Impacts of Climate Change on Urban Infrastructure & the Built Environment

A Toolbox

Tool 4.7: Adaptation by design: impact of climate and land use change on the sizing of stormwater management devices

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1. Introduction

This tool uses publically available guidance and design methods to investigate the possible impacts of climate change and continued urbanisation on the sizing of stormwater management devices. Stormwater management devices are becoming increasingly common in New Zealand and have been suggested as a possible means of adapting to climate change. The devices investigated are wet detention ponds and raingardens. The devices are fundamentally different in their size, function and where they are placed in the stormwater system. Ponds are large devices intended for both water quality and quantity control typically placed at or near the catchment outlet (i.e., end-of-pipe). Raingardens are small devices intended primarily for on-site water quality control.

1.1 Case-study context

Tools 2.4.2 and 2.4.3 showed that the main guidance material used by local government in the Auckland region for stormwater management is the *Preparing for Climate Change Guidance Manual* published by the Ministry for the Environment (MfE, 2008). This manual is also known as the *Red Book* and follows a risk assessment process to identify the impacts of climate change related hazards to local government services and activities, to evaluate their associated risks, and to adapt to those risks. Central to the risk assessment process is the use of mathematical models to qualify and quantify changes in system response to climate change. MfE (2008) recommends use of adjusted extreme rainfalls as part of preliminary screening within the risk assessment process. Extreme rainfalls are artificial events with an intensity, duration and frequency (IDF) relationship statistically derived from the historic rainfall record. Under the guidance, the intensity of an extreme rainfall with a particular frequency and duration is adjusted empirically as a function of the projected change in annual mean air temperature on the understanding that warm air is able to hold more moisture than cool air.

The IDF concept is very familiar to stormwater engineers and adjusted extreme rainfalls have been used for event-based modelling for system capacity and flood risk assessments (see Tools 2.4.2 and 2.4.4 for an overview of Auckland climate change examples). Use of extreme rainfalls is also at the heart of local and national design criteria for stormwater management devices (see Tool 2.4.3). That is, an IDF design-storm is an extreme rainfall with a specific duration and frequency that satisfies local water management goals in relation to the acceptable frequency of failure. Stormwater infrastructure including both pipe networks and stormwater management devices is then designed to accommodate the runoff generated by the design-storm. Familiarity with the concept of design-storms has meant that the MfE approach to adjusting extreme rainfalls is being incorporated into national and local design criteria as a means of taking climate change into account during the design phase. Examples include the NZ standards for Land and Subdivision Infrastructure (NZS 4404:2010) and the New Zealand Transport Agency criteria for managing road runoff (NZTA, 2010).

This tool has three objectives, to:

1. Assess how land use and climate change may affect the design of stormwater management devices in Auckland over the coming century;

2. Develop a method for communicating the range of sizes possible and the sensitivity of device design to both climate and land use change; and

3. Demonstrate the potential use of the method by investigating adaptation strategies for stormwater management.

Here, design refers to the sizing of stormwater management devices (i.e., volume and surface area). Other aspects of design, such as inlet and outlet type and configuration, vegetation and flow pathways are not considered. Changes in water quality due to changed contaminant sources and accumulation and wash-off rates are also outside the study scope. The investigation has been performed using guidelines and information publicly available in New Zealand to make the proposed methodology as accessible as possible to a wide range of stakeholders. The changes in size required are calculated using sizing criteria for the Auckland region (Auckland Regional Council Technical Publication 10, ARC, 2003 – henceforth referred to as TP10) Runoff is calculated according to Technical Publication 108 (ARC 1999 –TP108). Urban development is accounted for by changing imperviousness in the runoff calculation.

2. Stormwater management devices and adaptation

The impacts of urbanisation due to population growth and urban development on local water resources are generalised in Figure 1. The flow chart is separated into sections based on the European Environment Agency 'Drivers-Pressures-State-Impact-Response' (DPSIR) framework (Smeets and Weterings, 1999). Under the framework, drivers exert pressures on the system, changing the state of the environment, to cause an impact or risk of impact which elicits a response that feeds back to all stages in the system.

The move towards use of stormwater management devices in the region is largely a response to those impacts and has been encouraged in Auckland for a number of years (e.g. ARC, 2001). The devices are also known variously as sustainable urban drainage systems (SUDS) and structural best management practices (BMPs). They include detention and retention facilities (e.g., ponds and wetlands, downpipe water butts, green roofs), infiltration devices (e.g., infiltration trenches and surfaces, porous paving) and bio-filtration devices (e.g., raingardens, vegetated swales). These devices have dual stormwater management functions for water quantity and quality control. In some instances, they can also be used for rainwater harvesting to augment water supplies. In addition to stormwater management, the devices can offer ecological, social and amenity values and are often constructed as part of urban blue-green corridors. Their multi-functionality means that they can add resilience to urban water systems, and are therefore an integral part of low impact or water sensitive urban design (e.g., Wong and Brown, 2009; van Roon, 2007; Pahl-Wostl, 2007; Brown and Clark, 2007).

The emergence of stormwater management devices has been roughly parallel to, but separate from, rising concerns over global warming. Changes in climate enter Figure 1 as a third driver by changing rainfall and therefore runoff generation, and, during dry spells, water supply demands. The ability of stormwater management devices to store and attenuate surface flows means that they have been mooted as possible adaptations for reticulated stormwater and combined sewer networks to the long-term environmental risks associated with climate change, particularly in regions where increased rainfall is expected to lead to increased hydraulic loading and flood risk (e.g., Scholz and Yang, 2010; Semadeni-Davies et al., 2008 a and b; Ashley et al., 2008; Shaw et al., 2007; Watt et al., 2003). Stormwater management devices may also provide evaporative cooling for urban areas at risk of heat-waves (e.g., Coutts et al., 2010)

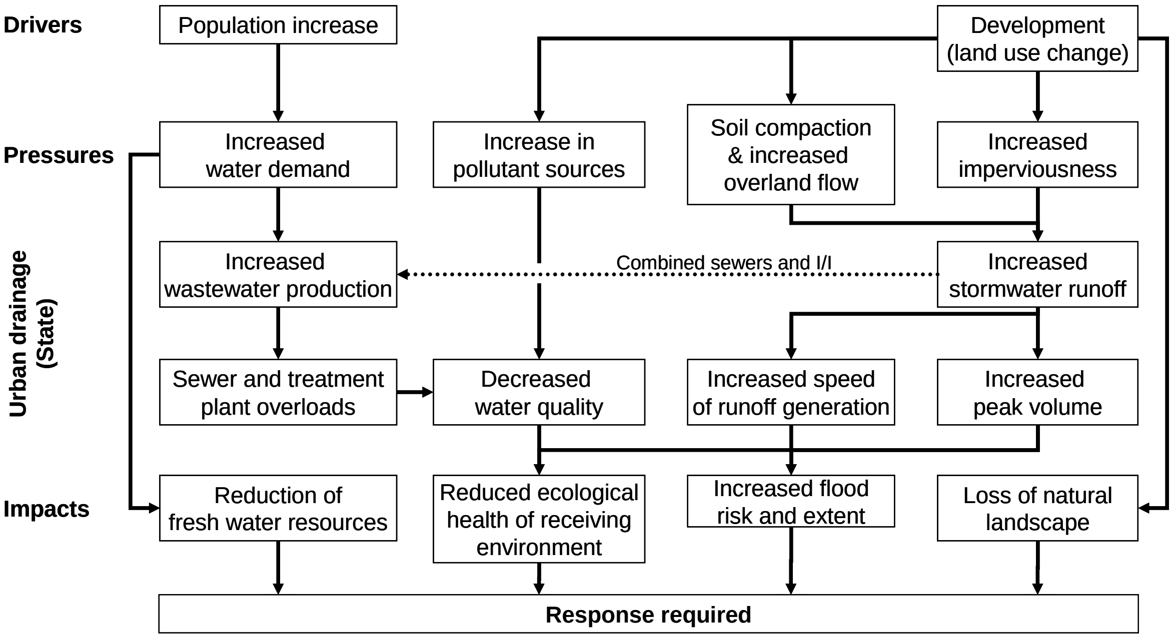


Figure 1: Effects of urbanisation on urban water resources following the DPSIR framework

While design criteria in New Zealand are starting to require adjustments to design-storms for new infrastructure, there is little guidance on how stormwater management devices can be used as part of the adaptation of existing reticulated networks. Neither has the possibility of new or existing stormwater management devices requiring progressive adaptation over their planned life-span due to anticipated increases in runoff generation been explored. Constructing drainage infrastructure today for a single possible future implies an assumption that the device will function as designed over its life-span and fails to address both uncertainty in climate projections This tool addresses these issues by demonstrating the range of impact of climate change on the size of ponds and wetlands both with and without concurrent land development.

2.1 Design for Adaptation

The Intergovernmental Panel on Climate Change (IPCC, 2007) defines adaptation as:

"*the adjustment of natural or human systems in response to actual or expected climatic stimuli, or their effects, which moderates harm or exploits beneficial opportunities*".

Adaptation can be reactive as a response to impacts or pro-active to avoid those impacts (i.e., risk management). The similarity in the impacts associated with population growth, urban development and climate change, along with the fact that these drivers are progressive and concurrent means that the IPCC definition has been extended in this tool to include the combined response to all three drivers.

Jones (2010) says that due to uncertainty in the probability of a particular climate outcome, planners should consider a range of future adaptation plans that they can call on as needs arise. He suggests that preparing a portfolio of possible actions that can be carried out quickly in response to changing circumstances may prove more cost-effective than constructing a system today according to a 'most-likely' future outcome which proves inaccurate over time. Such incremental adaptation may be a means of spreading costs over the life-span of the asset (*ibid*, Reisinger et al, 2010). Staggering construction also leads to the prospect of discounting to reduce the eventual costs of adaptation and can allow future adoption of emerging technologies. In the UK, Donovan et al. (2007) similarly recommend incremental adaptation for flood protection which tracks risk, that is, adaptation occurs at the point where risk increases to an unacceptable level in response to changes in the drivers. The strategy requires decision makers to evaluate potential decision pathways to determine which are most adaptable and robust under changing conditions.

With this advice in mind, stormwater systems should be designed and constructed to allow practical and affordable future adaptation if and when needs arise. The challenge for adaptation planning is to balance current costs of constructing and maintaining infrastructure against potential future risks of failure. The risk is that stormwater management devices which are either under or oversized and cannot be readily adapted may fail leading to negative impacts at receiving waters. On one hand, devices which are too small may be by-passed or flushed / flooded during high flows causing reduced capacity, on the other hand, devices which are too large may be vulnerable to low flows and drying-out during dry weather. A further complication is that a device sized correctly for future change may be incorrectly sized over the intervening time period.

Adaptation planning is further complicated in that these devices normally provide surface storage or treatment facilities for stormwater as part of a wider reticulated network. As such their continued operation is essential to the system function as a whole. Indeed, their installation may be part of the adaptation plan for existing networks which face increasingly high hydraulic loads. Due to their relative novelty, the asset life of stormwater management devices is uncertain but is likely to be in the order of 20-50 years (see review in Lampe et al., 2004). In contrast, the planned life-span of the reticulated networks they serve is typically 100+ years. Hence, the devices may need to be replaced or re-engineered in the future so that the network can continue operating as intended. Certainly, stormwater management devices will require long-term corrective maintenance such as dredging of accumulated sediments for ponds and replacement of the filter medium and geo-textile, and replanting for raingardens. This eventual need provides a potential opportunity for incremental adaptation that is not so readily apparent for reticulated networks.

3. Design methodology

This tool uses publically available guidance to illustrate the possible impacts, together and alone, of climate change and increased imperviousness, as a proxy for land use change, on the sizing of a hypothetical pond and raingarden. Response surfaces are created for each device to show the range of responses possible. The idea of response-curves was taken from Semadeni-Davies (2003; 2004) who demonstrated the use of a similar tool to show the range of changes in simulated seasonal inflows to a waste water treatment plant in Sweden. The steps followed are:

1. Create scenarios for climate change and urban development based on MfE (2008) climate projections and urbanisation trends for Auckland.

2. Calculate the volume of runoff generated by the adjusted design-storms using the method recommended for the Auckland Region (ARC, 1999 - TP108).

3. Size the hypothetical pond and raingarden for combinations of the climate change and urban development scenarios according to the regional design criteria (i.e., TP10).

While TP10 and TP108 do not currently contain guidance on climate change, these documents are under review and it is understood that later editions will require adjustments to design-storms with reference to MfE (2008) guidance (Matthew Davies and Bodo Hellberg, Auckland Council, pers. comm., 2011).

3.1 Scenario Creation

3.1.1 Climate change

The design-storms for stormwater design in the Auckland Region have a 24-hour duration and average recurrence intervals (ARI) of 2, 10 and 100 years depending on the primary function. For this study, design rainfalls were taken from NIWA's High Intensity Rainfall Design System (HIRDS, Thompson, 2002; http://hirds.niwa.co.nz) which returns design-storms for any location in New Zealand. HIRDS automatically applies the MfE (2008) adjustments for climate change given user specified temperature changes. Use of HIRDS to derive extreme rainfalls for climate change risk assessments is recommended by MfE (2008). The reference location is Henderson, Waitakere City (New Zealand Map Grid Easting 2655797 and Northing 6478716). Design-storms were derived for incremental changes in annual average temperature from 1 to 6°C. This range covers the range of temperature projections to 2090 for Auckland reported by MfE (2008; i.e., 0.6-5.8°C). The resulting 24-hour rainfall depths for the adjusted design storms are given in Table 1.

3.1.2 Urban development (imperviousness)

Auckland is undergoing rapid growth as a response to population growth leading to a demand for urban development. At the last census, the population of the region was approximately 1.3 million and had risen by 12.4% between 2001 and 2006; this trend is set to continue with a population of 2 million expected by 2050 (ARC, 2007). As the city grows, it is anticipated that there will be not only a change in city extent, but also a change in urban form towards more compact land use (Gamble, 2010).

Table 1: Design rainfall depths (mm/24 hours) for current climate and adjusted for incremental changes in mean annual temperature, Henderson, Auckland (derived using HIRDS)

ARI (years)	Current climate	Future Climate: change in temperature (°C)					
		1	2	3	4	5	6
2	80.3	83.8	87.2	90.7	94.1	97.6	101.0
10	122.4	130.1	137.8	145.5	153.2	161.0	168.7
100	207.2	223.8	240.2	256.9	273.5	290.1	306.7

Here, imperviousness is used as a proxy for change in land use intensity and urban form. The percentage imperviousness for stormwater catchments in Auckland City was reviewed as part of a study into roofing material by Kingett Mitchell Ltd. (2003). They found that imperviousness ranged from 28 % for a low density residential suburb to 85% for the central business district. The median imperviousness for an inner city suburb is 49%; imperviousness for industrial land was around 55%. These percentages are fairly typical of those reported in the literature (e.g., Butler and Davies, 2000). In this study, imperviousness is increased from 30 to 90% in increments of 15%.

3.2 Runoff volume

TP108 recommends a locally modified version of the SCS unit hydrograph method (U.S. Department of Agriculture, Soil Conservation Service, 1986) to calculate the 24-hour runoff volumes generated by the design-storms. The runoff volume is calculated separately for permeable and impervious surfaces which are then added to obtain the total runoff volume. This study used the parameters for abstraction recommended in TP 108 (i.e., 0 and 0.5 mm for impervious and permeable surfaces respectively) and set the curve number for permeable surfaces to 70 which is typical of urban lawns on clays.

3.3 Device sizing

3.3.1 Ponds

Wet detention ponds consist of a permanent pool of water into which stormwater is directed and detained for gradual release. It is essential for performance that stormwater ponds are neither under- nor over-sized in relation to runoff volumes. Pond removal efficiency is linked to the volume, depth and length-to-width ratio. The storage capacity of the pond must be large enough to detain inflowing stormwater for a length of time great enough to allow water treatment. The depth of the permanent pool is an important consideration to maintain pond ecological health and for public safety. Shallow ponds are prone to warming and drying. Increased water temperatures leads to reduced dissolved oxygen and increased heat stress on some organisms. Decomposition of organic material can both cause odour and further reduce water quality. Settled sediments may be scoured and resuspended due to wind driven turbulence as well as during high flows which could lead to their loss from the pond. Deeper ponds can be dangerous, especially to children, and can also be subject to stratification which could reduce mixing and settling and lead to anoxic conditions in the lower layers. The length-to-width ratio is a measure of the flow path form inlet to outlet, the longer a flow path, the greater the opportunity for settling.

Stormwater detention ponds in the Auckland Region can be designed for water quality or quantity control, however, it is common that the functions are combined by providing a set of outlet structures at different invert levels to regulate discharge. TP10 recommends that ponds have a catchment area of at least 2 to 3 hectares to maintain a permanent pool. Ponds are not considered suitable for areas with very intense land use or with high land costs due to the large surface area required.

TP10 requires water treatment ponds to be sized to accommodate the volume of runoff generated by $^{1}/_{3}$ of the 2-year 24-hour rainfall (i.e., the water quality volume, WQV). Ponds for flood risk management are generally sized to store and release the runoff generated by the 2- and 10-year 24-hour rainfalls at the pre-development discharge rate. Where there is an existing flood risk downstream, the 100-year 24-hour design-storm is also used. In addition to the design-storm runoff volumes, the pond should have a permanent pool (dead storage) with a volume half that of the WQV. A conservative approach to sizing is suggested where the pond is sized to store the entire runoff volume generated by the design-storm as well as the permanent pool. TP10 also requires extended detention for erosion control this is based on a prescribed rainfall depth rather than a design-storm, it is not considered here. TP10 specifies that water quality ponds should have flow path length-to-width ratio of at least 3:1 to promote settling. The average depth of the permanent pool should lie between 1 and 2 m. The basin sides should be gently sloped.

Here a hypothetical rectangular pond (Figure 2) is re-sized according to the runoff volumes calculated for changed design rainfalls and imperviousness. The catchment area is set to 4 hectares. It is assumed that the pond has a flow path length-to-width ratio of 3:1 when at the WQV level. The basin has a trapezoidal bathymetry with side slopes of 3:1 (horizontal to vertical ratio). The depth at the WQV level is 2 m. These basic relationships are unchanged when the WQV is increased according to the land use and climate change scenario – that is, the width, length and area vary with volume while the slope ratio and depth remain constant.

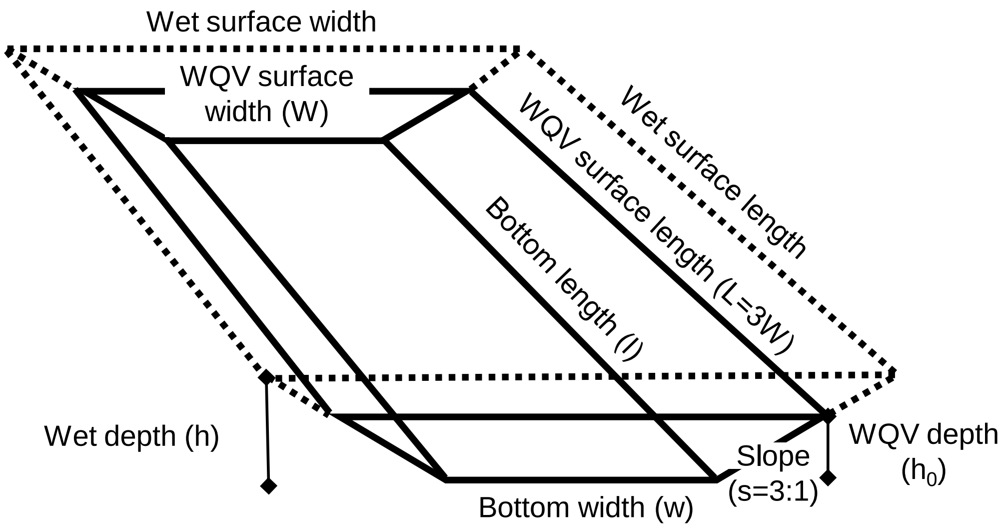


Figure 2: Layout of hypothetical pond with trapezoid bathymetry showing WQV and wet water levels

3.3.2 Raingardens

Raingardens treat water though filtration and bio-retention and consist of a lined-pit filled with a vegetated growing medium (i.e., a lower sand drainage layer, a soil layer and surface mulch). Raingardens are becoming increasingly common in New Zealand as they are compact, visually appealing and can be readily incorporated into landscaping. Typical locations include traffic islands and median strips, car parks, roadside berms and courtyards. Raingardens are generally used for water quality control; however, they can both attenuate and reduce flow volumes. Raingardens may have a separate fore-bay for pre-settling, though it is more common in New Zealand that runoff is ponded (i.e., live storage) on the surface for slow infiltration into the filter bed. The depth of the pooled water is regulated by a by-pass system where excess runoff is diverted away from the raingarden. While raingardens can reduce flows during low intensity events, their impact on flow volumes during extreme events is minor as peak flows are generally by-passed. The downstream risk associated with over-sizing a raingarden is negligible, although raingardens which are too large may need irrigation during dry summers. On the other hand, under-sized raingardens are at risk of by-passing untreated water to the reticulated network which could lead to downstream contamination.

TP10 recommends that raingardens have a maximum contributing area of 1000 m^2, stating that multiple smaller raingardens are preferable to a single large raingarden. Due to the risk of groundwater contamination, raingardens are not recommended for industrial land uses. Like ponds for water treatment, raingardens are to be sized for the WQV, which is the runoff volume generated by $^1/_3$ of the depth of the 2-year 24-hour design-storm. The planting depth should be 1 m and the suggested soil mix is a sandy loam with a minimum hydraulic conductivity of 0.3 m/day. The flow through time should be 1 day for residential areas and 1.5 for other land uses, the difference is due to concern that standing water for longer periods could upset some residents and is not related to raingarden performance. Live storage is the greater of the depth equivalent for 40% of the WQV or 0.22 m. It is assumed here that the raingarden is square.

4. Results

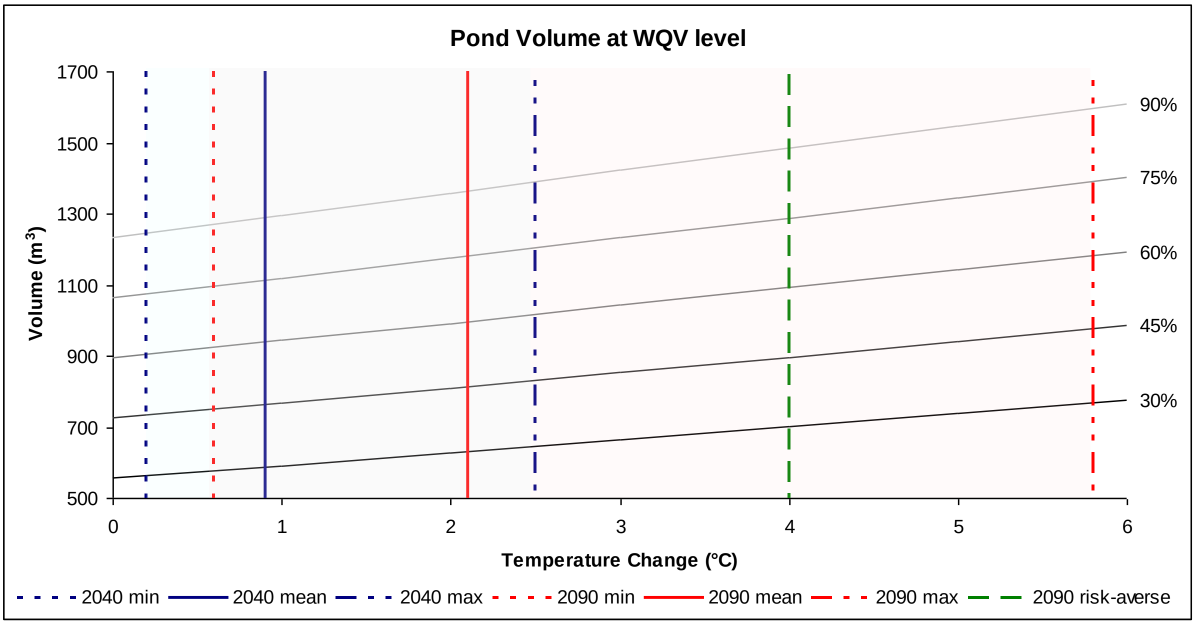
The results are reported using response-curves. These were created by plotting the change in device size (y-axis) against changes in temperature average annual temperature (x-axis). The change in temperature can also be seen as a proxy measure of time in that climate change is progressive. Bands for the lower, mean and upper annual temperature change projections for 2040 and 2090 given in MfE (2008). There is some indication (see Tool 2.4.2) that the mean temperature projection 2.1°C to 2090 is preferred by local stormwater managers for risk assessment which suggests that this projection may also be adopted for design. The maximum projection for 2090 of 5.8°C represents an extreme and NIWA suggest a risk-averse projection of 4°C by 2090 be used as an outer boundary which is also marked.

4.1 Ponds

Response-curves were constructed for water quality and quantity control and for pond detention volumes, surface area and the percentage of catchment covered by the pond. There are separate plots for each level of imperviousness.

4.1.1 Water quality control

For water quality control, the pond is sized to detain the WQV over a 24-hour period as well as a permanent pool which is half of the WQV. The response-curves for the pond volume and area for water quality control are given for the hypothetical pond in Figure 3. The range in volume without climate change is 556 (30% imperviousness) to 1233 m^3 (90% imperviousness respectively). With climate change included, the maximum volume required (5.8°C temperature increase, 90% imperviousness) becomes 1611 m^3. The equivalent range in the water surface area is from 574 (42 x 14 m) to 1024 m^2 (55 x 18 m) with no climate change and to 1261 m^2 (61 x 20 m) with climate change. These surface areas represent 1.4, 2.6 and 3.2 per cent of the catchment total area respectively.



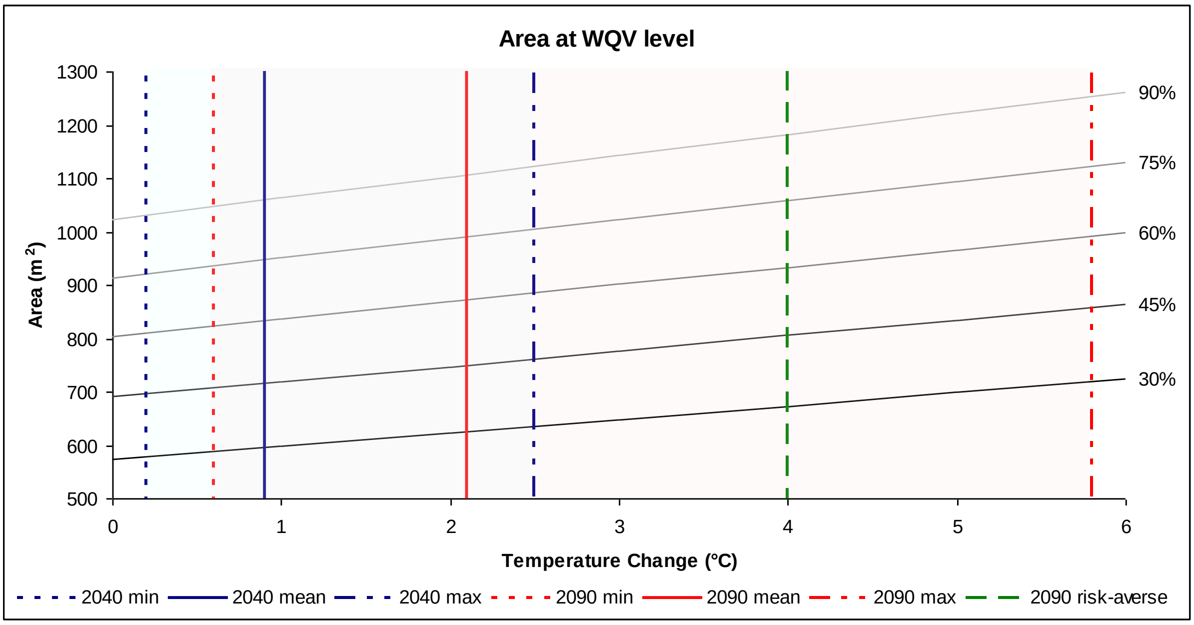


Figure 3: Pond total volume (above) and area (below) at the Water Quality Volume level calculated for design-storms adjusted by incremental changes in temperature. Catchment area is 4 ha. Imperviousness ranges from 30 to 90%. MfE (2008) temperature projection bands for 2040 and 2090 are overlaid.

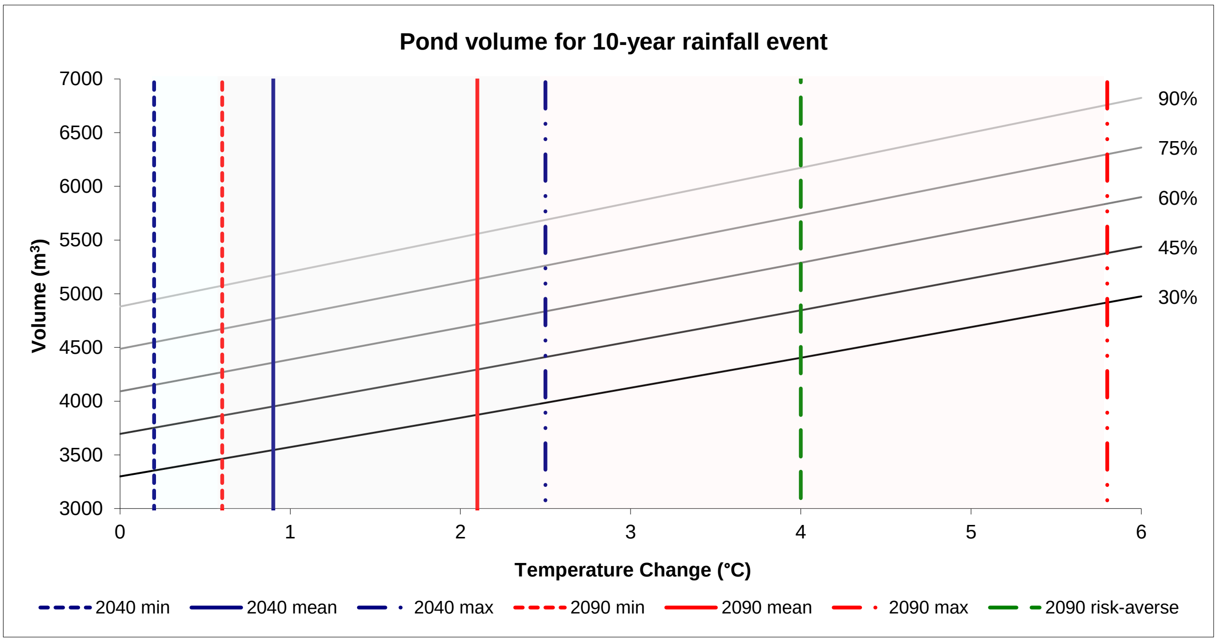
4.1.1 Water quantity control

Ponds for water quantity control for flood risk management are generally sized for the 2-year and 10-year design rainfall events; however, in areas with a known flood risk, ponds should be sized to contain runoff generated by the 100-year rainfall. The volumes and surface areas required for the 10-year design-storm in Figure 4. Note that a pond sized for the 10-year design-storm will also detain runoff generated by the 2-year design storm. The range in volume, including the permanent pool, for the 10-year event without climate change is 3300 to 4882 m^3 for 30% to 90% imperviousness respectively. With climate change included, the maximum volume required becomes 6823 m^3. The equivalent range in the water surface area is from 174 (30 x 58 m) to 2289 m^2 (33 x 70 m) with no climate change and to 2869 m^2 (37 x 79 m) with climate change. These surface areas represent 4.4, 5.7 and 7.2 per cent of the catchment total area respectively.

Ponds sized for 100-year events (not shown here) are only required where there is a significant downstream consequence to flooding. With no climate change, the 100-year volume ranges from 6291 to 8214 m^3, the maximum volume with 90% imperviousness and a projected temperature increase of 6°C is 12282 m^3. The equivalent range in the water surface area is from 2659 m^2 (40 x 67 m) to 3177 m^2 (41 x 78 m) with no climate change and to 4145 m^2 ((47 x 88 m)) with climate change. These surface areas represent 6.7, 7.9 and 10.36 m^2/ha per cent of the catchment total area respectively.

4.2 Raingardens

Response-curves were constructed for water quality control for the raingarden detention volume and surface area (Figure 5). Note that the detention volume is not the volume of the raingarden but rather the volume of runoff which needs to be detained. Increasing the annual average temperature by the maximum projected 5.8°C for 2090 increases the volume by around 8 m^3. The surface area required assumes that the raingarden is square and the depth of the planting medium is kept at 1 m. There are separate curves for residential and other land uses due to the different flow though rates required in the design criteria. For residential land use, the area ranges from 67 m^2 (8.2 m sides) for current climate to 88 m^2 (9.4 m sides). For other land uses, the area ranges from 45 m^2 (6.7 m sides) to 58 m^2 (7.6 m sides). The size difference between residential raingardens and for other land uses are greater than the increase in size required to account for climate change.



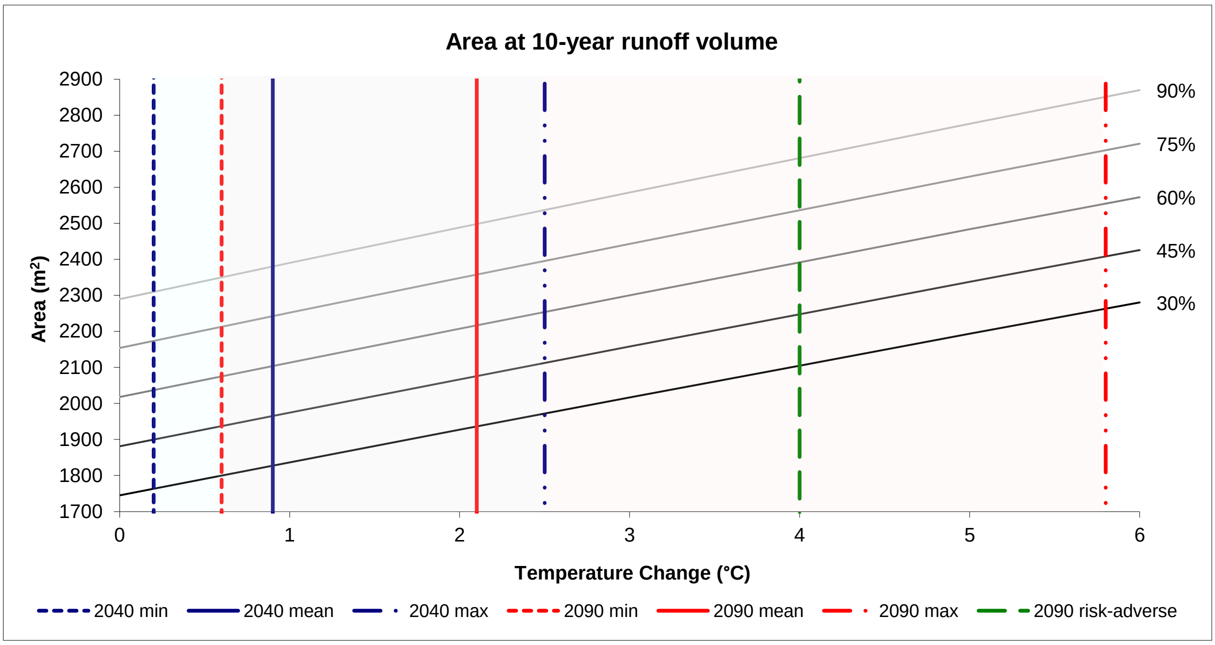
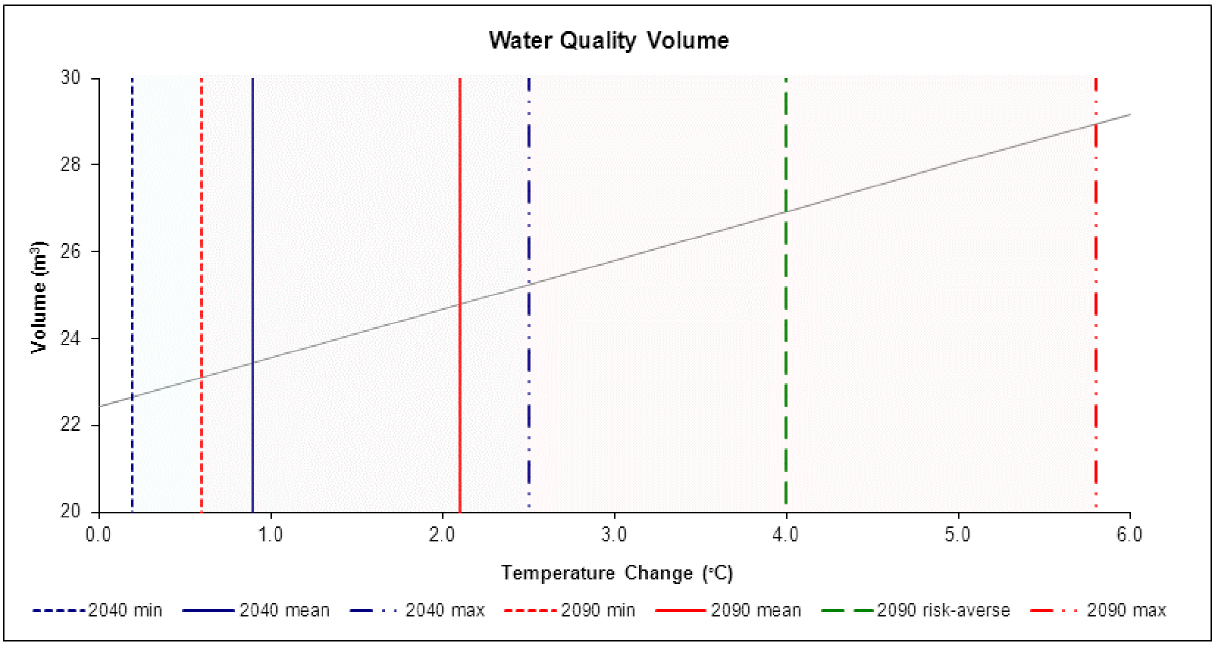


Figure 4: Pond total volume (above) and area (below) at the 10-year runoff volume level calculated for design-storms adjusted by incremental changes in temperature. Catchment area is 4 ha. Imperviousness ranges from 30 to 90%. MfE (2008) temperature projection bands for 2040 and 2090 are overlaid.



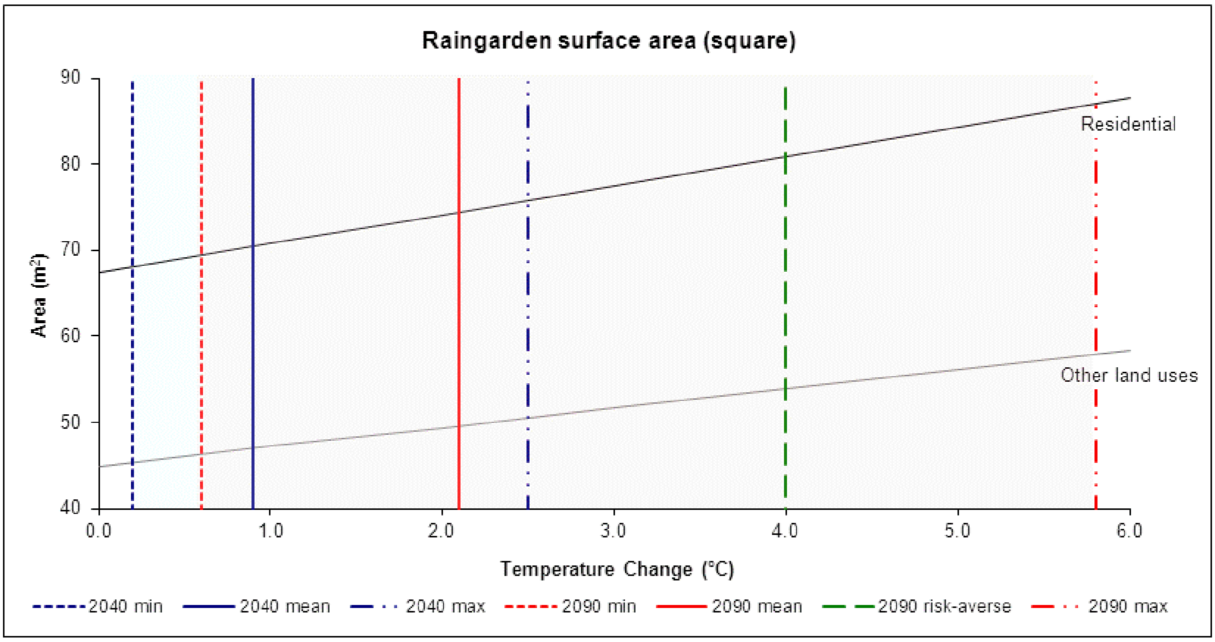


Figure 5 Water Quality Volumes (above) and surface area (below) calculated for a square raingarden serving a 1000 m^2 impervious surface with design-storms adjusted by incremental changes in temperature. Separate curves for residential and other land uses. MfE (2008) temperature projection bands for 2040 and 2090 are overlaid.

Due to the restriction of a maximum contributing area of 1000 m^2 and the assumption of 100% imperviousness, any change in imperviousness should be met with the construction of new raingardens. Assuming all impervious surfaces are treated with raingardens, the area of catchment covered by raingardens for residential land use ranges from 2% with 30% imperviousness and current climate to almost 8% with 90% imperviousness and the maximum projected temperature increase. The proportional areas are greater than those calculated for ponds sized for water quality control. However, the maximum coverage is conservative and does not take into account the fact that raingardens are site control devices that are unlikely to be installed for some types of impervious surface such as main roads.

5. Adaptation planning

There are a several adaptation strategies which can be followed, the choice of which depends on the type of infrastructure, whether adaptation is for existing or new infrastructure, the acceptable risk of failure and the relative costs of failure versus adaptation. The alternatives are:

- Reactive adaptation - do not adapt infrastructure until an unacceptable impact occurs;

- Proactive adaptation – adapt infrastructure for anticipated risks at either the time of construction of new infrastructure or as part of capital works for existing infrastructure.

- Incremental adaptation – flexible design which allows infrastructure construction to be staggered over time as needs arise (i.e., increased level of impact or risk) or knowledge about climate change improves. Incremental adaptation also allows the opportunity for new technologies to be used as part of adaptation.

This section illustrates how the response-curves presented above can be used as an aid to adaptation planning by showing multiple outcomes to a full range of climate change and urban development scenarios. The value of response-curves is that they can be used to visualise the relative and combined impacts of both land use change and climate change in combination and separately. By overlaying temperature projections for both 2040 and 2090, the change in temperature can also be seen as a proxy measure of time in that climate change is progressive. This means that the curves can provide a visual cue for when adaptation may be required. Sensitivity to each of the drivers is denoted by the relative distance between the plotted curves and their slope (Figure 6).

The use of response-curves should be seen as a complement to the guidance given by MfE (2008) as part of preliminary screening. Evaluating the actual performance of the devices for changed conditions requires detailed modelling of the drainage network and devices (see Tool 2.4.1). Suffice to say that if the response-curves show that the design of a particular stormwater management device is sensitive to the projected range of climate or land use change; detailed modelling may be required.

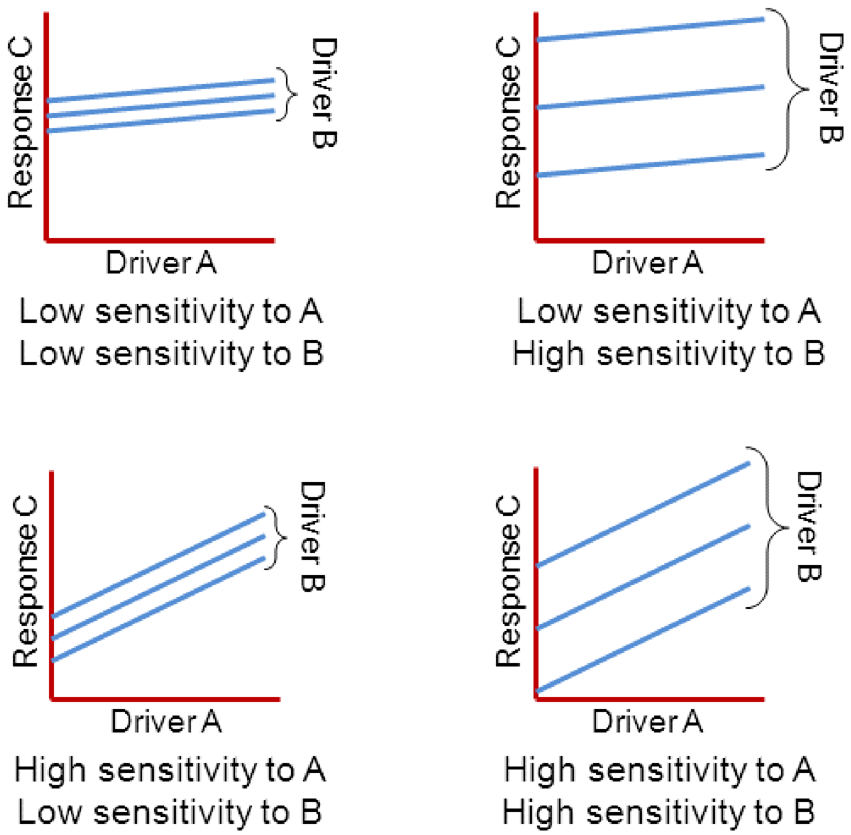


Figure 6 Generic response-curves showing relative sensitivity of the response, C, to drivers, A and B

The response-curves shown in Figures 3-7 convey two main messages:

- As the distribution in temperature projections from MfE (2008) is broad the choice of projection used to adjust design-storms will have a great effect on device design, particularly for ponds; and

- Land use change is equally, if not more, important to future proof design. For ponds, increases in imperviousness are likely to have a greater impact on size than climate change. For raingardens, whether the device is sized for residential land use or other land uses has a greater impact on sizing than climate change.

The adaptation strategies suggested below for ponds and raingardens are different due to the relative size and location of these devices in the stormwater system.

5.1 Pond adaptation strategy

The pond response-curves show that the design-size of detention ponds is likely to change significantly over the century. Given the sensitivity of pond function to sizing, an incremental adaptation strategy whereby land is set aside for future enlargement is appropriate for ponds in order to avoid ponds with are either too large or too small. While this would require a greater initial outlay for extra land, other costs associated with adaptation would occur as needs arise. The advantage of incremental adaptation is that, while provisions for possible adaptations may eventually be needed, there is no need to commit up-front to a specific design which could result in the pond being improperly sized for the future or not functioning as intended in the interim. Incremental adaptation also allows for the possibility of future design alternatives and adoption of new technologies. There is also the opportunity to discount future adaptations. The impact to costs is explored further in Semadeni-Davies et al. (2011).

The response-curves readily convey the fact that pond size is highly dependent on the land use and climate change scenarios chosen. Consider the case of a pond designed for a catchment that currently has medium intensity housing (45% imperviousness) but is planned for redevelopment over the coming decades with imperviousness to reach 60% (mid to high intensity housing) by mid-century and 75% (infilling with high intensity housing) by the end of the century. The changes in size for mid- and end of century conditions for this example as read from the response curves (e.g., Figure 7 for pond volumes required for the 10-year design-storms) are summarised in Table 2. It is clear that much of the increase in pond size is due to increased imperviousness rather than increased rainfall. For both mid- and end-of- century imperviousness, the differences between the pond size required with no climate change and with the lower MfE temperature projections are modest in comparison to imperviousness. The difference due to climate is more apparent for both mid- and end-of-century with the mean to upper temperature projections.

There are practical and economic limits to the size of a pond with respect to pond function, construction, operation and maintenance. Pond function and safety apart, size is also constrained by land availability and prices. Typical upper bounds to the surface area of water quality ponds are around 2.5 to 3 % of the catchment area (e.g., Persson and Petterson, 2009). At the most extreme (100-year design-storm with 5.8°C increase in temperature), the hypothetical pond would cover over 10% of the catchment area and require an unrealistic basin depth when full of 7 m. It is worth pointing out that TP10 does not recommend ponds for areas with intense land use due to the high surface area requirement.

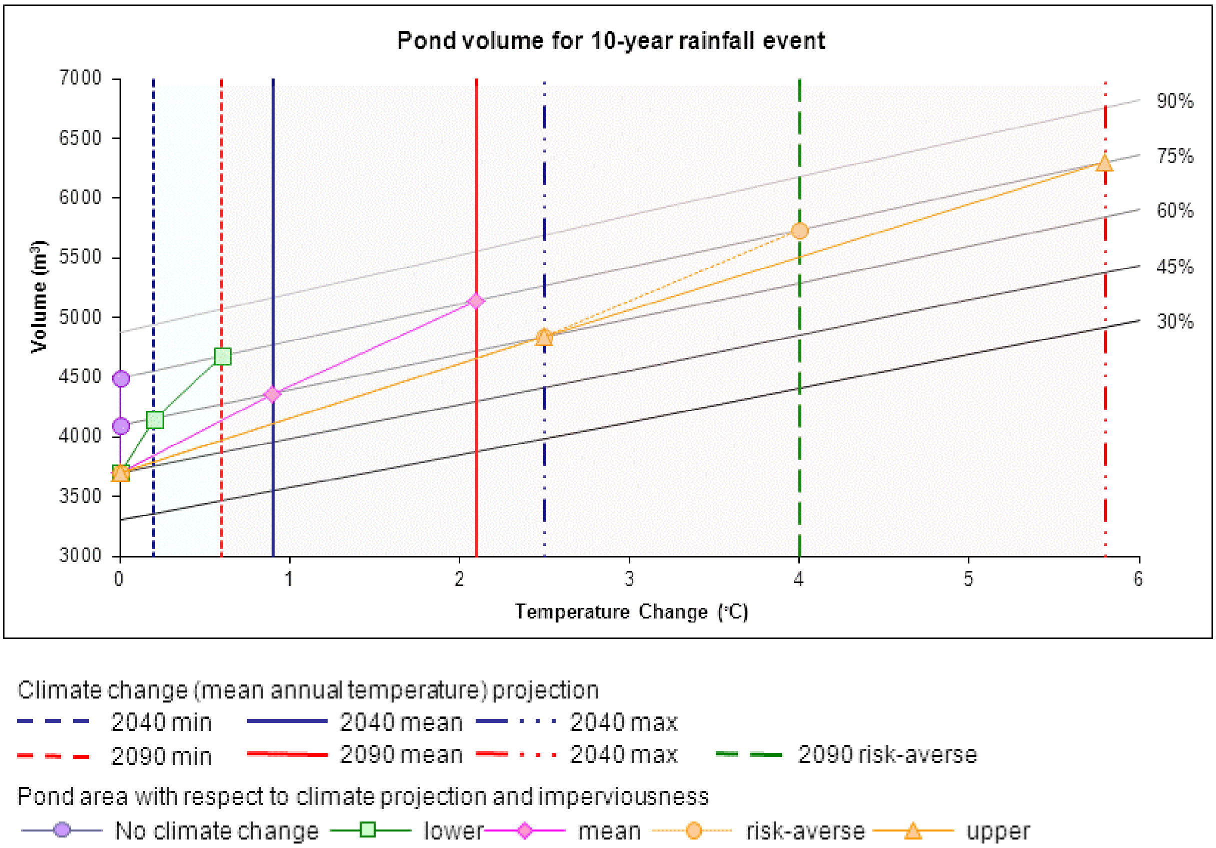


Figure 7 Change in pond volume required for the base-line, mid- and end-of-century scenarios plotted on the water quantity (10-year) control response curve.

With a generous upper threshold of 5% catchment area, the maximum pond area that can be constructed for the 4 ha catchment modelled here is 2000 m^2, which is large enough to accommodate all the resized WQVs. For the 10-year runoff volumes, only the pond sized for the "current conditions" would be accommodated. However, the area required to contain the 10-year runoff for mid-century imperviousness (60%) with the low temperature projection is fairly close to this threshold. The area would be inadequate for flood protection to the 100-year runoff level for all levels of imperviousness and climate change projections. For the hypothetical case, alternative or complementary adaptation options such as local disposal (e.g., infiltration surfaces) and rain water harvesting (i.e., water tanks), diverting surface flows to "emergency" detention facilities (e.g., car parks, sports fields) or artificial recharge in areas of Auckland underlain by basaltic aquifers (see Miselis and Captain, 2009 and Parkinson et al., 2008 for examples of options) may need to be considered for water quantity control.

Table 2 Pond areas and volumes at the WQV and 10-year levels as read from the response-curves for baseline, mid-century and end-of-century scenarios. Percentage increases from the baseline values are in (*parentheses*).

Scenario		**Volume (m^3)**		**Area (m^2)**	
		WQV	**10-year**	**WQV**	**10-year**
Baseline: Present climate, 45% imperviousness		725	3696	691	1881
2040 mid-century 60% imperviousness	No climate change	894 (23%)	4091 (11%)	804 (16%)	2018 (7%)
	Lower projection (0.2°C)	904 (25%)	4150 (12%)	811 (17%)	2037 (8%)
	Mean projection (0.9°C)	938 (29%)	4358 (18%)	833 (21%)	2104 (12%)
	Upper projection (2.5°C)	1018 (40%)	4837 (31%)	885 (28%)	2254 (20%)
2090 end-of-century 75% imperviousness	No climate change	1063 (47%)	4486 (21%)	915 (32%)	2154 (15%)
	Lower projection (0.6°C)	1097 (51%)	4672 (26%)	937 (36%)	2213 (18%)
	Mean projection (2.1C)	1181 (63%)	5138 (39%)	991 (43%)	2358 (25%)
	Risk-averse projection (4.0°C)	1289 (78%)	5731 (55%)	1059 (53%)	2537 (35%)
	Upper projection (5.8°C)	1391 (92%)	6297 (70%)	1124 (63%)	2702 (44%)

The option of sizing ponds for water quantity control with reference to attenuation and storage in up-stream stormwater management devices is not currently available in TP10. However, the criteria do state that this possibility is available for some water treatment devices within a treatment train (i.e., swales and filter strips). To assess pond performance as part of a wider stormwater management system would require detailed modelling to assess the way in which devices interact together and with the reticulated network in order to optimise design. An example of such an evaluation can be seen in Villarreal et al. (2004). They simulated the effectiveness of a variety of retro-fitted devices, including a pond, installed in series at reducing the volume of stormwater runoff reaching a combined sewer in Malmö, Sweden. They found that the devices could potentially detain the 10-year rainfall event, however, neither the impact of climate change nor the potential for water treatment were assessed.

5.2 Raingarden adaptation strategy

The situation with raingardens is quite different to ponds. The downstream risk associated with over-sizing a raingarden is negligible, although raingardens which are too large may need irrigation to maintain plant health during dry summers. On the other hand, under-sized raingardens are at risk of by-passing untreated water to the reticulated network which could lead to downstream contamination. The study assumed that raingardens serve only impervious surfaces, and are hydrologically isolated from lateral flows from surrounding soils. These assumptions, coupled with an upper limit of the contributing area, mean that increases in imperviousness should be met by construction of new raingardens as part of development rather than by incremental reconstruction of existing raingardens.

Similarly, a change in land use could result in a significant change in the required raingarden area – albeit due to regulation rather than function. Indeed, the change in size required to adapt for climate change is less than the difference between the raingardens designed for residential land and other land uses. The required change is due to a lower permitted detention time for surface ponding in residential areas. The restriction in detention time is for aesthetic reasons and is not related to raingarden performance. Hence, it is unlikely that a raingarden would be adapted for land use change once constructed.

Assuming that raingardens are sized for a fixed catchment area and 100% imperviousness at the time of construction, the primary consideration for future raingarden adaptation is climate change. Figure 5 showed that the area of a raingarden in a residential area increased from 67 m^2 to 88 m^2 with the maximum temperature projection to 2090 of 5.8°C. The equivalent change for raingardens in other land use zones is from 45 m^2 to 58 m^2. While these changes appear to be a relatively large (~30%), the absolute differences are fairly small. Assuming a square raingarden, the side lengths would increase by ~1 m for the maximum increase in area for both land use types. For the mean temperature change projection, the increase in side lengths would be only ~40 cm.

Given that raingarden function is unlikely to be affected if the raingarden is oversized, and the small increases in size required for climate change, incremental adaptation is not warranted. It would be pragmatic to construct the raingarden to accommodate anticipated maximum increased runoff rather than incurring the added costs of adaptation in the future. The costs associated with this adaptation strategy are explored in Semadeni-Davies et al. (2011).

6. Conclusions

Changes in the way in which stormwater is managed in Auckland are likely to be needed over the coming decades in order to adapt to both urbanisation and climate change. These drivers could exacerbate the already substantial problems related to stormwater drainage at receiving environments. The ability of stormwater management devices to both treat stormwater and modify flow rates and volumes has meant that they are increasingly being installed in the city, largely in conjunction with green- and brown-field developments. These devices have been suggested internationally as a means of adapting new and existing stormwater systems for climate change. However, there is little information locally or internationally on how they should be designed to ensure that they continue to function into the future.

This tool has used national and locally available guidance on climate change adaptation (MfE, 2008) and stormwater design (TP108; TP10) to investigate how the sizing of ponds and raingardens may need to change over this century. Response-curves have been constructed in order to convey the range of sizes possible for ponds and raingardens given our current understanding of climate change and trends in urbanisation.

The results suggest that an incremental adaptation strategy, whereby adaptation traces changes in risk over time, is appropriate for ponds. Increasing imperviousness and rainfall both increase the storage demand of ponds. Pond design is at least as sensitive to imperviousness as to changes in design rainfall. Adaptation at the time of construction is not recommended for ponds as it could lead to ponds which are either under- or over-sized in the future if the land use or climate change projections differ from reality. Additionally, even if ponds are correctly sized for a future 70 years hence, they may be incorrectly sized for current conditions leading to poor performance in the interim. There are limits to resizing ponds for adaptation and some of the results presented here in relation to water quantity control are unrealistic in terms of surface areas and ponds depth requirements to accommodate runoff volumes associated with upper temperature projections and high levels of imperviousness. Accordingly, pond resizing may need to be in conjunction with other adaptation options.

In contrast, raingardens generally serve impervious surfaces such that any increase in imperviousness is met by increasing the number of raingardens rather than resizing existing raingardens. Moreover, the small size of raingardens and the fact that climate change is likely to have a small impact on sizing means that it may be more appropriate to size them for anticipated climate change at the time of construction.

This tool has examined the relative effects of climate change and land use change on device sizing; however, the implications for device performance with respect to both water quality and quantity control have not been examined. To do so would require detailed modelling of each device which is not currently required for stormwater design in TP10 or other criteria cited (NZTA, 2010; NZS4404:2010). Instead, it is assumed that devices designed according to TP10 standards will function as intended. It is noted that detailed modelling is part of the risk assessment process recommended by MfE (2008) in cases where the impacts of climate change are significant. As such, detailed modelling should be considered part of adaptation planning, particularly if stormwater management device is being retrofitted as an adaptation for a potentially undersized reticulated network where it is essential for system function that the device performs as intended over its life-span.

Finally, while the relative costs associated with the adaptation strategies suggested have been alluded to, this aspect of adaptation planning has not been addressed here. Readers are instead directed to related study by Semadeni-Davies et al. (2011) for more information.

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References

Ashley, R.; Blanksby, J.; Cashman, A.; Fewtrell, L.; Jack, L. Wright, G.; Packman, J.; Maksimovic, C. and Kellagher, R. (2008) Building Knowledge for a Changing Climate (BKCC): Adaptable Urban Drainage - Addressing Change In Intensity, Occurrence And Uncertainty of Stormwater (AUDACIOUS). Main summary report. EPSRC/UKCIP.

Auckland Regional Council, ARC (1999). Guidelines for stormwater runoff modelling in the Auckland Region. Auckland Regional Council Technical Publication No. 108. (ARC TP108). Auckland Regional Council.

Auckland Regional Council, ARC (2001) Low Impact Design Manual for the Auckland Region. Primary Author, Earl Shaver. TP 124.

Auckland Regional Council, ARC (2003) Stormwater management devices: design guidelines manual. Second Edition, TP 10.

Auckland Regional Council, ARC (2007) Overview of results for the Auckland region, ARC Census Reports, Social and Economic Research and Monitoring Team, Auckland Regional Council.

Brown, R. and Clarke, J. (2007). The transition towards Water Sensitive Urban Design: The Story of Melbourne, Australia, Report of the Facility for Advancing Water Biofiltration, Monash University, Melbourne.

Butler, D. and Davies J.W. (2000) Urban Drainage. E. and FN Spon, London.

Coutts, A.; Beringer, J. and Tapper, N. (2010) Changing Urban Climate and CO_2 Emissions: Implications for the Development of Policies for Sustainable Cities. Urban Policy and Research, 28(1):27-47.

Donovan B, Von Lany P, Wells T, Hall J. 2007. Introducing the concept of decision-pathways to help make adaptive and robust flood risk management decisions under uncertainty. Paper presented at the 42nd Flood and Coastal Management Conference. July 2007. York, United Kingdom.

Gamble, S; (2010). Capacity for Growth Study 2006. Final Report. Auckland Regional Council Technical Report 2010/014.

Intergovernmental Panel on Climate Change, IPCC (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 976pp.

Jones, R. (2010) A risk management approach to climate change adaptation. In Climate change adaptation in New Zealand: Future scenarios and some sectorial perspectives. Nottage, R.A.C.; Wratt, D.S.; Bornman, J.F.; Jones, K. (eds), New Zealand Climate Change Centre 2010.Wellington, 136 p.

Kingett Mitchell Ltd; Diffuse Sources Ltd. (2003). A study of roof run-off quality in Auckland New Zealand: implications for stormwater management. Report to the Auckland Regional Council, TP 213.

Lampe, L.; Andrews, H.; Barret, M.; Woods-Ballard, B.; Martin, P.; Glass, C.; Weinstein, N. and Jefferies, C. (2004) Post-Project Monitoring of BMP's/SUDS to Determine Performance and Whole-Life Costs. WERF Report 01-CTS-21T. co published by WERF (VA) and IWA publishing (UK).

MfE, Ministry for the Environment (2008) Climate Change Effects and Impacts Assessment: A Guidance Manual for Local Government in New Zealand. 2nd Edition. Mullan B; Wratt D; Dean S; Hollis M; Allan S; Williams T, Kenny G and MfE. Ministry for the Environment, Wellington. p149.

Miselis, P.L., Captain, X. (2009) Development of multi-catchment flood reduction alternatives in Auckland. NZWWA Stormwater Conference, Auckland, May 2009.

New Zealand Standards (2010) Land development and subdivision infrastructure. NZS 4404:2010, pp 260.

New Zealand Transport Agency, NZTA (2010) Stormwater Treatment Standard for State Highway Infrastructure (available for download from http://www.nzta.govt.nz).

Pahl-Wostl C. (2007) Transition towards adaptive management of water facing climate and global change. Water Resources Management. 21: 49-62.

Parkinson, N.J., Hewitt, J., Summerhays, M., Ockleston, G. and Captain, X (2008) Optimisation of basalt aquifer stormwater disposal for flood hazard mitigation in Auckland City. NZWWA Stormwater Conference, Rotorua, New Zealand.

Persson, J. and Pettersson, J.R. (2009) Monitoring, sizing and removal efficiency in stormwater ponds. E-Water, Official Publication of the European Water Association (EWA) (On-line Journal).

Reisinger, A.; Mullan, B.; Manning, M.; Wratt, D. and Nottage, R. (2010) Global & local climate change scenarios to support adaptation in New Zealand. In Climate change adaptation in New Zealand: Future scenarios and some sectorial perspectives. Nottage, R.A.C.; Wratt, D.S.; Bornman, J.F.; Jones, K. (eds), New Zealand Climate Change Centre 2010.Wellington, 136 p.

Scholz, M. and Yang, Q. (2010) Guidance on variables characterising water bodies including sustainable flood retention basins. Landscape and Urban Planning, in press.

Semadeni-Davies, A. (2003) Response surfaces for climate change impact assessments in urban areas. Wat. Sci. Tech., 48(9):165-175.

Semadeni-Davies, A. (2004) Urban water management vs. climate change: impacts on cold region wastewater inflows. Clim. Change, 64:103-126.

Semadeni-Davies, A.; Hernebring, C.; Svensson, G. and Gustafsson, L.-G. (2008a) The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: combined sewer system. J. of Hydrology, 350:114-125.

Semadeni-Davies, A.; Hernebring, C.; Svensson, G. and Gustafsson, L.-G. (2008b) The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: suburban stormwater. J. of Hydrology, 350:100-113.

Semadeni-Davies, A., Vesely, E.-T. and Ira, S. (2011) Implications of climate change and urban development on the costs of stormwater management devices. Manuscript to be submitted to Landscape and Urban Planning.

Shaw, R.; Colley, M. and Connell, R. (2007) Climate change adaptation by design: a guide for sustainable communities. TCPA, London.

Smeets, E. and Weterings, R. (1999) Environmental indicators: typology and overview. European Environment Agency, Copenhagen. Technical Report No 25.

Thompson, C.S. (2002) The High Intensity Rainfall Design System: HIRDS. Proceedings, International Conference on Flood Estimation, March 2002, Berne, Switzerland. International Commission for the Hydrology of the Rhine Basin, CHR Report II-17, pp 273 – 282.

U.S. Department of Agriculture, Soil Conservation Service (1986) Urban hydrology for small watersheds. Tech. Rep. 55, Engineering Division, Soil Conservation Service, US Department of Agriculture.

Van Roon, M. (2007) Water localisation and reclamation: Steps towards low impact urban design and development. Journal of Environmental Management 83:437–447.

Villarreal, E.; Semadeni-Davies, A. and Bengtsson L. (2004) Inner city stormwater control using a combination of BMPs. *Ecological Engineering*, 22(4-5):279-298.

Watt, W.E.; Waters, D. and McLean, R. (2003) Climate Variability and Urban Stormwater Infrastructure in Canada: Context and Case Studies. Toronto-Niagara Region Study Report and Working Paper Series, Report 2003-1. Meteorological Service of Canada, Waterloo, Ontario.

Wong, T. and Brown, R. (2009). The Water Sensitive City: Principles for Practice, Water Science and Technology. 60(3):673-682.