Water Sensitive Urban Design in a changing climate: estimating the performance of WSUD treatment measures under various climate change scenarios

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ABSTRACT
Recent attempts to measure likely impacts of climate change on WSUD measures have focused on performance under a single scenario of adjusted historical rainfall and evaporation. This study adopted an approach whereby a limited number of time series were generated to represent the extremes of a number of projected ranges of climate change scenarios.

To support the Mornington Peninsula Shire's Integrated Water Management plan, analysis was undertaken to ensure that future stormwater management strategies were adaptable to a range of possible climate change conditions. Six different scenarios were developed, using stochastic downscaling of historical rainfall and evaporation, to represent predicted climate adjusted conditions under various emissions scenarios.

Pollutant generation across the entire municipality and various WSUD measures were modelled under each of climate change scenarios to better understand the sensitivities of both pollutant generation, and resilience of treatment measures including wetlands, raingardens, stormwater harvesting and rainwater tanks to the likely future changes in climate. Results were then used to determine appropriate design considerations for various WSUD measures as well as recommend appropriate climate change adaptations for a number of biological components of these systems such as wetland vegetation.

KEYWORDS
Climate; Future; Rainfall; Stormwater; WSUD.

INTRODUCTION

The Mornington Peninsula Shire covers over 720 square kilometres and supports a wide diversity of land uses. Key water resource management issues faced by Mornington Peninsula Shire relate to water use and water quality management. The Shire is committed to sustainable water management to ensure the long term resilience of key assets; from high quality bushlands to high yielding primary production. The Shire is committed to investing in a best practice approach to water management. The delivery of an Integrated Water Management Strategy was a key component of this.

Climate Change Modelling

For Victoria more broadly and the Mornington Peninsula, it is generally expected that there will be increases in temperature and evapotranspiration (Macadam et al, 2008). The long term increases in temperature for Australia (CSIRO & BoM, 2007) are consistent with the global temperature trends reported by the IPCC (2001). For rainfall, the results were less clear with decreases in mean annual rainfall evident, but weak relative to natural decadal-scale fluctuations. The intensity of summer storms is expected to increase.

While it is anticipated that mean annual rainfall will generally reduce in southern Victoria, it is conversely expected that intensities will generally increase (Abbs & Rafter, 2008; Tebaldi, 2006). For Melbourne, it is expected that the number of rain days will reduce by 4-10 days by 2030 (Ricketts & Hennessy, 2009).

Analysis of intensities for Western Port (Abbs, 2008) suggests that intensities are likely to increase. These changes are not uniform and the greatest increases are likely to occur for the larger and less frequent storm events with a high annual recurrence interval (in the order of the 1 in 10 to 1 in 100 year event). This has significant implications for flood management. For water sensitive urban design systems, this is less of an issue as they are generally designed to treat high frequency storms (up to the 1 in 1 or 1 in 2 year ARI). Nevertheless, there is potential for increases in intensity of more frequent events to impact adversely on the treatment effectiveness of stormwater treatment systems.

Representation of such changes in intensity for continuous time series would require direct application of time series data from the climate models; see for example Willems (2011). However, this will require downscaling of time series data for individual climate models for a range of scenarios and is beyond the scope of this work. Based on the work that has been undertaken in Europe (Willems, 2011), it could be expected that changes in intensities at the lower end of the frequency range could be in the order of up to 10-20%. It is recognised that the impacts of sub-daily changes in the intensity of storms is potentially significant and this has been identified as an area for further work.

METHODS

Rainfall data reference baseline

There is a high degree of variability of mean annual rainfall across the Shire. Generally rainfall is lower along the west coast (Mornington, Rosebud), and higher in the higher inland areas and east coast (Devilbend Reservoir, Flinders).

For the purposes of evaluating the impacts of climate change, it is necessary to choose a representative baseline as a starting point. The average rainfall for 7 selected rainfall stations (with greater than 30 years of data and no significant gaps) across the Shire is 817 mm/year, with an average number of days of rainfall of 142 days. These parameters were taken as being representative of the 1990 baseline to form the basis for comparison with climate change adjusted scenarios.

Pluviograph data

A suitable period of pluviograph data was selected that represented the baseline statistics with sub daily data.

Expected changes in climate for Mornington Peninsula

The best available estimates for projected climate changes for the Mornington Peninsula were obtained from 'Climate Change Projections for the Western Port Region (Macadam, et. al., 2008). These are based on the projections made for 'Climate change in Australia' (CSIRO & BoM, 2007) which represent the most recent available data for Australia. These were used as a basis for modifying the baseline scenario.

Climate Change Scenarios
Recent investigations of climate change impacts indicate that the design of stormwater treatment and reuse systems must be designed to be adaptive to a wide range of possible seasonal rainfall and evaporation scenarios. It is recommended that multiple time series are generated and modelled to simulate the various processes. It is suggested that these can be based on recommendations by CSIRO regarding 10^{th}, 50^{th} and 90^{th} percentile projected changes; however, it is acknowledged that at present there is no suitable method to incorporate these into high resolution rainfall time series. While dynamic downscaling offers a potential path, the computational demands make it difficult to implement for a large number of models at this time (Wong et. al., 2011).

Recognising these limitations, a simplified approach was employed whereby a limited number of time series were generated to represent the extremes of the projected ranges of change, that is, the 10^{th} and 90^{th} percentiles. The above seasonal changes were adopted as representative of likely changes, while the range from the 10^{th} to 90^{th} percentile was taken as being representative of the potential range of uncertainty that may be expected.

Three emissions scenarios were considered. A medium emissions scenario was adopted for 2030 since most changes that will occur by 2030 are already locked in and the choice of emissions scenario has lesser bearing on the expected impacts. For 2070, high (A1F1) and low (B1) emissions scenarios were adopted. The high scenario represents a world with high fossil fuel use, essentially business as usual, while the low scenario represents a shift towards a mix of more renewable energy sources and reduced emissions.

A set of 6 scenarios (as well as the baseline) was established to represent the extremes of the potential ranges for the three emissions scenarios. These are as follows:

- 2030 Medium emissions (A1B) Lower
- 2030 Medium emissions (A1B) Upper
- 2070 Lower emissions (B1) Lower
- 2070 Lower emissions (B1) Upper
- 2070 Higher emissions (A1F1) Lower
- 2070 Higher emissions (A1F1) Upper

Method for creating climate change adjusted scenarios
The data set was adjusted by applying season-specific stochastically generated percentage changes to each day of rainfall. This ensures that a range of changes occur, with some larger and some smaller, while preserving the median expected change. A second adjustment is then made to reduce the number of rain days and add the same amount of rainfall back to the remaining days. This is crucial as it ensures that reductions in rain days are also represented. These are adjusted such that changes in intensity on a broad scale are reflective of those expected. Finally, corrections are applied to ensure that the seasonal and annual percentage changes are preserved.

Modelling stormwater pollutant loads and water quality performance
Using modified rainfall files to represent the six climate change scenarios described above, the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) was used to assess a range of key criteria. Fletcher (2007) pollutant concentrations were adopted for storm flows for general surface, road and roof surface types

Municipal Stormwater Pollutant Budget. In order to determine likely changes in the municipal stormwater pollutant budget, data from a GIS 'Impervious' layer (supplied by Melbourne Water) was used to determine the area of each of the following surface types across the Shire: impervious road, impervious roof, other impervious surfaces (driveways etc) and pervious surfaces.

Unit Models. Unit models for a range of typical WSUD treatment types were developed using standard MUSIC nodes using design parameters typical of industry best practice WSUD standards. These were thought to be representative of WSUD measures likely to be installed across the Shire in the future. The treatment types modelled were: Stormwater harvesting (with a pre-treatment wetland, stormwater harvesting with a pre-treatment raingarden, a raingarden with a typical urban catchment, a swale with a road only catchment, tree pits with a road only catchment, a wetland with a typical urban catchment and rainwater tanks with a range of indoor and outdoor demands.

RESULTS AND DISCUSSION

The potential impacts of climate changes on three key issues relating to stormwater were tested. The first issue was around the likely changes to the municipal pollutant budget, the second was around the long term reliability of supply of stormwater from various harvesting schemes and the third was around the long term pollutant removal performance of various treatment types. For the WSUD wetland, an assessment was also made of the likely impacts on vegetation health under various climate change scenarios.

Municipal Pollutant Budget

The municipal pollutant budget was modelled under all climate scenarios including the baseline scenario. The mean annual pollutant loads and the mean annual flows generated, under each of the six climate change scenarios models, were then compared to the pollutant generation and flows for the baseline scenario. Table 1 below shows the percent variation, in pollutant generation and flows, from the baseline scenario.

Table 1. Percent variation in pollutant generation and flow for each climate scenario.

	Percent variation in loads from baseline scenario			
	TSS Mean Annual Load (% change)	TP Mean Annual Load (% change)	TN Mean Annual Load (% change)	Mean Annual Flow (% change)
1990 Baseline	0	0	0	0
Medium emissions 2030 Lower	3	2	3	0
Medium emissions 2030 Upper	-14	-20	-22	-27
Low emissions B1 2070 Lower	2	1	3	2
Low emissions B1 2070 Upper	-20	-28	-31	-35
High emissions A1F1 2070 Lower	7	8	6	3
High emissions A1F1 2070 Upper	-35	-46	-50	-57

Table 1 illustrates that under all emissions scenarios, the lower ranges of the predicted changes to the climate may result in a slight increase in the pollutant loads and flow volumes, by up to 8%. The largest change from the baseline is under a High emissions scenario (in the upper range), where mean annual pollutant loads and flow volumes are reduced substantially, including a reduction in TSS loads by 35% and a reduction in TN loads by 50%. This model does not take into account increases in pollutant loads due to increases in impervious areas as a result of future development.

A limitation in modelling the municipal pollutant budget exists due to the unknown impact of increasing antecedent dry days on pollutant wash off concentrations. However, a review of literature by Duncan (1995) found that it is likely that pollutant build up is not a key controlling factor in the concentration of pollutants in stormwater and rather, pollutant wash off, driven by rainfall energy and flow energy, have the greatest influence on stormwater pollutant concentrations. This finding lends support to the findings of the municipal pollutant budget modelling.

Stormwater Harvesting – Reliability of Supply

The reliability of supply, or the percent of a given water demand that can be met with a given harvesting scheme or tank, was modelled for a medium size stormwater harvesting scheme (with a 5ML/yr demand) as well as a number of household rainwater tanks with varying indoor and outdoor demands. Table 2 below shows the modelling results for the reliability of supply for these unit models under the six climate scenarios, as well as under the 1990 baseline scenario.

Table 2. Reliability of supply for different harvesting types, under various climate scenarios.

	Percent reliability of supply (%)				
	Stormwater Harvesting A*	Stormwater Harvesting B*	Rainwater Tank A*	Rainwater Tank B*	Rainwater Tank C*
1990 Baseline	80	80	80	76	90
Medium emissions 2030 Lower	81	80	80	76	91
Medium emissions 2030 Upper	78	78	79	74	87
Low emissions B1 2070 Lower	80	80	79	76	90
Low emissions B1 2070 Upper	75	77	78	73	83
High emissions A1F1 2070 Lower	80	80	79	75	90
High emissions A1F1 2070 Upper	69	73	76	69	76

*Stormwater Harvesting A with wetland pre-treatment and 160kL tank; Stormwater Harvesting B with raingarden pre-treatment and 180kL tank; Rainwater Tank A with 4kL tank for outdoor irrigation only; Rainwater Tank B with 4kL tank for toilet flushing and outdoor irrigation; Rainwater Tank C with 90kL tank for large indoor demand and no outdoor use.

The results in Table 2 demonstrate that the greatest loss in reliability of supply for all harvesting types is under the upper range of the High emissions scenario. A coarse analysis showed that to design these systems to provide reliability similar to the baseline year would require a 50% (under the Low emissions upper scenario) to 100% (under the High emissions upper scenario) increase in tank size. This is likely to be unfeasible given the uncertainties around future emissions. The key message from these results is that reliability of supply remains within 5% of the original estimates for all tanks and harvesting schemes under most emissions scenarios. Even under the harshest climate scenario (High emissions upper range) a typical stormwater harvesting scheme for irrigation of a sports field, as represented in these models, will still supply 3.5 ML/yr of a 5ML/yr demand.

WSUD Treatment Performance – Water Quality

The potential impacts of climate change on WSUD performance was measured by the changes in the pollutant removal efficiency of a range of typical WSUD treatment types. The following treatment types were assessed: a raingarden, a swale, tree pits and a wetland. Under each climate scenario, the percent load removed for TSS, TP and TN were determined. Each treatment type was developed to ensure it achieved best practice pollutant removal (of at least 80% TSS, 45% TP and 45% TN removal) under the baseline scenario. Table 3, Table 4 and Table 5 show the results for pollutant removal for each treatment type, under each climate scenario.

Table 3. TSS load reduction for a range of WSUD treatment types under various climate scenarios

	TSS load reduction (% of total load)

	Raingarden*	Swale*	Tree pits*	Wetland*
Unit models 1990 Baseline	79	96	90	81
Medium emissions 2030 Lower	78	96	90	80
Medium emissions 2030 Upper	79	96	90	83
Low emissions B1 2070 Lower	78	96	90	80
Low emissions B1 2070 Upper	78	96	89	83
High emissions A1F1 2070 Lower	78	96	89	79
High emissions A1F1 2070 Upper	78	96	90	86

Table 4. TP load reduction for a range of WSUD treatment types under various climate scenarios

	TP load reduction (% of total load)			
	Raingarden*	**Swale***	**Tree pits***	**Wetland***
Unit models 1990 Baseline	50	79	73	68
Medium emissions 2030 Lower	49	79	72	68
Medium emissions 2030 Upper	48	79	73	70
Low emissions B1 2070 Lower	50	79	72	68
Low emissions B1 2070 Upper	48	78	73	70
High emissions A1F1 2070 Lower	49	78	71	68
High emissions A1F1 2070 Upper	46	79	73	72

Table 5. TN load reduction for a range of WSUD treatment types under various climate scenarios

	TN load reduction (% of total load)			
	Raingarden*	**Swale***	**Tree pits***	**Wetland***
Unit models 1990 Baseline	51	46	47	47
Medium emissions 2030 Lower	51	45	46	47
Medium emissions 2030 Upper	49	46	46	48
Low emissions B1 2070 Lower	51	45	46	47
Low emissions B1 2070 Upper	48	45	46	48
High emissions A1F1 2070 Lower	50	45	45	47
High emissions A1F1 2070 Upper	45	46	45	50

*****Raingarden 15 m^2 with a general urban catchment; Swale 750m with a road only catchment; Tree pits $80m^2$ with a road only catchment; Wetland $2300m^2$ with a general urban catchment.

The analysis of treatment performance, in relation to pollutant load reduction, shown in Table 3 to Table 5, demonstrates that none of the modelled climate scenarios result in a substantial reduction in pollutant removal performance. In only two instances do the variations exceed 10% of the original design performance. Even in the cases where the performance differs by more than 10% (High emissions A1F1 2070 Upper, Raingarden, TP differs by 7% and High emissions A1F1 2070 Upper, Raingarden, TN differ by 13%) the degree by which they differ is likely to be an acceptable divergence from current best practice stormwater quality treatment given the climate models are the extremes of the range of likely future climate conditions.

An interesting outcome of the results in Table 3 to Table 5 is the estimated increase in treatment performance of constructed wetlands under the more severe climate scenarios. Wetland treatment performance improves by up to 6% (of the original design performance) under the scenarios which represent the harsher upper range of emissions scenarios. An analysis of the hydrologic effectiveness of all treatment types indicated that while raingardens, tree pits and swales showed a slight decrease in hydrologic effectiveness; the wetland showed up to 4% improvement in hydrologic effectiveness. The increase in draw down observed in the wetland inundation frequency analysis (Figure 1) may explain this slight increase in performance, in that some minor inflow events are completely lost to evapotranspiration. In addition, when water levels are drawn down further between rainfall events, the wetland will store and treat a larger proportion of subsequent inflows.

In summary, for most WSUD treatment types, a small loss in hydrologic effectiveness as a result of more intense rainfall events is offset by the overall reduction in flows and pollutant loads generated within the catchments as a result of a reduced mean annual rainfall volume.

Wetland Inundation and Vegetation Health

To understand potential impacts of climate change on wetland vegetation, under various climate scenarios, a water level exceedence curve was constructed by analysing the inundation frequency of the wetland extended detention for each climate scenario. The water level exceedence curve that deviated most from the baseline is represented in Figure 1 (along with the baseline).

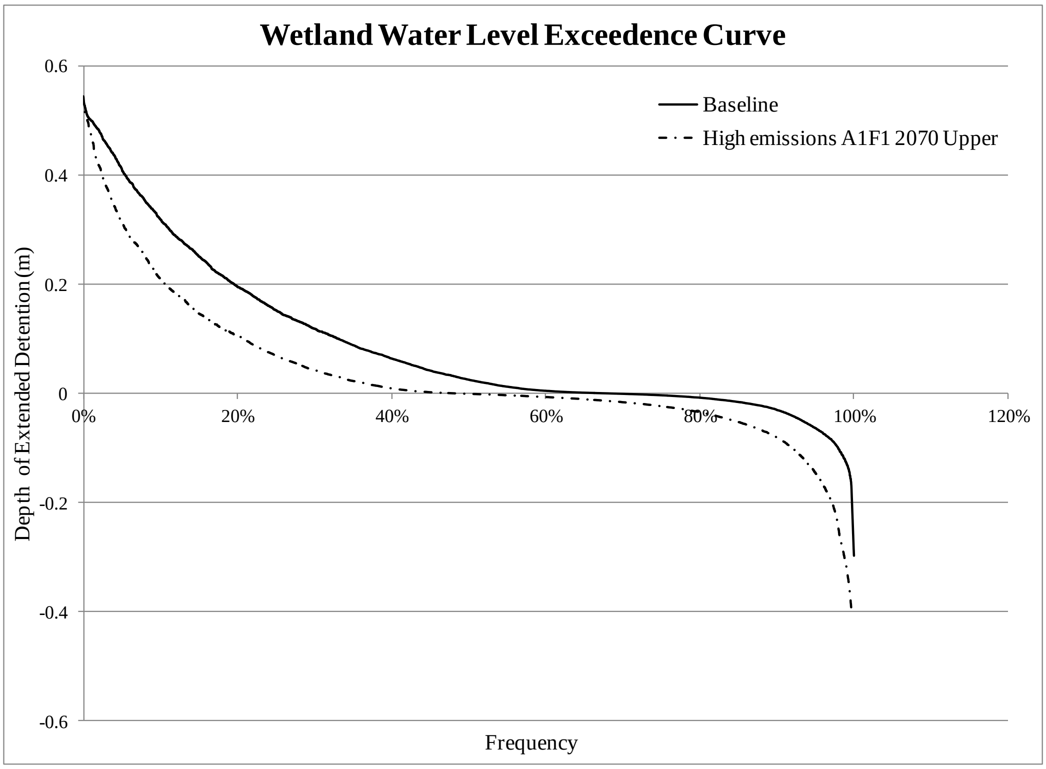

Figure 1. Wetland water level exceedence curve for Baseline and High Emissions (upper) scenarios

The baseline water level exceedence curve shows a pattern where the extended detention is regularly engaged. This pattern would require some adjustment to the permanent pool depth or the species mix to accommodate the effective water depth. The climate change water level exceedence curve actually represents a pattern that would be easier for many plants to tolerate and may support greater diversity (that is a balanced water level pattern with more equal periods above and below normal water level). The climate change scenario also suggests the wetland permanent pool draws down (water level is below – 0.2m for at least 5% of the time) and may completely dry. An occasional dry period is a natural pattern for most wetlands and is not considered a major issue but is an important design issue that needs to be understood.

Southern Australian Climate Variability

Southern Australia not only has a low annual rainfall compared to other continents, it also has high inter-annual rainfall variability (BoM, 2011). As a result, when treatment systems are designed and sized to meet best practice using long rainfall records, significant climatic variability is already accounted for in the modelling. The predicted climate change scenarios outlined in this study are well within the current inter-annual rainfall variability. This partly explains the minimal changes in performance of most stormwater treatment devices under all climate scenarios.

CONCLUSIONS

The Shire's Integrated Flood Mapping Program makes recommendations on the new assets required to address inland flooding; however the size and function of Water Sensitive Urban Design (WSUD) assets are not yet considered in this approach. The Shire has a strong commitment to a water sensitive approach in its development and landscape management. With over 100 individual assets including raingardens and tree pits, the Shire is active in the implementation of effective water sensitive solutions which best integrate flood mitigation and water quality improvements.

This study suggests that pollutant generation within the municipality may increase by up to 10% in the worst case climate change scenario. Most stormwater treatment devices cope very well with the climate change predictions, with a worst case load reduction performance of 6% for raingardens. The greatest impact of the climate change scenarios modelled is on stormwater harvesting and reuse. With the worst case resulting in a 24% reduction in security of supply, although in most cases the reduction was within 5% of the base case. The overall conclusion from this study is that potential climate change futures will have minimal impact on the efficiency and effectiveness of WSUD infrastructure.

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