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Integrating Aerial and 3D Data into a Data-Driven Decision-Making Workflow for Nature-Based Stormwater Solutions

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Abstract: Urbanization and climate change have increased the need for stormwater management and nature-based solutions. Decisions made at the project level impact the emergence of the systemic traits of the stormwater network and the functionality of the catchment areas in urban planning. To that end, it is vital to introduce the decision-making tools for analysing both the utilities and amenities of nature-based solutions (NBS) to increase their adoption to reduce the peak loads in the stormwater system and, to that end, mitigate the impacts of climate change. There is a deficiency in employing a software-based approach to analyse the qualitative and quantitative aspects of NBSs to back up design decisions. This paper demonstrates a workflow using drone-based photogrammetry, 3D modelling, and simulation software to generate visual and functional models assisting in informed decision-making in the design of stormwater systems as functional landscape architecture. Using aerial data from drones and modelled design solutions, the proposed workflow simulates rain events, infiltration, evaporation, water flow, and the accumulation of stormwater in a way that allows the visual and quantified analysis of detailed landscape architecture designs. The paper provides an example of a rooftop site simulation demonstrating the infiltration and flow of water to the drainage. The visual decision-making method provided can aid in investment decisions for functional landscape design in support of stormwater management.

Keywords: data; drones; urban; nature-based; photogrammetry; design; software; decision-making

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1. Introduction

Urban stormwater runoff is a significant environmental challenge that threatens human and ecological health across cities worldwide and calls for urban stormwater management (USM) [1–5]. The continued urbanization and changing climate have exacerbated the problem [6], highlighting the need for effective stormwater management solutions [7]. However, conventional engineered stormwater systems commonly lack combined functionality and design quality, leaving much to be desired in terms of visual and architectural quality in the artful rainwater design (ARD) [8]. The concept of ARD shares common objectives with an earlier approach of "infra-garden" to support ecological and social values in stormwater management [9]. Both approaches aim at combining functional performance and artistic, visual, and emotional qualities with architectural experiences that promote liveable and resilient cities.

Novel trends in stormwater management suggest the use of nature-based solutions (NBSs) in the planning of urban rainwater systems, mainly in the European Union since 2015 [10]. Apart from the functional performance, the social benefits with aesthetic and place-making qualities are considered as quintessential properties of NBSs [11]. However, small-scale NBSs associated with the urban fabric are effective only in large numbers and with a systemic implementation [12]. To that end, there is a need to investigate how to increase and encourage the adoption of NBSs as part of the urban drainage system. Here, NBSs are considered as nature-based and inspired design interventions in the urban fabric, being part of the design of the built environment.

The objective of this paper is to provide a demonstration of a drone-based data-collection and design workflow delivering an approach for assessing both the amenities and utility performance of a design for a specific project area. A green roof of a campus building was used in this study as a test and demonstration location for the workflow. The analysis of amenities of NBS is grounded in subjective and project-specific design aspirations while the investigation of utilities offers parameters with metrics, such as the infiltration capacity of the ground to absorb stormwater, to analyse the functionality of the stormwater system through a computational approach.

This study consisted of two phases: (1) the current applications of drone data to the design of stormwater management systems were investigated, and (2) the implementation of a design workflow was investigated. The aim of the first phase was to find out to what extent the current practice and workflows support the decision-making of the functionality and aesthetic quality of the stormwater systems in small and medium urban scale projects typically subject to real estate investments. In the second stage, a design workflow was investigated to provide prescriptive advice for design practitioners, the software development community, and researchers for further development of workflows based on aerial imaging, modelling, and design software to achieve more informative design methods for decision-making in projects having the potential to involve a small-scale urban NBS.

The paper aims to explore the use of aerial imaging to support the analysis of amenities and utilities of smaller-scale urban NBSs by answering the following research questions:

1. In what ways has aerial data been used in support of designing small-scale urban NBSs?
2. Is there a way to use aerial data as a rapid assessment method of the amenities and utilities of urban NBSs?
3. How could a computational workflow be established combining aerial data and 3D design information to create a visual and functional representation of a prospect NBS for decision-making purposes in urban projects?

Current Trends of Using Drone-Based Aerial Data for NBSs and Stormwater Design

The performance of stormwater systems has been under scrutiny for an extended period of time due to impairments and knowledge gaps in stormwater management actions and impacts of the urban landscape and grey infrastructure on local and regional hydrology [13,14] and pollution in the runoff waters [15,16]. At the same time, the municipalities commonly work under constrained resources for stormwater management resulting in the need to target the measures with the most impact on the water quality, which is a complex task to accomplish [17]. The effectiveness of the measures may not fully comply with the design intentions, and to that end, active monitoring has been suggested to ensure compliance [18]. However, laborious active monitoring and data collection on the properties of water, such as the surface flow or water quality, have limited capacities to provide direct prescriptive advice and guidance for designing stormwater solutions in other areas and specific sites. In turn, aerial data can offer a means for data-driven decision-making in the local design context. MacDonald [17] has proposed the following taxonomy for drone applications in the emerging field of using Unmanned Aerial Vehicles (UAVs) in stormwater management and system design:

1. An asset management tool. This category involves data collection and analysis of both built environments, such as sewer inlets [19], and green infrastructure, enabling, for example, the monitoring of plant health [20].
2. A water measurement tool, including both sampling [21] and imaging approaches such as fusion of RGB and multi-spectral imagery [22].
3. A vehicle for better model parametrization. Aerial data can provide spatial data on demand for higher spatial accuracy than other georeferenced data with low resolution and granularity for the improved performance of models [23,24]. More-

over, thermal imaging can produce fine resolution estimates on the ground surface temperatures [25] and surface imperviousness [26]. The detailed properties of the ground can significantly contribute to the development of the modelling approaches from the viewpoint of functional landscape architecture.

4. A way to support smart and connected stormwater systems. UAVs are considered as tools for generating data and improving situational awareness [27]. The advantage of emerging autonomous and frequent drone operations can be real-time and can frequently update aerial data as a side product of other smart city solutions such as drone logistics or first responders' operations. The increased availability of detailed and high-resolution data supports the adoption of data-driven stormwater design and management approaches.

The above taxonomy supports the aims of this research in three ways. First, aerial imagery and photogrammetry were investigated as asset management tools to (i) establish a mesh model created through photogrammetry that can be used as a preliminary model to study the stormwater features of the location by altering the assigned mesh properties, such as colour and texture, and functional properties, such as imperviousness and roughness of the surface impacting water flow, and (ii) deliver the surrounding context data of the design area to which the 3D model of the nature-based design solution can be inserted for analysing the utilities and amenities of the solution. The above approach helps to estimate the qualitative and quantitative performance of the intended design solution.

Second, for the aim of better parametrization of physical model parameters, it is possible to use measurement-based estimations of imperviousness for each soil and surface type and assign those values to corresponding areas of the surface mesh to simulate the infiltration and flow of the stormwater. For smaller surface areas, the approach can be applied manually by selecting the desired parts of the mesh. However, for efficiency and larger surface areas, machine learning using semantic segmentation could be applied [28]. The aerial data of UAVs can aid in this task, namely, by providing more detailed and unobstructed imagery in comparison to high-altitude aerial imagery. The tree canopies often prevent the surface analysis from aerial images taken from higher altitudes. Furthermore, in such aerial images, the resolution or point cloud densities are insufficient for determining very precise geometries of the surface, such as inclined surfaces or detailed curb sides, to analyse precise surface water flows and pooling of water in detail. To that end, the evaluation of functional landscape architectural design calls for more detailed data about the surroundings.

Third, smart and connected stormwater systems have their roots in individual projects and investment decisions concerning NBSs. To that end, each project and related nature-based design is part of a larger evolving network of site-specific stormwater solutions and contributes to the reduction of loads on the network. Therefore, the decision-making process at the project level should provide an informed process to consider the increased adoption of NBSs in support of creating the network in a coordinated manner.

In summary, drones can effectively collect data for creating 3D models of urban locations for the modelling of surface flows and the infiltration of stormwater in a detailed architectural context. Further, the paper aims to introduce a design software-based workflow to support such decision-making processes. The research problem of the study stems from the notion that there is a shortcoming in the available design workflows for analysing the visual and functional stormwater qualities of architectural nature-based solutions.

To conclude, the aim of the work is to investigate the ways drones are currently used for collecting data in support of designing and adopting nature-based stormwater management solutions in urban development projects. Moreover, the 3D models can be used as preliminary design tools by changing the parameters of the mesh to measure and visualize the functional properties of the design. Lastly, a detailed architectural design can be integrated into the 3D mesh model to provide a visual and functional simulation of the nature-based solution to support the decision-making in investment projects opting for implanting nature-based solutions.

2. Materials and Methods

2.1. Target of the Research

The research targets are urban sites and locations that become objects of urban development and investments. The scale of the site is not limited, but rather, it is connected to the investment decisions and ways to provide the stakeholders with the means for informed decision-making for the adoption of nature-based stormwater management techniques.

For the aims of the research, a test site was selected consisting of a green roof of a campus building. The size of the selected sedum green roof is 25 m × 25 m (625 m^2), and it is surrounded by terrace areas and hard roof surfaces. The size of the area fits well with the aims of the research to study the solutions as nature-based landscape architecture solutions applicable to areas other than green roofs, such as courtyards of residential blocks. Additionally, the compact size of the demonstration site helped in the development of the workflow while using limited computational resources.

2.2. Research Approach

First, the study used a literature search to investigate the current use of drones in support of stormwater management and design, covering peer-reviewed journals and using Google Scholar for the initial investigation of the literature and the Scopus search engine for refining the investigation by using the search terms described in Tables 1 and 2.

Table 1. The results of the Google Scholar literature search.

Search Terms	Results
"drones smart and connected stormwater systems"	6290
"drones for water measurement"	61,800
"drones monitoring plant health"	36,900
"drones surface imperviousness"	6120
"drones land surface temperature"	36,000

Table 2. The results of the Scopus literature search.

Search Terms	Results
drones AND stormwater	8
drones AND water AND measurement	347
drones AND monitoring AND plant AND health	71
drones AND surface AND infiltration	9 [1]
drones AND land AND surface AND temperature	45

[1] Search term "imperviousness" provided zero results.

Second, based on the findings of the literature search, the investigation used action research to discover and demonstrate a workflow that could fill the identified gap in the design methodology, supporting an increased adoption of nature-based stormwater management techniques. Action research is an approach commonly used in discovering workflow and software approaches to solve a practical need [29]. The method was used to investigate the functionality of NBSs in simulated rain events in 3D models that were prepared based on aerial data.

2.3. Creation and Application of 3D Mesh Models

2.3.1. Data Collection for Photogrammetry

The objective of the data collection was to create a visually high-quality mesh of the demonstration site. The creation of the mesh model needs to produce a unified mesh surface without any holes in it for the rain event simulations to perform properly. A DJI Mini 3 Pro drone was used to collect 550 aerial images of the test site. The images were post-processed into a 3D mesh model using WebODM 1.9.15 software. The demonstration site, illustrated in Figure 1, included diffused objects such as perforated steel structures to increase the complexity of the small-scale urban space.

Figure 1. Demonstration site. The area subject to investigation is marked with a dotted line.

2.3.2. Fast-Track Analysis with Photogrammetry 3D Models

After producing the 3D mesh of the site, the 3D mesh was processed using Blender 4.0 to initially develop and test the workflows that could later be developed inside Blender into more user-friendly design applications with user interfaces or software solutions using other applications, such as game engines.

The first workflow tested aimed to use the model with minimal interventions for analysing the amenities and utilities of an NBS. The test site contained an existing NBS comprising an extensive sedum green roof. After the initial tests without interventions, the following interventions were tested:

1. Changing the colour of the mesh surface and altering the topography of the surface. This approach can be used to analyse in a streamlined fashion the changes in the appearance of the demonstration site caused by desired amenities and the desired functional properties, such as the impact of adding a stormwater reservoir to the design (Figure 2). The deviation of the surface levels can provide liveliness and functional properties to the design such as a retaining pool for stormwater, without having to fully design and model the NBS. Later, if the design process is desired to be continued in more detail, the same volumes of stormwater retention pools can be adapted to a more detailed and realistic 3D model, which is also more time-consuming to produce. In a similar fashion, the existing hard surfaces such as terrace pavements can be re-coloured to provide an initial appearance of the NBS that can be later designed and modelled in detail.
2. Assigning physics properties to the surface. The last application is the most crucial one from the functional point of view as it enables the analysis of the utilities of the applied solutions. Physics properties of the surface may contain the following variables: (i) permeability as the property of the surface to prevent or allow the infiltration of stormwater, (ii) stickiness/surface roughness as the feature impacting the speed of surface flow and transfer through the structural ground layer. The assignment of the above properties to the mesh model is illustrated in Figure 3. Additionally, the rainwater particles may be assigned a parameter-estimating feature for evaporation by reducing the lifetime of the particles in the simulation. Finally, the stormwater outflow from a single NBS to the stormwater piping network can be simulated through the accumulation of rainwater particles in the stormwater tank (Figure 4).

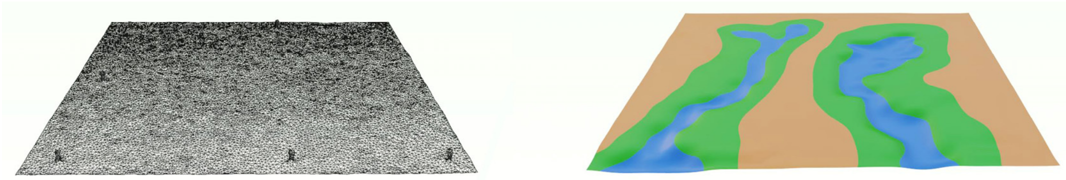

Figure 2. A rapid method for visualization by changing the colour scheme and topography of the mesh model. On the left side is the original 3D mesh of the test site based on photogrammetry. On the right side is the illustration of a surface water reservoir by altering the surface topography of the mesh. Further, the colour scheme has been enhanced to highlight the wider adoption of a green roof.

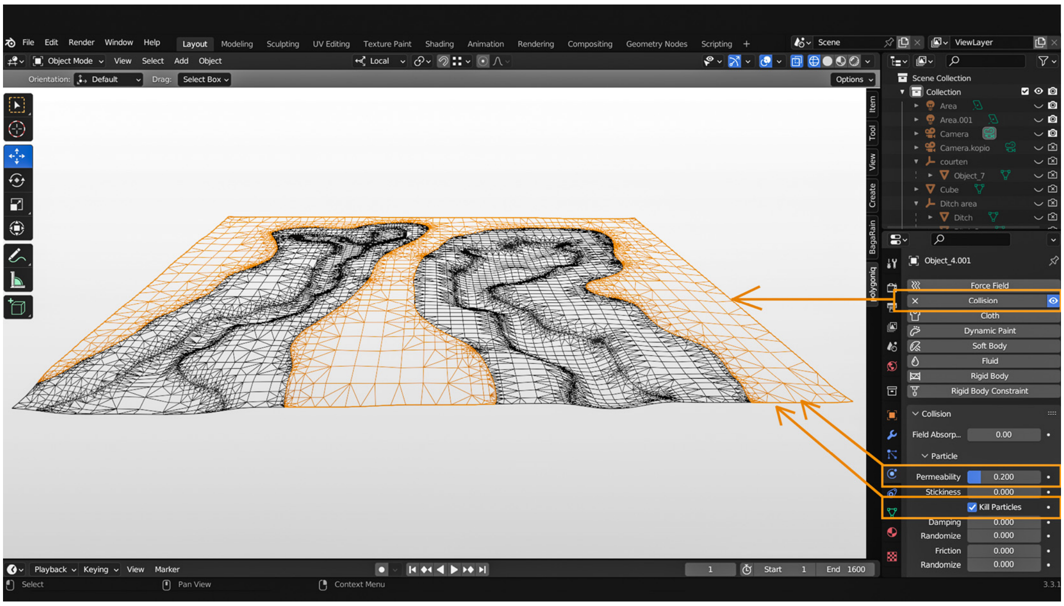

Figure 3. Illustration of the mesh surface with assigned physics properties.

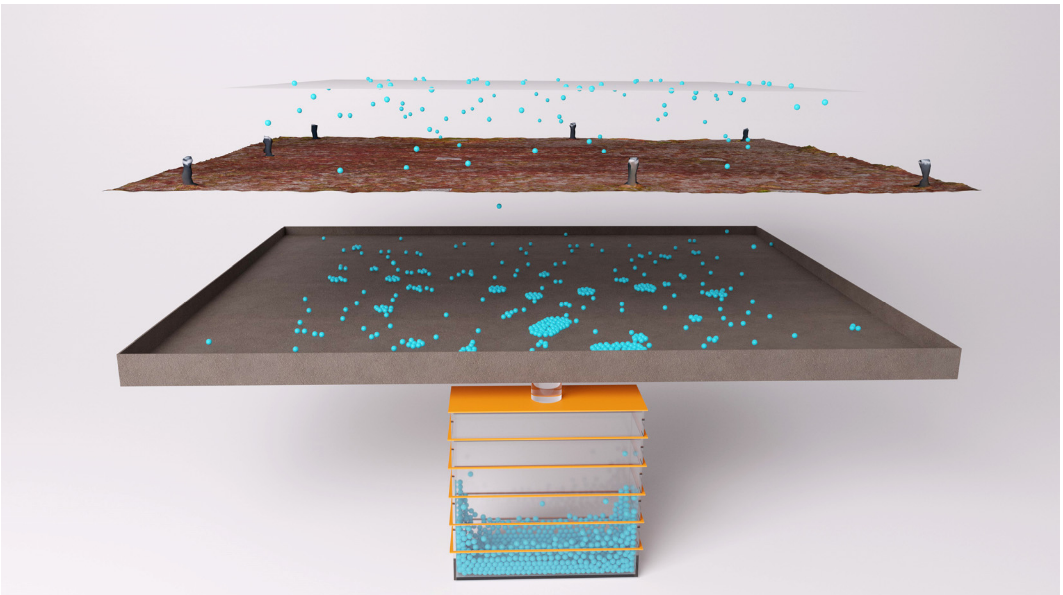

Figure 4. The principle of the system for the stormwater tank with a volume of 9.0 m^3.

2.3.3. Photogrammetry 3D Models for Creating Context Data for the Design

The created photogrammetry 3D model was used as context data for a proxy design of an NBS in the rooftop test location. The approach allows a fast-track design review in the urban context, that is, a rooftop location in the current study. The method is applicable to other locations such as, e.g., residential courtyards. The scale of the analysis is mainly limited by the available high-quality aerial imagery and computing capacity. To enable the analysis of the amenities of an NBS, a proxy design of an NBS was created for the demonstration location and inserted into the photogrammetry 3D model (Figure 5). The model was turned into a single unified mesh model with assigned physics variables for the functional mesh areas. Next, we will discuss the workflow for the analysis of the NBS designs based on the integration of a 3D NBS design and a 3D photogrammetry model.

Figure 5. Integration of a detailed 3D NBS design with the context of a photogrammetry model.

2.4. Workflow to Analyse NBS Designs

2.4.1. Parametrization and Features of the Model

The 3D NBS model was parameterized according to Figure 2, showing the applied physics parameter and the selected value for it. The surface areas of the mesh were selected manually and stored as selection values in Blender to maintain the option to edit both the selection itself as well as the physics properties assigned to the selection.

2.4.2. Simulation Settings of Rain Events

Next, a rain event was created over a selected period based on the efficient use of the available computing resources. The number and duration of rain events can be increased based on demand and the desired detail of the simulation. For efficiency and illustrative purposes, only one rain event is used here. Table 3 describes the rain event.

Table 3. Description of the rain event used in the simulation.

Number of the Rain Event	Start (min: s)	End (min: s)	Amount of Rain (mm/m^2)	Volume of Total Precipitation (mL)
1	0:00	1:06	34.23	5,230,000

2.4.3. Simulation

The simulation was implemented using the physics and Cycles render engine inside Blender. The hardware used consisted of a custom-built PC with Intel®Core™ i7-9700K CPU @3.60 GHz and 32 RAM by Jimmy's PC Store, Turku, Finland.

2.4.4. Analysis of the Utilities

The analysis of the functional performance of the design was enabled in two ways. First, the topography of the design with depressions allowed the pooling of the run-off water. The maximum capacity of the reservoir is achieved when the water starts to overflow from the designated pool area to the surroundings. This is an indication of a lack of infiltration capacity, the small size of the reservoir, or insufficient piping systems allowing excess water to run off.

Second, the functional performance of the utilities can be measured by modelling a stormwater tank to the system (c.f. Figure 4). The piping solutions correspond to the design requirements of each specific system. For example, the stormwater inlets of the current test site have been modelled and connected to the virtual stormwater tank. In different phases of the simulation, the volume of the run-off water can be measured in the tank. The objective of the approach is to provide a model for comparing different design solutions with different parameters, such as the infiltration capacity of the surface, against the same rain events. In other words, the simulations show the accumulation of stormwater in the tank over the same period and rain events under different design parameters, allowing for the analysis of, e.g., the retention capacity and rain event-related maximum flow peak reduction effects.

2.4.5. Analysis of the Amenities

The simulation can provide a highly visual presentation of the chain of events, depending on the selected approach. To that end, the ARD becomes possible when the design analysis is combined with integrated negotiation techniques. The aim of such techniques is to enable consensus building and lasting agreements on the selection of design alternatives [30].

3. Results

Based on the findings of the literature investigation, there is a shortage of applications for using drone-based aerial data in support of visual and functional analysis of the performance of architectural NBSs at a detailed design level. Grounded in the findings of the first research question, the second research question aimed to discover a way for rapid and agile use of aerial imagery to investigate the amenities and utilities of urban NBSs. Here, an approach to post-producing the 3D mesh based on photogrammetry was presented. The third research question targeted finding a software-based workflow to integrate detailed NBS architectural design solutions to the photogrammetry model and perform an analysis of the utilities of the solution. To that end, the paper has described an approach to simulate the rain events and their stormwater impact in a visual fashion while analysing the performance of the test site. The approach was tested with a selected rain event described in Table 2, and the results will be shown next using three different design solutions as the targets of the simulation.

Results of the Analysis with Design Solutions Integrated into the 3D Model

Three different design versions were analysed through a simulation: (i) a bitumen hard roof, (ii) an extensive sedum green roof (existing situation in the test site), and (iii) an intensive green roof with an NBS design. The run-off coefficients were 0.33 for the extensive green roof and 0.83 for the intensive green roof, and they were used as pessimistic values for the performance, drawing from a comparison of mineral-organic and mineral substrate-based extensive green roofs [31].

The three design alternatives were tested with the same simulated rain events, lasting 1:06 min with a total precipitation of 34 mm/m^2. The results are illustrated in Figures 6–8 (start stage and end stage of simulation shown) showing the amount of accumulated water on the ground and in the stormwater tank at the end of the rain event.

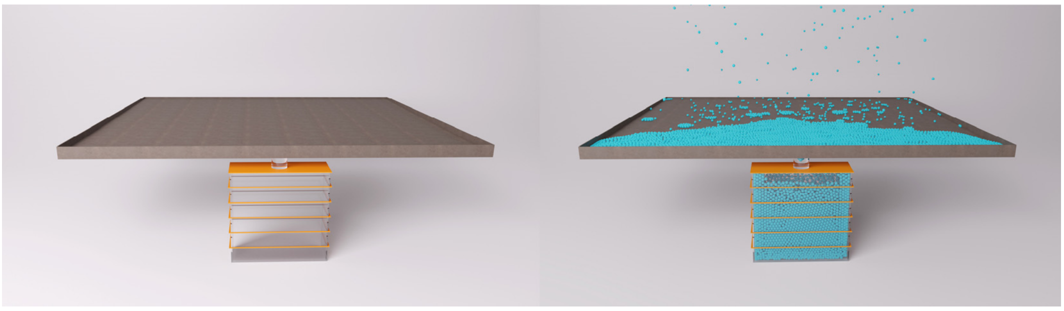

Figure 6. Visualization of the bitumen roof before and after the simulation. The total accumulated amount of runoff water to the stormwater tank is 8.5 m^3.

Figure 7. Visualization of the extensive green roof before and after the simulation. The total accumulated amount of runoff water to the stormwater tank is 7.25 m^3.

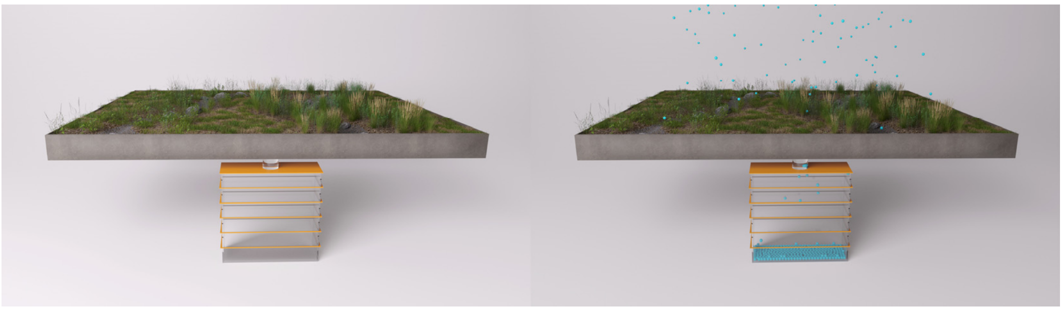

Figure 8. Visualization of the intensive green roof before and after the simulation. The total accumulated amount of runoff water to the stormwater tank is 0.25 m^3.

4. Discussion

The study investigated an analysis approach to the functional and aesthetic properties of roof designs. The utilities and amenities of three different roof typologies were studied as a demonstration of the approach, including (i) a bitumen hard roof, (ii) an extensive green roof with sedum, and (iii) an intensive green roof.

The study investigated the applicability of aerial imagery for the purposes of analysing and communicating nature-based solutions for stormwater management. Earlier taxonomies were reviewed in the research. Most of the earlier identified taxonomies focus on the use of drone data for direct measurement and near real-time monitoring [17]. The proposed approach in this study suggests a new taxonomy for strategic design and decision-making through data-driven design. The approach of data-driven design can be achieved by combining the aerial data with 3D modelling and simulation software.

The results of the study suggest that aerial imagery and powerful modelling tools can effectively be used for analysing the utilities and amenities of NBSs in urban developments at various scales. The use of drones enables the collection of high-resolution aerial images on demand, thus filling the gap in the availability of data as the satellite imagery fails to provide sufficient resolution for design analysis on a detailed urban scale. Further, the imagery collected at the street level provides little or no information on the rooftop level. Therefore, drones can provide a powerful tool for novel approaches to design analysis.

There are two hindrances to a larger-scale adoption of the approach. The first is the need to own and operate a drone to collect the data. The second is the availability of affordable photogrammetry software for occasional users. Both hindrances suggest that the approach is currently applicable mainly to professional users. The change may be introduced along the availability of autonomous drone services, such as data collection as a service, and machine learning-based tools enabling the reconstruction of 3D information, for example, through neural radiance fields (NeRFs), an emerging powerful tool to create 3D content from imagery [32]. Such an approach may provide new ways of illustrating the designs to a higher level of visual quality than the photogrammetry-based approaches.

In its current stage, the workflow presented supports the practical implementation of the ARD and fills the gap in the professional design and communication tools supporting the decision-making in the adoption of NBSs in urban contexts. Specifically, the smaller-scale solutions required a detailed study of the surface water flows and urban elements impacting the functionality and architectural quality of the design.

The results of the simulations in three different designs demonstrate the benefits of the NBSs, allowing for the quantification of the design alternatives. Importantly, the analysis of the visual and architectural qualities can be done within the same metrics; that is, the numeric performance of the designs can have the realistic representation of the design simultaneously available. To that end, complementary research on the functional properties of versatile green roof implementations is essential for gaining additional evidence-based knowledge for the parameters that can be used for setting the parameters of simulations.

5. Conclusions

This research investigated a method and a Blender 4.0 workflow to analyse the qualitative architectural content and the quantitative functional performance of NBSs within the same comparable and visual framework. The findings suggest that the workflow using aerial data for 3D modelling could be developed into a practical tool for supporting the decision-making and analysis of the impacts and functionality of NBSs in urban development projects.

Limitations of the study include the investigation of the workflow in a single software stack for demonstration purposes. Future studies should consider using different simulation and game development platforms. Additionally, what kind of classification of ground surface types is needed to address the relevant differences in the infiltration capacities of the ground should be investigated. For building automated and more easy-to-use applications with a high capacity for analytics, future research should also look at the applicability of machine learning-based solutions such as semantic segmentation to automatize the workflow and detection of surface properties.

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Data Availability Statement: The data presented in this study are openly available in the service provided by the CSC-IT Center for Science (csc.fi) at https://etsin.fairdata.fi (accessed 29 November 2023).

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