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MUSIC's Bioretention Node under climate change: what changes do we need?

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Abstract: Bioretention systems help to mitigate the impacts of urbanisation on receiving waters by enhancing infiltration, reducing runoff, and improving water quality. However, their performance may be affected by climate change, as shifts in rainfall patterns, intensifying droughts, and rising temperatures can alter the biophysical and biogeochemical processes that underpin their stormwater management capacity. It is therefore critical that modelling tools used to design these systems can accurately represent such changes. Through a comprehensive literature review, this study examines the potential impacts of climate change on bioretention performance and evaluates whether MUSIC (Model for Urban Stormwater Improvement Conceptualisation) can adequately simulate these effects. The review indicates that while MUSIC's bioretention module is relatively capable of modelling hydrological changes, it lacks mechanistic representations of key processes, including plant growth and microbial activity. For example, the effects of temperature on biogeochemical processes are not explicitly accounted for. Future research should focus on improving the mechanistic representation of these overlooked processes to strengthen MUSIC's capability in modelling climate change impacts on bioretention systems. While this study focuses on conceptual and theoretical adaptations to MUSIC and did not involve model testing, it serves as a preliminary step to guide and inform future development of MUSIC.

Keywords: *bioretention system, stormwater, MUSIC*

1. INTRODUCTION

Bioretention systems are essential for mitigating the impacts of urbanisation by managing stormwater quantity and quality through physical, chemical, and biological processes. In Melbourne and across Australia, these systems play a key role in reducing peak flows, pollutant loads, and runoff volumes (Payne et al., 2015).

However, there is still little understanding of how bioretention systems will work in the future under a changing climate. Current bioretention system installations and design assume stationarity in the underlying hydrologic and pollutant removal processes. However, there is increasing evidence that hydrologic processes (Peterson et al. 2021), vegetation health (Zhang et al. 2021, Hartmann et al. 2022), nutrient health and soil microbiomes (Jansson and Hofmockel, 2019) in the natural and urban environment will be altered under climate change. These are all processes that are put to action within bioretention systems, and it is unclear how the hydrological and pollutant removal performance of bioretention systems will be affected by climate change. Not only do we currently lack this understanding of how the bio-physical processes within bioretention systems respond to climate change, but we also do not know how our current models and modelling practices for bioretention system design are suited for a future with a changed climate.

Early climate resilience work by Burge et al. (2012) investigated the impacts of potential rainfall changes on Water Sensitive Urban Design (WSUD) treatment measures across the Mornington Peninsula under various climate scenarios in MUSIC. The authors found a worst-case pollutant load reduction performance of 6% for rain gardens, and suggested that 'potential climate change futures will have a minimal impact on the efficiency and effectiveness of WSUD infrastructure' (Burge et al., 2012). This study did not fully represent rainfall intensity changes, as this would require a downscaled, sub-daily time series. Instead, daily time series were generated to represent the extremes of projected changes (10th and 90th percentiles) for each emissions scenario. These were created using season-specific stochastically generated percentage changes to each day of rainfall from an established baseline.

More recently, and at a finer temporal and spatial scale, Zhang et al. (2019) examined the impacts of potential rainfall changes in Victoria on a range of WSUD systems' functioning under future climate scenarios. Using high resolution rainfall projections (1 km at 6-minute intervals) downscaled from eight General Circulation Models (GCMs), the authors modelled changes in pollutant treatment performance and flow frequency reduction at a single site in MUSIC. They found that future climate scenarios resulted in minimal differences in pollutant treatment and flow reductions by biofiltration systems, however the authors suggested increasing the sizing of WSUD systems to account for climate uncertainty. High resolution rainfall projections are important for accurate WSUD modelling, as system functioning can be influenced by short, intense rainfall fluctuations, which can influence runoff volume and frequency at a catchment or smaller scale.

eWater MUSIC is a widely adopted tool in Australia for modelling stormwater quantity and quality based on catchment characteristics and stormwater treatment system design. It is used by decision-makers to ensure water quality/treatment requirements are met using appropriate WSUD systems and design characteristics. This paper explores whether the bioretention modelling module in MUSIC is adequately equipped to represent how bioretention systems will perform under a changed climate. By consulting the existing literature, this paper first explores how the performance of bioretention systems may change under climate change (Figure 1), and then critically assesses whether MUSIC currently has the capability to accurately model these changes. Additionally, this paper proposes conceptual methods for adapting MUSIC to account for these changes, enhancing its effectiveness as a modelling tool for climate-resilient stormwater management. Finally, we propose several recommendations on how MUSIC could be updated to ensure better performance under a changing climate. This study focuses on conceptual and theoretical adaptations to MUSIC and did not involve empirical testing of MUSIC. This was intended as a preliminary step to guide future research.

2. METHODS

A comprehensive review of relevant literature and technical documentation was conducted to understand how bioretention systems may be impacted by climate change, and determine whether the underlying assumptions and calculations within MUSIC's bioretention node are equipped to accurately represent climate change impacts. Specifically, the literature survey was conducted using Google Scholar with a combination of keywords such as biofiltration, stormwater, bioretention, modelling, climate change, nutrient removal, MUSIC, WSUD and urbanisation.

Additionally, possible future adaptations of MUSIC's bioretention node have been proposed. Processes that could be adapted were selected based on their potential to influence bioretention system performance under future climate scenarios, as well as the feasibility of implementation within MUSIC.

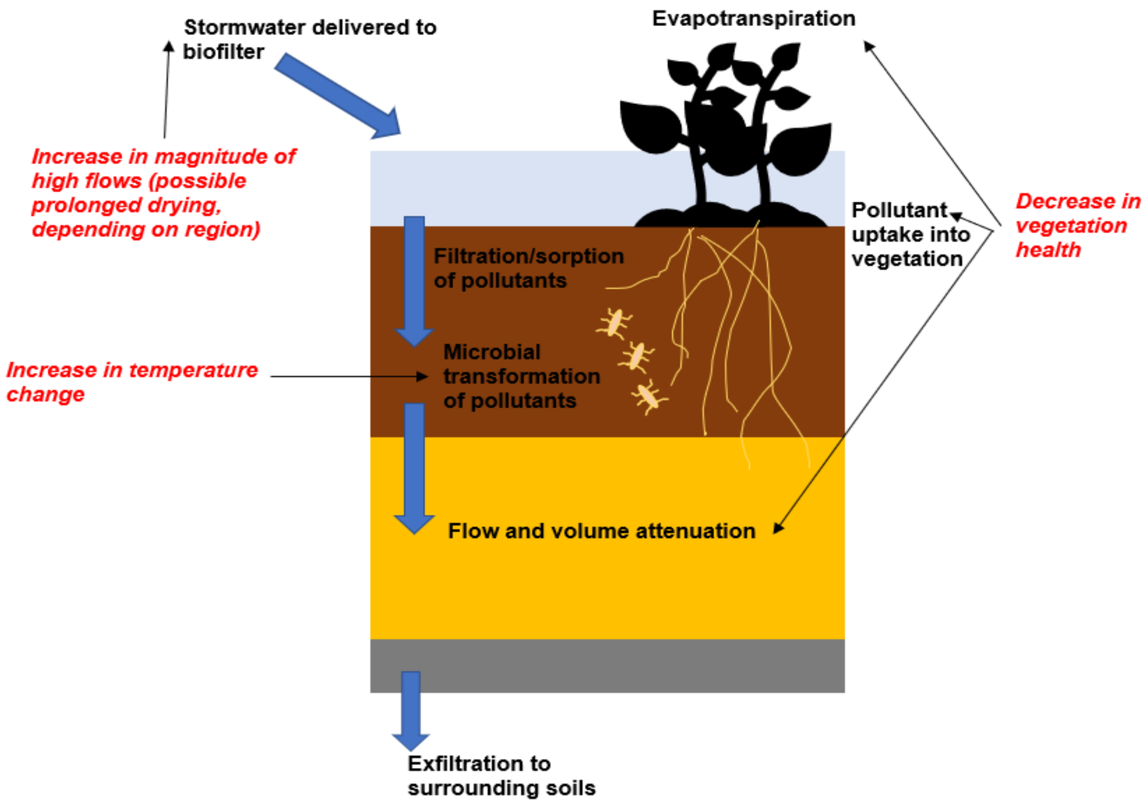

Figure 1. Key hydrologic and pollutant removal processes in biofilters (writing in black) and the processes likely to be affected by a changing climate (writing in red)

3. RESULTS AND DISCUSSION

3.1. Hydrologic performance of bioretention systems and impact of climate change

Previous studies have shown that MUSIC is able to achieve relatively acceptable results from its hydraulic and hydrological calculations. Although there is room for improvement in modelling complex bioretention designs, once calibrated, MUSIC is able to produce representative outflow hydrographs and mean annual flow volumes. For example, simulations by Sabbagh et al. (under review) achieved Nash-Sutcliffe Efficiency values ranging from 0.44 to 0.84 after calibration, indicating good model performance. Imteaz et al. (2013) also demonstrated reasonable accuracy within MUSIC's flow rate calculations, with an overall Root Mean Squared Error of 0.011 l/s across two bioretention sites.

Climate change is expected to generally increase rainfall variability in Australia, with more intense extreme events and reduced overall rainfall in southern Australia (CSIRO 2022). These changes are expected to slightly reduce the hydrological efficiency and pollutant treatment performance of bioretention systems, though further research is needed (Zhang et al., 2019, Burge et al., 2012). A notable limitation in the MUSIC model is its lack of feedback between soil moisture and actual plant water uptake, potentially causing a slight overestimation of evapotranspiration during droughts or periods when plant stomata close to conserve water, which may affect the accuracy of bioretention system simulations under prolonged droughts or increased heat stress.

Large bioretention systems, that is, systems covering a great percentage of the total catchment area, have been recommended for accounting climate uncertainties, as they may improve storage capacity and pollutant removal during more intense rainfall events (Zhang et al. 2019). However, these large systems can introduce trade-offs such as uneven flow distribution, reduced infiltration rates, and increased maintenance requirements, potentially reducing their overall efficiency. Despite these challenges, changes to the system's hydrological performance under climate change are able to be accounted for within MUSIC through the use of user-provided rainfall/inflow projections to account for rainfall runoff changes, or by directly altering parameter values in all other cases (e.g. changes to infiltration rate, field capacity, etc). Because of these factors, MUSIC is capable as a tool for modelling bioretention's hydrological performance under future climates.

3.2. Pollutant reduction performance of bioretention systems and impact of climate change

In contrast to hydrologic performance, it is less certain whether MUSIC's water quality calculations are able to accurately represent the impact of climate change on pollutant reduction performance. In a study exploring MUSIC's accuracy using field data for verification, Imteaz et al. (2013) found that MUSIC was able to simulate total suspended solids (TSS) removal in bioretention systems accurately across both sites. However, the Melbourne site overestimated total phosphorus (TP) and total nitrogen (TN) reductions. Predicted TP reductions ranged between 79.6% and 91.7%, while observations showed reductions between -214% and -129%, indicating TP had increased. MUSIC predicted TN reductions between 71.4% and 88.1%, despite observed TN reductions between 0% and -18%. The Brisbane site produced accurate TP reduction estimates (85.2% predicted vs. 83% observed), but overestimated TN reductions (19% predicted vs. 76.2% observed), likely due to leaching of the filter media. Therefore, even under current climate conditions (i.e., without considering future climate), there are uncertainties and errors in MUSIC models of TP and TN removal performance in bioretention systems.

Microbial functioning is highly sensitive to temperature. Blecken et al. (2007) observed that as temperatures increased, nitrification and nitrogen leaching in bioretention systems also increased. Søberg et al. (2020) found that higher temperatures reduced phosphorus removal, and Søberg et al. (2021) also observed higher TN outflow concentrations in bioretention systems as temperatures increased. As temperatures increase under climate change, temperature-related changes to microbial functioning within these systems may decrease the accuracy of MUSIC's pollutant reduction calculations.

Pollutant treatment performance is partially controlled by plant nutrient uptake. Payne et al. (2014) suggest that bioretention plant functioning (e.g. productivity, growth, nitrogen uptake, and biomass turnover) is highly dependent on seasonal changes in temperature, light, and rainfall. The timing of these productivity fluctuations is species dependent, meaning pollutant reductions may also vary throughout the year as a result of species choice. Longer drying conditions under climate change have the potential to stress vegetation, resulting in die-off and increased outflow pollutant loads. Submerged zone biofilter designs have been shown to protect plant health and reduce nitrogen leaching after two-week drying periods (Zinger et al., 2021), but longer periods typical of Mediterranean and arid climates showed no benefit of having a submerged zone (Winfrey et al., 2020).

3.3. Incorporation of climate change impacts in MUSIC's bioretention node

Table 1 outlines a range of parameters/processes expected to be influenced by climate change, their current representation in MUSIC, and how improvements could be made to increase MUSIC's accuracy in the future under climate change. Temperature emerged as a parameter of interest as it impacts a range of processes (nitrogen leaching, vegetation stress and TP removal) within bioretention systems despite its absence from MUSIC's calculations.

Table 1. Parameters and processes within MUSIC's Bioretention Node and proposed improvements to better adapt to future climate change scenarios

Parameter/ process	Potential impact on biofiltration under climate change	Current state within MUSIC	Method for incorporation within MUSIC	Expected benefits of incorporation into MUSIC
Rainfall patterns	Slight declines in hydrologic and pollutant treatment performance (Zhang et al. 2019, Burge et al. 2012).	MUSIC uses user-provided rainfall and potential evapotranspiration (PET) datasets. PET scaling can also be adjusted within MUSIC for further calibration. Emerging downscaling techniques, such as those used by Zhang et al. (2019), enable the creation of precise (1 km and 6-minute time step) future rainfall projections for use in MUSIC.	Investigate new partnerships to improve access to tools for generating high resolution, downscaled datasets. Create user guides detailing the process of conducting climate resilience analysis through MUSIC.	By improving data accessibility and providing new training resources, we can remove the barriers deterring decision-makers from using MUSIC for climate-resilient planning and design purposes.
Temperature	Declines in pollutant treatment efficiency (Blecken et al., 2007, Søberg et al. 2020, Søberg et al. 2021).	Temperature is not currently considered by MUSIC, meaning microbial processes and vegetation function are assumed to behave uniformly over time regardless of temperature.	Conduct a column study to examine the effects of temperature on bioretention pollutant loading.If relationships are found, MUSIC's pollutant models could be adjusted to incorporate temperature-dependent pollutant reduction calculations. Local temperature data could be user-provided alongside rainfall datasets	These improvements would increase the accuracy of MUSIC's pollutant removal calculations under future conditions and support the optimisation of system design for local conditions.
Seasonal vegetation productivity	Species-dependent changes to seasonal nutrient uptake rates (Payne et al. 2014).	Vegetation within the bioretention node in MUSIC can be classified as 'vegetated with effective nutrient removal species', 'vegetated with ineffective nutrient removal species' or 'unvegetated'.	Conduct a column study to investigate the effects of seasonal changes (e.g. temperature and length of daylight) on the pollutant loading capacity of effective nutrient removal species. This could be used to create season-specific nutrient uptake rates. As rainfall, temperature, and seasonal patterns change due to climate change, this data could be used to adapt nutrient uptake rates for effective nutrient removal species accordingly.	Understanding and incorporating season-specific nutrient uptake rates within MUSIC could improve the model's accuracy in simulating pollutant loading throughout the year. This information could be used to help inform species selection and optimise maintenance schedules.
Vegetation health	Prolonged drying periods cause vegetation stress, reducing pollutant treatment efficiency (Zinger et al. 2021).	Soil moisture and presence of a submerged zone are considered when modelling outflow TP concentration (though not for TN), which somewhat accounts for reduced plant function under dry conditions. However, MUSIC does not consider the impact of prolonged drying conditions (both water and heat stress) on vegetation health.	Update TN and TP calculations that account for the impacts of prolonged drying and re-wetting dynamics. Identify key indicators of heat/drought stress for plant species recommended for planting in bioretention systems. Use these indicators to flag periods of vegetation stress in MUSIC	Updating TN/TP calculations would improve model accuracy, allowing for better-informed system design choices. Flagged periods of vegetation stress could be used to inform cost-benefit analyses and tailor maintenance plans to reduce the risk of die-off events.

Parameter/ process	Potential impact on biofiltration under climate change	Current state within MUSIC	Method for incorporation within MUSIC	Expected benefits of incorporation into MUSIC
System Sizing	Larger systems may improve storage and pollutant removal under higher rainfall intensities, mitigating the negative impacts of climate change on system performance (Zhang et al. 2019).	MUSIC allows users to define bioretention system size based on catchment area and design goals. It is possible the efficiency of larger systems is overestimated.	Conduct field studies (or use existing data) to investigate the relationship between bioretention system size, hydraulic performance, pollutant/sediment loading, and climate change.	By verifying the relationship between system size, hydraulic performance, and pollutant loading, MUSIC can more accurately model bioretention systems under climate change. This would allow for optimised designs that balance size and performance, avoiding inefficiencies from oversized systems. This research would support a shift toward using multiple smaller systems to increase catchment treatment ratios to enhance climate resilience.

4. RECOMMENDATIONS

Given MUSIC has been determined to be relatively capable of modelling hydrological changes caused by climate change, future research should focus on improving the accuracy of pollutant reduction calculations. This can be achieved by understanding the impact of overlooked parameters and processes. Additionally, further enhancement of MUSIC as a tool for climate resilience should be developed.

The following recommendations outline key strategies to enhance MUSIC's capability for modelling bioretention system performance under climate change, based on the findings of this report.

4.1. Enhance rainfall data integration

- Develop training resources which provide users with the techniques necessary to create high-resolution, downscaled rainfall datasets for a range of climate scenarios, improving the accessibility and utility of MUSIC for future climate resilience planning.

4.2. Investigate temperature, vegetation, and seasonal dynamics

- Adjust MUSIC's pollutant model to incorporate temperature-dependent pollutant reduction calculations, supported by experimental findings.
- Develop season-specific pollutant removal rates and update vegetation parameter in MUSIC to reflect seasonal changes in plant functioning and nutrient uptake.
- Update TN/TP calculations to include prolonged drying and re-wetting dynamics
- Use plant stress indicators to flag periods of plant stress and inform species choice, maintenance plans, and cost-benefit analyses.

4.3. Optimise system sizing

- Conduct field studies and long-term monitoring to refine the relationship between system size, hydraulic performance, and pollutant loading, ensuring MUSIC accurately predicts system performance and supports climate-resilient design solutions, whilst taking into account variations in performance within systems.

5. CONCLUSION

This study discusses MUSIC's capability to represent the critical processes within bioretention systems that may be influenced by climate change. MUSIC has demonstrated relative capability in modelling hydrological changes driven by climate change. However, to improve its accuracy in pollutant reduction predictions, future research should focus on addressing overlooked parameters and processes, such as temperature dependency and vegetation health. Enhancing MUSIC's capability in modelling bioretention systems under climate change scenarios involves integrating high-resolution, downscaled rainfall data and incorporating seasonal vegetation dynamics, temperature-dependent pollutant removal rates, and plant stress responses. Finally, the relationship between system size, hydraulic performance, and pollutant loading can be refined by assimilating field studies and long-term monitoring data. Implementing these strategies will strengthen MUSIC's utility as a modelling tool under changing climate conditions.

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REFERENCES

Barron NJ, Hatt B, Jung J, Chen Y and Deletic A (2020) Seasonal operation of dual-mode biofilters: The influence of plant species on stormwater and greywater treatment. Science of The Total Environment 715, 136680.

Blecken GT, Zinger Y, Muthanna TM, Deletic A, Fletcher TD and Viklander M (2007) influence of temperature on nutrient treatment efficiency in stormwater biofilter systems. Water Science and Technology 56(10), 83–91.

Burge K, Browne D, Breen P and Wingad J (2012) Water sensitive Urban design in a changing climate: Estimating the performance of WSUD treatment measures under various climate change scenarios. WSUD 2012 - 7th International Conference on Water Sensitive Urban Design: Building the Water Sensitive Community, Final Program and Abstract Book.

Hartmann H, Bastos A, Das AJ, Esquivel-Muelbert A, Hammond WM, Martínez-Vilalta J, McDowell NG, Powers JS, Pugh TAM, Ruthrof KX and Allen CD (2022) Climate Change Risks to Global Forest Health: Emergence of Unexpected Events of Elevated Tree Mortality Worldwide, Annual Review of Plant Biology 73(1), 673–702.

Imteaz MA, Ahsan A, Rahman A and Mekanik F (2013) Modelling stormwater treatment systems using MUSIC: Accuracy. Resources, Conservation and Recycling 71, 15–21.

Jansson JK and Hofmockel KS (2020) Soil microbiomes and climate change, Nature reviews. Microbiology 18(1), 35–46.

Payne E, Hatt B, Deletic A, Dobbie M, McCarthy D and Chandrasena G (2015) Adoption Guidelines for Stormwater Biofiltration Systems. Cooperative Research Centre for Water Sensitive Cities, Melbourne.

Payne E, Fletcher TD, Cook P, Deletic A and Hatt B (2014) Processes and Drivers of Nitrogen Removal in Stormwater Biofiltration. Critical Reviews in Environmental Science and Technology 44(7), 796-846.

Peterson T, Saft M, Peel M and John A (2021) Watersheds may not recover from drought. Science 372, 745–749.

Sabbagh M, Browne D, Irani Z, Monettie J, Pickering L, Winston R, Spraakman S, Drake J, Fletcher TD, Hatt B, Poelsma P, Bonneau J, Lintern A and Winfrey B (2025) Reality-check of a stormwater bioretention modelling. [under review].

Søberg L, Al-Rubaei A, Viklander M and Blecken G (2020) Phosphorus and TSS Removal by Stormwater Bioretention: Effects of Temperature, Salt, and a Submerged Zone and Their Interactions. Water, air, and soil pollution 231(6).

Søberg L, Viklander M and Blecken G (2021) Nitrogen removal in stormwater bioretention facilities: Effects of drying, temperature and a submerged zone. Ecological Engineering 169, 106302.

Winfrey, B. K., Ho, M., Wang, W., Li, Y. J., & Ambrose, R. F. (2020). Design aspects and plant species affect pollutant removal in Southern California stormwater biofilters. Blue-Green Systems, 2(1), 300-317.

Zhang K, Manuelpillai D, Raut B, Deletic A and Bach PM (2019) Evaluating the reliability of stormwater treatment systems under various future climate conditions. Journal of Hydrology 568, 57–66.

Zhang W, Randall M, Jensen MB, Brandt M, Wang Q, Fensholt R (2021) Socio-economic and climatic changes lead to contrasting global urban vegetation trends. Global Environmental Change 71, 102385.

Zinger Y, Prodanovic V, Zhang K, Fletcher TD and Deletic A (2021) The effect of intermittent drying and wetting stormwater cycles on the nutrient removal performances of two vegetated biofiltration designs. Chemosphere 267.

