

# **Potential of Blue-Green Infrastructure for stormwater management in informal settlements upgrading programmes: Case study of Baan Mankong in Bangkok, Thailand**

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## **Abstract**

Cities increasingly rely on Blue-Green Infrastructure (BGI), such as green roofs or pervious pavements, to manage stormwater. The upgrading of informal settlements, areas characterised by low access to basic services, provides an opportunity to incorporate BGI in many Global South cities. However, few studies examine the hydrologic performance of BGI for the urban forms and climate conditions of such upgrading projects. Here, we explore the potential of BGI in reducing runoff volume in the Baan Mankong program in Thailand, a world-acclaimed, government-supported informal settlements upgrading initiative. Using the PCSWMM hydrological software, we compare the effectiveness of BGI scenarios in reducing runoff for different housing typologies. BGI scenarios include green roofs, pervious pavements, and raingardens in three existing sites and one reimagined design. Retrofitting the sites with green roofs and pervious pavements was generally the most effective option, although the results depend on the site design (2% to 48% runoff reduction in high rainfall events). An alternative design with less built-up area significantly reduced flooding (36% to 60% runoff reduction in high rainfall events). Overall, our study provides insights into the hydrological trade-offs and opportunities of implementing BGI in upgraded informal settlements, both for retrofitting upgrading projects and future flood-resilient designs.

**Keywords:** Blue-green infrastructure, Informal urbanisation, Floods, Informal settlement upgrading, Nature-based solutions.

## **Highlights**

- Blue-green infrastructure (BGI) has potential in the upgrading of informal settlements
- We compared the effect of BGI for three informal settlements upgrading projects
- Pervious pavement retrofitting was the most effective strategy for runoff retention
- The effect of BGI strategies was strongly influenced by the site specificities

## 1. Introduction

Cities globally face major urban flooding risks, and future climate projections anticipate an even higher risk for most Asian cities (Ranasinghe et al., 2021). Bangkok is one of the ten cities at higher risk of flooding globally (Berquist et al., 2014; Nicholls et al., 2007), which has large consequences for communities and individuals. For example, the 2011 floods in Thailand affected more than 13 million people, left 680 dead, and caused US\$46.5 billion in damages and losses (Loc et al., 2020 & 2023; UNDRR, 2011). The flooding affected particularly the city's poor and vulnerable communities (Williams et al., 2018). In Bangkok, the most vulnerable neighbourhoods often live in informal settlements or "slums", areas characterised by low access to basic services and uncertain land tenure, which account for the homes of 29% of the population of the city (Edelman, 2022).

One of the ways historically employed to reduce the vulnerability of informal settlements and improving living conditions is through "urban upgrading" programs. The main program, called Baan Mankong (BMK), is a housing upgrading programme managed by the government which provides funding at low interest rates to allow the residents to improve their housing conditions (Boonyabancha, 2005). BMK is unique as it uses non-conventional methods of informal settlement upgrading, like giving out resources and allowing the local community to develop their own housing upgrading solutions. This method is effective because housing is culturally viewed as a family-owned responsibility in Thailand. As such, the local community savings group would use the funds at their discretion – to purchase the land, construct, or improve their houses. Local residents work with community architects on the site design of their upgraded settlement and the use of infrastructure (Yap and De Wandeler, 2010).

While the program has oversight over the re-design of the settlements, the housing typologies implemented rarely include blue-green infrastructure (BGI) as a tool to mitigate floods and enhance climate resilience (Rauf et al., 2021). BGI are vegetated systems or water bodies increasingly used around the world to manage floods under the different concepts of 'Nature-based Solutions' (NbS), 'Water Sensitive Urban Design' (WSUD), and 'Low Impact Development (LID) Measures' (Hamel and Tan, 2022, Fletcher et al., 2015). BGI include a range of infrastructure such as green roofs, pervious pavements, and rain gardens (Vojinovic et al., 2021). Green roofs are roofs covered with vegetation to allow rainfall infiltration and water storage. Pervious pavements are ground areas made of porous material that enables stormwater to infiltrate. Rain gardens are sunken gardens to allow runoff retention and

infiltration. Together, these BGI help mitigate floods by reducing peak flow (Ercolani et al., 2018; Yang and Chui, 2018), delaying peak flow (Ishimatsu et al., 2016), and reducing the runoff volume (Lee et al., 2013; Loc et al. 2017; Shafique and Kim, 2018). BGI are particularly effective in urban areas to retain, infiltrate, and treat stormwater. This helps to both mitigate floods and improve water quality (Ferreira et al., 2021).

The use of BGI in informal settlement upgrading projects is still nascent and there are only limited studies examining its potential for stormwater management. In Southeast Asia, evidence base for BGI and nature-based solutions for urban water management is growing but applications to upgrading programmes are rare (Hamel and Tan, 2022; Wolff et al., 2023). Rather BGI case studies have focused on formal residential areas and public spaces such as parks, canals, and wetlands. In a recent review, Hamel and Tan (2022) found evidence of the high runoff reduction potential (up to 100%) of BGI in the region. Specific to Thailand, Majidi et al. (2019) explored the effectiveness of BGI for flood risk reduction in formal residential areas and public facilities in central Bangkok, Thailand, finding that green roofs had higher potential than other BGI with runoff reduction values of 32% for a 20-yr return period storm. In contrast, Vojinovic et al. (2021) found that among small-scale BGI, bio-retention cells were the most effective with runoff reduction of more than 40% in formal residential and commercial areas in Ayutthaya. Chaosakul et al. (2013) examined the impact of large-scale implementation of rain barrels and bioretention cells in a peri-urban community North of Bangkok, Thailand, demonstrating that a combination of both systems could reduce runoff volume by 41% for a 2-yr return period storm.

While demonstrating the potential of BGI in the tropical climate of Thailand, these studies have not examined urban forms privileged by informal settlements upgrading programs such as the settlements participating in the BMK program. As such, our understanding of BGI hydrologic performance in such environments, characterised by tight budget and space constraints, is still limited. Although some general principles and guidelines have recently been developed (e.g., RISE and ADB, 2021), scholars call for more thorough examination of the flood reduction performance of BGI in informal settlement upgrading programs to provide a more nuanced understanding of its potential (Payne et al., 2019, Hamel and Tan, 2022).

To address this gap, this study seeks to understand how effective BGI would be at reducing flooding if they were included in BMK designs. Three present-day BMK projects in Bangkok

were used as case studies. Since the BMK program is ongoing, our analyses also explore alternative designs for future BMK sites that provide higher stormwater retention benefits. Hence, the research questions we sought to answer were:

1. What is the potential impact of BGI on runoff reduction for existing upgraded BMK sites?
2. How would more compact BMK site designs compare to the BGI retrofits in terms of runoff reduction?

Examining the effectiveness of BGI in the BMK case studies can contribute new insights to informal settlements upgrading design by comparing different options to improve stormwater management. Because informal settlements are prevalent in Bangkok, we also discuss how the cumulative effects of increased runoff retention throughout the landscape could be beneficial at the city-scale.

## **2. Methodology**

### **2.1 Study area**

Bangkok, Thailand, has a Tropical wet and dry climate with an average annual precipitation of approximately 1400 mm over the period 1991 to 2020 (WBG, 2024). We examined the potential of BGI within three different typologies of upgraded settlements in Bangkok by analysing three BMK housing projects (Fig. 1). The first site, representing a multi-building housing block, is a complex called Sirin and Friends (SF) located near the Bang Philia canal in the neighbourhood of Phasi Charoen. The waterbody is partially lined with concrete and is upstream from the main Chao Phraya River. SF is a canal-adjacent settlement comprised of 153 households, founded as part of the BMK project in 2008. Being well-established, the project has been part of different research projects throughout the years (Archer et al., 2019; Natakun et al., 2022).

The second and third typologies investigated in this study are representative of linear housing projects constructed alongside canals, characterised by developments with one or two rows of buildings (Fig. 1). The second case study is the site here referred as the Chatuchak Community (CC), located in Chatuchak Lat Yao. CC is characterised by its white roofs and double-lined houses along the major canal Klong Prem Prachakon. The third site, also located in the vicinity of CC, is an ongoing BMK project under construction – Pracha Ruamjai (PR). PR is more impervious, and characterised by its blue roofs and single-lined houses along the same major

canal. Historically, SF is an older BMK project, followed by CC, and then the newest site PR. The three case studies are situated within the Chao Phraya River basin.

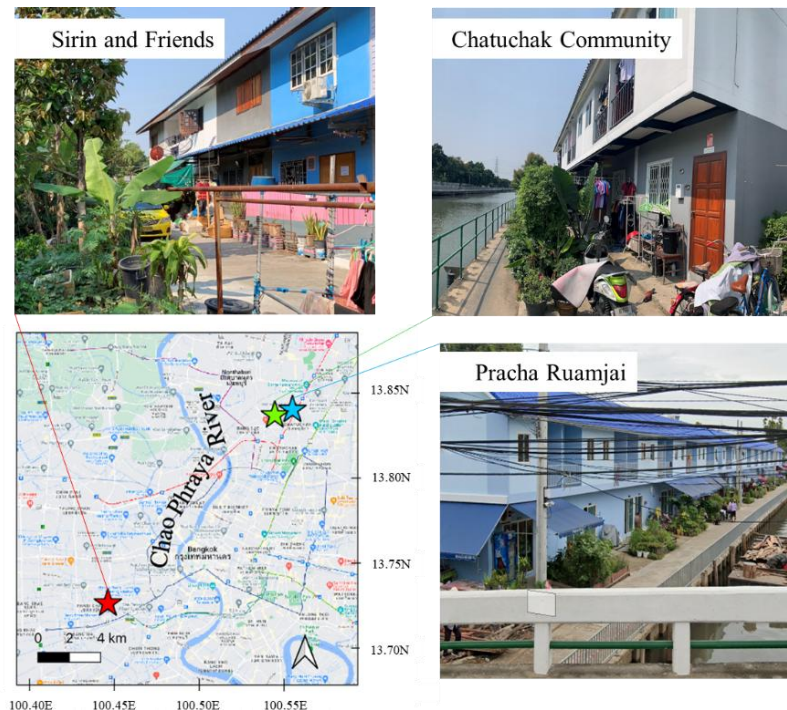


Figure 1: Location of the settlements (SF, CC, PR) in relation to the Chao Phraya River and the Bangkok metropolitan area. Source: Author's archives.

## 2.2 PCSWMM model inputs and simulation options

For each of the three case study sites (SF, CC, PR), we developed a hydrological model of the settlement using PCSWMM 2022 Professional 2D model version 7.5.3406 (64 bit), SWMM 5.0.013 – 5.1.015 (Appendix A.1). PCSWMM, a commercial implementation of the Stormwater Management Model (SWMM), was selected due to the wide popularity of the SWMM model for hydrologic modelling studies (Rossman and Simon, 2022) and the convenience of the built-in geospatial information system (GIS) capabilities. The detailed workflow is provided in Appendix, with Fig. A1 showing an overview of the PCSWMM software settings, model inputs along with its sources, data processing, and outputs.

To delineate the subcatchments within each site, we identified the manholes from Google Street View (Appendix A1). These nodes were then connected via conduits to represent the runoff flowing through the settlement into the outfall. Next, we estimated pervious and impervious areas in the subcatchments using land use/land cover maps, soil data, and cross-checked with satellite images from Google Earth (Appendix A2).

Horton infiltration method was chosen given that local soil data were not available, and as a common approach to infiltration in the region (Irvine and Chua, 2016; see details in Appendix A). Dynamic wave routing method was used to model flow routing. The models were ran using hourly historical rainfall time series for the year 2011 obtained from the Thai Meteorological Department. This was chosen to ensure a recent, representative rainfall time series that also included the devastating 2011 flood event.

### **2.3 BGI application and scenarios**

BGI were included in the model as scenarios. Three common BGI were chosen following previous work in Bangkok and Ayutthaya, Thailand (Majidi et al., 2019; Vojinovic et al., 2021) and modelled using the LID toolbox: green roofs (GR), pervious pavements (PP), and rain gardens (RG). As there were limited studies about BGI in Bangkok’s informal settlements, the BGI parameters were based on the standard parameters published in literature (Table A1 and A3).

As the BMK program is an ongoing housing upgrading programme, we considered how runoff volume could be reduced by BGI in both the present-day sites and in future BMK site designs. We examined three different types of scenarios for each of the BMK housing typologies. Firstly, we considered the retrofit of a single BGI to the sites. Three different types of BGI were modelled individually, namely: GR, PP, and RG. Secondly, we considered the retrofit of multiple different BGI together. The combination of GR and PP to the sites formed the “GRPP” combination BGI scenarios. Thirdly, we reimagined what a future BMK housing typology with less built-up area could look like. In this reimagined scenario, a site design with higher buildings that frees up pervious green spaces was explored. The present-day sites were each used as a baseline – whereby half of the houses were kept and built higher to free up additional green space. This scenario is realistic given that the current sites have a maximum of two storeys, while other BMK sites across Bangkok were designed with 3 to 4 storeys (IIED, 2013). A graphic illustration of all the BGI application methodology and scenarios is shown in Fig. 2.

To simulate these scenarios, 10 new models were developed for each case study, totalling 30 models.

All proposed scenarios considered the implementation of BGI over specific areas of the existing sites: GR is only applied on existing buildings, PP is only applied to existing pavements, and RG is only applied on the currently pervious area. As such, the terminology of GR100 represents the retrofitting of GR to 100% of the suitable roof areas only and not on any other non-suitable available space. GR50 would hence represent the application of GR to 50% of the suitable roof areas. The rationale for the 100% and 50% application scenarios was to acknowledge that retrofitting BGI to all the available areas was likely unfeasible. The 100% BGI scenario provides valuable insights of the maximum outflow and flood reduction that the BGI could provide for the site. The 50% BGI application scenario would then inform of the outflow reduction by BGI in a more realistic scenario.

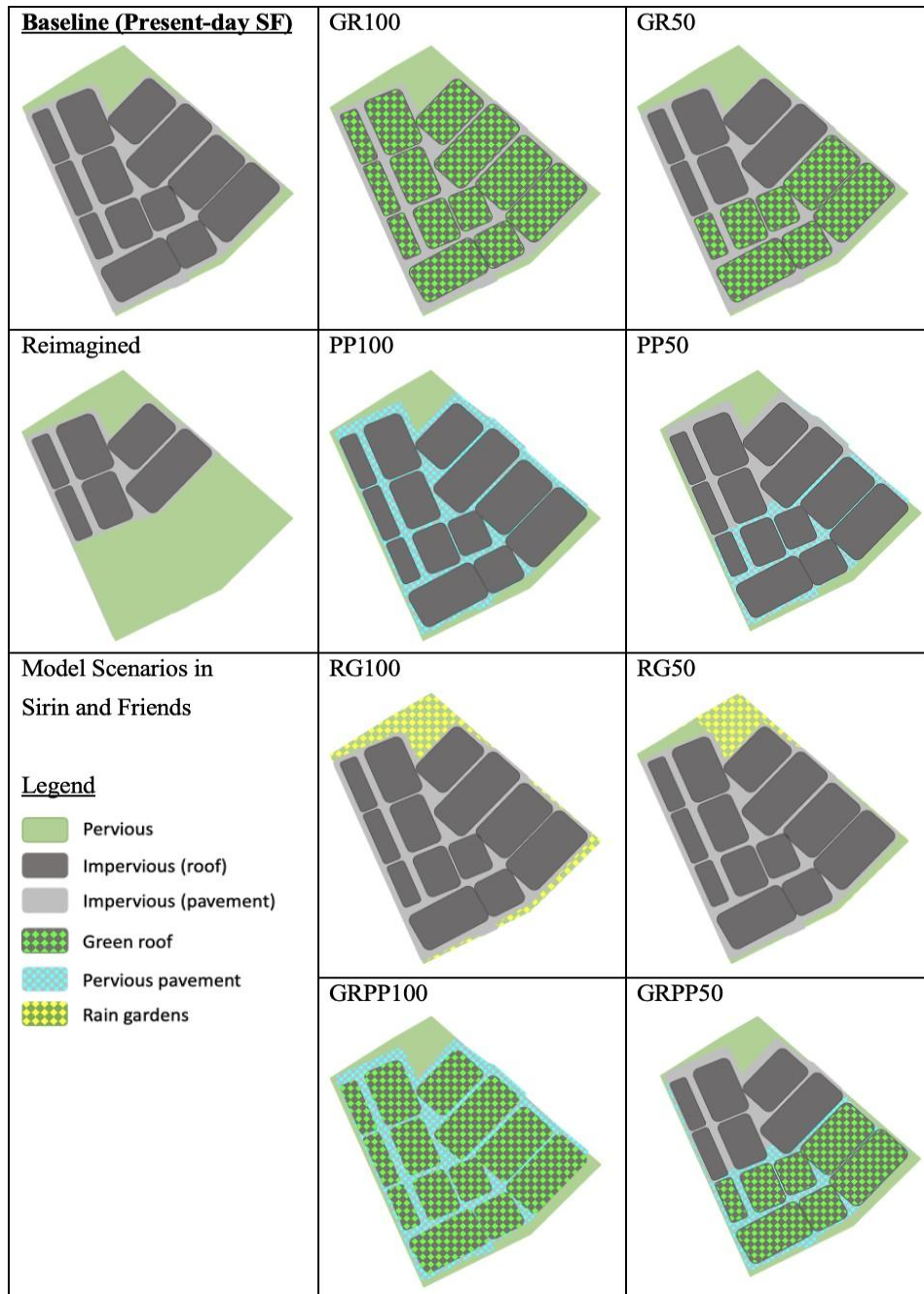


Figure 2: Illustration of the ten BGI scenarios for SF site.

## 2.4 Data processing

We used a continuous year-long simulation to comprehensively evaluate the potential of the BGI in terms of reducing runoff. Continuous simulation was used because it had an advantage of incorporating and accounting for the catchment moisture state prior to the flood-producing

rainfall event (Pathiraja et al., 2012), making the model more realistic. To assess BGI performance, we identified individual rainfall events on R using the “hydromad” package and “eventseq” function. Individual events were defined in line with previous work as events with a minimum inter-event time step of 6h (Joo et al., 2013; Tu et al., 2023). Because BGI has the potential to reduce outflow differently depending on the rainfall intensity, its performance had to be analysed separately in high and low rainfall events. A high rainfall event was defined as one reaching an intensity of 10mm/h (Hadi et al., 2014; Met Office, 2012) while a low rainfall event was defined as one reaching an intensity of 1-5mm/h (Hadi et al., 2014; Monjo, 2016). It should be noted that, within the scope of this study, other factors that might limit the applications of BGI are not considered, for instance the additional load of green roofs, the acceptance of the communities for BGI interventions or the economic efficiency.

BGI performance was analysed separately for high-rainfall and low-rainfall events. The key output of interest was total outflow for each event. Specifically, we quantified outflow reduction as the amount of outflow the BGI scenarios reduced in relation to the present-day sites without BGI.

### **3. Results**

#### **3.1 Pervious-impervious areas**

The three sites have a varying degree of impervious areas (roof and paved areas), ranging from 67.2% to 94.7% (Fig. 3). The PR site with the linear single row of houses was the most impervious site with 94.7% of imperviousness, mainly due to the high proportion of pavements in its site design. The area of roofs in all three typologies was comparable as the buildings occupied around 50% of the total area dedicated to each project. The CC site with its double-lined buildings running parallel to the canal has the highest proportion of green spaces while the SF multi-building block had an intermediate portion of its area dedicated for gardens (around 18.6 % of the total of the development). Of note, the PR settlement is significantly smaller, totalling around half of the area of CC, the second largest site.

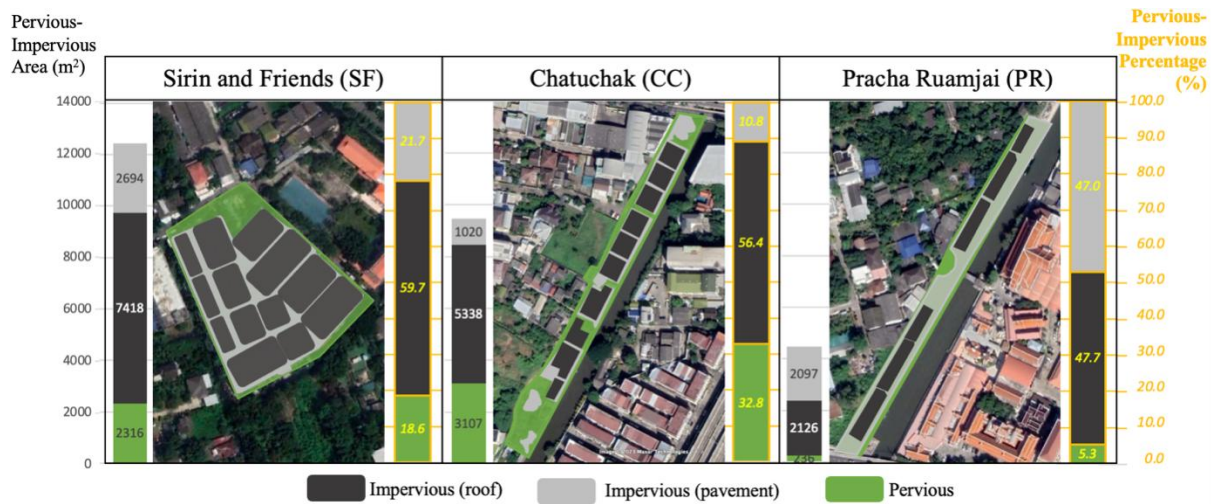


Figure 3: Impervious areas (grey) and pervious areas (green) identified in the three settlements. The bar on the left of each settlement image represents absolute areas. The bar on the right represents relative proportions.

### 3.2 High and low rainfall event identification

Across 2011, 10 events were classified as high rainfall and 98 were classified as low rainfall events (Fig. 4). From these events, 10 events for each rainfall intensity category were chosen at equal intervals to keep the number of rainfall events the same and their statistical powers comparable (Appendix Table A5). High-rainfall events ranged from 10.35 mm to 126.74 mm while low-rainfall events ranged from 3.15 to 21.25 mm.

### 3.3 Single-BGI outflow reduction

The outflow reduction achieved by the scenarios with 50% of their total potential BGI was approximately half of the BGI 100% scenarios (Appendix Table B1 and Table B2). In the sections below, we focus on the BGI 100% scenarios, summarised in Fig. 5.

*Green roofs.* Across the three sites, the full-scale application of GR (GR100) reduced outflow poorly in high rainfall events but well in low rainfall events. GR100 reduced outflow by an average of -10% to 5% in high rainfall and 30% to 40% in low rainfall (Fig. 5). The negative percentages of outflow reduction by GR100 were unexpected and suggest that the GR, once saturated by the previous storm, were releasing water during the events we analysed

instead of storing water (see Discussion). The performance of GR100 in individual rainfall events was also rather variable as seen in the large standard deviation.

*Pervious pavements.* The full-scale application of PP (PP100) was, on average, the best performing single-BGI scenario. PP100 reduced outflow strongly and consistently in both high and low rainfall events for SF and PR sites (>22% reduction), although its performance for CC was modest, barely above 10% on average (Fig. 5, Tables B1 and B2). PP100 also reduced outflow consistently as shown by the small error bars.

*Rain gardens.* The full-scale application of RG (RG100) was generally poor at reducing outflow for the SF and PR sites, reducing outflow by less than 8% for high and low rainfall events, but higher for the CC site, where RG100 managed to reduce outflow by around 20% (Fig. 5). The performance of rain gardens was thus found to be site dependent but consistent for a given site, as seen by the small error bars.

In summary, for single-BGI scenarios in high rainfall events, PP performed the best, followed by RG and then GR. In low rainfall events, conversely, GR performed the best, followed PP and RG. In both high and low rainfall events, PP performed best for the two sites that have the highest level of imperviousness (SF and PR).

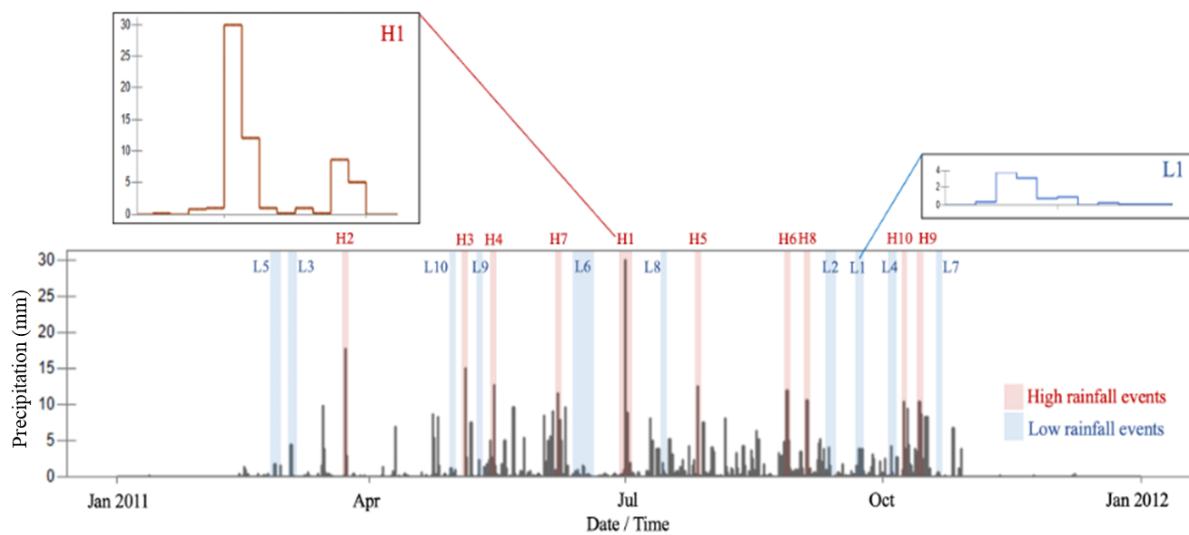


Figure 4: Hourly rainfall series of year 2011, with the high rainfall highlighted in red and the low rainfall events highlighted in blue. Characteristics of each rainfall event are shown in Table A5 in Appendix.

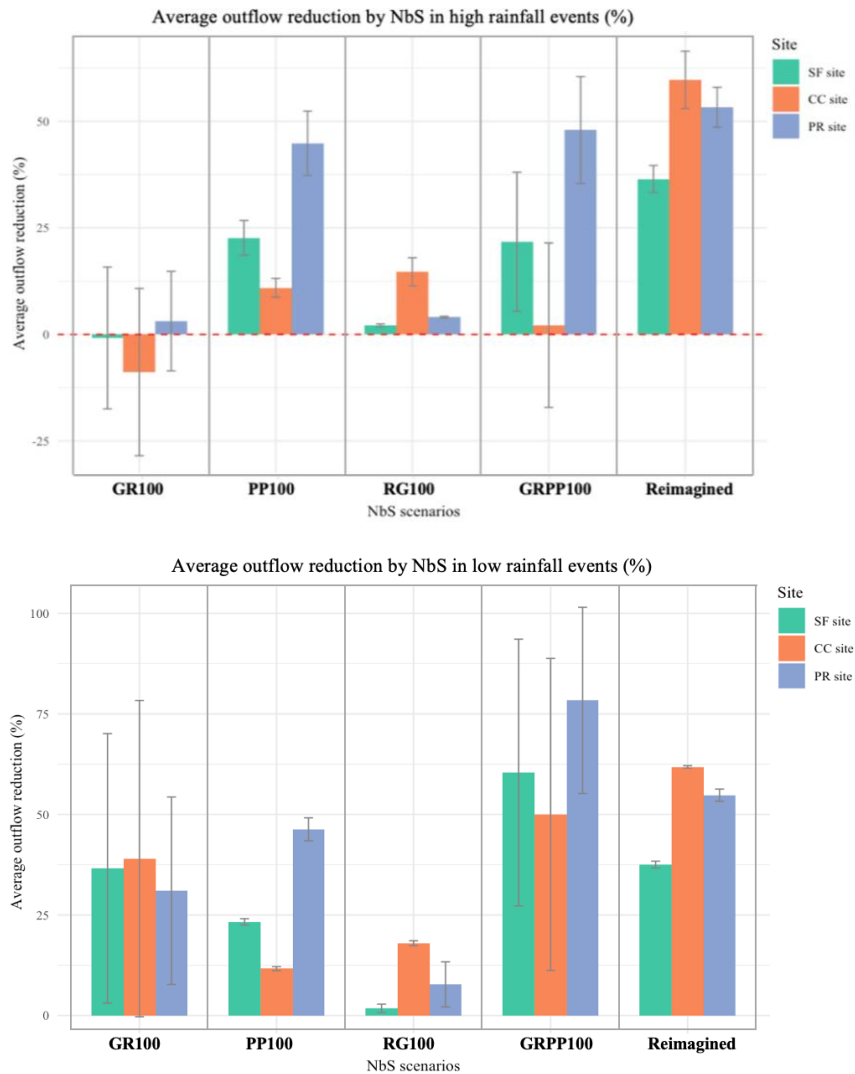


Figure 5: Average outflow reduction by BGI in high rainfall (top) and low rainfall (bottom) across the three BMK case study sites. Error bars of standard deviation representing the variability of BGI performance in different individual rainfall events. Note the difference in scale on the y-axis between the top and bottom panel.

### 3.4 Combination-BGI outflow reduction

The combination of GR and PP (GRPP100) generally reduced outflow considerably in low rainfall events and fairly well in high rainfall events. Across the three sites, GRPP100 reduced outflow by 50% to 78% on average in low rainfall events and 2% to 48% in high rainfall events (Fig. 5, Appendix B2). GRPP100 performance mirrored closely the performance of GR100:

whereby outflow reduction was significantly better in low rain compared to high rain conditions. Similarly, GRPP100 had negative outflow reductions in some of the rainfall events (Tables B1 and B2 in Appendix) and large variability in individual event performance as seen in the error bars (Fig. 5). This showed that the performance of the combination BGI scenario was largely influenced by GR.

### **3.5 Future reimagined scenario outflow reduction**

This scenario reimagined a future site design with more pervious green spaces and double the height of most BMK houses. This greener scenario managed to reduce outflow well in both high and low rainfall events. On average, it reduced outflow by 36% to 60% (38% to 62%, respectively) in high (low, respectively) rainfall events across the three sites (Fig. 5, Appendix B). This reimagined scenario's capacity to reduce runoff was also very consistent in the individual high and low rainfall events represented by error bars. Compared to the other modelled scenarios, the reimagined scenario was the best performing scenario in high rainfall and the second-best in low rainfall. This demonstrates that halving the built-up area (and promoting more vertical designs) can thus be a key strategy to reduce runoff in Bangkok.

## **4. Discussion**

### **4.1 Performance of single BGI scenarios**

*Green roofs.* Consistent with previous work (e.g., Sims et al., 2016; Bortolini et al., 2021), GR generally performed well at reducing outflow in low rainfall events but poorly in high rainfall events – on average worse than the present-day conditions. Analyses of individual hydrographs showed GR performance depended on antecedent precipitation: low rainfall events with large amounts of precipitation in the previous two days (e.g., events L2, L7 in Table B2) generated more runoff than higher rainfall events with low antecedent precipitation (e.g., events H1, H2, H3 in Table B1). This means that GR released a significant amount of stormwater stored from previous events, suggesting that the GR design derived from literature values might not be suitable for Bangkok's climate conditions. Future research could test for a context-specific GR parameter design for the region.

*Pervious pavements.* PP had strong and consistent performance throughout all rainfall events. This is aligned with other reports of strong PP outflow reduction by Brattebo and Booth (2003) and Wang et al. (2019). While previous studies like Chen et al. (2021) and Liu et al. (2020) have shown that the runoff retention performance of PP decreases with increased

rainfall volumes, our study suggests that the threshold occurs between H1 (>150 mm) and H2 (56 mm, Table B1). Compared to the other sites, PP performance was the lowest in the CC site, likely because the site had the least available areas of pavement to retrofit PP. As expected, areas currently containing more impervious surfaces would allow for greater outflow reduction after the implementation of PP.

*Raingardens.* RG were only effective in reducing outflow in the CC site. This was because the performance of RG was highly dependent on space availability, in relation with imperviousness, and location (downstream of impervious areas). While this reflects findings from others (Tansar et al., 2022; Loc et al., 2017 ; Liu et al., 2015), it suggests that finding a suitable area in the present-day BMK sites might be difficult, especially since most sites contain large impervious areas. Hence, RG may not be the most feasible option for retrofitting present-day BMK designs.

#### **4.2 Implications for BMK site design**

Operating as an ongoing informal settlement upgrading programme in Bangkok, the BMK program serves as a relevant case study on how BGI can be incorporated into existing policies in Thailand. In this sense, the insights provided by this case study are valuable to inform future strategies to adapt Bangkok to the effects of climate change.

A combination of different types of BGI may be the most realistic option to retrofit projects that have been developed within the BMK program, similar to other BGI projects in Bangkok (e.g., Sukhumvit area, Furnage et al., 2022; Linh et al., 2022). Consistent with the findings of Liu et al. (2015), we found that the combination of different types of BGI generally performed well in both high and low rain events. However, the performance of this scenario was also dependant on the intensity of the rainfall events.

The reimagined scenarios confirm that designs with less impervious areas and larger pervious green spaces could ensure that the BMK program contributes to runoff retention and, ultimately, flood risk reduction in Bangkok. Such a site design is realistic given that several BMK sites (not studied here) feature three- to four-storey housing (IIED, 2013). Such design proved to be more consistent and better at reducing outflow than the best of the present-day sites retrofitted with BGI. Furthermore, the greater ratio of green spaces is expected to provide other co-benefits, including heat mitigation, spaces for recreation, and an overall increase in well-being (Ramsay et al., 2023). These are benefits seldom planned for, but relevant in informal

settlements (Cobbinah et al., 2021). As such, designing BMK sites with more green spaces could be more than a viable reimagination for future settlements. Considering the scale of the BMK program, and its influence over hundreds of housing projects over the years, the decision of incorporating BGI in housing projects can play a central role in making Bangkok more adapted to deal with unprecedented rainfall in the future.

### **4.3 Study limitations and implications beyond Bangkok**

Urban form in Southeast Asia is characteristically different from the West where most BGI studies are found. Density patterns, land-use mix, architecture, drainage design, topography, and climate are some of the key differences in urban form that would affect how BGI can be used. As such, models like those developed in this study are important to gain local understanding of the strengths and limitations of BGI in local contexts. Importantly, our analyses are limited by the absence of model calibration or validation due to the unavailability of local flow time series as in many regional studies (almost two thirds of the peer-reviewed studies, in the recent review by Hamel and Tan, 2022). As such, results are best interpreted as reflecting the *potential* of BGI, especially relative to the urban site design (with lower or higher levels of imperviousness, space for BGI, etc.) Monitoring of water levels or flow rates could help gain confidence and refine the interpretation of the results. We note, however, that the retention values for individual BGI systems align well with the literature and previous synthesis work (see Section 4.1 and review by Hamel and Tan, 2022), suggesting that the assumptions made for the BGI design in Table A3 are realistic for the region.

To better support policy, future studies should incorporate costs and other factors that may influence the selection of BGI, including community preferences (e.g., Ahmed et al., 2024). For example, the simulation of GR in our study remains highly hypothetical as GR remain costly in Southeast Asia (Pratama et al., 2023; Payne et al., 2019), which explains the lack of evidence of their use in informal settlements upgrading programs (Wolff et al., 2023). Overall, our exploratory analyses revealed the differentiated potential of BGI to provide flood mitigation services under different site designs, supporting future projects aiming to implement BGI in upgrading programs. Such projects need to consider communities' values and perceptions of costs, maintenance, and benefits (Rauf et al., 2024).

The approach used in this study is applicable to other sites incorporating BGI and nature-based solutions in Southeast Asia. With 50% of people in Southeast Asia living in informal settlements or slums (UN-Habitat, 2020), this study may be relevant to other cities in Southeast

Asia that are considering the use of BGI. An important finding is that the three sites had considerably different proportions of impervious areas (both roads and roof areas), and those characteristics influenced the impact of BGI (Fig. 3) – suggesting that the best BGI strategy will be site specific.

## **5. Conclusion**

This study compared how BGI – such as green roofs, pervious pavements, and rain gardens – could contribute to stormwater management in Bangkok’s informal settlements upgrading programme both for current and in future site design. It adds to the emerging BGI literature in the Global South, by highlighting the potential for BGI to be used in informal settlements.

From the PCSWMM models for the case studies of three BMK projects, we found that overall, the effect of single BGI strategy was strongly influenced by local specificities and spatial constraints. Overall, in the case of retrofitting present-day BMK sites, PP was the most effective strategy for reducing floods as it consistently reduced outflow in both high and low rainfall events. Combining multiple BGI was also shown to be a valuable strategy to support flood risk reduction. Beyond retrofitting the present-day BMK sites, this study confirmed the importance of reimagining the design of future informal settlements as a strategy to reduce runoff and, consequently, to improve Bangkok’s climate resilience. Designing settlements with a larger proportion of green spaces was found to be a more reliable and effective option for reducing floods in the process of providing adequate housing to the residents of existing informal settlements in Bangkok.

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## Appendix A: Methodology supplementary material

The modelling overview is provided in Figure A1 below.

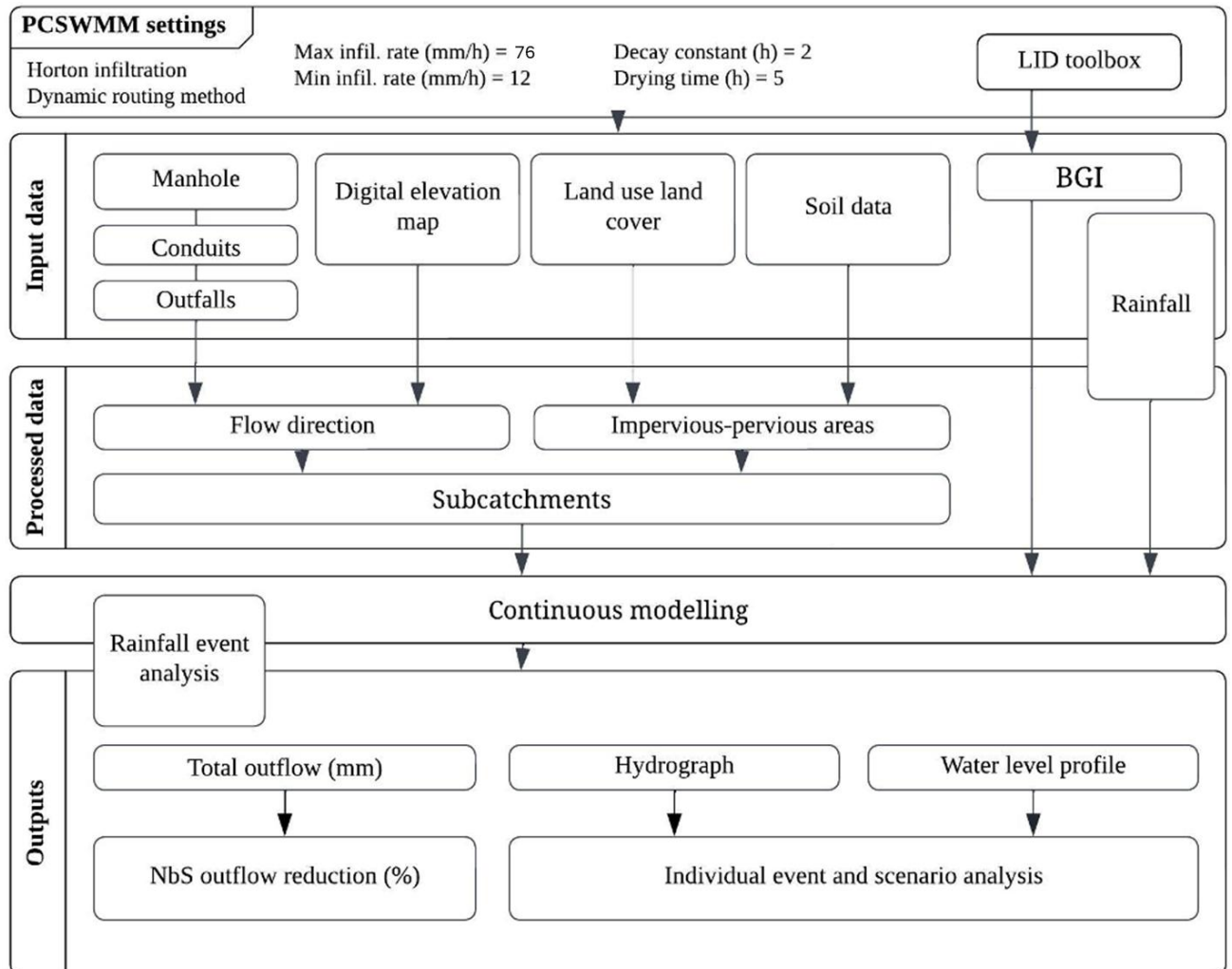


Figure A1: Overview of the model inputs, processed data, and outputs for each of the three case studies. Sources are detailed in Table A1. BGI=Blue-Green Infrastructure. LID=Low Impact Development

Based on the SWMM guide for Horton Infiltration parameters, maximum infiltration rate was set at 76 mm/hr for Bangkok's moist soil with high 80-140% water content (Sunitsakul et al., 2010; Soralump, 2004), minimum infiltration rate was set at 12 mm/hr for Bangkok's clay (Teerachaikulpanich & Phupat, 2003; Seah & Lai, 2003), decay constant at default 2/hr, drying time at default 5 days, and maximum infiltration volume at default 0 mm. These parameters

were adapted with reference to PCSWMM and SWMM publications from Chaosakul et al. 2013 work on Thailand, and Wu et al. 2018 work on China.

### A1: Subcatchment establishment and properties

Subcatchments were identified via Theissens Polygon method. For this method, all the manholes in the study area are first identified (blue dots). Manholes were identified using Google Earth Pro, Google Street View, and cross-validated with site visit pictures and on-site observations. From the manholes identified, we can establish the subcatchments in the study areas. DEM (Digital Elevation Map) and topography data – from NASA’s ASTER Global DEM V003, Marc Souris’s GIS DEM ([www.savgis.org/thailand.htm](http://www.savgis.org/thailand.htm)), and Google Earth – were then overlaid to establish the elevation and water flow direction (Fig. A1). The free outfall nodes were placed at the respective canals.

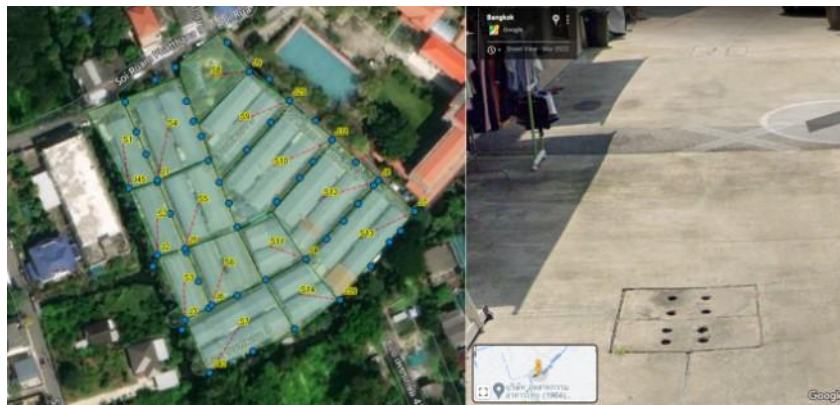


Figure A2: (Left) Pictures of the manholes input on PCSWMM in Sirin and Frends. (Right) Picture of one of the identified manholes using Google Earth Pro.

Table A1: Subcatchment simulation options

Subcatchment Parameters	Model input	Source and methodology for measurement
N-Imperv	0.015	Based upon SWMM Manual (A.5) for smooth grass, Wu et al. (2018)
N-Perv	0.15	Based upon SWMM Manual (A.6) of short grass
Dstore-Imperv (mm)	2	Based upon SWMM Manual (A.5), Vojinovic et al. (2021), Chaosakul et al. (2013), Wu et al. (2018)

Dstore-Perv (mm)	5	Based upon SWMM Manual (A.5), Vojinovic et al. (2021), Chaosakul et al. (2013), Wu et al. (2018)
Zero-Imperv (%)	25	Based upon Vojinovic et al. (2021)
Slope	0.65	The subcatchment slope should reflect the average slope along the pathway of overland flow to inlet locations. This was measured from Google Earth Pro and DEM elevation datasets.
Imperv (%)	Varies	Measured from aerial images from Google Earth Pro Impervious areas include roofs, roads, buildings.
Outfall type	Free	Free outfall for canal
Outfall elevation (m)	0	Canal outfall
Conduits	Circular, 0.5 m	Marks (2021) research on Bangkok

### A2 LULC and soil data

Land use/land cover (LULC) maps were sourced from ESRI's Sentinel-2 Land use/Land cover Time series 10m dataset (<https://www.esri.com/partners/impact-observatory-a2T5x0000084pJXEAY/sentinel-2-10m-land--a2d5x000005jw9NAAQ>) and Marc Souris's website on Thailand (<http://www.savgis.org/thailand.htm>). The LULC maps were used to derive the pervious percentage. Pervious areas included green spaces while impervious areas included houses, buildings, and pavements. Soil data were gathered from Teerachaikulpanich and Phupat (2003) and Seah and Lai (2003).

### A3 BGI parameters

Table A3: Shared PCSWMM input parameters of all the BGI scenarios.

Structure	Parameter	Value	Source
Soil	Porosity (volume fraction)	0.5	Wu et al., 2018
	Field capacity (volume fraction)	0.2	Wu et al., 2018
	Wilting point (volume fraction)	0.024	Wu et al., 2018
	Conductivity (mm/h)	30	Wu et al., 2018
	Conductivity slope	5	EPA, 2015; Wu et al., 2018
Drainage mat	Suction head (mm)	60	EPA, 2015; Wu et al., 2018
	Thickness (mm)	3	EPA, 2015; Wu et al., 2018

	Void fraction	0.5	EPA, 2015; Wu et al., 2018
	Roughness (Manning's n)	0.1	EPA, 2015; Wu et al., 2018
<b>Green roof</b>			
Surface	Berm height (mm)	3	(Wu et al., 2018)
	Vegetation volume fraction	0.1	(Wu et al., 2018)
	Surface roughness (Manning's n)	0.017	(EPA, 2015; Wu et al., 2018)
	Surface slope (%)	1	(Assumption; Wu et al., 2018)
Soil	Thickness (mm)	100	(Wu et al., 2018)
<b>Pervious pavement</b>			
Surface	Berm height (mm)	2	(Wu et al., 2018)
	Vegetation volume fraction	0	(Wu et al., 2018)
	Surface roughness (Manning's n)	0.014	(EPA, 2015; Wu et al., 2018)
	Surface slope (%)	1	(Assumption; Wu et al., 2018)
Pavement	Thickness (mm)	100	(Wu et al., 2018)
	Void ratio (voids/solids)	0.25	(Wu et al., 2018)
	Impervious surface fraction	0	(Wu et al., 2018)
	Permeability (mm/h)	250	(Wu et al., 2018)
	Clogging factor	0	(Wu et al., 2018)
Storage	Thickness (mm)	150	(Wu et al., 2018)
	Void ratios (voids/solids)	0.4	(EPA, 2015; Wu et al., 2018)
	Seepage fate (mm/h)	1.2	(EPA, 2015; Wu et al., 2018)
	Clogging factor	0	(EPA, 2015; Wu et al., 2018)
<b>Raingarden</b>			
Surface	Berm height (mm)	3	Assumption
	Vegetation volume fraction	0.5	(EPA, 2015; Wu et al., 2018)
	Surface roughness (Manning's n)	0.017	(EPA, 2015)
	Surface slope (%)	1	(Assumption; Wu et al., 2018)
Soil	Thickness (mm)	1000	(EPA, 2015)
Storage	Seepage fate (mm/h)	1.2	(EPA, 2015; Wu et al., 2018)

#### A4 Time series

Historical rainfall hourly time series were gathered from the Thai Meteorological Department ([http://www.aws-observation.tmd.go.th/web/climate/climate\\_past.asp](http://www.aws-observation.tmd.go.th/web/climate/climate_past.asp)) and the Visual Crossing (<https://www.visualcrossing.com/weather-history/Bangkok, Thailand>).

Table A4. Monthly evaporation (mm/day) data for Bangkok. Source: Hirota (2021)

Jan	Feb	Mar	Apr	May	Jun
3.7	3.5	4.5	5.3	4.8	4.6
Jul	Aug	Sep	Oct	Nov	Dec
4.5	4.6	4.0	3.2	2.0	1.6

Events were identified from the hourly precipitation time series as described in the main text. Table A5 provides the characteristics of each event used in the statistical analyses.

Table A5. High and low rainfall events used to calculate the runoff retention of BGI features.

High rainfall events				Low rainfall events			
Index	Date/Time	Duration /h	Volume of event /mm	Index	Date/Time	Duration /h	Volume of event /mm
H1	2011-07-01 00 : 00 : 00	7	126.74	L1	2011-09-22 15 : 00 : 00	7	21.25
H2	2011-03-23 06 : 00 : 00	4	56.73	L2	2011-09-08 18 : 00 : 00	7	21.08
H3	2011-05-05 03 : 00 : 00	4	47.62	L3	2011-03-03 18 : 00 : 00	7	18.57
H4	2011-05-15 06 : 00 : 00	4	37.76	L4	2011-10-04 00 : 00 : 00	7	15.92
H5	2011-07-26 21 : 00 : 00	4	37.59	L5	2011-02-26 03 : 00 : 00	7	9.99
H6	2011-08-27 18 : 00 : 00	4	36.25	L6	2011-06-15 21 : 00 : 00	13	8.92
H7	2011-06-07 03 : 00 : 00	4	35.12	L7	2011-10-13 04 : 00 : 00	5	6.22
H8	2011-09-03 21 : 00 : 00	4	32.95	L8	2011-07-14 15 : 00 : 00	4	5.71
H9	2011-10-14 00 : 00 : 00	4	32.06	L9	2011-05-12 21 : 00 : 00	4	4.97
H10	2011-10-08	2	10.35	L10	2011-04-30	4	3.15

	07 : 00 : 00				00 : 00 : 00		
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## Appendix B: Outflow reduction results

### B1 High rain

Table B1: Outflow reduction percentage of BGI scenarios in high rainfall

High rainfall event index		H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	Average reduction
Rainfall volume/mm		126.74	56.73	47.62	37.76	37.59	36.25	35.12	32.95	32.06	10.35	-
Outflow in no BGI scenario / mm	SF site	0.34433	0.13615	0.11566	0.10066	0.09538	0.09095	0.09111	0.08137	0.07903	0.02665	-
	CC site	0.25798	0.09598	0.08151	0.07097	0.06723	0.06411	0.06424	0.05730	0.05573	0.01874	-
	PR site	0.18284	0.07478	0.06353	0.05532	0.05239	0.04998	0.05008	0.04464	0.04342	0.01460	-
BGI scenario outflow reduction in relation to baseline no BGI scenario (%)												
GR100	SF site	9.58	14.20	38.59	-10.11	-10.13	-10.22	-10.13	-10.02	-10.12	-9.82	-0.82
	CC site	5.53	8.40	37.00	-19.90	-19.93	-19.88	-19.78	-19.92	-19.90	-19.91	-8.83
	PR site	10.03	13.72	30.96	-3.34	-3.36	-3.33	-3.28	-3.37	-3.39	-3.37	3.13
GR50	SF site	4.76	7.10	19.23	-5.06	-5.07	-5.08	-5.07	-4.91	-5.17	-4.91	-0.42
	CC site	2.70	4.36	18.66	-9.96	-9.99	-10.02	-9.90	-9.98	-9.95	-9.95	-4.40
	PR site	4.98	6.90	15.48	-1.66	-1.66	-1.63	-1.63	-1.66	-1.70	-1.69	1.57
PP100	SF site	11.10	23.95	23.89	23.96	23.98	23.90	23.96	24.02	23.71	24.18	22.66
	CC site	4.67	11.64	11.63	11.64	11.62	11.61	11.63	11.71	11.63	11.63	10.94
	PR site	23.40	47.19	47.22	47.20	47.22	47.23	47.27	47.21	47.21	47.21	44.84
PP50	SF site	5.82	12.56	12.40	12.53	12.50	12.43	12.53	12.67	12.41	12.39	11.82
	CC site	2.33	5.84	5.85	5.84	5.82	5.79	5.83	5.92	5.86	5.84	5.49
	PR site	10.32	23.12	23.55	23.61	23.51	23.60	23.60	23.57	23.56	23.48	22.19
RG100	SF site	3.10	2.00	2.00	2.00	1.99	1.94	2.00	2.12	1.91	2.18	2.12
	CC site	21.29	17.38	17.38	13.71	13.64	12.32	15.77	9.86	13.21	12.47	14.70
	PR site	4.62	3.97	3.99	3.98	3.97	4.05	4.03	4.00	3.97	4.08	4.06
RG50	SF site	1.52	1.04	1.02	1.00	1.00	0.85	1.00	1.00	0.81	0.49	0.97
	CC site	10.41	8.69	8.70	8.70	8.70	8.70	8.69	8.75	8.70	8.69	8.87
	PR site	2.07	2.01	2.04	2.07	2.01	2.07	2.06	2.03	2.01	1.98	2.03
GRPP100	SF site	20.72	38.09	62.60	13.85	13.87	13.84	13.84	13.80	13.75	13.14	21.75
	CC site	10.17	20.39	48.97	-8.28	-8.29	-8.25	-8.14	-8.24	-8.27	-8.25	2.18
	PR site	33.20	61.00	78.16	43.86	43.83	43.89	43.90	43.84	43.84	43.85	47.94

GRPP50	SF site	10.33	19.17	31.19	6.99	6.99	6.93	6.98	7.00	6.83	6.93	<b>10.94</b>
	CC site	5.01	10.18	24.49	-4.13	-4.16	-4.14	-4.07	-4.12	-4.12	-4.12	<b>1.08</b>
	PR site	15.81	30.20	38.12	22.25	22.23	22.11	22.27	22.23	22.25	22.31	<b>23.98</b>
Reimagined	SF site	29.60	33.62	33.19	38.32	38.39	38.44	38.33	38.61	38.19	37.80	<b>36.45</b>
	CC site	40.57	61.82	61.82	61.84	61.82	61.83	61.83	61.80	61.83	61.84	<b>59.70</b>
	PR site	39.94	54.75	54.74	54.76	54.73	54.75	54.74	54.74	54.76	54.79	<b>53.27</b>

## B2 Low rain

Table B2: Outflow reduction percentage of BGI scenarios in low rainfall

Low rainfall event index		L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	Average reduction
Rainfall volume/mm		8.92	9.99	18.57	21.08	21.25	15.92	6.22	3.15	4.97	5.71	-
Outflow in no BGI scenario / mm	SF site	0.01499	0.01993	0.04683	0.05348	0.05068	0.03892	0.01537	0.00299	0.01170	0.00999	-
	CC site	0.01094	0.01415	0.03332	0.03791	0.03597	0.02756	0.01095	0.00224	0.00829	0.00710	-
	PR site	0.00858	0.01100	0.02597	0.02938	0.02819	0.02145	0.00851	0.00177	0.00647	0.00548	-
BGI scenario outflow reduction in relation to baseline no BGI scenario (%)												
GR100	SF site	61.80	62.51	62.66	-10.14	29.81	-5.51	-13.53	54.26	62.26	61.74	36.59
	CC site	69.05	68.88	66.43	-19.25	28.05	-5.80	-19.52	68.00	67.13	67.14	39.01
	PR site	48.23	48.07	48.11	-3.47	25.25	3.48	-3.20	48.20	47.46	48.14	31.03
GR50	SF site	29.67	30.64	31.17	-5.07	14.75	-2.72	-7.26	23.13	31.14	30.25	17.57
	CC site	32.98	33.34	33.14	-7.04	14.02	-3.35	-9.81	35.54	33.06	34.08	19.60
	PR site	24.03	24.17	24.09	-1.68	13.05	1.62	-1.53	24.10	22.60	24.08	15.45
PP100	SF site	21.59	23.75	23.73	23.96	23.78	23.64	23.04	22.23	23.69	23.50	23.29
	CC site	11.22	12.49	11.62	12.41	11.62	11.65	11.64	11.52	11.67	10.82	11.67
	PR site	45.72	47.57	47.23	47.14	47.56	46.96	47.41	38.33	46.91	48.05	46.29
PP50	SF site	11.91	12.05	12.39	12.53	12.44	12.48	12.38	9.05	12.35	11.94	11.95
	CC site	5.84	5.87	5.85	6.21	5.86	5.84	5.87	5.78	5.86	4.54	5.75
	PR site	23.71	23.55	23.54	23.48	23.58	23.53	23.68	29.99	22.53	23.47	24.11
RG100	SF site	2.08	2.38	2.02	2.00	2.06	1.90	2.36	-1.20	2.01	2.15	1.78
	CC site	17.99	18.79	17.56	17.76	17.46	17.51	17.57	18.97	17.50	18.72	17.98
	PR site	13.10	5.82	5.36	4.01	5.50	4.49	5.88	21.95	5.07	6.36	7.75
RG50	SF site	0.80	1.38	1.01	1.00	1.06	0.90	0.21	-0.18	1.04	1.64	0.88
	CC site	8.45	9.53	8.71	8.46	8.71	8.69	8.69	8.77	8.71	10.80	8.95
	PR site	2.20	2.07	1.99	1.97	2.69	1.99	2.17	2.07	1.99	2.07	2.12
GRPP100	SF site	83.52	86.59	86.80	13.83	53.57	18.75	11.25	78.12	86.27	85.52	60.42
	CC site	78.29	79.12	77.69	-7.99	39.76	6.27	-7.82	78.98	77.59	78.25	50.02
	PR site	95.22	95.28	95.29	43.80	72.60	51.69	44.08	95.07	95.27	95.29	78.36
GRPP50	SF site	40.79	42.57	43.09	6.98	26.75	9.22	3.68	40.19	42.97	43.32	29.96
	CC site	38.92	39.39	38.40	-3.28	19.87	2.96	-3.96	42.95	38.90	39.89	25.40

	PR site	46.77	46.02	46.09	22.09	35.53	25.48	22.37	51.36	47.28	46.36	<b>38.94</b>
Reimagined	SF site	37.44	37.72	37.87	37.76	37.94	38.13	37.90	35.19	37.73	37.76	<b>37.54</b>
	CC site	61.43	61.85	61.82	61.97	61.81	61.82	62.01	61.09	61.93	62.26	<b>61.80</b>
	PR site	51.10	55.11	54.75	54.39	55.00	54.68	54.92	57.24	55.02	55.66	<b>54.79</b>