TRACK 07: PLANNING FOR RESILIENCE: TERRITORIES, COMMUNITIES AND ENVIRONMENT

ENHANCING RAIN-FLOOD RESILIENCE IN URBAN PLANNING: A PARAMETERIZED DESIGN APPROACH INTEGRATING SCS-CN METHOD AND GRASSHOPPER (1032)

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Abstract. Urban flooding has become an increasing issue due to climate change and urbanization. To address this, urban resilience and parameterized design frameworks for flood-resilient urban planning are crucial. This study presents a framework that integrates the SCS-CN method and Grasshopper software. The SCS-CN method estimates urban runoff and infiltration, while Grasshopper creates adaptable planning workflows. A custom Grasshopper component automates SCS-CN calculations, generating design parameters for optimal flood resilience. The component considers land use, topography, and drainage infrastructure to evaluate design alternatives. This framework is valuable for examining trade-offs and identifying suitable design solutions, incorporating a multi-objective optimization approach for land-use configurations. Ultimately, this parameterized design framework aids urban planners in creating resilient and sustainable cities.

Keywords: urban flooding, climate change, flood resilience strategies, parameterized design framework

1. Introduction

Urban flooding has become a prominent issue worldwide due to the rapid urbanization and climate change(Li et al., 2023), which not only leads to significant economic losses but also threatens human life and ecosystem health. As cities continue to expand, impervious surfaces, such as concrete pavements and buildings, are replacing natural land cover, altering the hydrological cycle and reducing the infiltration capacity of urban areas. Consequently, urban areas are more prone to flooding, especially during heavy rainfall events(Tingsanchali et al., 2010). Therefore, it is essential to develop effective strategies to enhance flood resilience in urban planning, ensuring the sustainability and resilience of cities in the face of increasing flood risks.

One approach to tackle this issue is to integrate hydrological modeling methods into urban planning processes to simulate and analyze the impacts of different land use patterns and urban design interventions on stormwater runoff and flood risk. The Soil Conservation Service Curve Number (SCS-CN) method(Cai et al., 2022) is a widely recognized and applied hydrological model for estimating direct runoff volume and peak flow rates in response to rainfall events. The SCS-CN method has been extensively used in various hydrological studies and applications due to its simplicity, flexibility, and robustness. In recent years, parametric design has emerged as a promising approach to urban planning and design, enabling the exploration of complex relationships between design variables and the generation of multiple design alternatives. The utilization of parametric design tools, such as Grasshopper, a visual programming plugin for Rhino, allows urban planners and designers to create flexible, data-driven, and performance-oriented design solutions. By incorporating hydrological models like the SCS-CN method into parametric design workflows, it is possible to develop a more comprehensive and integrated approach to urban flood resilience.

This paper presents a novel parameterized design approach to enhance urban flood resilience by integrating the SCS-CN method into the Grasshopper parametric design environment. The primary motivation behind this research is to leverage the advantages of Grasshopper, such as its flexibility, adaptability, and interactivity, in combination with the SCS-CN method to assess and optimize urban design interventions concerning flood risk reduction. The integration is achieved through C# programming, allowing the development of custom components to implement the SCS-CN method within the Grasshopper computational workflow. The proposed approach aims to achieve a multi-objective optimization process by considering economic, ecological, and precipitation-related indicators, ensuring a balance between ecological and economic sustainability while improving urban flood resilience. By conducting case studies in selected urban areas, this research demonstrates the effectiveness and applicability of the proposed approach in addressing urban flooding challenges. By presenting a novel and integrated approach to urban flood resilience, this research contributes to the growing body of literature on the intersection of hydrological modeling, parametric design, and urban planning. The proposed method offers urban planners and designers a valuable tool for understanding and managing urban flood risks, ultimately fostering more resilient and sustainable urban environments.

2. Methodology

2.1 Integrated Parameterized Urban Planning Design Framework with SCS-CN

This section introduces the overall framework for the integrated parameterized urban planning design process incorporating the SCS-CN method, as illustrated in Figure 1.

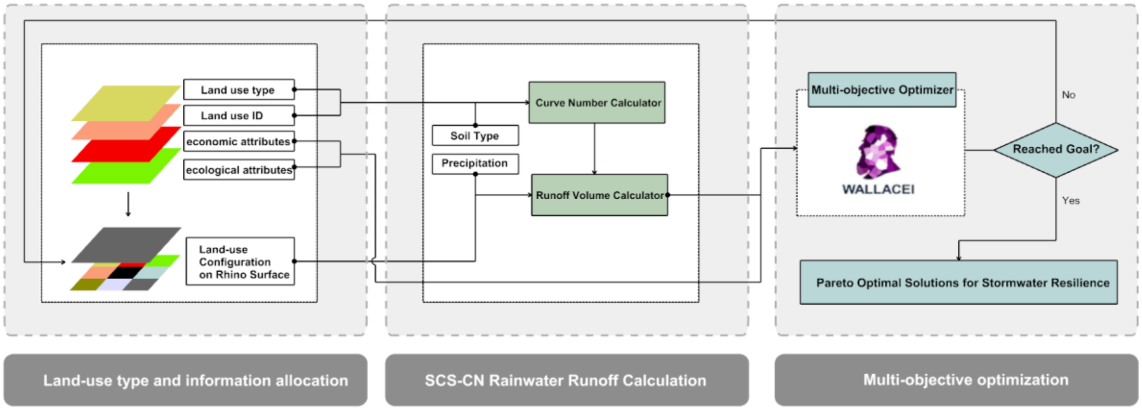

Figure 1. Integrated Parameterized Urban Planning Design Framework with SCS-CN

As shown in Figure 1, the first component, Land-use type and information allocation, focuses on assigning land-use types, IDs, and relevant indicators, such as economic and ecological metrics, to planar elements within Rhino, a 3D modeling software. This process is carried out using Grasshopper, a visual programming plugin for Rhino, which enables the efficient and flexible manipulation of urban planning data. Once the land-use information is assigned, the framework can proceed with land allocation planning, taking into account the designated land-use types and associated indicators. The second component of the framework, SCS-CN Rainwater Runoff Calculation, integrates the SCS-CN method into Grasshopper using two custom components: Curve Number Calculator and Runoff Volume Calculator. The Curve Number Calculator estimates the curve number (CN) values for different land-use types based on their hydrological properties, while the Runoff Volume Calculator computes the runoff volume generated during rainfall events. These components enable the quantification of rainwater runoff associated with various land-use configurations and facilitate the incorporation of hydrological considerations into the parameterized urban planning design process. The third component of the framework, Multi-objective optimization, employs the Wallacei plugin for Grasshopper to optimize flood resilience, economic, and ecological objectives simultaneously. This optimization process generates a set of Pareto-optimal solutions that represent a balance between the competing objectives. If the optimization results meet the desired performance criteria, the framework produces a range of optimal design alternatives. If the performance criteria are not met, the framework iteratively adjusts the land-use configuration to further optimize the design.

The integrated parameterized urban planning design framework presented in this paper offers a systematic approach to incorporating hydrological considerations into the urban planning process. By leveraging the flexibility and adaptability of Grasshopper and Rhino, this framework provides urban planners and designers with a powerful tool for managing flood risks and enhancing urban flood resilience through the exploration of various land-use configurations and design interventions.

2.2 Incorporating the SCS-CN Method into Grasshopper

The Soil Conservation Service Curve Number (SCS-CN) method is a widely used empirical model developed by the USDA Natural Resources Conservation Service (NRCS) for estimating direct runoff volume and peak flow rates in response to rainfall events(Mishra et al., 2003). The method has gained popularity due to its simplicity, effectiveness, and relatively low data requirements. In this section, we will provide a comprehensive overview of the SCS-CN method, including its underlying principles, key equations, and limitations, before describing the process of integrating it into the Grasshopper environment using custom C# components.

The SCS-CN method is based on the concept of a curve number (CN), which is a dimensionless parameter that represents the combined effects of land cover, soil properties, and antecedent moisture conditions on runoff generation. The CN values range from 0 to 100, with higher values indicating greater runoff potential. These values are determined using a predefined table that accounts for various land-use types and soil hydrologic groups, ranging from A (highly permeable) to D (least permeable).The primary equation of the SCS-CN method estimates runoff depth (Q) as follows(Hawkins et al., 2008):

$$Q = (P - Ia)^2 / (P - Ia + S)$$

P represents the rainfall depth, Ia denotes the initial abstraction (i.e., the portion of rainfall that is lost due to interception, infiltration, and surface storage before runoff begins), and S signifies the potential maximum retention after runoff begins. The initial abstraction is generally approximated as 0.2 * S, and S is related to the CN value through the equation:

$$S = (1000 / CN) - 10$$

Despite its simplicity, the SCS-CN method has been widely applied in various hydrological studies and engineering projects, including flood forecasting, stormwater management, and watershed modeling. However, it should be noted that the method has certain limitations, such as its empirical nature, reliance on static CN values, and lack of consideration for spatial variability in rainfall and other hydrological factors. To incorporate the SCS-CN method into the Grasshopper environment and enable its seamless integration with the parameterized urban planning design process, two custom C# components were developed: CurveNumber Calculator and RunoffVolume Calculator (Figure 2).

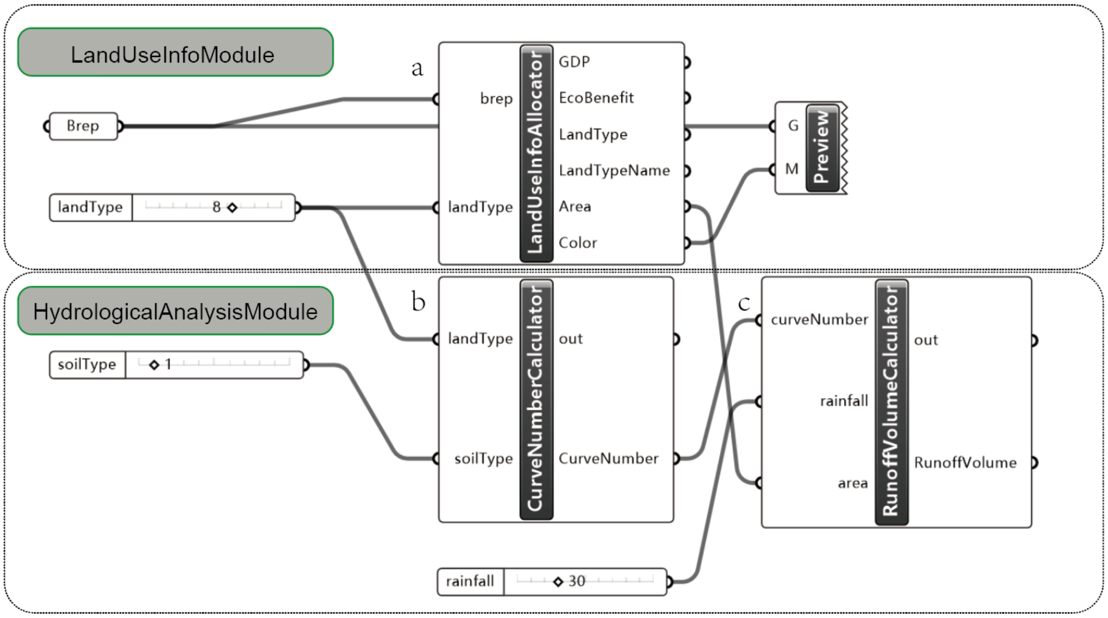

Figure 2. Custom SCS-CN components in Grasshopper: (a) LandUseInfoAllocator, (b) CurveNumberCalculator, and (c) RunoffVolumeCalculator

The CurveNumber Calculator component (Figure 2b) calculates the CN value based on the input land-use type and soil group. The C# code for this component defines a class named SCS_CN, which includes properties for land-use type, soil group, and CN value. The class constructor initializes the properties and computes the CN value using a predefined lookup table containing CN values for different land-use and soil group combinations. This table is implemented as a two-dimensional array of integers, with rows representing land-use types and columns representing soil groups. The component also includes error handling to ensure that the input values for land-use type and soil group are within the valid range. If the input values are outside the valid range, the component returns an error message and sets the CN value to -1, indicating invalid input. The RunoffVolume Calculator component (Figure 2c) computes the runoff volume generated during a rainfall event based on the input CN value, rainfall depth, and catchment area. The C# code for this component defines a class named RunoffCalculation, which includes properties for CN value, rainfall depth, catchment area, and runoff volume. The class constructor initializes the properties and calls the CalculateRunoffVolume method, which computes the runoff depth using the SCS-CN equation.

3. Multi-Objective Optimization

To achieve urban flood resilience, a careful balance between multiple objectives is essential, including the minimization of stormwater runoff, the maximization of ecological sustainability, and the promotion of economic development. In this research, we employ the Grasshopper plugin Wallacei(Navarro-Mateu et al., 2018) to deploy the Non-dominated Sorting Genetic Algorithm II (NSGA-II)(Back et al., 1997), thereby simultaneously optimizing these objectives. Wallacei which is an extensive optimization platform, empowers designers and planners to navigate and comprehend complex solution spaces by offering a diverse set of analytical tools and visualizations. It utilizes NSGA-II, a widely-used and efficient multi-objective genetic algorithm (MOGA), to balance multiple conflicting objectives. The algorithm achieves this by generating and scrutinizing a varied set of design alternatives. MOGAs, like NSGA-II, are especially beneficial for urban planning issues, given their capacity to effectively balance trade-offs amongst competing objectives, while pinpointing optimal solutions that satisfy multiple criteria. We incorporate the SCS-CN method within the parametric design process to quantify stormwater runoff volume resulting from varying land-use configurations. The reduction of stormwater runoff is a critical facet of urban flood resilience. Hence, the objective is to minimize this volume, consequently diminishing the potential for urban flooding and its associated damage. Ecological sustainability is of paramount importance for the long-term wellbeing and resilience of urban environments. Our goal is to optimize green space provision, biodiversity, and ecosystem services, while mitigating habitat fragmentation and other adverse environmental impacts. This goal can be quantified using a range of ecological indicators, like the total area of green spaces, habitat connectivity, and species diversity. In the context of successful urban planning, promoting economic development and maintaining a vibrant urban economy is a must. This goal can be assessed through indicators such as job creation, property values, and the overall economic performance of the urban area. We have referenced the ecological and economic indicators of relevant parcels of land to establish a foundation for multi-objective optimization(Pan et al., 2023). By optimizing these indicators with NSGA-II, a balance between flood resilience, ecological sustainability, and economic growth can be realized. In Figure 3, we illustrate the site in Yulin that requires optimization, alongside various scenarios derived from the multi-objective optimization process.

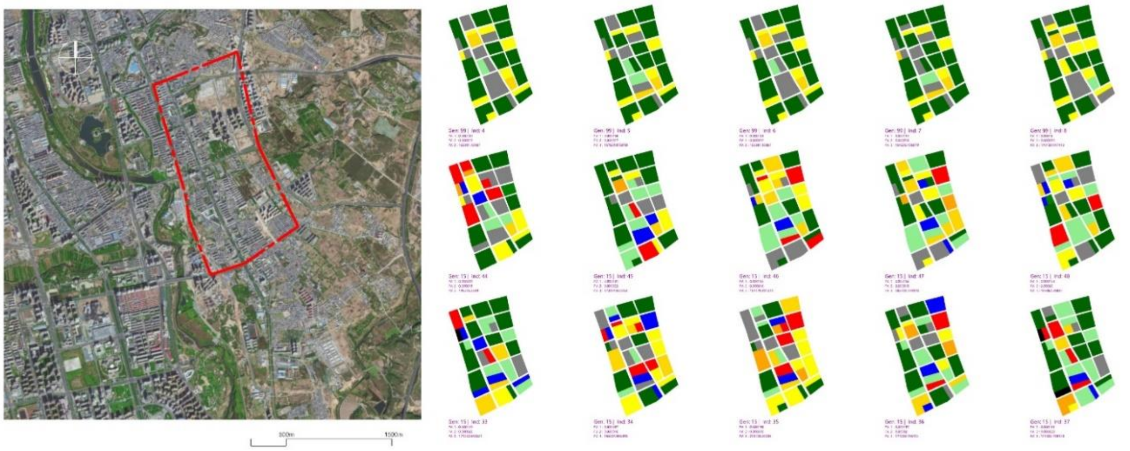

Figure 3. The left panel displays the site in Yulin earmarked for optimization. The right panel shows different scenarios arising from the multi-objective optimization process, depicting distinct solutions derived from different objective weightings.

Employing Wallacei, we organize the multi-objective optimization process with NSGA-II, to find solutions that simultaneously optimize the three defined objectives. We establish fitness functions for each objective, grounded in the indicators described above. To ensure an equal contribution from each objective to the overall optimization process, the fitness functions should be normalized. Subsequently, we set up the Wallacei plugin within the Grasshopper environment, linking the custom SCS-CN components and other relevant design parameters to the plugin. The NSGA-II settings, such as population size, mutation rate, and crossover rate, should be chosen based on the problem's specific characteristics and adjusted as necessary to achieve satisfactory results. Upon initiation of the optimization process, Wallacei generates and evaluates a diverse set of design alternatives. The NSGA-II iteratively refines the solutions and identifies optimal trade-offs between the competing objectives. The resulting Pareto front represents a set of non-dominated solutions - optimal in the sense that no single solution outperforms the others across all objectives. The final step in the multi-objective optimization process is to analyze and select the most suitable solutions for implementation. Wallacei offers various visualization and analytical tools to assist decision-makers in understanding the trade-offs between objectives and in selecting the most appropriate design alternatives to enhance urban flood resilience. Figure 4 showcases the optimized process.

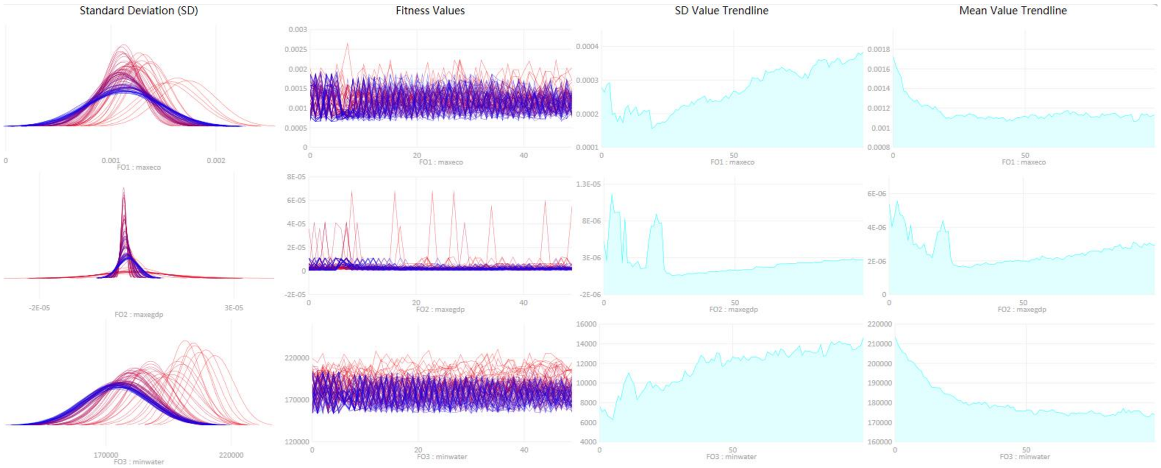

Figure 4. This visual representation depicts the results of the optimization process. It demonstrates the performance of each solution in relation to the set objectives, highlighting the trade-offs involved in selecting an optimal strategy.

The multi-objective optimization process provided by Wallacei and NSGA-II demonstrates a powerful approach to urban planning and design. By considering multiple objectives simultaneously and exploring a wide range of design alternatives, it allows planners and designers to make informed decisions that balance competing objectives and foster urban flood resilience, ecological sustainability, and economic growth.

4. Conclusion

In conclusion, this study has presented an innovative approach to urban planning and design by integrating parameterized design, hydrological modeling, and multi-objective optimization. Through the application of Grasshopper plugins, including Rhino and Wallacei, and the development of custom components for implementing the SCS-CN method, we have demonstrated the potential of computational design tools in promoting resilient and sustainable urban development. The proposed method offers a comprehensive solution for evaluating and optimizing the hydrological impacts of different land-use configurations. Incorporating the SCS-CN method into the Grasshopper environment allows for seamless integration of hydrological considerations into the parameterized urban planning design process, enhancing the accuracy and reliability of urban design decisions. The multi-objective optimization process, implemented using the Wallacei plugin and the NSGA-2 algorithm, facilitates simultaneous consideration of multiple objectives, such as minimizing runoff volume, maximizing economic benefits, and enhancing ecological value. This process enables the identification of optimal solutions that balance these competing objectives. The case study of Yulin City showcases the applicability and effectiveness of the proposed method in real-world urban planning contexts. The optimized land-use configuration resulting from the multi-objective optimization process provides a blueprint for enhancing urban resilience and reducing flood risks in Yulin City, considering its unique ecological constraints.

Overall, the proposed method holds significant potential for advancing urban planning and design, offering a powerful tool for navigating the complexities and uncertainties of urban development, especially in the face of environmental challenges such as climate change and urban flooding. We hope this study will encourage further exploration and adoption of computational design tools and multi-objective optimization techniques in urban planning and design practice and research.

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