional scale for a number of reasons (Patterson et al., in press) First, global climate change is anticipated to have geographically distinct impacts. For example, global climate models predict the annual average rainfall will increase in the west of New Zealand but decrease in many eastern areas (Boustead and Yaros, 1994). As a consequence, analyses that apply a uniform temperature increase over nations may miss important geographic impacts on infrastructure. The ability to capture and interpret geographical variations in climate change impacts on infrastructure systems is particularly important for New Zealand due to its diverse climate.

A second justification for carrying out a local or regional assessment lies in the differences of infrastructure systems within regions (Lakshmanan and Anderson, 1980; Sailor and Munoz, 1997). Regional infrastructure systems differ in terms of physical structures, age of assets and associated institutional structures.

A third justification is that different economic sectors exhibit distinct sensitivities to climate. Since sectoral compositions vary across regions, the structure of a region's economy significantly influences the sensitivity of that community to climate (Penney, 2001).

For these reasons, the CLINZI project aims to investigate the vulnerability of ISS to climate change at a local scale. The current case study focuses on Hamilton City—a medium-sized urban centre in New Zealand. We chose this case study for three reasons. First, the local government agencies offered support for this research. Second, the agencies had not considered the impact of climate change on their city. Indeed, many stakeholders implicitly considered their city to be robust to climate changes. We wanted to test this assumption. Finally, it appeared that the necessary data for this study would be available.

### 2.2. *The case study area—Hamilton, New Zealand*

Hamilton City is situated in New Zealand's North Island (Fig. 1) along the banks of the Waikato River. A major service centre for the Waikato region, which has a strong agricultural sector, Hamilton is also strategically located 126 km from Auckland, New Zealand's largest city.

The city is home to more than 115,000 people and occupies 9400 ha.

Statistics New Zealand's projections of Hamilton City's population for 2030 range from 150,300 (low scenario), 164,476 (median scenario) to 179,000 (high scenario) (Statistics New Zealand, 2000).

## 3. Climate change and Hamilton City

To explore potential future performance of infrastructure in Hamilton City, we first collected historical data on temperature, precipitation, humidity, wind speed and gust speed from the Ruakura stations (East Hamilton) for the period 1940–2004 (Penney, 2001). Some of the data are available at hourly, daily and monthly reporting intervals. From these data, we created monthly time series, standardised to a month length of 365/12 days. From the historical data we sampled observations using moving block bootstrapping (Vogel and Shallcross, 1996; Kirshen et al., 2006) and created new time series to simulate possible future climate conditions for the years 2005–2030, such that the new time series exhibits the same intra-annual statistical properties as the historic data. Repeating the process 50 times then yields 50 alternative futures consistent with the assumption that the future climate is, in essence, like the past. This set of 50 scenarios provides the base case against which we compare the impacts of climate change.

In the second step of our analysis we applied regional trends from climate scenarios developed by NIWA, which in turn are based on the CSIRO and Hadley models (Houghton et al., 2001) for a total of four climate change projections (S1—CSIRO Low; S2—CSIRO High; S3—Hadley Low; S4—Hadley High) (see Tables 2 and 3). With these trends, we have five sets of 50 scenarios: a base

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[1] See http://www.niwa.cri.nz/rc/prog/c01x0202.

Table 1
CLINZI and its Predecessors

| Location | (Koteen et al., 2001) New York City, USA | (Rosenzweig et al., 2000) Greater Los Angeles, USA | (Kirshen et al., 2004) Metropolitan New York, USA | (Amato et al., 2005) Metropolitan Boston, USA | CLINZI Hamilton, New Zealand |
|---|---|---|---|---|---|
| Coverage: | | | | | |
| Water supply | X | X | X | X | X |
| Water quality | | | | X | X |
| Water demand | | | | X | X |
| Sea-level rise | X | | X | X | N/A |
| Transportation | | | | X | X |
| Communication | | | | | |
| Energy | | | X | X | X |
| Public health | | | | | |
| Vector-borne diseases | | | | | |
| Food-borne diseases | X | | | | |
| Temperature-related mortality | | | | | |
| Temperature-related morbidity | X | X | | X | X |
| Air-quality related mortality | | | | | X |
| Air-quality related morbidity | | | X | | X |
| Other | X | X | X | | X |
| Ecosystems | | | | | |
| Wetlands | | | | | |
| Other (Wildfires) | X | X | X | | X |
| Air quality | | X | | | |
| Extent of: | | | | | |
| Quantitative analysis | Low | Medium | Medium | High | High |
| Computer-based modelling | None | Low | Low | High | High |
| Scenario analysis | None | None | Medium | High | High |
| Involvement of: | | | | | |
| Local planning agencies | None | None | High | High | Low |
| Local Government agencies | None | None | High | High | Medium |
| Private industry | None | None | None | Low | Low |
| Non-profits | None | None | Low | High | None |
| Citizen | None | None | None | Medium | None |
| Identification of: | | | | | |
| Adaptation options | X | X | X | X | X |
| adaptation cost | | | X | X | |
| Extent of integration across systems | None | None | Low | Medium | Low/ Medium |

scenario (S0) and four alternative scenarios consistent with historical patterns *and* possible future climate change trends as derived from global circulation models.

According to Mullan (pers. comm.), relative humidity remains fairly unchanged in most climate modelling scenarios. Also, wind gusts cannot be scaled specifically from monthly data (Mullan, pers. comm.). Consequently, humidity and wind gusts were not included in our climate projections or in our analyses.

The bootstrapped projections for temperature and precipitation showed a progressive increase in temperature (Fig. 2) and an increased range of monthly precipitation (Fig. 3) over the 2005–2030 period. The S2 scenario results in the greatest monthly maximum temperature by 2030 and the S3 scenario in the lowest monthly minimum temperature (Fig. 2), which is still higher than that in S0. Higher monthly precipitation is projected in the S4 scenario, while the lowest monthly precipitation projections occur on the S1 scenario (Fig. 3). These scenarios present conservative estimates to the extent that they do not reflect potential changes in the frequency and severity of extreme weather events—sampling from historical data and then scaling the scenarios with trends from global circulation models does not yield events with rare occurences, such as events with 200- or 500-year recurrence intervals. To explore effects of more extreme climate conditions, we carried out work on individual infrastructure systems of Hamilton City, varying monthly precipitation and temperatures within two- and three- times their (current) standard deviations. While quantitatively different, the qualitative model results presented below still hold. We therefore chose to report on the results that were explicitly based on historical data and trends from global circulation models, rather than arbitrary choices of variations within standard deviations.

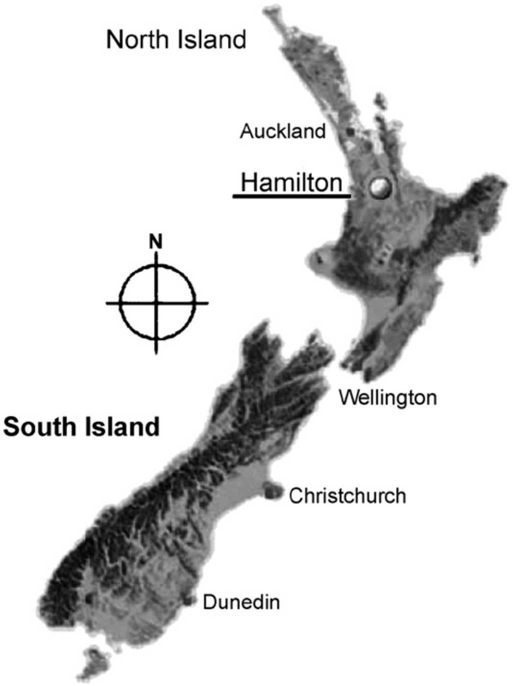

Fig. 1. Location map showing Hamilton in the North Island of New Zealand.

Table 2
Modelled temperature change (°C) between 1990 and 2030 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 | 0.4 | 0.87 |
| Spring | 0.29 | 0.62 | 0.3 | 0.65 |

Table 3
Modelled precipitation change (%) between 1990 and 2030 under four climate change scenarios at Ruakura station (Mullan, pers. comm.)

| | S1 | S2 | S3 | S4 |
|---|---|---|---|---|
| Summer | −12.7 | −5.8 | −2 | −0.9 |
| Autumn | 0.7 | 1.5 | −5.8 | −2.7 |
| Winter | −1.8 | −0.8 | 5.5 | 12 |
| Spring | −2.9 | −1.4 | −12 | −5.5 |

## 4. Methods overview

This study is interested in the interrelated performance of a broad set of Hamilton's ISS: water supply, transport, energy, ecosystems and public health under different assumptions about future climate. In particular, we investigate in detail the following aspects of this ISS set: water delivery and quality (water supply), road repairs and vehicle trips (transport), electricity distribution (energy), air quality (ecosystems) and mortality and morbidity (public health). These aspects were chosen because they present vital components of the quality of life and economic activity in Hamilton City and because at least a minimum amount of reliable and detailed data was available to establish empirical relationships between climate variables and system performance. Several other ISS, most notably communication and flood control, are not analysed here because of a current lack of access to data at the level and detail needed to carry out statistical analyses and computer modelling.

As a first step, the project team engaged local government agencies to help identify likely climate change impacts and relevant data sets. On the basis of historical information we received, we estimated the functional relationships between climate variables (see Appendix A) and observed infrastructure (dependent) variables. For each of these regression equations, we conducted standard statistical significance tests and, where necessary, we corrected for autocorrelation (using either Yule–Walker or Prais–Winsten transformations) and heteroscedasticity. For many of the models we employed monthly dummy variables for January–November to control for non-climate-related intra-annual variation in the dependent variables.[2] These intra-annual fluctuations provide the backdrop against which climate impacts must be assessed. Consequently, the utility of including climate variables in any analysis of potential future impacts on ISS increases to the extent that climate variables capture effects in addition to "normal" seasonal and annual trends.

The regression results were used to calculate potential future demand on the ISS for assumed changes in economic activity and population size, as well as the five different sets of climate scenarios described above. For all models we ran sensitivity analyses for the functional specifications by sampling parameters from a normal distribution around the mean parameter estimates in the regression results. Fifty such sensitivity runs were conducted for the base case and compared with the results (and standard deviations) derived from mean parameter estimates. The variation of results observed in those 50 sensitivity runs was within the range of results generated by the 250 model runs.

## 5. Results and discussion

The following sections summarise the results for climate impacts on water supply and quality, transport, energy demand, public health and air quality. In addition, we discuss the integrated impacts across the range of ISS. Note that while this study is focusing on the impacts on a local

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[2] We also investigated the importance of demographic changes (e.g. changes in household size) where appropriate. However, we found that available data and projections suggests that while population grows, the household size in Hamilton has remained, and is expected to remain, relatively constant over the analysis period.

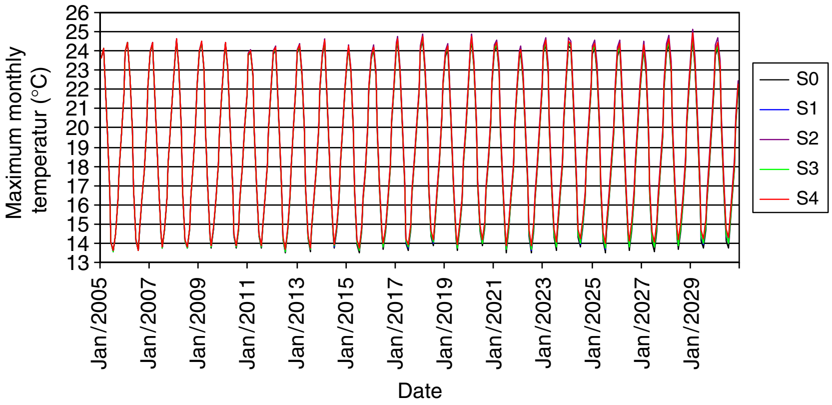

Fig. 2. Projected temperature regimes for Hamilton, 2005–2030, based on historical temperature (base case) and four climate change scenarios.

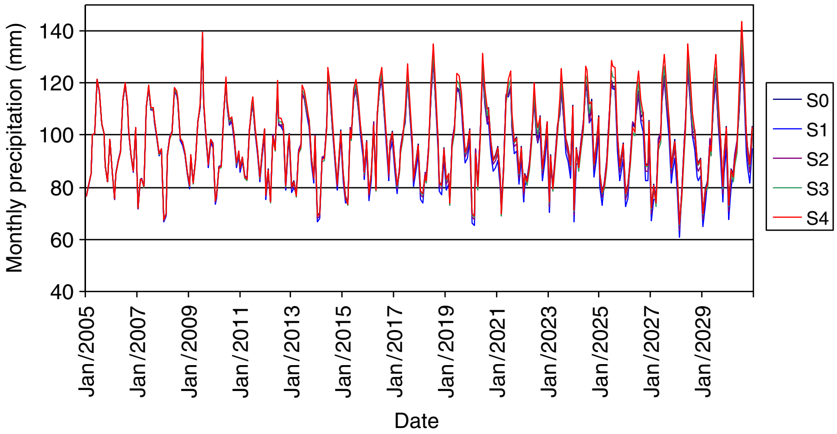

Fig. 3. Projected precipitation regimes for Hamilton, 2005–2030, based on historical precipitation (base case) and four climate change scenarios.

community, we expect that some of the lessons will be of relevance to cities in other temperate areas.

### 5.1. Water (supply and quality)

Hamilton city operates a single water treatment facility with a capacity of 85million litres (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 (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 use, this supply capacity could require extension to keep pace with demand. This supply capacity constraint is particularly an issue in the north of Hamilton City. This is because the water is abstracted from the river in the south of the city, while the city is growing to the north. The city has decided to upgrade its water supply infrastructure to the north to address this issue.

Furthermore, climate changes may make it either harder or easier to clean river water: increased rainfall might stir up more debris, whereas shifting temperatures could increase or decrease biological activity. Using turbidity as a proxy for how difficult the river water is to process, we also produced a model projecting climate change's impact on water processing.

Based on the regression analysis described in Appendix B, we found a significant and positive relationship between per capita water consumption and two temperature variables (MeanLgtTemp and Streaks26_3day (see Appendix A for a list of variables) and two measures of rainlessness (MaxRainlessStreak and DaysNoRain). The rainfall variable, Max3DayRain, exhibits a significant and negative relationship.

For water quality (turbidity) the regression analysis (Appendix B) indicates that every rainless day and every frost day lowers water turbidity. This is consistent with expectations because rain tends to wash debris into the river, which increases turbidity and frost days retard biological activity, which can cloud waters.

Using the functional relationships between water supply and quality and the socioeconomic and climate scenarios reveals that water usage is likely to increase under every scenario as a result of population growth (Fig. 4). By 2030, peak summer usage is 2800 ML/month under a "high" population projection, compared with 2350 ML/month

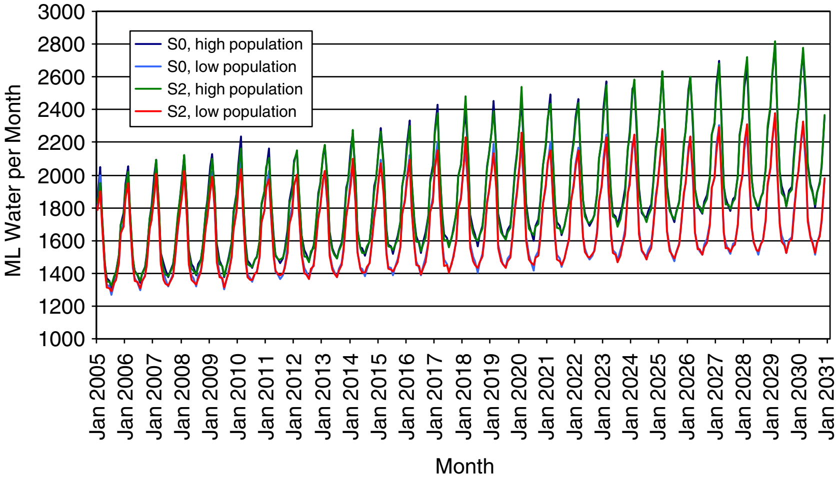

Fig. 4. Hamilton City water usage, 2005–2030.

under a "low" population projection. The impact of different climate scenarios, however, is much smaller. As Fig. 4 shows, the difference between S0 and one of the more extreme climate scenarios (S2) is negligible (less than 1% difference). 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.

Turbidity, as modelled, was not affected by the differences in population projection. However, the impact of differences in the climate scenarios was more noticeable than it was for water use. As Fig. 5 shows, by the end of the projection (2026–2030), monthly average turbidity is different—on the order of 10–20%—between two climate scenarios and the base case.[3] During winter months, as frost days decrease, turbidity tends to be higher than S0, although scenario outcomes are still relatively close to the base case.

This analysis offers a number of key insights into the next 25 years of drinking water supply/demand in Hamilton City and possible policy orientations that can address these issues. 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.

Second, as temperatures and rainfall increase, Hamilton should expect the turbidity of its waters to increase. While decreases in water clarity should have negligible impact on water treatment costs, city planners should keep such changes in mind when making equipment investment decisions. Hamilton City would be wise to consider other climate-affected factors, beyond turbidity, that may influence the costs and/or effectiveness of water treatment. For example, anecdotal evidence suggests that the incidence of toxic algal blooms in the Waikato River is increasing, but no accurate data was available for modelling the impact of this on water treatment.

### 5.2. Transport

Hamilton City's transport system is dominated by road[4] vehicle transport. Road length in Hamilton City has grown on average by 1.7% per annum since 1991 and vehicle-kilometres travelled increased from 465 million km in 1999 to 545 million km in 2004.

Our analysis of climate impacts on road transport looks at two aspects for which data are available; road repair costs and vehicle trips. It is acknowledged that the impacts of climate change on the transport system may transcend road repair and total trip demand. For example, extreme events may result in disruption of transport infrastructure, leading to some trips being impossible and others needing more circuitous routes. Unfortunately, in this study it was not possible to model these impacts from extreme events. This will be the focus of future CLINZI studies.

Data for cost of road repairs of Hamilton City (cf state-owned) roads are collected by the Hamilton City Council's transportation unit. No data for costs of repairs on state roads in the area could be obtained from Transit New Zealand. Data for the number of vehicle trips in Hamilton City come from seven permanent traffic monitoring stations maintained by the City Council's transportation unit.

The estimated relationship between climate and road repairs (see Appendix B) does not include temperature-related independent variables. This was consistent with

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[3] To show the results in greater detail, the time series is truncated to the last 5 years of the projections.

[4] A significant rail corridor passes through Hamilton City, but this is mostly used for through freight from Tauranga to Auckland. The Waikato River is also used for transport, but this is negligible.

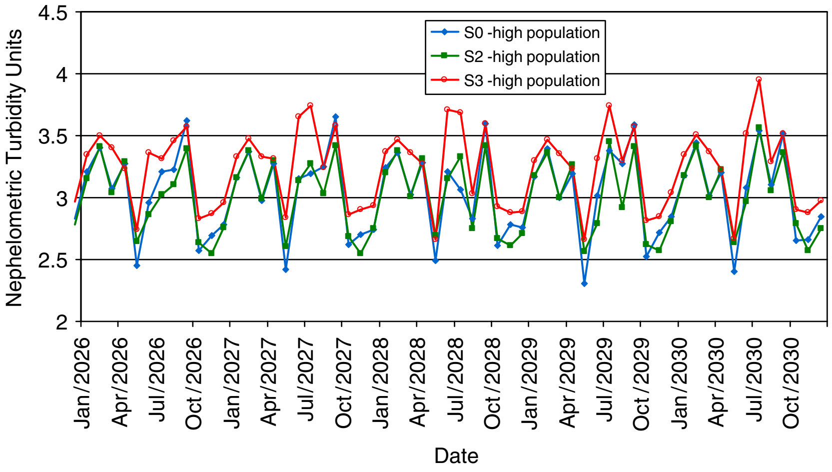

Fig. 5. Turbidity projections, 2005–2030.

comments made by the Roads and Traffic Unit's Asset Systems Manager that the major cause of road damage in Hamilton City is prolonged periods of rain (Cantlon, pers. comm.). Consistent with Cantlon's observations, the amount of rain above 20 mm, per day was significant at the 10% level and positive—the more days with more than 20 mm of rain, the more repairs were necessary. Similarly, the rainless streak variable has a significant and negative coefficient—longer periods with no rain reduce the costs of road damage in a given month.

The statistical model for trips per capita (see Appendix B) demonstrates that extended hot weather and heavy rainfall both correspond to depressed driving activity in Hamilton City. However, variability in driving behaviour is rather low to begin with, reflecting relatively little net climate impact on driving decisions on these roads.

In every scenario, total trips are projected to increase due largely to population growth. By 2030, total trips peak at over 5.4 million under a "high" population projection, compared with 4.5 million under a "low" population projection. The impact of different climate scenarios, however, is much smaller. The difference between S0 and one of the more extreme climate scenarios (S3) amounts to less than 0.2%. Despite the significance of climate variables in explaining the variation in monthly trips taken, the small magnitude of the change during the next 25 years combined with low variability in monthly trips results in a small magnitude of climate-change induced changes in the number of trips. Thus, in planning for changes in transport volumes and patterns, city planners should continue to pay greater attention to issues of economic and population growth than to gradual climate change.

Scenarios showed that road repair costs are tied indirectly to population growth. There are significant differences between repair cost projections under high and low population growth forecasts. On average, the high population scenarios have roughly 20% more road repair costs than the low growth cases.

Projected changes in rainfall lead to higher repair costs during the spring for S 2 (37% higher) and during the winter for S3 (34% higher) (Fig. 6). Decreases in rainfall during the spring and autumn for S3 balanced some of these costs increases by decreasing costs during those months relative to the base case. By 2030 we project 6% and 9% increases in road repair costs under S1 and S2, respectively, while S3 and S4 yield no change in the annual costs of repairs and a 4% reduction, respectively (Table 4).

While this translates into only small monthly costs, it does highlight the benefit of analysis of such detailed issues. Given this, further investigation into possible impacts on other road-related repairs and maintenance (such as road furniture, markings and even repair equipment itself) would be advised.

### 5.3. Energy

The energy module concentrates on impacts of climate change on electricity use and distribution assets. This focus was dictated by three considerations. First, electricity is one of the largest sources of energy in Hamilton City (about 25% of total delivered energy (Energy Efficiency and Conservation Authority, 2004)). Second, electricity use data at the desired level of temporal (monthly) and spatial (Hamilton City) detail are readily available. Unfortunately, this is not the case for other sources of energy such as natural gas, petroleum and wood. Third, as with most areas in New Zealand, Hamilton City has a relatively high temperature-sensitive electricity load (about 17% of total Hamilton City electricity load (Energy Efficiency and Conservation Authority, 2004)).

For our analysis, Hamilton City electricity use data were obtained from New Zealand's Electricity Commission. Half-hourly electricity distribution data (in kW) through the Hamilton area substations were available for the period 1 April 1984–31 March 2005. These data were

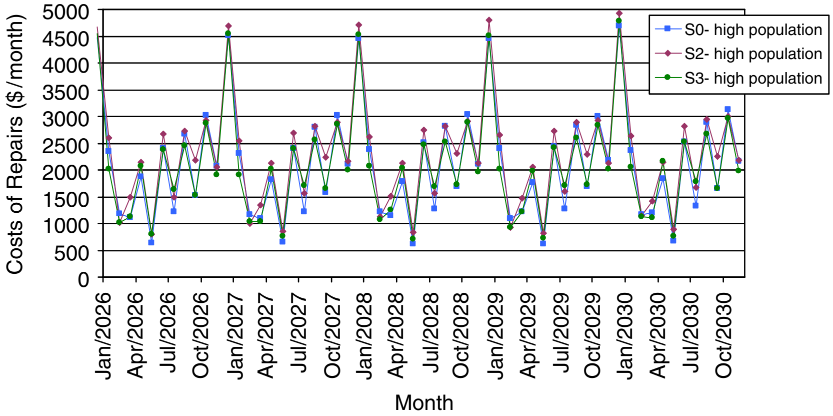

Fig. 6. Projected costs of road repairs under different climate scenarios, 2026–2030.

Table 4
Annual costs of road repairs relative to base case as of 2030

| Scenario | Change in cost |
|---|---|
| S1 | +6% |
| S2 | +9% |
| S3 | +0% |
| S4 | −4% |

aggregated to provide per capita monthly daily average electricity use.

With respect to physical distribution infrastructure, Hamilton City is fed by three substations, each operating 3-phase transformers, totalling 118 MVA theoretical capacity. However, the network is always operated to allow for one 23 MVA transformer to fail at any given time (Blackburn, pers. comm.). This means available capacity is essentially 95 MVA (or an equivalent of 81,225 kW).[5]

Regression analysis (see Appendix B) suggests Hamilton City's average monthly electricity consumption per capita is sensitive to changes in the total monthly heating degree days (HDD), calculated for 24-h mean temperatures using 15 °C as the threshold (HDD24_15). Electricity consumption in Hamilton is also influenced by the number of working days in the month (as a proxy for the economic activity in that month), a yearly dummy variable to account for changes in demand patterns that occur over time, monthly dummy variables to account for seasonal changes and heating degree days in May and July. The two monthly HDD variables were dominant in the model, indicating people are more sensitive to changes in temperature in May and July as they 'acclimatise'.

This model is similar in many ways to the model estimated by Fitzharris and Garr (1996) for New Zealand as a whole. Our model is also similar to the model developed by Amato et al. (2005) who find that when controlling for socioeconomic factors, degree day variables have significant explanatory power in describing historic changes in electricity demand.

In our modelling framework, climate change appears to have limited impact on electricity demand. Despite the significance of climate variables in explaining the variation in monthly electricity consumption, the small magnitude of the climate change during the next 25 years results in limited climate-change induced changes in electricity consumption. In Fig. 7 there appears to be little difference between climate scenarios. The two 'low climate-change' scenarios, not surprisingly, exhibit the least difference in electricity consumption to the base case (Table 5). Of these two scenarios, S3 (Hadley Low) suggests the least impact.

As noted above, Hamilton City's capacity infrastructure is relatively robust. However, two areas of potential interest are climate's impact on the proximity of peak-load electricity consumption to supply capacity constraints (see above) and climate's impact on conductor resistivity. Our analysis suggests Hamilton City is well endowed with supply capacity. Hamilton's electricity consumption and its progress towards the supply constraint, are more affected by the city's population than by climate and even in the high population scenario, power consumption in 2030 falls well below the supply constraint. Nevertheless, our analysis suggests that, as a result of climate changes, electricity distribution infrastructure is likely to require upgrading earlier (but only by 1 or 2 years) than would otherwise have been the case.

The impact of climate changes on conductor performance is also interesting to investigate because the performance of the electricity supply circuit significantly affects the quantity of electricity that can be supplied to consumers. In general, the higher the ambient temperature, ceteris paribus, the higher the resistivity of the circuit, until a design maximum, at which stage system failure is likely. Hamilton City's supply cables are all

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[5] Assuming a power factor of 0.95 and an availability of 0.9 (R. Blackburn, pers. comm.).

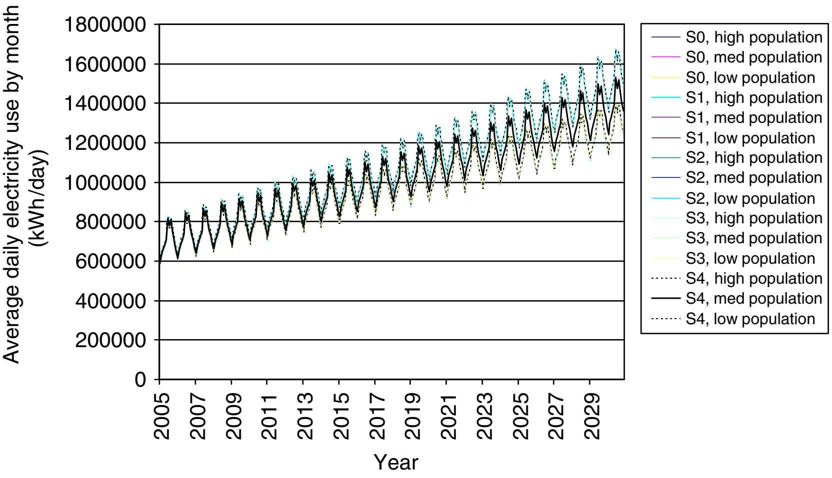

Fig. 7. Electricity use for all 15 Scenarios, 2005–2030.

Table 5
Summary statistics from the four scenarios, percent difference in electricity consumption from the base case

| Scenario | Mean | Std Dev | Maximum | Minimum | Range |
|---|---|---|---|---|---|
| S1 | −0.12% | 0.07% | −0.52% | 0.00% | 0.52% |
| S2 | −0.25% | 0.13% | −0.77% | −0.02% | 0.76% |
| S3 | −0.09% | 0.05% | −0.42% | −0.01% | 0.41% |
| S4 | −0.17% | 0.09% | −0.54% | −0.01% | 0.53% |

underground and are designed for the following climate parameters[6]:

- ground temperature (summer mean daily maximum) 25 °C,
- air temperature (summer mean daily maximum) 28 °C.

As none of the climate scenarios predict increased summer mean daily maximum air temperatures exceeding 28 °C, we can conclude that mean climate changes are unlikely to cause ambient-temperature-related failure of the conductor circuit.

However, the climate change scenarios will have an impact on the resistivity of the circuit. According to our calculations,[7] the climate scenarios are likely to reduce the circuit rating (in MVA) by 0.25–1% in summer and autumn, 0.3–0.7% in winter and 0.29–0.6% in spring. While these are not large changes, they do add additional restrictions on the circuit over and above those already planned for.

In summary, the Hamilton City electricity infrastructure distribution system appears to be very robust to mean climate change impacts. The City's physical infrastructure is well specified and designed to accommodate both growing loads and physical weather-related events. Hamilton's institutional capability in WEL Networks is also in excellent shape to address any climate-change related impacts.

### 5.4. Air quality

Air quality is the only aspect of ecosystem services for which we could access accurate data. Although weather conditions in Hamilton do not encourage extreme air pollution, future climatic conditions may alter emissions and thus exacerbate health impacts. Three types of air pollutants are examined in this study: particles less than 10 μm in size (Particular matter, $PM_{10}$), which are the main air quality parameter of concern in Hamilton (R. Jones pers. comm., Wilton, 2005), carbon monoxide (CO) and nitrogen oxides ($NO_x$). Each of these can have adverse impacts on ecosystem and human health. Human health impacts are assessed in the following section.

Daily time series of $PM_{10}$, CO, NO and $NO_2$ measured in Hamilton were acquired from Environment Waikato's regional monitoring database (1995). All air pollution components vary seasonally, with peaks in winter months.

Regression analysis (see Appendix B) suggests $PM_{10}$ concentrations are a nonlinear, increasing function of the number of heating degree days (calculated over a 24-h period at a balance point temperature of 14 °C). $PM_{10}$ concentrations tend to decrease with the amount of rainfall in a month. Particulate matter increases in May, as the cold season sets in and decreases in August, as the cold season eases. Through all of its significant variables, this model reflects the increased levels of $PM_{10}$ concentrations during cold weather, when the number of heating degree-days increases. This points to the well-known primary source of $PM_{10}$: emissions from heating, especially from wood fuel (Ministry for the Environment, 2003).

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[6] Faxed document from R. Blackburn—received 5 March 2005.

[7] Using the WEL Networks 33 kV line rating calculator.

The estimated equation for CO (Appendix B) indicates that the level of carbon monoxide varies positively with the number of cold days (as represented by HDD24_14) and negatively with the log of average wind speed. No time trend or seasonality have been detected for CO. However, the model shows increased levels of CO concentrations during cold weather, when the number of heating degree-days increases, which most likely implicates heating sources in CO generation.

A model of the influence of climatic variables on NO per capita included variables for average wind speed, monthly mean maximum temperature and the autumn season. Concentrations of NO vary seasonally (weakly significant), insofar as they are higher in the autumn.

The $PM_{10}$ forecasts show the most differentiation of all the air pollution models between climate change scenarios. Projections of $PM_{10}$ under climate scenarios are similar to the base-case scenario, with no distinguishable temporal trend but strong seasonal cycles (Fig. 8). The highest emissions occur in the base-case scenario, followed by S1, then S3, S2, and S4. In other words, due to increased temperatures, $PM_{10}$ emissions decline most under the extreme climate change scenarios as a result of reduced need for heating. Calls for improved housing standards, including better insulation and increased use of double-glazed windows, may contribute to quality improvements of residences in terms of dryer, warmer homes (Ministry for the Environment, 2005). This could further reduce the need for heating, regardless of the temperature and precipitation trends and thereby decrease the need to use home heating sources. (Fig. 9)

There is little difference between the scenario projections for the CO emissions, though the degree of differentiation increases somewhat through time, starting around 2010. CO emissions exhibit a smoother seasonal cycle than those for $PM_{10}$; the same cycle occurs with minima in summer

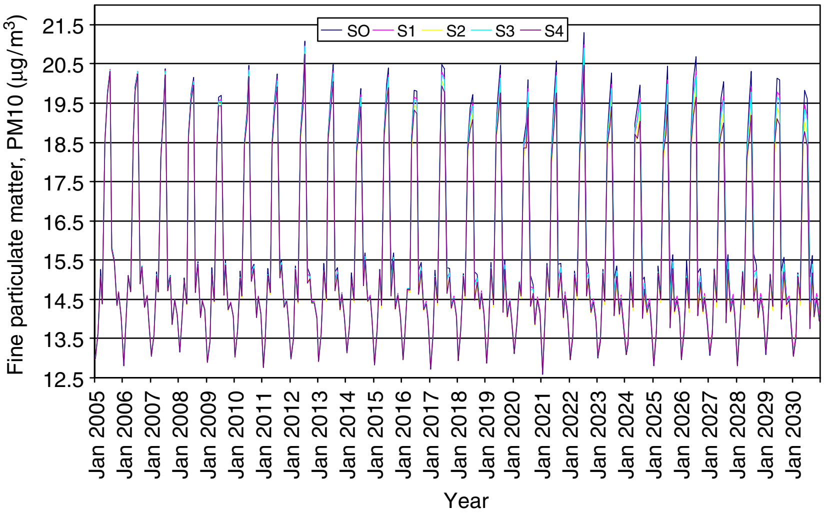

Fig. 8. Projections of fine particulate matter ($PM_{10}$), 2005–2030.

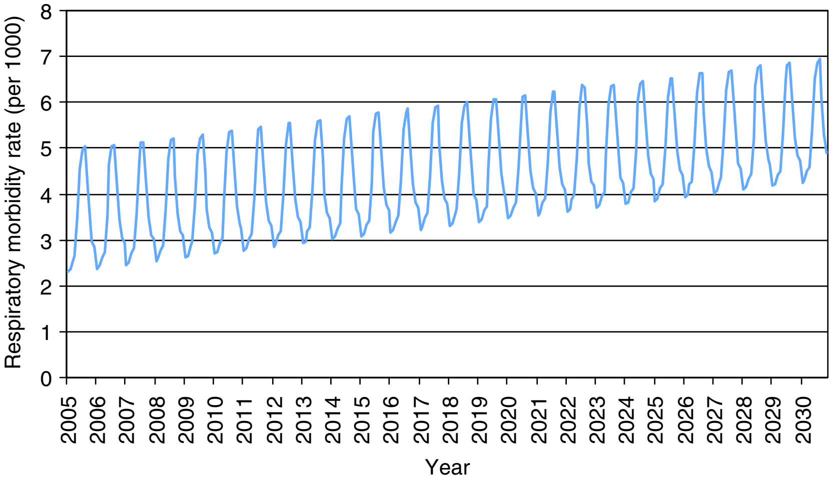

Fig. 9. Projected respiratory morbidity rate for the base-case scenario (S0), 2005–2030.

and maxima in winter. The amplitude remains consistent throughout the 2005–2030 time series and there is no temporal shift through this period.

Similar to other ISS, the effect of future population scenarios far outweighs the effect of mean climate changes for per capita nitric oxide emissions. Under every population scenario, the highest emissions occur under the base-case scenario. Among the climate change scenarios, S3 results in the highest NO emissions by 2030 (followed closely by S1 and S4). The S2 climate change projection results in the lowest NO emissions by 2030. Similar to other air pollutants, the same seasonal cycle is retained throughout the projection period. Emissions maxima occur in the autumn and winter, with a primary peak in May and a secondary one in July.

Overall, changes in average temperature and precipitation may play a small role in emissions of air pollutants in Hamilton. Population trends will drive an increase in air pollution; climate changes may ameliorate this effect slightly insofar as air pollutants have negative relationships with those climate variables that are projected to increase. To the extent that climate change contributes to more weather instability—with greater likelihood of extreme events, wind gusts and windier conditions overall—future conditions may result in fewer opportunities for air pollutants to concentrate over the city. Increasing wind may actually help curb air quality problems from climate change. From the projections run in this study, it seems unlikely that climate change alone would cause exceedances of any of New Zealand's ambient air-quality standards.

## 5.5. *Public health*

Several studies suggest climate change is likely to induce higher incidences of many human health problems. For example, Elmwood (1995) suggests greater exposure to ultra-violet radiation will increase the frequency of cataracts, skin cancers and sunburn. Also, as temperatures rise, summer smog is likely to cause more respiratory problems, particularly in the Auckland region (Woodward et al., 2001). Woodward et al. (2001) points out that new health problems may result from both heat waves and the colonisation of mosquitoes that carry diseases like malaria and dengue fever; pest eradication programmes are expensive and only partially successful, with many people reporting health complications from spraying. Further, warmer winters are expected to reduce the incidence of winter-related illnesses such as colds and flu and the need for open fires for heating, which contribute to air pollution.

Indirect health impacts are likely to occur as a result of floods and droughts. Heavy rain may disperse pathogens such as cryptosporidiosis into water supplies (Ministry for the Environment, 2001, p. 29). Drought periods will require the extraction of water from poorer quality sources with the resultant health risks.

The data used to quantify relationships between climate and morbidity and mortality rates have been supplied by the New Zealand Health Information Service. The data consist of admissions to the regional hospital and are classified by the primary cause of admission. Because only a fraction of people with health problems seek medical help and only a fraction of these do so at the general hospital, the analysis is clearly underreporting morbidity rates in the region. Furthermore, not all admissions to the regional hospital are of people from Hamilton, so the results are biased to the extent that visitors seek medical help in Hamilton and residents may seek help elsewhere.

We grouped the morbidity data into five major classes: injuries, circulatory problems, respiratory problems, infections and skin ailments. We report aggregate mortality rates as the statistical analysis did not support treating causes of mortality separately from each other.

### 5.5.1. *Morbidity*

For each morbidity variable we estimated separate equations (Appendix B). Of particular note in these regression equations are the results for per capita injuries, respiratory health problems per capita and mortality. Regression results for per capita injuries show that over time, the number of per capita injuries increases, though at a low rate and increases with the number of rainless days. These results are consistent with observations that the tendency for people to seek medical attention for injuries is increasing and that the number of injuries increases with more opportunities for outdoor activities (as inferred from an increase in rainless days).

The results for the respiratory illness equations have been derived in a two-stage least squares regression, because one of the explanatory variables of the model—the air quality indicator $PM_{10}$—is present in the regression equation in squared form and $PM_{10}$ is itself a function of climatic variables and seasonal change. $PM_{10}$ concentrations are a nonlinear, increasing function of the number of heating degree days (calculated over a 24-h period at a balance point temperature of 14 °C). $PM_{10}$ concentrations tend to decrease with the amount of rainfall in a month. Hospitalisation for respiratory ailments per capita increase over time and increase nonlinearly with increases in $PM_{10}$.

For all morbidity indicators climate change scenarios make no difference. That is, under the assumption that the future climate is like the past and that past trends in hospitalisation for injuries persist, then morbidity rates will continue to fluctuate seasonally and to increase slightly over the simulated 30-year time horizon. Furthermore, comparisons for selected years between the base case and scenarios reveal virtually indistinguishable dynamics. Results suggest that morbidity will predominantly be affected by past trends and seasonal fluctuations, but not by climate change. Amplitude of seasonal fluctuations also remains largely unchanged over time.

Except for circulatory morbidity, all results show increasing trends. Similar to the findings about changes

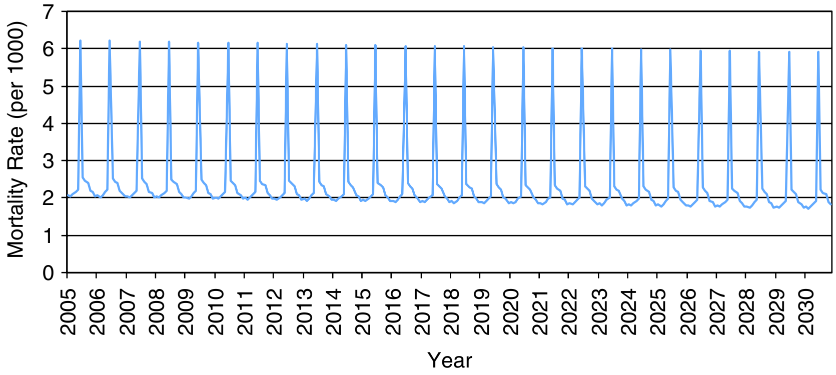

Fig. 10. Projected mortality rates for the base-case scenario (S0), 2005–2030.

in injuries, circulatory morbidity demonstrates clear seasonal fluctuations. However, circulatory morbidity rates show no discernable trend and remain, in the long term, around three cases per 1000. That pattern remains virtually unaffected by climate change.

### 5.5.2. *Mortality*

Our regression model for mortality finds an overall decline of mortality rates through time, but a persistent, statistically significant seasonal signal (Appendix B). Seasonality by itself explains nearly 30% of the variation in the data. Consistent with the literature, there are nonlinear relationships between increases in mean temperatures and increases in mortality rates. However, no impacts of daily extreme temperatures on mortality rates were found. The absence of clearly discernible heat or cold thresholds from our analysis is in large part due to the small number of temperatures on record which are sufficiently extreme to trigger increases in mortality rates. Nonetheless, regression results indicate that prolonged cold spells (events with 3 or more days below 0 °C) do tend to increase mortality rates.

For the purposes of this section, we compare the usual suite of scenarios with a hypothetical "extremes" climate change case.[8] The assumptions for this hypothetical case are well outside the extremes reported for CSIRO and Hadley Centre climate models and were chosen to explore the implications of unprecedented variation in climate conditions.

The morbidity rates discussed above all show notable seasonal fluctuations and long-term increases. In contrast, mortality rates—though also exhibiting marked seasonal fluctuations—tend to decline slightly over time (Fig. 10). The differences in the behaviour of these two sets of health indicators may largely be attributable to a combination of changes in behaviours and health care provision. While improvements in care tend to induce demand for care, they tend also to reduce mortality rates. However, even though mortality rates do decline, the extent of that decline is rather small (compared with the extent by which some of the morbidity rates increase).

In summary, the results indicate that seasonal fluctuations and annual trends are likely to be far more relevant in explaining possible future variations in morbidity and mortality than are climate parameters. However, the annual trend embeds information about changes in behaviours, improvements in healthcare (such as early detection, education, patient care) and improvements in and diffusion of technology (from ointments for protection of skin against UV radiation to inhalers for treatment of asthma or proliferation of air conditioning to reduce impacts of heat), all of which counteract any of the adverse health impacts associated with longer-term climatic conditions. Reducing vulnerability to climate change will require maintaining the changes in behaviours and improvements in health care and technology at rates comparable to those observed in the past.

## 5.6. *Climate change impacts on the interconnected ISS*

The emphasis of this project was on understanding the impact of climate changes on the interconnected ISS in Hamilton City. Limited project budget and data constraints us from quantifying all interactions between and within ISS. Nevertheless, it is possible to qualitatively assess the impacts of climate change on the integrated ISS network.

Our analysis and interviews with ISS managers and policy makers in Hamilton city, suggest several areas where impacts in one infrastructure system could influence another (see Table 6). Reading the table horizontally shows the impacts of one infrastructure system on another. Reading the table vertically shows possible impacts on that infrastructure system from all the systems analysed.

As can be seen, the impacts of one infrastructure system in many cases could also negatively impact on the

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[8] In this hypothetical extreme case the deviations from past climate are assessed as a gradual increase in temperatures by 5 °C between 1990 and 2030, which is uniformly applied across the seasons. Additionally, we assume precipitation will decline between 1990 and 2030 by 24% on average in summer months, by 10% in autumn, and by 5% in spring, while precipitation in winter is assumed to increase by 12%.

Table 6
Evaluation of climate-change impacts across and between different ISS

| | Water | Transport | Energy | Air quality | Public health |
|---|---|---|---|---|---|
| Water | Little impact on water consumption, possible increase in turbidity—increased treatment costs? | NA | Possible increase in energy use for water treatment if increases in turbidity require larger energy inputs into treatment | NA | Little impact on water demand potential for health impacts if water supply disrupted by extreme events |
| Transport | NA | Little impact on trips. Possible increase in road repair costs—consequent increase in congestion? | NA | Increased trips due to population pressure likely to increase traffic-based atmospheric pollutants | Increased air emissions from increased traffic provide potential for increased health impact |
| Energy | Disruption of electricity supply could disrupt water supply and treatment | Disruption of electricity supply could disrupt traffic signals—unlikely except in extreme events | Extension of summer conditions into autumn means less electricity demand and reduced use of wood burning stoves<br>Increased penetration of AC in summer increases summer peak | Potential for less emissions from wood burning stoves in autumn | Disruption of electricity supply could disrupt public health provision |
| Air quality | Pollution to acid rain impacts on acidity of water supply | NA | NA | Little impact from gradual climate change on air quality | Potential decrease in air emissions-related public health issues in autumn |
| Public health | NA | NA | NA | NA | Little impact from gradual climate change on public health |

performance of other infrastructure systems. Our analysis suggests that the ISS that are likely to impact the widest range of other ISS are energy and transport. That is, these two ISS have the largest number of impacts cutting across infrastructure systems. While discussion with ISS managers suggests that the energy system is relatively robust, this is not necessarily the case with the road transport system. There is a potential that the flow on effects from climate-related events could cause significant disruption to road transport in Hamilton city. This impact was not captured in the quantitative modeling.

Reading the table vertically indicates that public health followed by air quality are the ISS most effected by other systems. These interactions are important because they have the potential to magnify any negative impacts caused by climate change alone in an infrastructure system. For example, the water consumption analysis found that climate change generally has limited impact on water use. We consider that once the combined impacts due to water quality, energy supply and other impacts are included, then the overall impact due to climate change will likely be negative.

As a result of the potential for unquantified climate-related flow-on impacts between interconnected ISS, we conclude that the picture of Hamilton city as being immune from climate change impacts is imprudent. We urge ISS managers in Hamilton city to continue to assess the risk of climate change to the interconnected network of Hamilton city infrastructure.

## 6. Recommendations and conclusions

As a result of this study, we are able to make several recommendations relating to ISS policies as well as data requirements and areas for future research. These recommendations were presented to stakeholders and are now the focus of discussions as part of the follow up to this study.

The results of this study differ significantly from those of other studies such as Kirshen et al. (2006) on metropolitan Boston, Bloomfield et al. (1999) on Los Angeles or Rosenzweig et al. (2000) on New York. This is because the Hamilton climate is quite different from the climates of other cities studied. For example, climate scenarios for Hamilton suggest mild mean temperature and preciptation changes compared to the more severe predictions for the Boston area. Also, Hamilton differs geographically from other cities—for example, Hamilton does not suffer from the sea-level-rise risk that threatens Boston. The clear differences between Hamilton and other urban centres where climate change impacts have been studied supports our claim that climate change impact studies must be conducted at a local scale.

While our findings are specific to Hamilton City, New Zealand, some of the lessons will be of interest to researchers and ISS managers around the globe, particularly those investigating impacts on communities in temperate climates. Nevertheless, there are some climate-related issues that are unique to Hamilton. In particular, Hamilton's inland location means it does not have an issue with sea-level changes. Also, most of Hamilton sits 30 m above the Waikato river. Therefore, it is not prone to widespread flooding risk.

## 6.1. Policies

### 6.1.1. General

Across all infrastructure systems, policy makers would be wise to continue to focus on demographics when planning for system upgrades. Many of the infrastructure systems we investigated demonstrated greater responsiveness to population changes than changes in gradual climate change. However, as a result of the potential for unquantified climate-related impacts between interconnected ISS, we conclude that the picture of Hamilton city as being immune from climate change impacts is imprudent. Future planning decisions should still be sensitive to the risk of climate change.

### 6.1.2. Water treatment

With respect to water treatment, while modest decreases in water clarity would have negligible impact on water-treatment costs, city planners should keep such changes in mind when making equipment investment decisions. This thinking also extends beyond turbidity and water treatment, in that some of the more subtle impacts of climate change—such as water clarity—may occur where cities face unforeseen impacts on infrastructure capabilities. Hamilton City would be wise to consider what other factors, beyond turbidity, influence the costs and/or effectiveness of water treatment and ascertain whether changes in climate could lead to changes in these factors, which in turn could lead to costly changes in equipment or process needs.

### 6.1.3. Water supply

If climate change produces conditions that lead to heightened water use, urban supply capacity could require extension to keep pace with demand. This is particularly likely to be the case in the north of the city.

### 6.1.4. Electricity use

In addition to planning for changes in Hamilton City demographics, electricity distribution and retail companies need to consider the impact of changes in ambient temperatures on circuit resistivity and consequent operating costs. Changes in operating costs—even small increases—could impact on the company's profitability. Further, our analysis suggests that, as a result of climate changes, electricity distribution infrastructure is likely to require upgrading slightly earlier (by 1 or 2 years) than would otherwise have been the case.

### 6.1.5. Air quality

From projections run in this study, it seems unlikely that climate change alone will cause exceedance of ambient air standards.

### 6.1.6. Public health

Reducing vulnerability to climate change will require both the public and health providers to maintain the changes in behaviours and improvements in health care and technology at rates comparable to those observed in the past.

## 6.2. Data needs and future research

As with all research projects, the scope of this study has been dictated to a large extent by the availability of data. More extensive collection and more efficient sharing of time series data for each of the relevant infrastructure systems and services would enable research expansion in three aspects: temporal detail, spatial scope and climate extremes. Rather than modelling climate changes and impacts on infrastructure using a monthly time step, it is necessary to conduct future research at a daily level because it is often peak events that determine the adequacy of an infrastructure system. This will allow greater connection among climate events, infrastructure impacts and infrastructure management.

The spatial scope of this study was limited because of resource constraints. However, future research needs to expand the study boundary to include the wider infrastructure systems that feed Hamilton City. For example, it is important to consider not only the electricity distribution system within Hamilton City, but also the electricity generation and supply systems that feed the city. These physical structures, which lie outside the city boundary, are also vulnerable to changes in climate and this vulnerability needs to be considered an integral part of any future research on climate change impacts on Hamilton City.

The relevance of this study has also been limited by investigating only gradual climate changes. Many infrastructure systems are designed on the basis of accommodating extreme events and future research on climate change impacts on infrastructure must include an allowance for changes in the frequency and intensity of extreme weather events.

Despite these limitations, we do not resile from the assertion that communities need to consider the impacts of climate change on their ISS. We hope that this research has contributed to an improved understanding of these issues.

## Acknowledgements

This paper was made possible, in part, by support from Landcare Research Ltd's Non-Specific Output Funding, the University of Maryland's Roy F. Weston Chair in Natural Economics, Environment Waikato's Lifelines Group and Australia's CSIRO.[9]

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[9] This project would not have been possible without assistance from several local Hamilton agencies. In particular, the Hamilton City Council has provided significant assistance with data collection across a range of different areas. The project has also benefited from the strong support of WEL Networks and Transit New Zealand. The authors would also like to thank Brett Mullan of NIWA for the generous assistance with climatalogical data.

## Appendix A

See Table 7.

Table 7
Monthly climate variables used in regression analysis

| Variable | Description |
|---|---|
| AvgWindSpd | Monthly average wind speed (mps) |
| CDD24 X | Total cooling degree days during month based on 24 h mean temps, using $X$ °C as the threshold temperature |
| CDDL X | Total cooling degree days during month based on daylight mean temps, using $X$ °C as the threshold temperature |
| DaysAbove26 | Number of days during the month with max temperature above 26 °C |
| DaysBelow0 | Number of days during the month with min temperature below 0 °C |
| DaysNoRain | Number of days during the month with no rainfall |
| DaysRainAbove20 | Number of days during month with rainfall above 20 mm |
| HDD24 X | Total heating degree days during month based on 24 h mean temps, using $X$ °C as the threshold temperature |
| HDDL X | Total heating degree days during month based on daylight mean temps, using $X$ °C as the threshold temperature |
| MaxMean | Monthly mean maximum daily temperature (°C) |
| MaxRainlessStk | length, in days, of the longest period with no rainfall (counting streaks that begin before the month in question) |
| Mean24Temp | Monthly mean of daily mean 24 h temps (calculated as a daylight-dependent weighted average of min and max temps for each day) (°C) |
| MeanLgtTemp | Monthly mean of daily mean daylight temps (calculated as .71*maxtemp + .29*mintemp for each day) (°C) |
| MinMean | Monthly mean minimum daily temperature (°C) |
| MonthRain | Total monthly rainfall (mm) |
| MaxXDayRain | Maximum total rainfall during a $X$-day period during the month (values generated for $X = 1, 3, 7$ and 10) |
| Maxtemp | Maximum max temperature during month |
| Mintemp | Minimum min temperature during month |
| Streakabove26 | Longest streak of days at or above 26 °C |
| Streakbelow0 | Longest streak of days at or below 0 °C |
| Streaks26_3day | Number of 3-day streaks at or above 26 °C |
| Streaks0_3day | Number of 3-day streaks at or below 0 °C |
| MMrain20 | Total number of millimetres of rain above 20 per day during the month (similar to heating/cooling degree days) |

## Appendix B. Results from regression analysis

See Table 8.

Table 8

| Independent variable | Dependent variable | | | | | | |
|---|---|---|---|---|---|---|---|
| | Water consumption | Turbidity | Trips per capita | Costs of repairs per capita | Electricity demand | Fine particulate matter (PM10) | Carbon monoxide (CO) |
| Constant | 9.11<br>(0.000) | 9.26<br>(0.000) | 28.84<br>(0.000) | 0.032<br>(0.000) | | 245.33<br>(0.000) | |
| Intercept | | | | | 2.56<br>(<0.0001) | | 0.43<br>(<0.0001) |
| Workday_percent | | | | | 1.01<br>(<0.0001) | | |
| Year_dummy | | | | | 0.0099<br>(<0.0001) | | |
| 1norain | | −2.29<br>(0.003) | | | | | |
| LogAvWindSpd | | | | | | | −0.42<br>(0.0385) |
| DaysBelow0 | | −0.351<br>(0.004) | | | | | |
| DaysNoRain | 0.0075<br>(0.000) | | | | | | |
| HDD24_14_sq | | | | | | 0.0067<br>(0.000) | |
| HDD24_14 | | | | | | | 0.0025<br>(<0.0001) |

Table 8 (*continued*)

| Independent variable | Dependent variable | | | | | | |
|---|---|---|---|---|---|---|---|
| | Water consumption | Turbidity | Trips per capita | Costs of repairs per capita | Electricity demand | Fine particulate matter (PM10) | Carbon monoxide (CO) |
| HDD24_15 | | | | | 0.0021 | | |
| | | | | | (<0.0001) | | |
| HDD_15_May | | | | | 0.0026 | | |
| | | | | | (0.0177) | | |
| HDD_15_July | | | | | 0.0021 | | |
| | | | | | (0.0022) | | |
| MaxRainlessStk | 0.00076 | | | −0.00046 | | | |
| | (0.0026223) | | | (0.019) | | | |
| Mean24Temp | 0.0026 | | | | | | |
| | (0.001277) | | | | | | |
| MeanLgtTemp | 0.011 | | | | | | |
| | (0.002) | | | | | | |
| MonthRain | | | | | | −0.49 | |
| | | | | | | (0.002) | |
| Max3DayRain | −0.00082 | | | | | | |
| | (0.001) | | | | | | |
| Streaks26_3day | 0.0026 | | −0.75 | | | | |
| | (0.001277) | | (0.002) | | | | |
| MMrain20 | | | −.014 | 0.00014 | | | |
| | | | (0.028) | (0.076) | | | |
| January | 0.027 | 0.71 | −0.34 | −0.013 | −0.15 | −38.20 | |
| | (0.192) | (0.226) | (0.684) | (0.039) | (<0.0001) | (0.232) | |
| February | 0.052 | 1.00 | 0.99 | −0.021 | 0.20 | −18.64 | |
| | (0.033) | (0.088) | (0.047) | (0.005) | (<0.0001) | (0.569) | |
| March | −0.024 | 0.56 | 0.93 | −0.020 | 0.25 | 23.73 | |
| | (0.273) | (0.356) | (0.038) | (0.001) | (<0.0001) | (0.458) | |
| April | −0.16 | 0.69 | −0.42 | −0.014 | 0.24 | −1.55 | |
| | (0.000) | (0.275) | (0.350) | (0.038) | (<0.0001) | (0.964) | |
| May | −0.17 | 0.0065 | .47 | −.025 | 0.23 | 73.40 | |
| | (0.000) | (0.991) | (0.286) | (0.001) | (0.1097) | (0.024) | |
| June | −0.13 | 1.86 | −0.13 | −0.013 | 0.89 | −2.23 | |
| | (0.000) | (0.005) | (0.763) | (0.044) | (<0.0001) | (0.953) | |
| July | −0.16 | 2.29 | 0.18 | −0.019 | 0.54 | −30.35 | |
| | (0.000) | (0.010) | (0.674) | (0.004) | (<0.0001) | (0.495) | |
| August | −0.13 | 1.01 | 0.36 | −0.013 | 0.84 | −120.17 | |
| | (0.000) | (0.178) | (0.395) | (0.104) | (<0.0001) | (.002) | |
| September | −0.13 | 0.86 | 0.25 | −0.017 | 0.52 | −24.22 | |
| | (0.000) | (0.122) | (0.539) | (0.013) | (<0.0001) | (0.437) | |
| October | −0.11 | −0.14 | 0.58 | −0.011 | 0.28 | −16.01 | |
| | (0.000) | (0.797) | (0.119) | (0.059) | (<0.0001) | (0.602) | |
| November | −0.017 | −0.128 | 1.39 | −0.015 | 0.21 | 8.21 | |
| | (0.346) | (0.792) | (0.000) | (0.0.016) | (<0.0001) | (0.785) | |
| Observations | 108 | 46 | 30 | 61 | 179 | | 86 |
| Adjusted $R^2$ | 0.9849 | 0.4762 | 0.9900 | 0.2317 | 0.9508 | | 0.5106 |
| Durbin-Watson (trans) | 2.002040 | 1.832980 | 2.420853 | 1.893188 | 1.8297 | | 1.995 |

| Indep variable | Dep variable | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Nitric oxide (NO) | Per capita injuries | Circulatory health problems per capita | Respiratory health problems per capita | Pm10sq | Infections per capita | Skin diseases per capita | Mortality per capita |
| Intercept | 0.0010 | 0.0029545 | 0.0027943 | 0.0010436 | 245.332 | 0.0003094 | 2.05e−06 | 0.0016359 |
| | (<0.0001) | (0.000) | (0.000) | (0.019) | (0.000) | (0.000) | (0.988) | (0.000) |
| time | | 8.87e−06 | | 6.50e−06 | | 3.31e−06 | 3.36e−06 | −1.02e−06 |
| | | (0.000) | | (0.005) | | (0.000) | (0.000) | (0.000) |
| Pm10sq | | | | 2.00e−06 | | | | |
| | | | | (0.037) | | | | |

Table 8 (*continued*)

| Indep variable | Dep variable | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Nitric oxide (NO) | Per capita injuries | Circulatory health problems per capita | Respiratory health problems per capita | Pm10sq | Infections per capita | Skin diseases per capita | Mortality per capita |
| logWind | −0.00032 | | | | | | | |
| | (0.0039) | | | | | | | |
| summer | 0.000080 | | | | | | | |
| | (0.25) | | | | | | | |
| fall | 0.00011 | | | | | | | |
| | (0.067) | | | | | | | |
| winter | 0.000018 | | | | | | | |
| | (0.69) | | | | | | | |
| CDD24 22sq | | | | | | | | 1.30e—06 |
| | | | | | | | | (0.000) |
| Days Below0 | | | 0.0000158 | | | | | |
| | | | (0.123) | | | | | |
| DaysNo Rain | | 0.0000101 | | | | | | |
| | | (0.038) | | | | | | |
| Hdd118 | | | | | | 5.93e−07 | | |
| | | | | | | (0.001) | | |
| | | | | | 0.0066685 | | | |
| | | | | | (0.000) | | | |
| MaxMean | −0.000029 | | | | | | | |
| | (0.0008) | | | | | | | |
| Month | | | | | −0.4891948 | | | |
| | | | | | (0.002) | | | |
| Rain Maxtemp | | | | | | | 0.0000105 | |
| | | | | | | | (0.041) | |
| Streaks0_3day | | | | | | | | 0.0000273 |
| | | | | | | | | (0.087) |
| January | | −0.0001607 | −0.0001712 | −0.0004163 | −38.2036 | | 0.0000335 | 0.0000182 |
| | | (0.088) | (0.025) | (0.092) | (0.232) | | (0.145) | (0.777) |
| February | | 0.000159 | −0.0001592 | −0.0004086 | −18.63959 | | 0.0001333 | −0.0000173 |
| | | (0.197) | (0.112) | (00.097) | (0.569) | | (0.000) | (0.774) |
| March | | 0.0002222 | −0.000052 | −0.0003116 | 23.73192 | | 0.0001136 | 0.0000389 |
| | | (0.057) | (0.620) | (0.211) | (0.458) | | (0.000) | (0.558) |
| April | | −0.0000518 | 0.0000825 | −0.0001759 | −1.54848 | | 0.0001016 | 0.0001171 |
| | | (0.672) | (0.498) | (0.504) | (0.964) | | (0.000) | (0.080) |
| May | | −0.0001526 | 0.0002755 | 0.0003413 | 73.39592 | | 0.0001014 | 0.0001773 |
| | | (0.197) | (0.031) | (0.223) | (0.024 | | (0.009) | (0.005) |
| June | | −0.0002807 | 0.00027 | 0.001351 | −2.232946 | | 0.0001121 | 0.0003713 |
| | | (0.019) | (0.042) | (0.000) | (0.953) | | (0.028) | (0.000) |
| July | | −0.000455 | 0.0003787 | 0.0016988 | −30.34519 | | 0.0001041 | 0.0004535 |
| | | (0.000) | (0.005) | (0.000) | (0.495) | | (0.045) | (0.000) |
| August | | −0.0002159 | 0.0003186 | 0.002094 | −120.1727 | | 0.0000728 | 0.0003996 |
| | | (0.067) | (0.010) | (0.000) | (0.002) | | (0.165) | (0.000) |
| September | | −0.0001885 | 0.0002608 | 0.0012427 | −24.22444 | | 0.0000632 | 0.0003582 |
| | | (0.097) | (0.010) | (0.000) | (0.437) | | (0.154) | (0.000) |
| October | | −0.0000889 | 0.0002421 | 0.0005088 | −16.00725 | | 1.00e−05 | 0.0001498 |
| | | (0.414) | (0.003) | (0.031) | (0.602) | | (0.796) | (0.024) |
| November | | 0.0001284 | 0.0002136 | 0.0000914 | 8.212153 | | 0.0000133 | 0.000102 |
| | | (0.150) | (0.000) | (0.697) | (0.785) | | (0.634) | (0.107) |
| Observations | 28 | 192 | 192 | 66 | 66 | 192 | 192 | 168 |
| Adjusted $R^2$ | 0.82 | 0.5178 | 0.1634 | 0.8374 | 0.6943 | 0.4510 | 0.7278 | 0.5561 |
| Durbin-Watson(trans) | 1.91 | 2.237482 | 2.675609 | 1.51 | 1.51 | 2.025194 | 2.045048 | 1.929921 |

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