

A Catchment-Scale Nature-Based Solutions Planning Framework for Urban Flood Mitigation

(Un dispositif pour planifier des solutions basées sur la nature pour réduire les effets des inondations urbaines à l'échelle d'un bassin versant)

Wenhui Wu^{1*}, Behzad Jamali², Kefeng Zhang¹, Lucy Marshall^{1,3}, Ana Deletic^{1,4}

1 Water Research Centre, School of Civil and Environmental Engineering, UNSW Sydney, NSW 2052, Australia

2 WMAwater Pty Ltd, Sydney, NSW 2000, Australia

3 Faculty of Science and Engineering, Macquarie University, NSW 2109, Australia

4 School of Civil and Environmental Engineering, Engineering Faculty, Queensland University of Technology, Queensland 4001, Australia

*Corresponding author email: wenhui.wu2@unsw.edu.au

RÉSUMÉ

Les solutions basées sur la nature constituent une méthode de gestion durable pour réduire les inondations pluviales en capturant les eaux de ruissellement par des mesures distribuées comme la biorétention. La planification holistique de ces solutions est essentielle pour atténuer efficacement les inondations. Cependant, les difficultés sont grandes en raison de la forte variabilité des types, tailles, et dispositions spatiales de ces solutions dans le bassin versant, ainsi que des interactions complexes entre les solutions et les réseaux de drainage existants. Pour résoudre ce problème, nous avons développé un cadre innovant qui permet de sélectionner rapidement le modèle optimal de solution naturelle à placer dans différents sous-bassins versants pour limiter les inondations à l'échelle du bassin versant. Ce dispositif, qui utilise la réduction de la surface imperméabilisée effective du sous-bassin versant pour représenter la mise en œuvre de la solution, étudie les scénarios éligibles de réduction du volume d'inondation du bassin versant, pour fixer des objectifs individuels de réduction du volume de ruissellement pour le sous-bassin versant. On peut rapidement sélectionner l'ampleur de la solution adaptée pour atteindre ces objectifs, en fonction de courbes de conception de réduction du volume de ruissellement. L'application du dispositif à un bassin versant urbain à Sydney, en Australie, a validé son utilité pour identifier des méthodes efficaces de mise en œuvre de la biorétention afin de réduire les intervalles de récurrence des dégâts causés par les inondations.

ABSTRACT

Nature-based solutions (NBS) is a sustainable stormwater management approach for reducing pluvial flooding by capturing runoff through distributed measures such as bioretention. Catchment-based holistic NBS planning is vital for effective flood mitigation. However, it has been challenging due to high variability of NBS types, sizes and spatial layouts across the catchment, as well as complex interactions between NBS and existing drainage networks. To address this issue, we developed a novel framework that enables rapid selection of optimal NBS designs to be placed in different subcatchments for catchment-scale flood mitigation. Using reduction in subcatchment effective impervious area to mimic NBS implementation, the framework explores eligible catchment flood reduction scenarios to set individual subcatchment runoff volume reduction targets. Suitable NBS sizes can be rapidly selected to meet these targets using NBS runoff volume reduction design curves. Applying the framework to an urban catchment in Sydney, Australia validated its usefulness for identifying effective bioretention implementation strategies to reduce the return periods of flood damage.

KEYWORDS

BMP spatial planning, performance curves, pluvial flood reduction, SUDS placement, sponge city

INTRODUCTION

Nature-based solutions (NBS) has been found to be a sustainable and cost-effective approach to reduce pluvial flooding (Jamali et al., 2020). While NBS planning models have been developed for selecting NBS types, sizes and locations, NBS planning at catchment-scale remains a challenge due to the diverse and distributed nature of NBS, and complex hydrological and hydraulic processes in the catchment (Fiori and Volpi, 2020). There is a large number of possible NBS design parameters and implementation scenarios across the catchment that need to be tested. Simple trial-and-error approaches are not sufficient for identifying effective NBS strategies to meet a catchment-scale flood mitigation target. There is a need to develop an approach for fast exploration of NBS options to meet flood mitigation targets. Rapid, exploratory NBS planning has been realised in a well-tested NBS planning software UrbanBEATS (Bach et al., 2020), which rapidly identifies futureproofed NBS options and spatial layouts for stormwater harvesting and pollutant reduction purposes. The rapid exploration is enabled by the development of NBS “design curves”, which act as look-up tables that allow rapid sizing of NBS for a specific reduction target for runoff volume or pollutant load. However, design curves for NBS performance in flood reduction has not been developed.

In this study, we introduce a novel and parsimonious framework for rapid exploratory NBS planning for flood mitigation. Using reduction in subcatchment effective impervious area to mimic NBS implementation, the framework generates tens of thousands of catchment flood volume reduction scenarios, and filters eligible scenarios to set individual subcatchment runoff volume reduction targets. This offers simplicity in estimating the amount of runoff reduction needed in each subcatchment to reach catchment-scale flood volume reduction threshold whilst taking into account the complex interaction with connected urban drainages systems. Using bioretention as an example, we investigated the influence of site characteristics and NBS design parameters on NBS runoff volume reduction performance and developed a set of representative NBS design curves. The curves enable fast sizing of suitable NBS to meet the subcatchment runoff volume reduction targets. To the authors’ knowledge, this is the first time that a rapid exploratory NBS planning framework for catchment-scale flood mitigation has been developed. The framework’s usefulness is tested on an urban catchment in Sydney Australia to identify effective bioretention implementation strategies that can reduce flood damage from a design storm of 10%AEP to the level of 20%AEP (i.e., reducing the return periods of flood damage).

METHODS

The framework involves five steps. Step 1 sets a flood damage reduction target of reducing the return period of flood damage and computes a minimum catchment flood volume reduction as a guided threshold based on flood damage and volume relationships. Using U.S. EPA Storm Water Management Model (SWMM), Step 2 applies a Monte Carlo approach to explore tens of thousands of flood volume reduction scenarios by reducing imperviousness in flood-source subcatchments. For each eligible scenarios that reach the threshold, the required subcatchment runoff reductions were set as subcatchment runoff volume reduction targets. The top scenarios closest to threshold were selected for NBS placement. Step 3 focuses on rapid sizing of bioretention (as an example of NBS). Generic bioretention design curves for runoff volume reduction were created based on influential parameters identified through sensitivity analysis. In Step 4, NBS placement strategies were generated by placing bioretentions of appropriate sizes in the subcatchments according to the subcatchment runoff reduction targets in each scenario. Changes in damage were computed using a rapid flood model Cellular Automata Fast Flood Evaluation (CA-ffé). In Step 5, three representative NBS placement strategies were selected based on cost-benefit analysis. These include strategies that achieves the most flood damage reduction (Most Benefit); requires the least land to be replaced with bioretention (Least Cost); and the average between the two (Average). Their effectiveness for damage mitigation under different design storms were assessed.

The framework was applied to an urbanised catchment in Sydney, Australia to reduce \$1.133 mil AUD flood damage, which effectively reduces the flood damage from a design storm of 10%AEP to the level of 20%AEP (Figure 1).

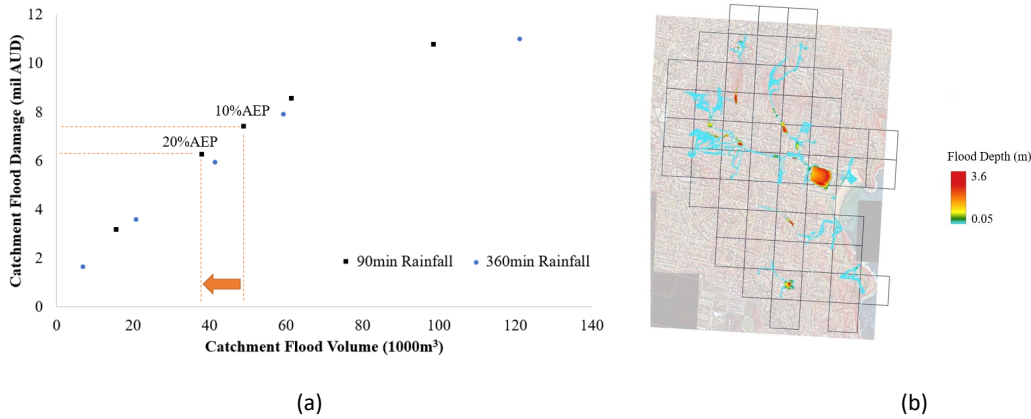


Figure 1 a) Baseline Catchment Flood Volume and Damage under 90-min and 360-min rainfalls of 1-50%AEP.
 b) Flood Depth and Flooded Area under 90-min rainfall of 10%AEP.

3. RESULTS AND DISCUSSION

3.1 NBS Design Curves

Sensitivity analysis on the influence of site characteristics and bioretention design parameters revealed that changes in bioretention surface area ratio (as % of subcatchment impervious area), storage layer depth and filter layer depth were the top three dominating influencers, accounting for 95% of the variations in bioretention runoff volume reduction across all design rainfalls. Therefore, representative design curves were generated targeting these three parameters whilst keeping other parameters fixed.

3.2 Effectiveness of Representative Strategies

The three representative strategies selected all exceeded the flood damage reduction target under 90-min design rainfalls of 5% to 50%AEP, and 360-min design rainfalls of 5%-10%AEP (Figure 2). It can be argued that there is over-design of NBS as some of the strategies achieved more than 130% of the reduction target. However, the strategies were created based on optimal performance of NBS with an aim to serve as a general guide for early-stage high-level NBS planning. Buffer for malfunction is needed and detailed performance assessment of specific NBS designs at later stage would be necessary.

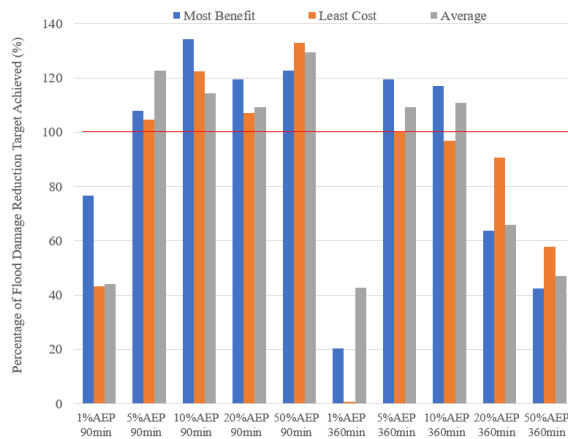


Figure 2 Performance of Representative Strategies in Achieving Flood Damage Reduction Target (\$1.133 mil AUD reduction) under Different Design Storms.

As expected, the representative strategies were most effective under the 90-min design rainfall of 10%AEP because there were designed for reducing flood volume under that design storm to the level of 20%AEP. Due to limited storage capacity, the strategies were not able to cope with high rainfall intensity under 1%AEP events, especially with less bioretention surface area (Least Cost strategy). Similarly, as reported in the literature, NBS tend to perform less well under longer duration storms as

they become saturated under prolonged rainfall.

In addition, the strategies were able to reduce the return period of flood damage for both design storms of 5%AEP and 10%AEP. The effectiveness of the Most Benefit strategy in reducing flood damage return period is shown in Figure 3. Such result can be easily conveyed to flood risk managers, urban planners and community members to understand the effectiveness of the NBS strategies in reducing flood damage.

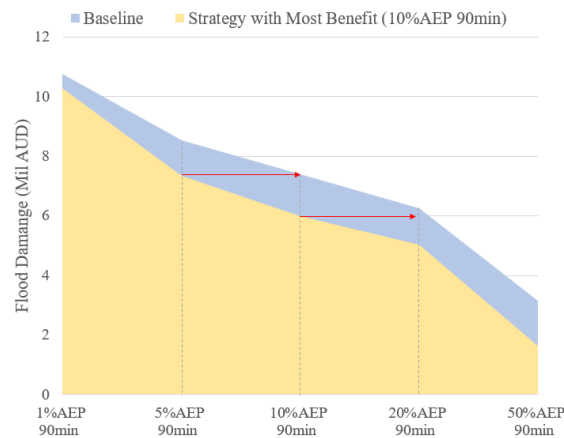


Figure 3 Flood Damage under Baseline Condition (without NBS) and with NBS (Most Benefit Strategy, Selected Using 90-min Design Storms of 10%AEP). Red arrows show how the flood damage have reduced to the level of a more frequent design storm when NBS strategy is implemented.

CONCLUSION

We demonstrated an effective catchment-scale NBS planning framework for flood mitigation. Taking advantage of the fast flood simulation by coupling SWMM and CA-ffé, and the rapid WSUD sizing based on design curves, this framework realises rapid exploratory planning and enables identification of effective WSUD implementation strategies that can reduce return period of flood damage. It enables robust high-level NBS planning to pre-screen large number of NBS strategies to identify futureproofed ones, and provides ease in communication in terms of the effectiveness of the strategies for flood damage reduction.

LIST OF REFERENCES

- Bach, P. M., Kuller, M., McCarthy, D. T. and Deletic, A. (2020). A spatial planning-support system for generating decentralised urban stormwater management schemes. *Science of The Total Environment*, 726, 138282.
- Fiori, A. and Volpi, E. (2020). On the Effectiveness of LID Infrastructures for the Attenuation of Urban Flooding at the Catchment Scale. *Water Resources Research*, 56.
- Jamali, B., Bach, P. M. and Deletic, A. (2020). Rainwater harvesting for urban flood management - An integrated modelling framework. *Water Research*, 171, 115372.