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Integration of Building Information Modeling and Stormwater Runoff Modeling: Enhancing Design Tools for Nature-Based Solutions in Sustainable Landscapes

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Abstract: Building information modeling (BIM) has been used by the architectural and engineering disciplines to streamline the building design, construction, and management process, but there has been much more limited experience in extending the application to landscape design and implementation. This study integrated BIM software (Autodesk InfraWorks 2024.1) with a dynamic, process-oriented, conceptual hydrologic/hydraulic model (PCSWMM 2023, version 7.6.3665) to enhance the analytical tools for sustainable landscape design. We illustrate the model integration through a case study that links an existing nature-based solution (NbS) development, the PTT Metro Forest Park, Bangkok, Thailand, with theoretical new-build NbS for an adjacent property. A BIM school building was virtually situated on an empty lot beside the Metro Forest Park and seven NbS scenarios were run with design storms having 2-year, 5-year, and 100-year return intervals. The combination of a rain garden, permeable pavement, a retention pond, and a green roof was effective in sustainably managing runoff from the theoretical new-build site discharging to the Metro Forest. NbS design characteristics such as rain garden substrate depth and green roof area were optimized using the hydrologic/hydraulic model. Model results showed that even with the 100-year rainfall event, the existing Metro Forest pond storage capacity was sufficient so that flooding on the property would not occur. The consideration of connectivity between NbS features is facilitated by the modeling approach, which is important for NbS planning and assessment at a regional scale.

Keywords: nature-based solution design; building information modeling; PCSWMM; rain garden; pervious pavement; green roof; sustainable urban water management

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Citation: Petschek, P.; Aung, A.P.P.; Suwanarit, A.; Irvine, K.N. Integration of Building Information Modeling and Stormwater Runoff Modeling: Enhancing Design Tools for Nature-Based Solutions in Sustainable Landscapes. *Sustainability* **2024**, *16*, 3694. https://doi.org/10.3390/su16093694

Academic Editor: Aliakbar Kamari

Received: 31 January 2024
Revised: 18 April 2024
Accepted: 24 April 2024
Published: 28 April 2024

1. Introduction

High-profile but way-over-budget construction projects like the many-year-delayed Berlin Brandenburg Airport [1] or the Morandi Bridge collapse in Genua [2] created considerable negative press for local governments and private infrastructure operators. To address such issues, different parallel national and transnational governmental organizations realized the need to deal with the digitalization of the building industry. "Similar to other sectors, construction is now seeing its own "digital revolution", having previously benefitted from only modest productivity improvements. Building Information Modelling (BIM) is being adopted rapidly by different parts of the value chain as a strategic tool to deliver cost savings, productivity and operations efficiencies, improved infrastructure quality and better environmental performance" [3] (p. 2). The European Commission created a BIM task group and in 2016 issued the *Handbook for the Introduction of Building Information Modelling by the European Public Sector*. In 2002, Autodesk published a white paper on BIM [4]. It was an important step for defining the term BIM from the software developer side. The paper listed three characteristics of a BIM model: a digital database for collaboration, change management, and reuse of information. It argued that industries like manufacturing are more advanced and already benefit from nongraphical, parametric information, while in the architecture and construction industry, graphic modeling with CAD was still the standard. The white paper names higher quality, greater speed, and lower costs as benefits of a new BIM process.

Despite the benefits of implementing the BIM process to better integrate architectural design and construction, including the clash detection of design elements, 3D modeling, team collaboration to reduce inefficiency, and constructability issues of design, some barriers remain for full uptake by stakeholders [5–8]. These barriers potentially are even greater when extending BIM application to landscape architecture. Early in the BIM evolutionary history for landscape design applications, Flohr [9] suggested that BIM software was "currently not a practical tool for landscape architects", particularly because it was "incompatible with the workflow of landscape architects". Conversely, seven years later, Carr [10] concluded "Extending the workflow of Building Information Modeling (BIM) to the field of landscape architecture has significantly improved the workflow across design disciplines". Nonetheless, barriers with respect to the standardization of design elements, data formats, design scale, and user penetration remain within the landscape architecture discipline [11–13]. This implementation and barriers discourse primarily has focused on practices in the global north and even greater challenges exist with respect to uptake in the global south and smaller design companies with limited staffing [14–16].

BIM is a collaborative construction process, with shared model data at its center. Its focus is the construction process of buildings or infrastructure. When the construction project is finished, the data should represent an exact replication of the built project. The data (models, reports, schedules, monitoring, analyses, simulations) of the BIM process should be used and constantly updated during project operation. Data-driven decisions can be made to extend the project life cycle. Furthermore, as we will show in this paper, data generated through the BIM design process can be used directly by stormwater models to support these data-driven decisions. Hence, we have an efficiency of data sharing between the landscape architect and engineering teams.

Nature-based solution(s) (NbS; here, NbS can be used interchangeably to represent nature-based solution or solutions) is an important design direction that increasingly is being implemented to holistically improve the urban environment. Ruangpan et al. [17] define NbS, at least in the context of water resources, as "...participatory, holistic, integrated approaches, using nature to enhance adaptive capacity, reduce hydro-meteorological risk, increase resilience, improve water quality, increase the opportunities for recreation, improve human well-being and health, enhance vegetation growth, and connect habitat and biodiversity". Mathematical modeling to assess performance of NbS design (and related green infrastructure) with respect to urban runoff management historically has been performed by engineers, although there is a recent push to better integrate modeling and design in an effort to optimize planning and visioning form and function [18–25].

BIM can be used to support NbS initiatives by providing a virtual representation of natural systems and processes for the simulation, monitoring, and analysis of their behavior. For example, a BIM for a wetland restoration project could be used to simulate the impact of different restoration scenarios on water quality, flood risk, and habitat for wildlife. This information can be used to select the most effective restoration approach and to monitor the performance of the restored wetland over time. There is limited research to date on integrating mathematical modeling of urban hydrologic/hydraulic systems, NbS, and BIM [26–31]. There are a number of barriers to implementing this type of approach, some of which are similar to those of general BIM implementation (in particular, see [9] regarding software workflow), and the challenges are exacerbated by the need to have a deeper, multidisciplinary collaboration [32,33].

Given the relatively new directions of linking BIM, hydrologic/hydraulic modeling, and NbS, the objectives of this paper are (i) to develop an implementation and analytical framework that can guide BIM/hydrologic/hydraulic modeling (in this case, specifically for NbS); (ii) demonstrate a more seamless approach to linking BIM and hydrologic/hydraulic modeling software; and (iii) apply the BIM and hydrologic/hydraulic models for a case study that links an existing NbS development, the PTT Metro Forest, Bangkok, Thailand, with theoretical new-build NbS for an adjacent property.

2. Methods

2.1. BIM Basics

BIM is a model-oriented process certified under ISO 19 650, which considers the BIM standards for architecture and civil engineering work and applies for the whole life cycle of a built asset. ISO 19 650 consists of several parts that define the collaborative process for effective management of information in a construction project [34].

Informed models play a central role in the BIM process. The single and central model all project partners use and that contains all project information is a myth [35]. In a BIM project, different groups like architects, engineers, HVAC engineers, surveyors, landscape architects, etc., are involved. They all use different modeling software. The orientation of architecture is the vertical. Modeling programs like Archicad, Revit, Rhino 3D, Sketchup, Tekla, and Vectorworks support this type of structure. Tools for civil engineering include Allplan, Civil 3D, and Microstation. They are applied for horizontal structures like roads or in large earthwork projects. Structural engineers and HVAC engineers use the above tools with additional plug-ins or again different software. Landscape architects either mix architecture and civil engineering BIM modeling software, or they stay in one area depending on their job requirements.

Baldwin [35] (p. 49) writes: "There is no question that BIM must deliver project information to all parties from a central source but in practice this is not a single model. Rather it is a network of models and databases". All models developed with different programs need to "talk" with each other by exchanging data. BuildingSmart International [36] is the organization that is supported by the most important players in the planning and construction industry worldwide. The interest group stands behind the two terms openBIM and IFC. openBIM defines software standards so that all stakeholders can work with the building data throughout the whole life cycle of a project. The Industry Foundation Classes (IFCs), a standardized, digital description of buildings and civil infrastructure, are a core element of openBIM.

Communication is essential in a BIM project. "In practice, the central source of project information is not a single project model, but a common data environment" [35] (p. 50). ISO 19 650 defines the common data environment (CDE) and its workflow. The CDE is the platform for all project partners. A CDE "…is a digital information platform that centralizes project data storage and access, typically related to a construction project and building information modeling (BIM) workflows. The data stored in a CDE originally consisted of BIM data and information. Today, a CDE also includes documents like project contracts, estimates, reports, material specifications, and other information relevant to a project's design and construction processes" [37].

2.2. Stormwater Modeling

Generally, three categories of models exist, hardware models, analogue models, and mathematical models. Hardware modeling for engineering purposes could include flumes or Class 'A' evaporation pans. This category of model facilitates experiments and can isolate and examine certain key variables, but faces challenges of scaling. Architects also commonly use hardware (or physical) models to visualize the design process [38]. Analogue models involve a radical change in the media used to represent the environment, for example, kaolin clay to examine glacier physics. Maps and digital architectural designs are a form of analogue model. In this paper, we essentially are discussing the nexus between analogue models and mathematical models. There is a long history of mathematical modeling to characterize and assess urban stormwater runoff and watershed hydrology, starting with the development of the rational method in 1850 [39,40]. The rational method estimates peak runoff for small watersheds as

$$Q_p = 0.278(C \cdot I \cdot A) \tag{1}$$

where Q_p is peak discharge (m^3/s); I is rainfall intensity, mm/hA is watershed area (km^2); and C is a runoff coefficient, with C being related to land surface characteristics, generally having values of 0.75–0.95 for downtown urban areas and 0.1–0.25 for parks. The value of C also may be impacted by storm characteristics. Despite its simplicity (or perhaps because of its simplicity), the rational method is still in use today for engineering design work [41,42]. The rational method is an example of a deterministic, empirical model, deterministic in that given a particular input (e.g., rainfall), the output (e.g., runoff) always will be the same, with no consideration of randomness within the system, and empirical in that values of C should be empirically derived and are site-specific. With the advent of better computing power in the 1970s, deterministic, conceptual modeling became possible and a number of such models were developed, including the U.S. EPA SWMM (Stormwater Management Model) and HSP-F (Hydrologic Simulation Program—Fortran; also known as the Stanford Watershed Model) [43,44]. Since the 1970s, a large number of deterministic, conceptual hydrologic/hydraulic models have been developed, including SWAT, WinSLAMM, SHE, MIKE, HEC-HMS, MUSIC, Topmodel, and SOBEK [45–53]. It is beyond the scope of this paper to review and compare attributes and results of these various models, but model summaries and historical trajectories of model development and application can be found in [39,40,54,55]. More recent advances in deterministic, conceptual modeling have included integration with GIS, 2D computation and visualization of watershed flooding (based on DEMs), seamless linkage of 2D and 3D watershed and reservoir/nearshore coastal models, enhanced graphical user interfaces for data management, analyses and visualization of model output, cloud computing for improved model run times, and evolution in coding formats, for example, from Fortran, to C, to Python.

For this study, we used PCSWMM (Personal Computer version of the Stormwater Management Model) to model the NbS design scenarios and the existing NbS site. PCSWMM is a fully dynamic, hydrologic/hydraulic and water quality model that employs the U.S. EPA SWMM5.1 computational engine and includes a graphical user interface for enhanced data management, model setup, and model output analysis and visualization. Subcatchment surface hydrology and infiltration, as well as drainage network hydraulics, are represented in either 1D or 2D. NbS-oriented options (e.g., rain gardens, grassed swales, green roofs, porous pavement, rainwater harvesting, and constructed wetlands) can be explicitly modeled within PCSWMM. PCSWMM sits on a scalable GIS engine, which facilitates workflow with GIS/CAD-based data, enabling engineers and GIS professionals to work on the same data, thereby improving collaboration potential and workflow efficiency. Clients sometimes require consulting engineers to conduct a cross-check on dynamic model results and to facilitate this need; PCSWMM includes an option to run the rational method. PCSWMM is used globally for water resource management problems, including in Southeast Asia [56–69]. The authors elected to apply PCSWMM in this study for a number of reasons. First, they have used PCSWMM extensively, including integrating the model with architectural designs (e.g., [24,25]). Second, PCSWMM can work directly with Civil 3D files; and third, we are investigating other aspects of the Metro Forest study site, including the provision of ecosystem services and 2D modeling that are facilitated by PCSWMM. While we have elected to use PCSWMM in this study, we note that other BIM/stormwater modeling combinations are possible and should be critically explored. For example, the Autodesk Civil 3D add-in, Storm and Sanitary Analysis, includes options to run the U.S. EPA SWMM5 model and also can apply the rational method.

2.3. Sustainability, NbS, BIM, and PCSWMM

While NbS has gained traction in the past decade to better manage the environment, considerable challenges remain for the approach to be mainstreamed as policy, including the difficulty in integrating concepts, planning, and design techniques from multiple disciplines, and questions regarding a coherent set of guiding principles, standards, and typologies [24,70–74]. Indeed, NbS has been used in diverse contexts and disciplines, including product design [75], contaminated soil remediation [76], climate change adaptation and mitigation [77–79], air quality [80–82], aquaculture [83], food security [70,84], human health [70,85], disaster risk reduction [70,86], water management [87–89], coastal areas [90], and architecture [91–93].

Sowińska-Świerkosz and García [72] summarized 20 definitions of NbS that they identified in a literature search and concluded there were four common elements characteristic of NbS: (1) inspired and powered by nature; (2) address (societal) challenges or resolve problems; (3) provide multiple services/benefits, including a biodiversity gain; and (4) are of high effectiveness and economic efficiency. In this paper, we generally use the ideas of NbS proposed by [17,72] and outlined in the Introduction as a working definition. As NbS takes a broad, integrative approach to connect community and ecosystem wellbeing, accordingly, it has the potential to enhance community sustainability and resilience [73,74,84,94–100]. NbS can address a number of ecosystem service benefits, including climate change resilience, urban heat island mitigation, carbon sequestering, food provisioning, flood mitigation, improvement in water quality, biodiversity, and aesthetics [25,101–105]. Indeed, if we examine the 17 Sustainable Development Goals, NbS potentially addresses at least 9 (Goal 2, Zero Hunger; Goal 3, Good Health and Wellbeing; Goal 6, Clean Water and Sanitation; Goal 9, Innovation, Industry, and Infrastructure; Goal 10, Reduced Inequalities; Goal 11, Sustainable Cities and Communities; Goal 13, Climate Action; Goal 14, Life Below Water; and Goal 15, Life on Land).

Regarding the concern reflected above about the integration of multidisciplinary design techniques as a barrier to the mainstreaming of NbS, we see BIM and PCSWMM as important tools that can address this issue. Yet, as noted in the Introduction, while BIM is making inroads with the architecture community, and more recently with landscape architecture, barriers also remain with implementation in landscape architecture. Catalano et al. [106] noted that real-time environmental data integrated into BIM and GIS software would facilitate the implementation of biodiversity components in project design, but that this option had not yet been implemented. Başoğlu et al. [107] integrated aspects of Life Cycle Assessment and measures of urban metabolism to evaluate NbS features that included BIM as a data management and visualization tool. More recently, Dervishaj [108] sought to develop a framework of digital tools and indicators, including BIM software, to characterize elements of climate, people, and nature for regenerative, sustainable design. Stangl et al. [109] explored the use of BIM software for design of blue–green infrastructure that would be related to NbS, including an online decision support tool based on fact sheets for sustainable designs of green roofing, vertical greening, and plant-based infiltration, although the toolbox did not explicitly represent dynamic processes and was targeted towards non-experts in water management.

PCSWMM has been used extensively to model WSUD features at sites throughout the world as the software has the ability to explicitly represent processes related to bioretention cells, pervious pavement, green roofs, grassed swales, rainwater harvesting, and wetlands/storage/retention ponds [110–119]. Although some of the studies using PCSWMM will discuss results in terms of NbS, often the focus truly is on the WSUD component of NbS, while relatively fewer studies have holistically incorporated PCSWMM into a full NbS assessment (e.g., [25,120]).

A novel contribution of this study is the development of an implementation and analytical framework that can guide BIM/hydrologic/hydraulic modeling for NbS that could be used by a multidisciplinary design and engineering team. Although Brasil et al. [121] identified potential benefits of integrating BIM and hydrologic/hydraulic models to better design, manage, and implement NbS projects, a working platform was not established. We also note that while the DLA (Digital Landscape Architecture) conference is the most popular platform for publishing IT research in landscape architecture and the Bauhaus Dessau in 2023 included the section "Landscape and Building Information Modeling (LIM + BIM) and other Standardizations in Digital Landscape Architecture", no paper dealt with the topic of combining BIM and stormwater management modeling. In previous conferences, the topic also was not present (see [122]). The German FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau) has a working group on BIM. The recent conference on BIM in landscape architecture in February 2024 covered the topic of a Digital Twin [123], but no papers were presented on combining BIM and stormwater modeling. Recent CELA (Conference of Educators in Landscape Architecture) conferences and research papers also did not cover the topic [124]. We conclude here that researchers in landscape architecture write about the importance of sponge cities, but BIM/stormwater management on an implementation scale is not a topic that has yet been developed.

2.4. Study Site, Metro Forest Park, Thailand

Urban sprawl from Bangkok's core area (BMA) into the surrounding peri-urban provinces (BMR) has been well documented [125,126] with attendant impacts on the agricultural and natural landscapes [127,128]. Friend and Hutanuwatr [129] explicitly explored the complex intersection and challenges of politics, capital, and environment in the development of the Suvarnabhumi International Airport on land that is at risk for flooding. Suvarnabhumi not only plays a central role as a gateway for Thailand's large tourism industry, but also as a key node in the development of the Eastern Economic Corridor [130,131]. There has been some progress in pursuing more nature-based development policies within the BMA [132] and examples of NbS implementation in both the BMA and BMR are beginning to appear. However, the NbS implementation remains fragmented and a longer-term goal of this BIM/environmental software research is to scale up and provide a decision and design support platform that could be implemented for coordinated, regional NbS planning, including assessment of ecosystem services [25].

The Metro Forest Park site was chosen for study because it represents an award-winning NbS design that mindfully integrates the built environment, a variety of forest habitats native to Thailand, and a natural waterscape [133] (Figure 1). The design team was led by TKStudio under the principal visioning of Tawatchai Kobkaikit [134] and was commissioned by the PTT Reforestation Institute, part of Thailand's largest petrochemical company, the PTT Group. Completed in 2015, the site previously had been used for illegal waste dumping. Located near Suvarnabhumi Airport, and approximately 20 km south of central Bangkok, this restoration project included the planting of 60,000 trees, representing 279 species, selected in consideration of the different topographic conditions and water characteristics of Thailand: lowland Dipterocarp forest, mixed Deciduous forest, brackish water forest, and mangrove forest [133]. The site is bounded by engineered bunds that provide a suitable soil medium and topographic conditions for the tree planting [134], as well as giving form to a circulating waterfall, stream, and storage/retention pond system. The park includes an observation tower and learning center that has the goal of educating the surrounding urban population about Thailand's natural ecology and forest preservation concepts (Figure 1). While the Metro Forest Park area is small (2 ha), perhaps it can serve as a model on how effective, small-scale development could be scaled up to address Friend and Hutanuwatr's [129] observation that the BMA masterplan specifies the area north of Suvarnabhumi's perimeter should be maintained as "open space to preserve natural drainage condition".

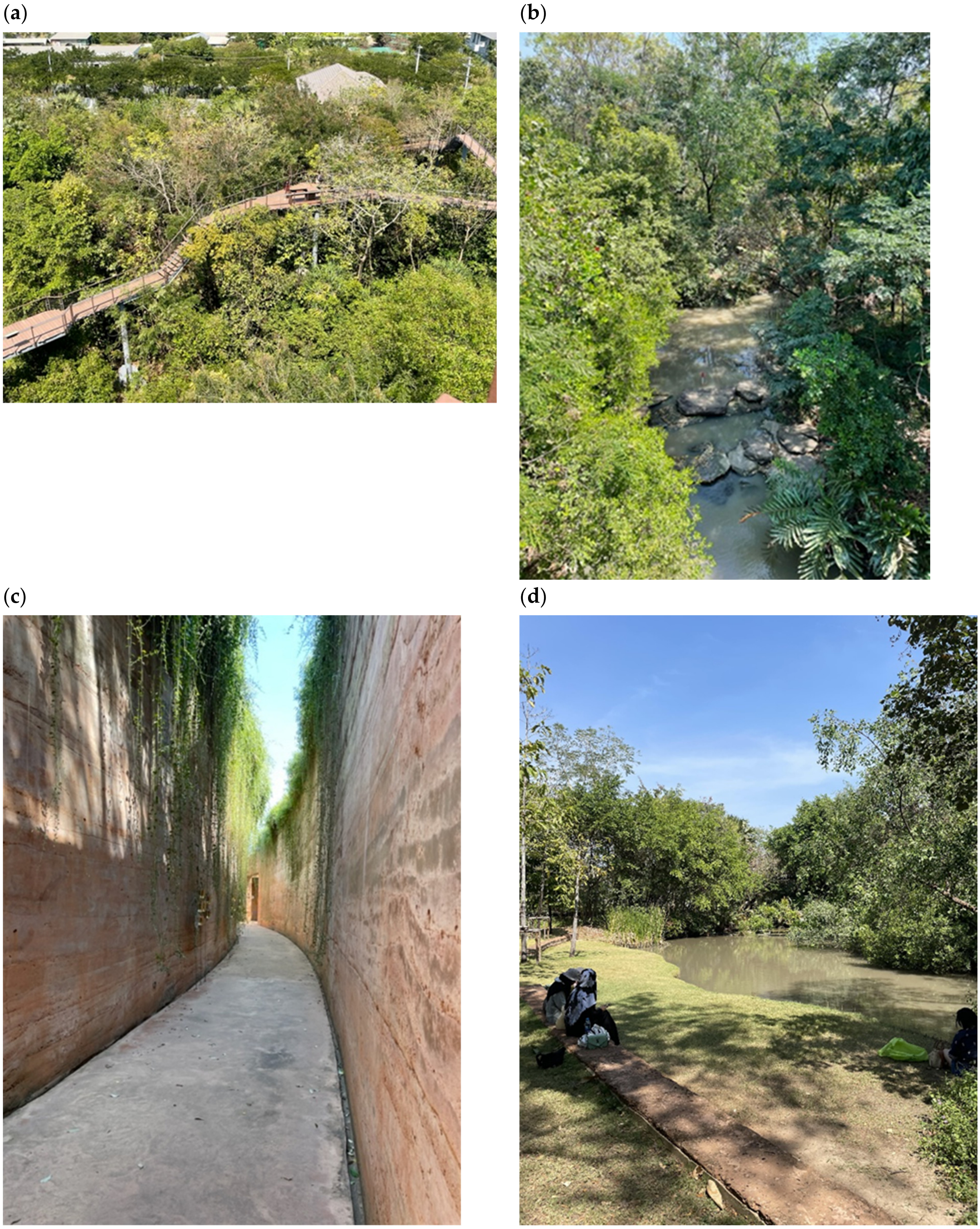


Figure 1. (**a**) Metro Forest Park boardwalk, (**b**) water circulation, (**c**) entry to public education center (with green roof) (photos by K. Irvine), and (**d**) storage pond with visitor reflection area (photo by A.P.P. Aung).

2.5. BIM/PCSWMM Case Study Model for Metro Forest Area

Mensch und Maschine (M+M), a leading supplier of BIM solutions located in Munich, Germany, provided a best-practice BIM model (including architecture, structural engineering, and HVAC/MEP) in the form of a school building for this study (Figure 2).

It represents an exact replication of a project at the end of a BIM process and therefore is ideal for the site design investigation in this study. Here, the BIM school building was virtually situated on an empty lot immediately adjacent to the Metro Forest Park to explore runoff characteristics associated with different NbS design scenarios and illustrate how BIM and deterministic, conceptual models can be integrated to optimize stormwater management. In undertaking this research, we follow Steinitz' Framework for Theory [19,135], as modified by Irvine et al. [24], and include considerations of hydrologic modeling to guide our design evaluations. The first three models in the modified Steinitz Framework for Theory provide an understanding of current conditions (physical/ecosystem and human/social) and landscape/waterscape principal drivers. The current conditions were modeled using PCSWMM to assess existing hydrology at the Metro Forest NbS site, with a focus on storage/retention pond performance. The second three models in the modified Steinitz Framework for Theory visualize alternative landscape development designs in which the BIM layers are integrated with PCSWMM to assess the impact of alternative school site designs on the Metro Forest Park NbS storage/retention pond. We emphasize here that the primary objective of this exercise is to illustrate how BIM and PCSWMM can be linked in elucidating aspects of NbS design performance. While we also assess the ability of the existing Metro Forest Park NbS storage/retention pond to manage runoff with design storms having different return intervals under current and potential build-out conditions, such build-out plans are not being considered by planning officials. Nonetheless, this type of investigation allows us to gauge the flexibility of existing NbS design to accommodate new conditions (e.g., new build-out or climate change) in the effort to enhance community resilience.

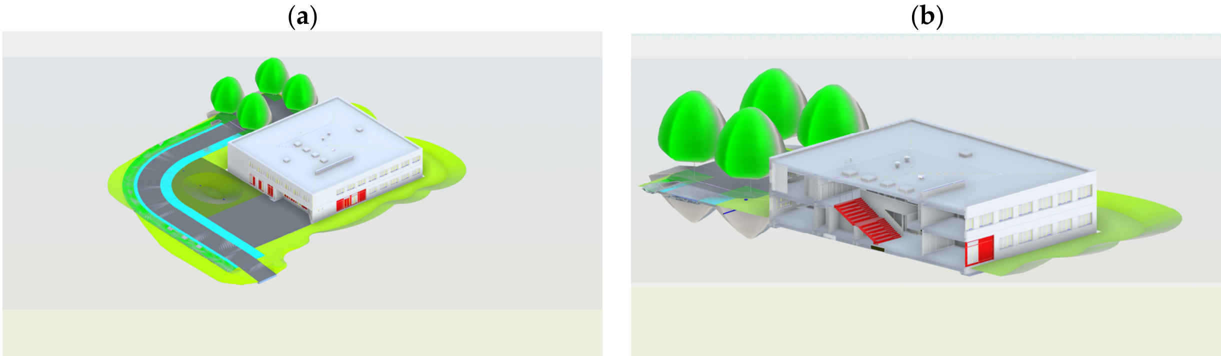


Figure 2. (**a**) BIM school (courtesy of Mensch und Maschine (M+M)) and immediate school property in Civil 3D, and (**b**) BIM school cutaway with tree pits (design by P. Petschek).

The BIM model of the school, placed on the property adjacent to Metro Forest, is shown in Figure 3. We modeled 7 different design scenarios with the BIM/PCSWMM software, but any number of design scenarios could be assessed:

i. Base case scenario—current conditions under which the empty lot adjacent to Metro Forest has no school building and is not connected to Metro Forest.
ii. The school with a full green roof and parking lot draining to a pond, having an underdrain to Metro Forest. The driveway and secondary parking lot drain to a grassed swale system. All pavement is standard, impervious, asphalt.
iii. The school with a full green roof and parking lot draining to a pond, having an underdrain to Metro Forest. The driveway and secondary parking lot drain to a rain garden bioretention system, having an underdrain to Metro Forest. All pavement is standard, impervious, asphalt.
iv. The school with a full green roof and parking lot draining to a pond, having an underdrain to Metro Forest. The driveway and secondary parking lot drain to a rain garden bioretention system, having an underdrain to Metro Forest. All pavement is porous pavement.

v. The school with a full green roof and parking lot draining to a pond, having an underdrain to Metro Forest. The driveway and secondary parking lot drain to a rain garden bioretention system, having an underdrain to Metro Forest. The bioretention system is expanded to explicitly consider the Stockholm pit system design for trees. All pavement is porous pavement.
vi. The same as Scenario v, except that the school green roof area is reduced to 30% of the total roof area.
vii. The same as Scenario v, except that the school green roof substrate depth is reduced.

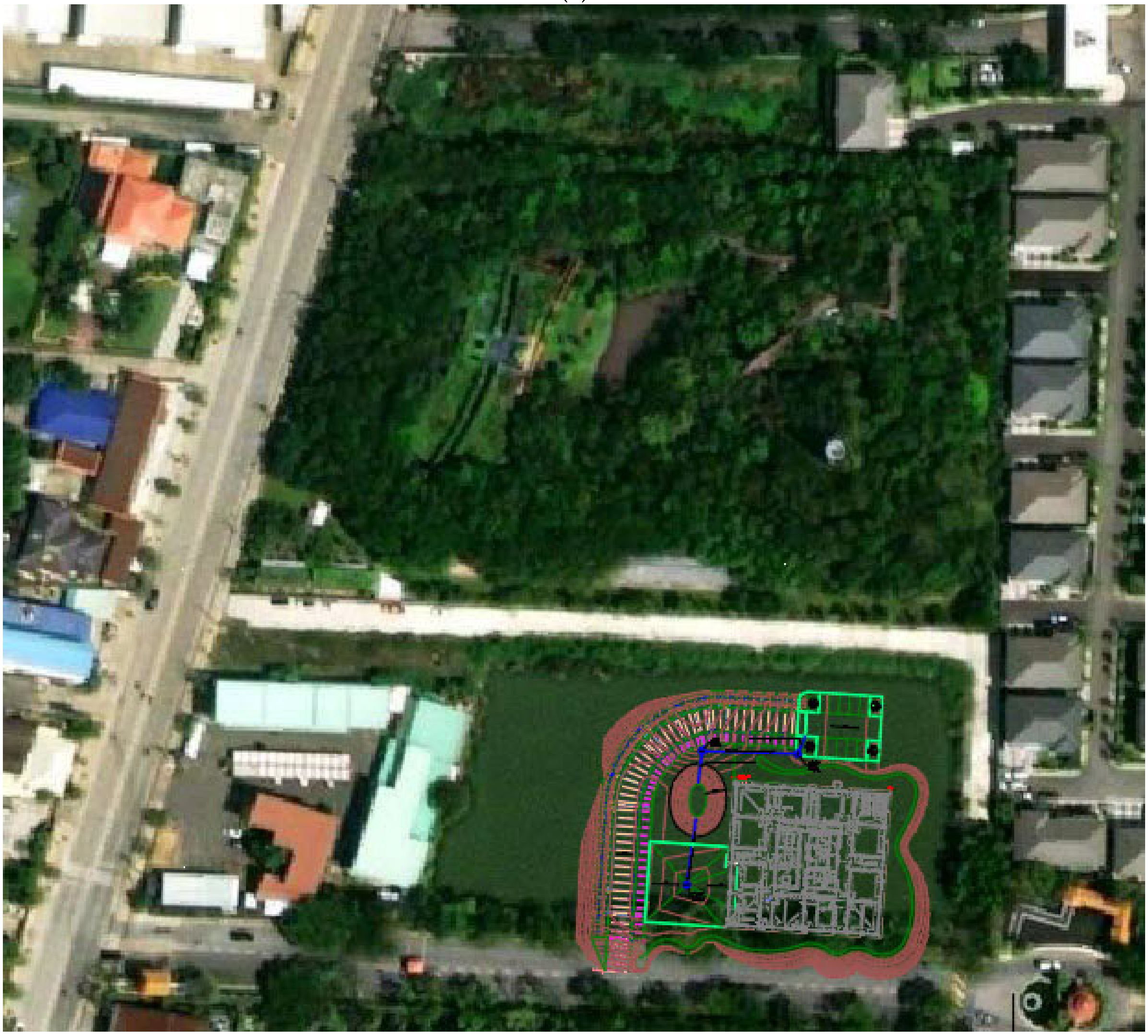
The initial site designs for Scenarios i–vii were created in Autodesk InfraWorks 2024.1 and specifically implementing Autodesk Civil 3D 2024.3; the general workflow for the project is summarized in Figure 4. The project utilized the THAI-W75 coordinate system, referencing locations in Thailand west of 102 degrees east under the Indian 1975 datum for geospatial settings, and subsequently a Digital Elevation Model (DEM) was constructed in Autodesk InfraWorks 2024.1. using the model builder option. The IMX file for the DEM was exported to Civil 3D for further design of specific elements, including the retention pond, schoolyard/parking lot, tree pits, secondary parking lot with a tree pit, school green roof, and swale. This allowed for a comprehensive layout of the school project, including the NbS features. Following this initial design set up in Civil 3D, the workflow continued in PCSWMM 2023, using the Professional 2D version 7.6.3665, where the same DEM data as used in Civil 3D were imported to generate subcatchment boundaries. Although it is possible to design the drainage network within Civil 3D and export the georeferenced file to PCSWMM, in our case, we developed the project drainage network directly in PCSWMM. Civil 3D was instrumental in precisely determining the design dimensions and configuring the design space for the NbS features as well as facilitating the examination of as-built drawings (e.g., storage pond and bunds) from TKStudio before importing and inputting data into PCSWMM 2023.

The school building is a complete BIM model with all architectural, structural, and MEP information. The NbS green roof was modeled in Revit 2024 as the plant cover, and the thickness of each substrate layer provides important information for structural and cost calculations. The Revit 2024 design also gives important, reliable information for the stormwater calculations, as the data are used for construction later on. All the NbS sloped pavement surfaces and subsurfaces in Civil 3D provide necessary data for cost calculation. IFC 4.3 provides the link to the cost calculation program. The pavement surfaces and slope data also were used to operationalize runoff estimates in PCSWMM. The modeled layers of the NbS tree pits for the shade-casting trees have the same function: information for construction and information for stormwater modeling.

As all team members have equal access to the data on the Common Data Exchange platform ACC (Autodesk Construction Cloud), the information exchange is democratized. All members of the project team have the ability to access current data, which creates a more connected construction operation, with ongoing data-centric and collaborative communication flowing seamlessly between the back office, field, and extended project teams. No one holds back information; all information can be found in the models. Structural, cost, and rainwater calculations are model-based with the same source of information. The project ultimately then can be built as modeled.

IFC 4.3 is the new scheme for the infrastructure industry. It also will be the data exchange format between BIM and stormwater management moving forward. The format of IFC 4.3 was just recently approved by ISO as the latest version of ISO 16739 [136]. In Civil 3D, an additional extension of IFC 4.3 for Autodesk Civil 3D 2024 needs to be installed. Revit 2024 can read the format without an additional extension. PCSWMM is working on an IFC 4.3 import/export function. In the meantime, traditional CAD exchange formats have to be used, with the disadvantage of losing information. Autodesk is working on a new Civil 3D version, which will integrate Innovyze stormwater information (release: end of April 2024). The combination of Civil 3D and Innovyze products like InfoDrainage could develop as an alternative workflow for BIM and stormwater modeling.

(**a**)



(**b**)

Figure 3. (**a**) BIM school placement on vacant property adjacent to the Metro Forest site. Base image from Google Earth, and (**b**) view of existing vacant property for the BIM school placement, from Metro Forest observation tower (photo by A.P.P. Aung).

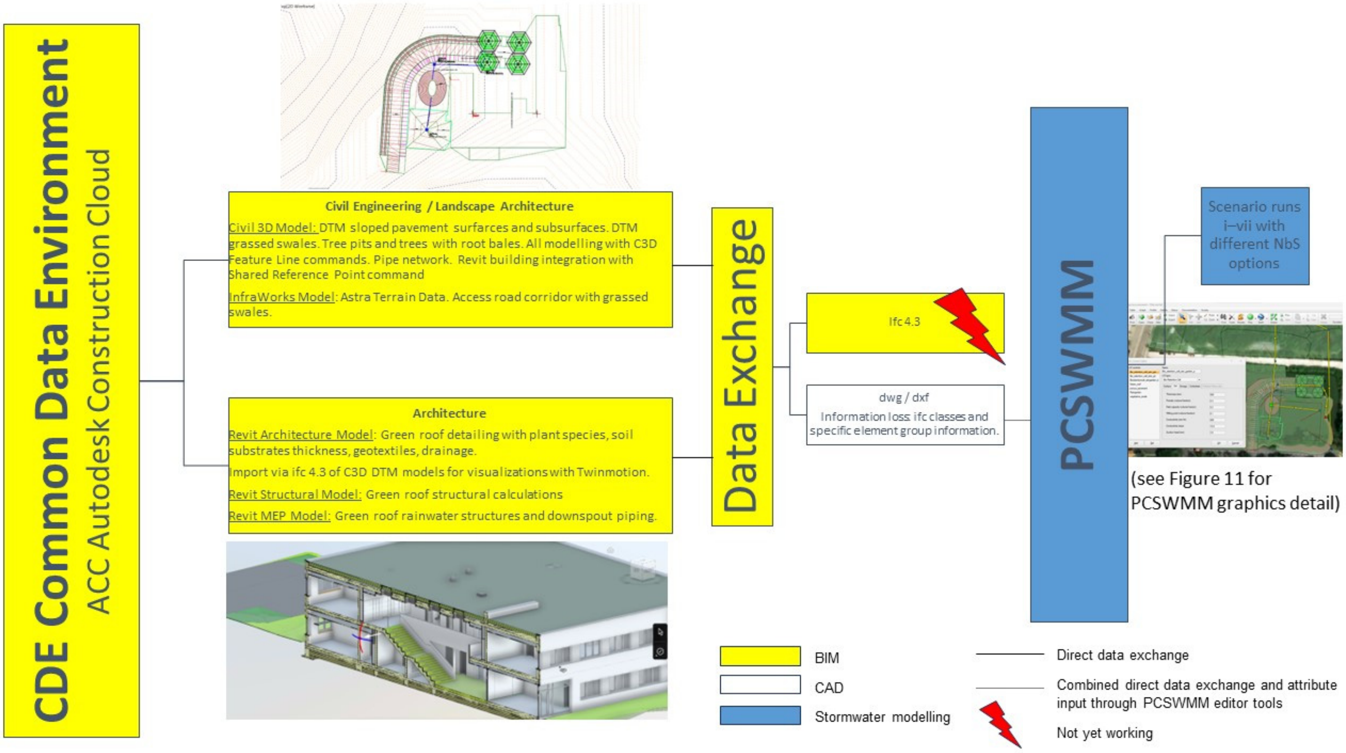


Figure 4. BIM/PCSWMM workflow. In this study, certain specific NbS attributes (e.g., hydraulic conductivity) from the BIM design were entered manually in the PCSWMM pulldown dialogue tools such as the LID editor.

2.6. Workflow for the BIM Model Integrating PCSWMM—Rationale for the Nature-Based Construction Solutions (NBCSs) Applied in the BIM

Nature-Based Construction solutions are construction techniques that try to reduce the impact on the environment. Sorvig and Thompson [137] give the following recommendations for sustainable landscape construction:

- Use vegetation wherever it is possible;
- Pave less or reduce existing pavement;
- Gutters and curbs should be permeable;
- Bioswales;
- Porous surface material;
- Unit pavers with wide joints on permeable subgrade (unbound construction method);
- Pavement with high reflection (albedo effect).

2.6.1. Pavement

Problem

In case of heavy traffic, a bound construction method has to be applied to pavement. These zones exist in almost every project (access for trucks, delivery zones, bus stops, etc.). In many countries, the same mistake can be observed: pavement areas are built with a mortar base on reinforced concrete slabs (bound construction). The water is not able to percolate through the concrete slab. In addition, the concrete foundation has no slopes. After a while, the water affects the mortar base and the pavement loses its stability. Niall Kirkwood states in the chapter on Issues of Detail Failure in *The Art of Landscape Detail* that water is one of the main causes for property damage [138]. Figure 5 was captured on a large construction site in Thailand (Pattaya beach boulevard renovation, January 2023) and illustrates bound construction where water will not drain and eventually will affect the mortar base.

(**a**) (**b**)

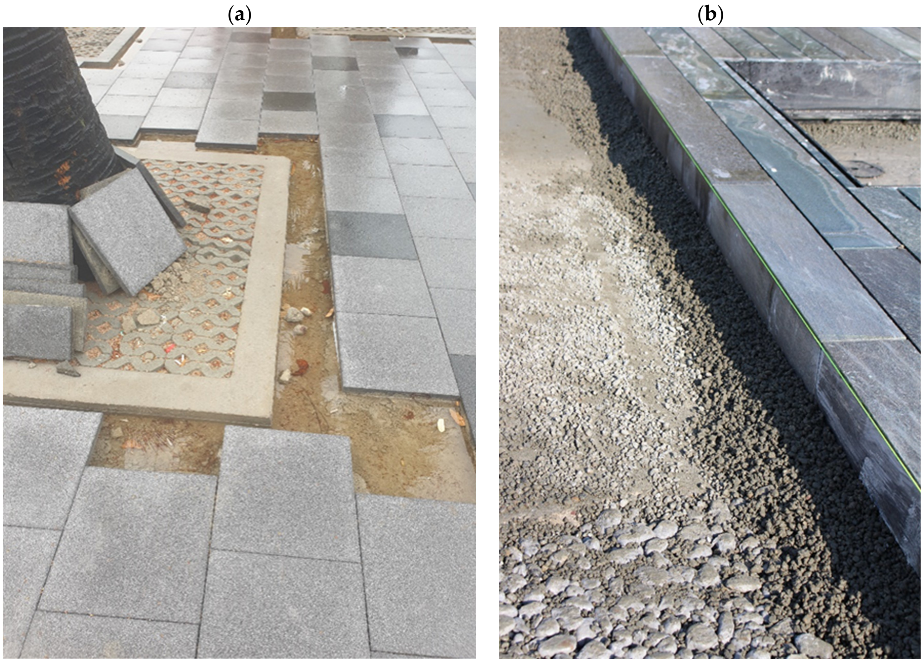


Figure 5. (**a**) Bound construction where pavement areas are placed directly on concrete slab and water will not drain, and (**b**) bound construction where pavement areas are placed on monograin concrete for drainage (photos by P. Petschek).

Nature-Based Construction Solution

Research shows that monograin concrete 4/8 mm (bedding) and porous concrete (foundation) on top of porous gravel or aggregate 0/45 is best for pavement areas with a bound construction method [139]. All water, which collects under the pavement because of humidity and temperature changes during the year, percolates. The construction method was successfully applied at Sechseläuten Platz in Zürich (2014) (Figure 6). With 16,000 m^2 of nature stone pavement, it is the largest square in Switzerland. The central area is used all year long for different events, with heavy truck traffic on it. The pavement functions well after almost 10 years and resilience is very high.

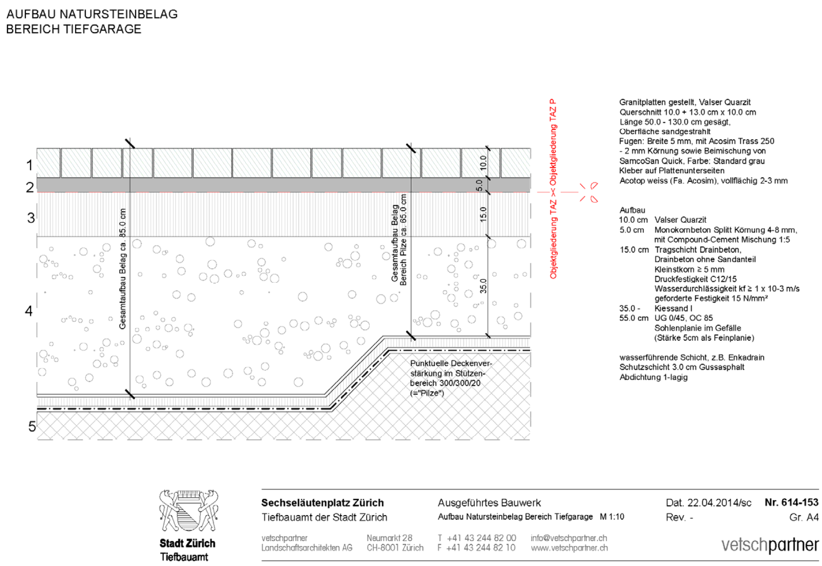


Figure 6. Pavement construction section of Sechseläutenplatz, Zürich by Vetschpartner AG. 1. Granite stone—0.1-meter thickness, 2. Monograin concrete 4/8 mm (bedding), 3. Porous concrete (foundation), 4. Porous gravel 0/45, 5. Parking garage concrete slab [140].

Based on the Construction Material Pyramid [141], which was developed by the Centre for Industrialized Architecture (CINARK) at the Royal Danish Academy and which shows the CO_2 footprint of construction materials, reused brick or reused concrete pavement from the area should be applied in the BIM Metro Forest school design.

Carbon-free concrete could be an option [142]. Unfortunately, it has not been tested yet for the outdoors (e-mail 6 February 2023 by Prof. Simone Stürwald, School of Civil Engineering, OST, Switzerland). In Thailand, Zaetang et al. [143] assessed the properties of pervious concretes containing recycled block aggregate and recycled concrete aggregate, showing that both could be successfully used. Vojinovic et al. [144] included pervious pavement as an option in their NbS modeling exercise for Ayutthaya, although pervious pavement implementation is not widely practiced in Thailand. Pervious interlocking pavers are commonly used for parking areas in Singapore [145].

2.6.2. Trees

Problem

Trees cast shadows and improve the local climate by evapotranspiration. They are the most important for thermal comfort improvements, especially in urban areas [146–149]. But trees need space to grow. As a rule of thumb, a one-square-meter projection of a tree to the ground needs 0.75 cubic meters of soil for the tree roots [150]. Very often in urban situations, especially in parking lots, there is not enough available space for tree pits. If trees are planted, the space is too small and this can impact tree health [151].

Nature-Based Construction Solution

The minimum size of a tree pit should be 6 m^2 [152]. Different cities in Europe are experimenting with expanding the space for tree roots underneath paved areas. Well known is the Stockholm tree pit system [153]. Structural soil with stones <150 mm and gravel 32/62 is combined with a mix of enriched biochar and compost. The City of Zürich optimized the Stockholm tree pit system and uses three layers of a soil substrate from fine to coarse for their tree pits (Figure 7).

Tree Substrate Layer A

Top soil layer for herbaceous plantings in the tree pit: The soil should not be compacted by car tires and it should be sloped for rainwater percolation:

- 45% Gravel 8/16;
- 5% Sand (broken sand or washed sand) 1/4;
- 30% Expanded Slate 8/16;
- 5% Enriched Biochar [154];
- 15% Silt Soil.

Tree Substrate Layer B

Soil layer underneath layer A in the tree pit: The soil should not be compacted by car tires and it should be sloped for rainwater percolation:

- 40% Gravel 16/32;
- 10% Gravel 8/16;
- 10% Sand 1/4 (broken sand/washed sand);
- 25% Expanded Slate 8/16;
- 5% Enriched Biochar [154];
- 10% Silt Soil.

Tree Substrate Layer C

Soil layer underneath layer B in the tree pit and underneath compacted pavement: Material is delivered mixed on the construction site, with 0.3 m layers installed and a maximum compaction of 80 MN:

- 30% Stone 64/125;
- 30% Gravel 32/64;
- 10% Sand 1/4 (broken sand/washed sand);
- 15% Expanded Slate 8/16;
- 10% Enriched Biochar [154];
- 5% Organic Compost (30% Biochar).

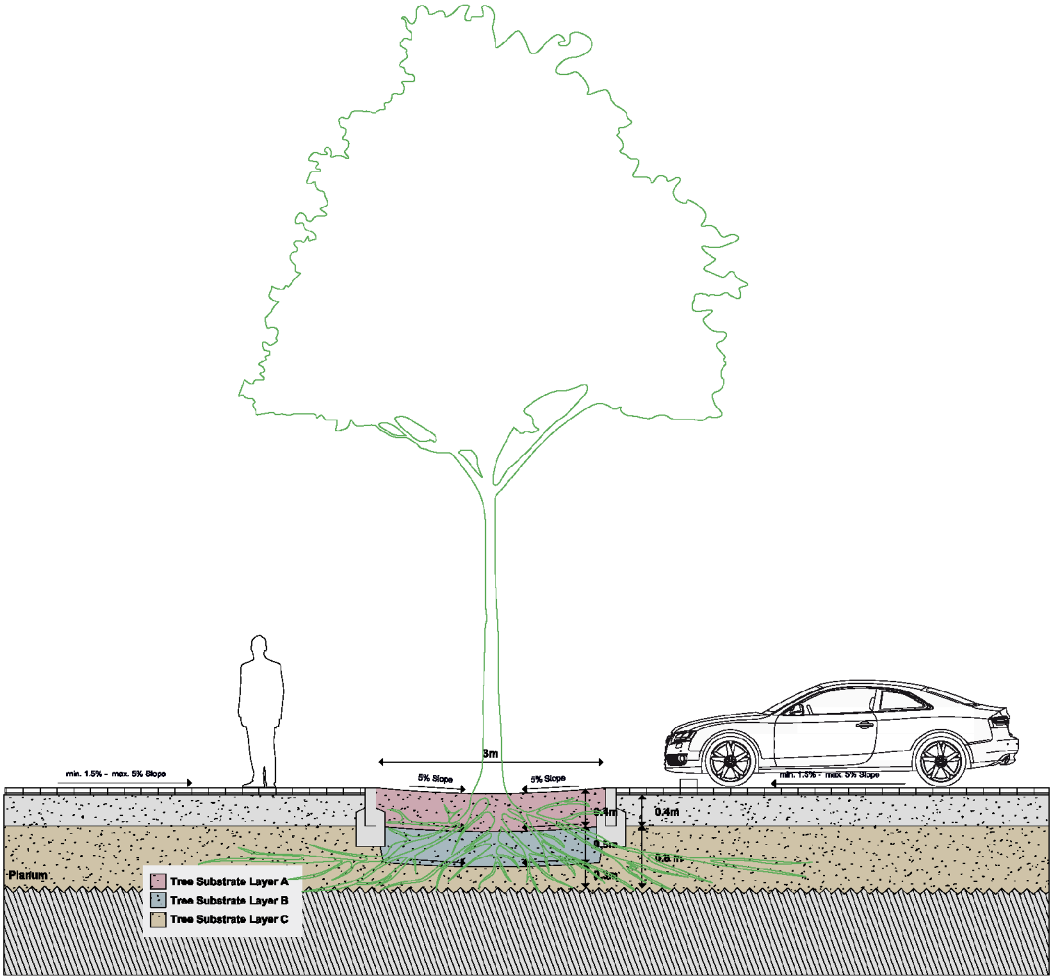


Figure 7. The sloped tree substrate system for tree pits in the city of Zürich, which provides more tree root space.

The Zürich tree pit systems serve as an orientation. Based on weather conditions, availability of material, etc., the BIM Metro Forest school tree pit system needs to be adapted, but for the purposes of this paper, the Zürich design characteristics were modeled.

The tree pits in parking lots also can be used to percolate the water. In Switzerland, the following rule applies for a first rough calculation: If the soil has sufficient permeability and absorption capacity and the ratio of the surface to be drained versus the surrounding ground that can be infiltrated is smaller or equal to 5, then the rainwater can be diverted to the surrounding ground. If the ratio is higher than 5 or the surface does not have sufficient permeability or absorption capacity, then experts must be consulted for more precise inspections [155]. For example, a tree pit on a parking lot with 15 square meters of soil, having sufficient capability for infiltration, divided by 75 square meters of asphalt has a ratio of 5. There is enough space for infiltration. Hence, after five parking spaces (one space: 5 m × 3 m = 15 m^2) with recycled pavement, a tree pit with a shadow-casting tree should be placed on the parking lot in the Metro Forest project.

2.6.3. Rain Gardens and Grassed Swales

Problem

Rain gardens and grassed swales have been implemented extensively in the global north and moderate climates [156–158], although there was early concern that the heavier rainfall in tropical areas may result in relatively poorer water retention and water quality treatment. The experience in Singapore has illustrated that the adaptation of rain garden and swale design, particularly with respect to storage area and substrate type, can successfully accommodate tropical climates [23,67,159–161].

Nature-Based Construction Solution

It is important to address the balance between effective water quality treatment (e.g., through substrate amendments and longer hydraulic residence time) and effective runoff quantity management (e.g., surface storage and substrate hydraulic conductivity that is sufficient to avoid rapid saturation and ponding) for rain garden design. Furthermore, connectivity of the design must be considered. Rain gardens either may have a soakaway design in which the runoff drains from the bioretention feature into the soil below or an underdrain that removes water from the bioretention feature into the drainage network (e.g., Figure 8). The soakaway design is less expensive to construct but is only viable if the subsoils have sufficient permeability to avoid saturated conditions. The rain garden in Figure 8 was constructed with two parallel underdrains leading to a cement discharge sump that connected to a larger surface drainage canal and subsequently a receiving reservoir. To accommodate larger events (>2 years), an overflow sump was constructed adjacent to the underdrain sump, which allowed ponded water (e.g., Figure 8d) to connect directly to the larger surface drain without infiltrating through the rain garden substrate layers. The overflow water would be temporarily stored, but water quality treatment would be limited because the runoff would not pass through the substrate layers. In this example, connectivity occurs between the rain garden, underdrain, larger surface drain, and receiving reservoir. NbS treatment trains, in which grassed swales may drain to a rain garden or a rain garden may connect to a retention pond, also represent forms of connectivity [67,162].

2.6.4. Green Roofs

Problem

Green roofs, also known as eco-roofs and living roofs, potentially can deliver a number of benefits, including urban heat island mitigation, insulation to reduce energy use, carbon sequestration, recreational and aesthetic services, food provisioning, and runoff quantity and quality management, air quality, and noise mitigation [163,164]. Green roof implementation has been practiced in Europe and North America for more than 30 years. Despite the sponge city initiatives, implementation has lagged in China [165], while Sangkakool et al. [166] noted that green roof implementation in Thailand also was fairly low, although there seems to be a growing interest based on the construction of several high-profile projects at Thammasat University, Chulalongkorn University, PTT Nong Fab LNG Receiving Terminal, and The Forestias Forest Pavilion, as well as in the condominium market [167]. Pratama et al. [168] concluded that in Southeast Asia, green roof development was best established in Singapore and Malaysia, while barriers to implementation included expertise, government regulations, and public awareness.

Nature-Based Construction Solution

Green roof construction cost is greater than conventional roof construction, particularly due to the additional load-bearing considerations for the building design. Green roof design can be categorized as intensive, semi-intensive, or extensive, depending on the substrate depth and plant type. Intensive green roofs have substrate layers in the range of >15–20 cm, sufficient to accommodate even small trees. Extensive green roofs have shallower substrate layers (<15 cm), which will limit root depth to mosses and grasses, but also incur lower construction cost [163,169,170]. Alternatively, the spatial extent of the green roof can be reduced through the use of discrete tree pits and planters that can be interspersed with walkways/accessways and traditional roofing, thereby reducing weight (Figure 9).

Figure 8. (**a**) Rain garden construction in Singapore showing geotextile and underdrain connecting to the discharge sump (left concrete sump) and overflow sump (right concrete sump), (**b**) vegetation coverage three weeks after planting, (**c**) vegetation coverage and infiltration measurements two months after planting, and (**d**) surface water storage storm event six weeks after planting (photos by K. Irvine).

(**a**) (**b**)

Figure 9. (**a**) Green roof with walkway and benches, Metro Forest education center (photo by A. Suwanarit) (see Figure 1), and (**b**) intensive green roof with walkways, Singapore (photo by A. Suwanarit).

3. Results and Discussion

3.1. BIM Scenario Designs and PCSWMM Configuration

The general PCSWMM schematic, connecting the BIM study area with the Metro Forest NbS site, is shown in Figure 10. The school and property design created in Civil 3D was imported into PCSWMM. The configurations of the different NbS features under the seven scenarios are summarized in Appendix A [139,171–179]. As can be seen in Appendix A, our focus is on addressing the Nature-Based Construction problems identified in the previous section through the PCSWMM model representation. The principal features are a green roof for the school; a retention pond (storage); a rain garden; a grassed swale; pervious pavement; and tree pits as bioretention cells. The parameter values to operationalize the NbS simulations were entered through the PCSWMM LID editor (Figure 11). The pond on the existing Metro Forest site was represented as a storage node in PCSWMM using a depth-area curve developed from the as-built bathymetric drawings provided by TKStudio, Bangkok. The subcatchment boundaries contributing runoff to the Metro Forest pond were defined based on the bund topography and grading information also from the as-built drawings provided by TKStudio.

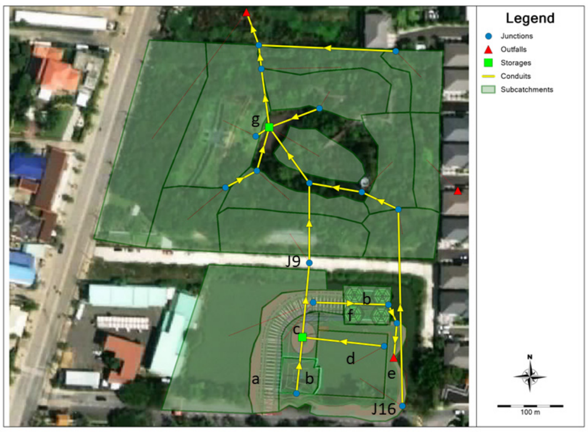


Figure 10. A schematic representation of NbS features and drainage in PCSWMM. For the BIM school site design, (a) is a driveway (either impervious or permeable pavement, depending on scenario); (b) are parking lots (either impervious or permeable pavement, depending on scenario); (c) retention pond; (d) school green roof; (e) grassed swale or rain garden, depending on scenario; (f) tree pit bioretention cells; and (g) Metro Forest pond. J9 and J16 are model points (junctions) at which hydrographs are evaluated.

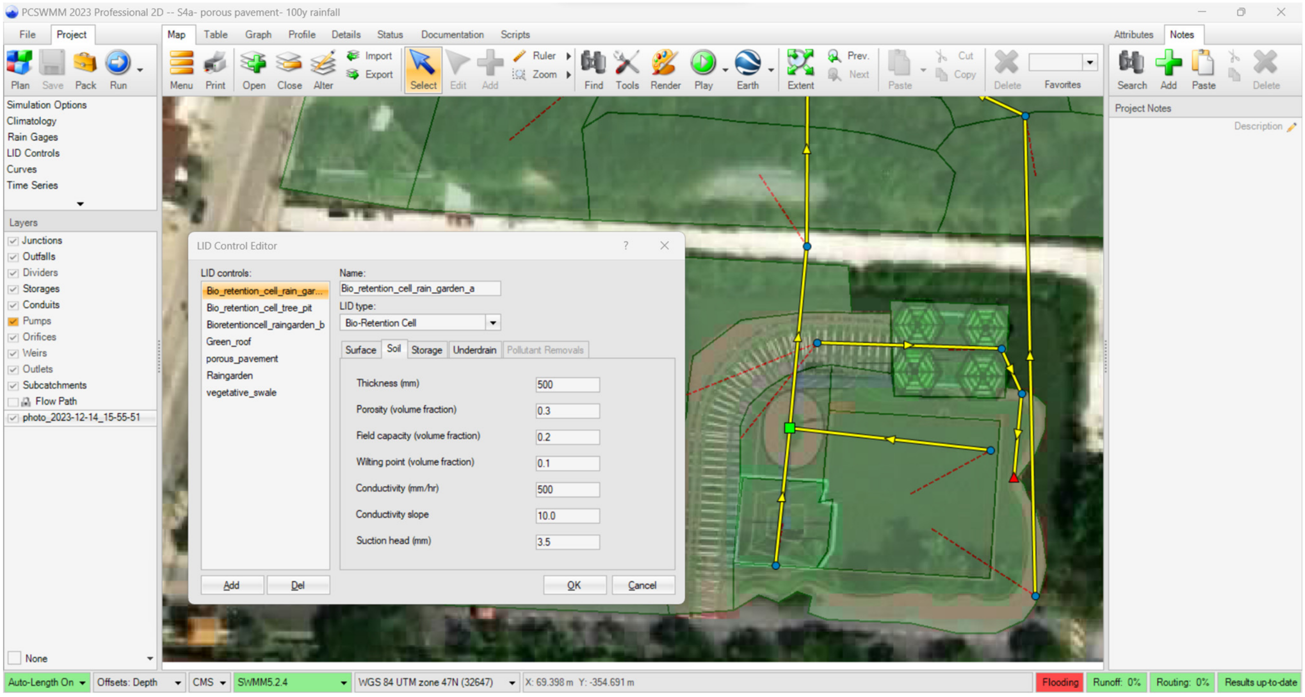


Figure 11. PCSWMM LID editor for NbS features associated with BIM school.

The intent of this research is to illustrate integrated design and modeling workflow as well as address design and Nature-Based Construction considerations for an example new-build NbS area. We also wanted to assess the potential for the existing NbS site, Metro Forest Park, to manage additional inflow from the new, small site, as an indicator of NbS ability to effectively accommodate new development. For simplicity, we did not model the existing pump and circulation operations within Metro Forest Park but this would not have a large impact on model outcomes. We also have assumed that the new-build BIM school for Scenarios iii–vii would connect to the Metro Forest Park via underdrains.

PCSWMM was run in 1D using 6-hour design storms based on IDF curves for central Thailand available from the Thai Meteorological Department, but modified according to an SCS Type II distribution with 6-minute time steps. The total depth and peak intensities for the modeled design storms were as follows: 2-year return interval—68.2 mm and 132 mm/h; 5-year return interval—93.7 mm and 182 mm/h; 100-year return interval—163.6 mm and 317 mm/h. Runoff was calculated at 5 min time steps, and to minimize the continuity error, hydraulic routing was performed at 5 s time steps using the dynamic wave approach that includes a momentum term.

3.2. Scenario Runoff Results—BIM School NbS

The runoff volumes and peak flows associated with the different scenarios are summarized in Table 1. We note here that Scenarios iii, iv, v, vi, and vii have two versions each. Not surprisingly, in general, as the return interval increases, the total volume and peak flow discharging from the BIM school increase. However, we also see some important differences between the scenarios. Under Scenario ii, the grassed swale does not allow infiltration to occur and is not fitted with an underdrain, connecting to the Metro Forest site. The flow discharging from the swale (at junction J16) would need to be directed off-site to a nearby small lake. Furthermore, compared to either the standard rain garden design or the rain garden design with reduced storage, the total flow volume generated for the swale is greater because in PCSWMM, swales are represented as conveyance features only, which may have channel storage, but do not allow infiltration storage.

Table 1. PCSWMM NbS BIM School Scenario Design Results.

Scenario Number and Description	PCSWMM Junction	Total Inflow (m^3) for Each Return Interval			Peak Flow (m^3/s) for Each Return Interval		
ii. Grass swale, 100% green roof, impervious pavement		2-year	5-year	100-year	2-year	5-year	100-year
	J9	137.4	219.4	438.3	0.04984	0.09116	0.1974
	J16	334.9	470.5	782.7	0.1316	0.1803	0.2718
iii. Rain garden with underdrain, impervious pavement, 100% green roof		2-year	5-year	100-year	2-year	5-year	100-year
(a) Standard rain garden design	J9	137.3	218.7	437.8	0.04971	0.09109	0.1974
	J16	0	0	0	0	0	0
(b) Rain garden design with reduced storage	J9	137.3	218.7	437.7	0.04971	0.09109	0.1974
	J16	16.07	46.47	131.9	0.02678	0.0772	0.1096
iv. Rain garden with underdrain, permeable pavement, 100% green roof		2-year	5-year	100-year	2-year	5-year	100-year
(a) Standard rain garden design	J9	107.9	193.6	408	0.04142	0.07532	0.1975
	J16	0	0	0	0	0	0
(b) Rain garden design with reduced storage	J9	107.9	193.6	408	0.04142	0.07532	0.1975
	J16	0	16.41	92.8	0	0.02735	0.07756
v. Rain garden with underdrain, permeable pavement, 100% green roof, and tree pit in parking lot		2-year	5-year	100-year	2-year	5-year	100-year
(a) Standard rain garden design	J9	107.9	193.6	408	0.04142	0.07532	0.1975
	J16	0	0	0	0	0	0
(b) Rain garden design with reduced storage	J9	107.9	193.6	408	0.04142	0.07532	0.1975
	J16	0	16.41	92.8	0	0.02735	0.07756

Table 1. *Cont.*

Scenario Number and Description	PCSWMM Junction	Total Inflow (m^3) for Each Return Interval			Peak Flow (m^3/s) for Each Return Interval		
vi. Rain garden with underdrain, permeable pavement, 30% green roof, and tree pit in parking lot		2-year	5-year	100-year	2-year	5-year	100-year
(a) Standard rain garden design	J9	137.4	212.1	428.2	0.04432	0.07979	0.1974
	J16	0	0	0	0	0	0
(b) Rain garden design with reduced storage	J9	137.4	212.1	428.2	0.04432	0.07979	0.1974
	J16	0	16.39	93.37	0	0.02731	0.07756
vii. Rain garden with underdrain, permeable pavement, reduced green roof soil depth, and tree pit in parking lot		2-year	5-year	100-year	2-year	5-year	100-year
(a) Standard rain garden design	J9	132.9	218.9	425.6	0.052	0.08996	0.1976
	J16	0	0	0	0	0	0
(b) Rain garden design with reduced storage	J9	132.9	218.9	425.6	0.052	0.08996	0.1976
	J16	0	16.84	93.34	0	0.02806	0.07758

Initially, the rain garden design in Scenario iii (i.e., Scenario iiia) was developed based on information from Bai [173] as well as author experience from Singapore (e.g., Figure 8) and James et al. [172]. Results showed that this design was capable of storing all runoff, up to the 100-year event. This is an example of the value in modeling the designed NbS system. In Scenario iiib, we were able to reduce the surface storage depth, as well as the depths of the substrate materials (Table 1), thereby providing a savings in construction costs without substantial reduction in performance.

Under Scenario iv, the impervious driveway areas and parking lots were replaced with permeable pavement that likely would be designed as some type of interlocking pavers [180]. Scenario iv was run with both the standard rain garden design (iva) and the reduced-storage rain garden design (ivb). The permeable pavement was effective in reducing the event volume discharging from the BIM school site, as compared to the impervious pavement from Scenario iii. For example, with the 2-year event, which is typically used for NbS design, no flow leaves the BIM school under Scenario ivb at junction J16, while 16.07 m^3 of water would leave under Scenario iiib, a 100% reduction. For the larger 100-year event, the discharge volume reduction from the BIM school site associated with the permeable pavement is 30%.

Tree pits (total of 4) were explicitly modeled as bioretention cells in the smaller, secondary parking lot, in addition to the permeable pavement, for Scenario v. The event volume results (at junction J16) for Scenario v were not different from Scenario iv, indicating that the tree pit design was sufficient for healthy growth of the trees (and associated ecosystem service benefits of shading for thermal comfort), but were not large enough to have an appreciable benefit for water storage.

Scenarios vi and vii examined different designs for the school green roof, but in all other design aspects were the same as Scenario v. A reduction in the green roof area to 30% coverage from the original 100% coverage (Scenario vib) resulted in a 27% increase in total volume discharging from the BIM school at junction J9. Given the size reduction in the green roof and attendant construction and maintenance cost savings, the increase in total volume of runoff may be acceptable. However, we emphasize that other ecosystem service benefits noted above also should be considered under this green roof reduction scenario. Scenario vii, the reduction in green roof substrate depth, had a similar result to Scenario vi, which provides some flexibility in considering the final green roof design.

As with volume, peak runoff increased with the return interval. The peak runoff for the grassed swale (junction J16) was noticeably greater at 0.1316 m^3/s (2-year return interval) than for the rain garden design (e.g., 0.02678 m^3/s for Scenario iiib). The reduction in green roof area or substrate depth (Scenarios vi and vii) also increased peak runoff at junction J9. In general, however, peak runoff was less impacted than volume for the different NbS scenarios, with peaks for the 2-year storm at junction J9 ranging between 0.02678 m^3/s and 0.052 m^3/s.

3.3. Potential Impact of BIM School Scenarios on Metro Forest Storage Pond

Under current conditions, without the BIM school property connected to the Metro Forest site, PCSWMM results indicated that the maximum Metro Forest pond depth would be 2.11 m, 2.167 m, and 2.234 m for the 2-year, 5-year, and 100-year storms, respectively. No flooding is expected to be generated at the pond for these design storms under current conditions. Water levels in the pond are expected to increase under the BIM school scenarios, but the greatest increase would be 0.05 m for Scenario iiib. Flooding at the pond is not expected for any of the modeled scenarios and in general, the total volume of flow from the BIM school property would have a relatively small impact on the Metro Forest site. These results indicate first that the NbS designs for the BIM school property were effective in managing runoff onsite, and second that the Metro Forest site design is robust enough to accommodate the additional flow. This latter result is particularly encouraging as it indicates that NbS designs can be developed to help manage additional runoff associated with urban build-out or climate change.

4. Conclusions

Integrating BIM and PCSWMM in NbS design offers an opportunity to enhance workflow and facilitate quicker assessment of competing design scenarios. Per the Autodesk [4] definition of BIM, here, we worked with a digital database for collaboration and reused information. In taking the integrated BIM/PCSWMM approach, it was shown that a combination of a rain garden, permeable pavement, a retention pond, and a green roof was effective in managing runoff from a theoretical new-build site discharging to an existing NbS site, Metro Forest. The modeling approach emphasized the connectivity of the individual NbS design features within an overall system structure and also indicated where the design might be optimized in the consideration of cost. For example, it was possible to reduce rain garden surface storage and substrate depths and green roof area or substrate depth with small changes to the volume of flow and peak discharge from the BIM school site. The BIM school NbS scenarios explored in this study were for illustrative purposes to examine the linkage of BIM and stormwater modeling and do not represent any existing plans to hydrologically link the Metro Forest site with the adjacent open property. However, this study did show that even with the 100-year rainfall event, the Metro Forest pond storage capacity would be sufficient so that flooding would not occur. This suggests that, in scaling up, prudent future NbS design in combination with green space and wetland preservation have important regional planning implications for flood management specifically related to Friend and Hutanuwatr's [129] observation that the BMA masterplan specifies the area north of the Suvarnabhumi Airport perimeter should be maintained as "open space to preserve natural drainage condition".

The importance of considering spatial and temporal scales for NbS design features goes beyond this case study and should be a standard component in BMA/BMR regional development planning. Indeed, spatial scale is a critical consideration in landscape design and planning moving along a continuum from site to neighborhood to city to region and even global [74,181–183]. As noted in the Introduction, different disciplines will tend to use different software packages in a BIM project, but BIM can provide superior productivity through the use of a common, central database that should be seamlessly accessible by the different models. Clearly, the centrality of GIS software should facilitate the geospatial scaling within a project. However, in their review of BIM applications, Nikologianni et al. [13] concluded that "... most efforts have looked into the impact of BIM at a micro scale (e.g., buildings and developments) with limited focus at the macro scale (e.g., landscape design and climate change)". Some of the barriers to BIM implementation for landscape planning and design were noted above in the Introduction and Methods (Section 2.3), but specifically with respect to spatial scaling, issues remain in the areas of data and attribute sharing and integration with respect to a seamless scaling up or down within a project [184–186]. Some of these barriers are being addressed by linking different software packages using custom scripting in Python, for example (e.g., [186]), but seamless spatial scaling issues within BIM primarily remain a research undertaking. Considerations of the temporal scale in landscape design and evolution probably are more challenging to address than geospatial scaling. Tree-shading and Universal Thermal Comfort Index simulations (including animation), representing short temporal scales, are available in BIM software such as Revit or Rhino 3D and Grasshopper. Shu et al. [187] recently proposed development of TIM (Tree Information Modeling) as a data exchange and model-sharing complement for BIM to help avoid grow-out clashes with structures and drainage. However, much work remains with respect to acquiring detailed vegetation growth characteristics, incorporating these data into a modeling package, and even resolving issues related to contractual arrangements specifying intellectual property rights, legal access, and liabilities for the tree data. Because PCSWMM sits on an open-source GIS platform, it is possible to spatially scale down or up within the same model, adding detail as needed. PCSWMM has been applied for water resource design and management at the site scale (e.g., [24,56,117]), city scale [23,56,68], and larger watershed scale [62,188,189]. Tansar et al. [190] noted at the site scale that NbS design parameters within PCSWMM could differ under different storm conditions and at the catchment scale, vegetation and substrate characteristics became important considerations in model output. Zhang and Veleo [191] also explored NbS model performance in PCSWMM across spatial and temporal scales, particularly emphasizing event-based versus continuous modeling. They concluded that for continuous modeling and under larger spatial scales, PCSWMM could be revised to better represent soil layer dynamics and vegetation cover. While challenges remain with respect to spatial and temporal scale issues in hydrologic/hydraulic modeling, the analytical techniques currently are more mature than the BIM software accommodation of spatial and temporal scales for landscape planning and design. Nonetheless, future work should consider a more seamless transfer of design detail input to PCSWMM through the BIM linkage, thereby further streamlining project workflow.

This study emphasizes the need for a multidisciplinary collaboration to effectively develop and assess NbS design. Certainly, the call for a multidisciplinary approach in design is not new [19,24] but the integration of digital approaches should facilitate this collaboration. The visualizations of the NbS designs also will assist with the better communication of NbS concepts to the general public.

Future work for the case study area will focus more specifically on the Metro Forest site through the implementation of a water quality and quantity sampling program to support PCSWMM application in a more holistic assessment of water management characteristics. The water quality and quantity assessment will be a component of a larger effort to identify and value the suite of ecosystem services provided by Metro Forest.

Author Contributions: P.P. conceived and was the lead in writing the manuscript. He also organized and refined the BIM school design and provided technical support for the BIM software. A.P.P.A. integrated the BIM and PCSWMM software and conducted all NbS scenario simulations in PCSWWM. A.S. co-conceived the manuscript, collaborated in writing and editing the manuscript, and provided detailed insights on green roof design. K.N.I. co-conceived the manuscript, collaborated in writing and editing the manuscript, and provided supervision on the PCSWMM modeling. All authors have read and agreed to the published version of the manuscript.

Funding: Partial funding for the project was provided by the Faculty of Architecture and Planning, Thammasat University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All PCSWMM simulation information and data are provided in the manuscript.

Acknowledgments: This paper is a contribution from the Nature-based Solutions for Water Management Research Unit, Faculty of Architecture and Planning, Thammasat University, Rangsit Campus, Pathum Thani, Thailand. We thank Khun Tawatchai Kobkaikit, founder and managing director, and his staff at TKStudio, as well as staff at PTT, in providing the site information for Metro Forest. We also thank Khun Tawatchai for reviewing an earlier version of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Parameter Values to Operationalize PCSWMM Simulations of NbS Features

Surface	Vegetated Swale	Reference	Notes
Berm height (mm)	200	[171]	
Vegetation volume (fraction)	0.1	[172]	
Surface roughness (Manning's n)	0.1	[172]	
Surface slope (%)	1	[172]	
Swale side slope (run/rise)	5	[172]	

Surface	**Rain garden Scenario a**	**Reference**	**Rain garden Scenario b**
Berm height (mm)	150	[173]	25
Vegetation volume (fraction)	0.1	[173]	0.1
Surface roughness (Manning's n)	0.12	[173]	0.12
Surface slope (%)	0.3	[173]	0.3
Soil layer			
Thickness (mm)	500	[173]	200
Porosity (volume fraction)	0.3	[173]	0.3
Field capacity (volume fraction)	0.2	[172]	0.2
Wilting point (volume fraction)	0.1	[172]	0.1
Conductivity (mm/h)	500	[173]	500
Conductivity slope	10	[172]	10
Suction head (mm)	3.5	[172]	3.5
Storage layer			
Thickness (mm)	250	[172]	100
Void ratio (voids/solids)	0.3	[172]	0.3
Seepage rate (mm/h)	400	[173]	400
Clogging factor	0	[172]	0
Underdrain			
Drain coefficient (mm/h)	0	[173]	0
Drain exponent	0.5	[173]	0.5
Drain offset height (mm)	6	[173]	6
Surface	**Green Roof**	**Reference**	**Parameters of reduced soil depth for Green Roof (Scenario vii)**
Berm height (mm)	50	[173]	25
Vegetation volume (fraction)	0.2	[173]	0.2
Surface roughness (Manning's n)	0.2	[174]	0.2
Surface slope (%)	2	[175]	2
Soil			
Thickness (mm)—extensive	110	[175]	55
Porosity (volume fraction)	0.5	[172]	0.5
Field capacity (volume fraction)	0.2	[172]	0.2
Wilting point (volume fraction)	0.1	[172]	0.1
Conductivity (mm/h)	0.5	[172]	0.5
Conductivity slope	10	[172]	10
Suction head (mm)	3.5	[172]	3.5
Drainage mat			
Thickness (mm)	60	[173]	30
Void fraction	0.43	[173]	0.5
Roughness (Manning's n)	0.03	[173]	0.1

Surface	Parameters of Permeable Pavement	Reference
Berm height (mm)	100	[139]
Vegetation volume (fraction)	0.1	[173]
Surface roughness (Manning's n)	0.12	[173]
Surface slope (%)	1	[173]
Pavement		
Thickness (mm)	150	[139]
Void ratio (voids/solids)	0.16	[176]
Impervious surface (fraction)	0	[176]
Permeability (mm/h)	254	[176]
Clogging factor	0	[176]
Regeneration interval (days)	0	[176]
Regeneration fraction	0	[176]
Soil		
Thickness (mm)	50	[139]
Porosity (volume fraction)	0.35	[177]
Field capacity (volume fraction)	0.2	[177]
Wilting point (volume fraction)	0.08	[177]
Conductivity (mm/hr)	445	[177]
Conductivity slope	10	[177]
Suction head (mm)	3.5	
Storage		
Thickness (mm)	520	[139]
Void ratio (voids/solids)	0.48	[177]
Seepage rate (mm/h)	600	
Clogging factor	0	
Underdrain		
Drain coefficient (mm/h)	1180	[177]
Drain exponent	0	
Drain offset height (mm)	6	[177]
Surface	**Parameters of Bioretention Cell Tree Pit**	**Reference**
Berm height (mm)	400	[178]
Vegetation volume (fraction)	0.1	[179]
Surface roughness (Manning's n)	0.3	[179]
Surface slope (%)	5	[179]
Soil		
Thickness (mm)—intensive	500	[178]
Porosity (volume fraction)	0.45	[179]

Field capacity (volume fraction)	0.121	[179]
Wilting point (volume fraction)	0.057	[179]
Conductivity (mm/h)	0.5	
Conductivity slope	44	[179]
Suction head (mm)	3.5	
Storage		
Thickness (mm)	300	[178]
Void ratio (voids/solids)	0.54	[179]
Seepage rate (mm/h)	2.6	[179]
Clogging factor	0	
Underdrain		
Drain coefficient (mm/h)	152	[179]
Drain exponent	0.5	
Drainage offset height (mm)	200	[179]

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