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Assessing Urban Resilience Through Physically Based Hydrodynamic Modeling Under Future Development and Climate Scenarios: A Case Study of Northern Rangsit Area, Thailand

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Abstract

Urban flooding represents a growing concern on a global scale, particularly in regions characterized by rapid urbanization and increased climate variability. This study concentrates on the Rangsit area in Pathum Thani Province, Thailand, an urbanizing peri-urban area north of Bangkok and within the Chao Phraya River Basin where transitions in land use and the intensification of rainfall induced by climate change are elevating flood risks. A physically based hydrodynamic model was developed utilizing PCSWMM to assess current and future flood scenarios that considered future build-out plans and climate change scenarios. The model underwent calibration and validation using a continuous modeling approach that conservatively focused on wet year conditions, based on available rainfall and water level data. In assessing future scenarios, we considered land use projections based on regional development plans and climate projections downscaled under RCP4.5 and RCP8.5 pathways. Results indicate that both urban expansion and intensifying rainfall are likely to increase flood magnitudes, durations, and impacted areas, although in this rapidly developing peri-urban area, land use change was the most important driver. The findings suggest that a physically based modeling approach could support a smart-control framework that could effectively inform evidence-based urban planning and infrastructure investments. These insights are of paramount importance for flood-prone regions in Thailand and Southeast Asia, where dynamic modeling tools must underpin governance, climate adaptation, and risk communication. Furthermore, given the greater impact of future build-out on flood risk, as compared to climate change, there is an opportunity to effectively and proactively improve flood resilience through the implementation of integrated Nature-based Solution and hard engineering approaches, in combination with effective flood management policy.

Keywords: hydrodynamic modeling; climate change adaptation; land use change; flood risk management; Thailand

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Academic Editors: Lidija Tadic, Enikő Anna Tamás and Melita Mihaljević

Received: 15 July 2025
Revised: 19 September 2025
Accepted: 22 September 2025
Published: 24 September 2025

Citation: Chitwatkulsiri, D.; Irvine, K.N.; Chua, L.H.C.; Teang, L.; Charoenpanuchart, R.; Likitswat, F.; Sahavacharin, A. Assessing Urban Resilience Through Physically Based Hydrodynamic Modeling Under Future Development and Climate Scenarios: A Case Study of Northern Rangsit Area, Thailand. *Climate* **2025**, *13*, 200. https://doi.org/10.3390/cli13100200

1. Introduction

Urban flooding presents a challenge for cities worldwide, particularly in the Global South where rapid land use changes, limited infrastructure, tropical climates, and climate change can exacerbate risks [1,2]. Southeast Asia, including Thailand, is currently experiencing increased flooding due to a confluence of increasing urban population, inadequate drainage systems, and intensifying rainfall attributable to climate change [3]. The Rangsit area, situated north of Bangkok in Pathum Thani Province, has transformed from a predominantly agricultural region into a mixed-use urban and industrial corridor over recent decades. This transition has led to the extensive replacement of pervious surfaces with impervious urban development, thereby disrupting natural hydrological pathways and increasing surface runoff [4,5]. As such, this study aims to utilize a physically based hydrodynamic modeling approach to evaluate the effects of climate change and urban development on runoff and flooding. It assesses these impacts under current, individual, and combined scenarios, while also identifying opportunities to enhance community resilience against such disruptive events.

Flood events in Thailand, exemplified by the catastrophic flood of 2011, have underscored the socio-economic vulnerability of urban areas, particularly those surrounding Bangkok. In such instances, infrastructure, livelihoods, and public health systems experience severe impacts [6–8]. This emphasizes the imperative to enhance flood risk management through a comprehensive understanding of both natural and anthropogenic drivers of flooding. Rangsit, with its dense canal networks and rapidly changing land use, is particularly susceptible to both fluvial and pluvial flooding. Notwithstanding the existence of certain structural flood control measures, such as manually operated gates and fixed pumping stations, their static operation and limited predictive capacity undermine their efficacy during extreme or compound weather events. For instance, during the 2011 flood and more recent storm events in 2021, delayed gate operations and uncoordinated pumping schedules contributed to prolonged inundation in areas like Rangsit Municipality and the Nava Nakorn Industrial Zone, highlighting the limitations of existing infrastructure under rapidly changing hydrological conditions [9–11]. Furthermore, we need to embrace the opportunity of proactively including Nature-based Solution approaches to water management, thereby avoiding mistakes and limitations of past development practice [12–15].

Projections regarding climate change further aggravate this dilemma. Research conducted by the Thai Meteorological Department and international agencies forecasts increased rainfall intensity and frequency under both moderate and extreme emissions scenarios (RCP4.5 and RCP8.5) [16–18], although, as discussed below, the dynamics of these changes are complex. When coupled with unregulated urban expansion, these climatic changes cultivate a high-risk environment that jeopardizes both economic activities and public safety [19,20].

As noted, this study aims to address the pressing need for assessing and managing urban flood risks through physically based hydrodynamic modeling. By integrating geographic information systems (GIS), historical flood records, and considerations of floodgate control strategies within a physically based hydrodynamic model framework that considers both land use and climate change, this research contributes to evidence-based and actionable planning for urban resilience that is urgently needed in peri-urban areas of the Global South. Numerous definitions of community resilience exist, although generally there are broad similarities between these definitions, with varying emphasis on the characteristics of the shock, framing the recovery, and the scale of assessment [21–23]. In this paper, we will adapt the UNDP definition of resilience: "an inherent as well as acquired condition achieved by managing risks over time at individual, household, community and societal levels in ways that minimize costs, build capacity to manage and sustain development momentum, and maximize transformative potential". We believe the UNDP's definition conveys the intent of our study and includes consideration of building back better. The PCSWMM platform specifically serves as a tool to simulate current and future flood conditions, evaluate infrastructure adaptation strategies, and inform long-term urban water management policies to address changing land use and climate adaptation objectives [24,25]. This approach is consistent with the need for flood management decision-making to provide a more inclusive resilience building process that addresses concerns for marginalized low-income urban communities as well as rural communities [20,26].

This study represents one element of a larger project on Real-Time Flood Modeling for Improved Community Resiliency in Southeast Asia that also incorporates community-based workshops to better understand local flood-related risk issues and enhance community resilience [27]. A first step in the study framework is the development and application of PCSWMM, as described herein. Our work fits well with the themes of this special issue on Modelling for the Influences of Climate and Landscape Processes on Hydrology, as we specifically address climate and landscape change impacts (separately and collectively) on the water budget by employing a landscape-based hydrological/hydraulic model and considering how mitigation measures, like possibilities of landscape rehabilitation and Nature-based Solutions, can enhance resilience.

2. Materials and Methods

2.1. Study Area Description

Rangsit is a peri-urban area located approximately 55 km north of Bangkok and lies within the lower Chao Phraya River Basin (Figure 1). The study area covers 77,881 hectares and is characterized by a complex hydrological network of canals and drainage channels that were originally constructed between 1869 and 1900 for agricultural irrigation purposes. These canals, which form a north–south grid approximately 2.5 km apart and bounded by main east–west canals, are referred to locally as "khlongs," and now function as irrigation and urban drainage infrastructure. The area's topography is predominantly flat, with elevations ranging from 0.5 to 2.0 m above mean sea level. This low-lying terrain makes Rangsit particularly susceptible to surface water accumulation during intense or prolonged rainfall events, especially in areas that lack engineered drainage systems.

The study area includes various land uses, such as residential zones, industrial parks, commercial developments, educational institutions, and agricultural land (Figure 1) [28]. Residential development varies from low-density gated communities (moo baan) to moderate-density, older traditional communities, to high-rise apartments, resulting in a mosaic of impervious surfaces. Due to extensive paved areas, industrial zones like the Nava Nakorn Industrial Estate and commercial districts along major roads may contribute relatively greater volumes of runoff. The region is affected by both fluvial and pluvial hydrological processes [29,30]. Water inflows from upstream provinces, such as Ayutthaya and Saraburi, are channeled through natural pathways and irrigation systems [31], while the area also experiences localized runoff from storm events. The region's drainage system is partially regulated by a series of pumping stations and manually operated floodgates managed by the Royal Irrigation Department (RID) [32]. Nevertheless, in practice, flood management faces challenges due to delayed responses, a lack of automation, and inadequate integration with predictive weather and hydrological data.

The proximity to major transportation corridors, such as Highway 305 and the Bangkok–Chiang Mai railway, has stimulated significant urban growth in recent years. Urbanization also has encroached upon natural flood detention areas, diminishing the system's flood buffering capacity [33]. With ongoing development pressures, Rangsit serves as a critical testbed for evaluating urban flood management strategies in peri-urban Southeast Asia [34].

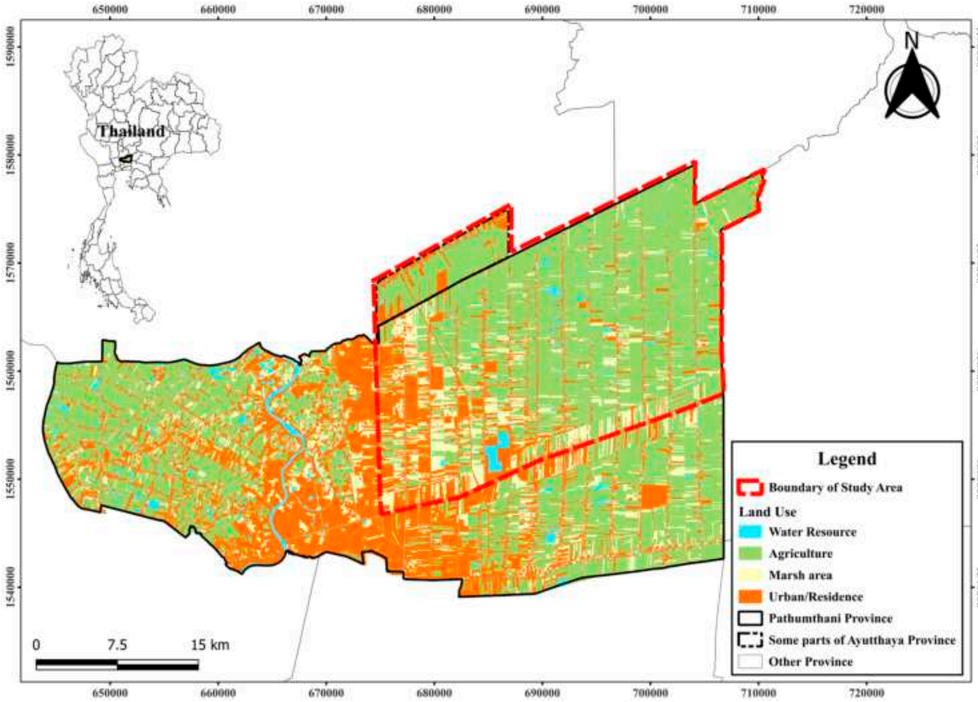

Figure 1. Pathum Thani province in Thailand and Rangsit study area in Pathum Thani province.

2.2. Hydrological and Hydraulic Model Setup

In order to evaluate flood dynamics and assess urban resilience across various future development and climate scenarios, a physically based hydrological and hydraulic model was developed utilizing the PCSWMM platform. PCSWMM has been used extensively for urban and mixed land use runoff modeling throughout the world, including Southeast Asia [35–46]. The authors used PCSWMM in this study for several reasons. First, it seamlessly represents the hydrology of both rural and urban land uses, as occurs in the study area, but also accommodates the hydraulics of subsurface piped drainage systems as well as natural and open channels with irregular cross-sectional bathymetry. As such, it is not necessary to link different models to represent the mixed land use of the study area. The team has experience with PCSWMM in mixed land use watersheds, as well as urban and peri-urban areas of Thailand [35,47–51]. PCSWMM can explicitly represent more complicated hydraulic conditions such as pumps and dynamic gate operation rules [37], as well as green infrastructure features such as wetlands, raingardens, swales, pervious pavement, and greenroofs and other green space [50,52], consistent with our goal of developing a modeling tool that could be used to explore Nature-based Solutions to enhance community resilience.

The modeling framework incorporates detailed spatial data, hydraulic infrastructure layouts, and calibrated rainfall–runoff relationships throughout the Rangsit study area. PCSWMM's watershed delineation tool was employed to initially define the boundaries of 1094 subcatchments using a 30 m resolution Digital Elevation Model (DEM) sourced from the Royal Thai Survey Department. This delineation was subsequently refined through site investigation and visualization with Google Earth Imagery in ArcGIS. The delineated subcatchments range in size from approximately 5 to 60 hectares, contingent upon topography and land use heterogeneity. Drainage pathways were accurately mapped to reflect the actual routing of stormwater across urban and peri-urban surfaces (Figure 2). For clarity of interpretation, a simplified schematic of the drainage network is provided in Figure 3.

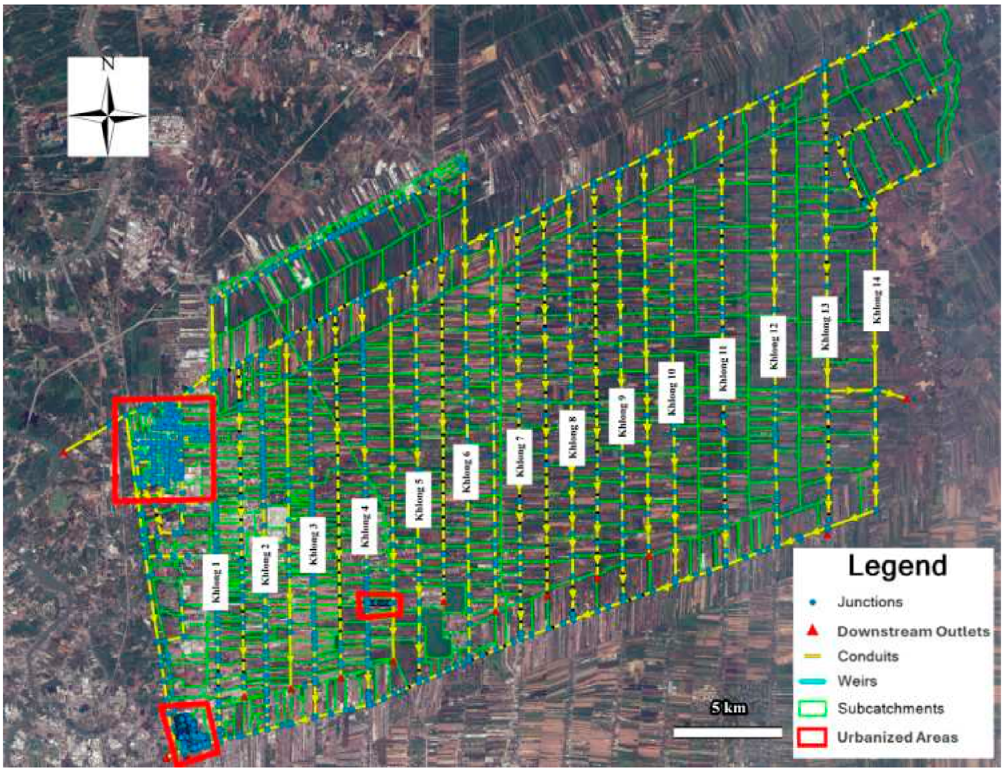

Figure 2. Drainage network for PCSWMM simulation. Flow direction in the conduits (khlongs) is denoted with yellow arrows. Weirs are located at the head of each khlong but also can be noted as the khlong gates in Figure 3. Urbanized areas highlighted by red borders are Nava Nakorn industrial estate (northern polygon), Ratanakosin Village, Rangsit (southern polygon), and moo baan (eastern polygon).

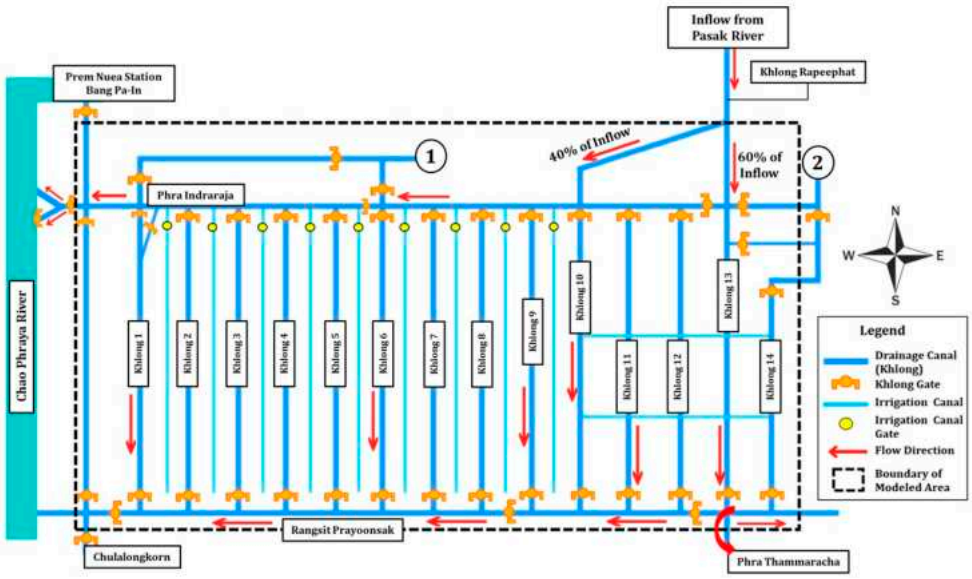

Figure 3. Schematic of the drainage network for the study area. The inflows from upstream Pasak River are theoretical targets from RID. The boundary of the modeled area is shown by the black dashed line. Channel inflow at point ❶ originates in a small agricultural area near Khlong 26 and is not routinely monitored due to the small volume. This flow would have minimal impact on Khlong 1 and was not represented in the model. Channel inflow at point ❷ is derived from upstream but would flow to the east and have no impact on the study area to the west.

The hydraulic model encompasses 1557 canal segments corresponding to the region's primary and secondary khlongs (canals) (Figure 2). These segments are characterized by

41 surveyed cross-sections representing at least one for each khlong and their hydraulic properties including channel width, slope, and Manning's roughness coefficient have been assigned based on field data obtained from the Royal Irrigation Department (RID). The model also includes 47 hydraulic structures (e.g., weirs, sluice gates), 13 downstream outlets, and 2 active pumping stations. All hydraulic links and nodes were georeferenced and digitized using QGIS and the built-in interface of PCSWMM. Land use maps from 2019, derived from Sentinel-2 imagery and validated through ground-truthing, were utilized to assign surface characteristics such as imperviousness. Residential and commercial zones exhibited imperviousness levels ranging from 60 to 95%, whereas the agricultural areas displayed values below 20%. Infiltration was modeled using the Horton method, with infiltration parameters selected to represent the marine clay soils of the floodplain study area. More specifically, data regarding soil type and texture were extracted from the Land Development Department (LDD) soil database, which includes the necessary hydrological soil group classification for infiltration modeling. In general, the runoff from the subcatchment areas is drained directly into the adjacent khlong, but we also represented three urbanized areas in more detail, including their subsurface pipe network and pump operations. These sites were selected as case studies to investigate urban flooding in more detail, specifically the broad runoff and flooding trends expected for each type of development. The three sites include a new single family residential estate (moo baan) on Khlong 4, a mixed, mature, industrial/residential estate (Nava Nakorn), and the older, established community of Ratanakosin Village, Rangsit (Figure 4). Each of these detailed study areas had been modeled using PCSWMM under earlier studies [47–49].

Figure 4. Drainage system components visualized in PCSWMM for selected urbanized areas, moo baan (**left**); Nava Nakorn industrial estate (**middle**); and Ratanakosin Village, Rangsit (**right**). Pump locations are circled in orange for clarity.

An important consideration in this mixed land use watershed was the surface storage in rice paddy fields. We set this storage to 450 mm, based on field observations, land use mapping, and a study by [34] for an adjacent area (Figure 5).

Figure 5. Land use map highlighting paddy fields and surface storage assumptions in the study area (**left**) and example paddy field storage (**right**).

Hydraulic routing was performed using the dynamic wave approach. This methodology allows the model to capture essential hydraulic interactions, including the propagation of surges through canal segments, water ponding in low-lying areas, and flow reversals due to downstream obstructions [52]. Catchment runoff and drainage simulations were structured into three principal modules: (1) rainfall–runoff transformation, (2) hydraulic conveyance, and (3) storage and outflow regulation. This structure enables the model to simulate both rapid-onset (pluvial) and compound (fluvial–pluvial) flooding scenarios.

Boundary conditions were defined by the inflow from upstream river systems, which include contributions from the Pasak River and adjacent catchments. Meetings with the Royal Irrigation and Drainage Department (RID) indicated that their target rainy season inflow conditions of 140 m^3/s from the Pasak River should be used to define the upstream boundary conditions, and this target was used in the preliminary model runs. However, this approach provided an unsatisfactory fit to the observed flow data for the individual khlongs. After further discussions with RID, we obtained observed inflow values to the study area for the Pasak River, and observed values can be quite different from the target inflow conditions of 140 m^3/s, as shown in Figure 6. The 2022 peak inflow rates from the Pasak River, for example, were more than four times greater than the target value. The 2022 peak inflow rate was also greater than that observed for the historic 2011 Chao Phraya flood.

2.3. Data Sources and Processing

The quality, resolution, and temporal coverage of the input data significantly influence the performance of a model. This study incorporated diverse datasets collected from government agencies, field surveys, and satellite imagery.

Topographic Data: A Digital Elevation Model (DEM) with a resolution of 30 m was acquired from the Royal Thai Survey Department. The DEM underwent preprocessing utilizing hydrological conditioning techniques, such as sink filling, depression breaching, and stream burning, to precisely delineate watershed boundaries and flow paths using the PCSWMM watershed delineation tool. Moreover, supplementary vertical control points and canal bathymetric cross-sections were incorporated from field surveys conducted between 2021 and 2022 to improve elevation accuracy in low-lying and canalized regions.

Land Use and Land Cover (LULC): Land use data were derived from Sentinel-2 satellite imagery with 10 m resolution and processed using supervised classification techniques. The classification schema included built-up areas, roads, agricultural fields, water bodies, and vegetation [53]. Ground truthing was performed in coordination with local authorities and community mapping initiatives. For future land use scenarios (to 2035), projections from the National Urban Development Plan and local government zoning documents were digitized and spatially reclassified to match model parameter categories [54].

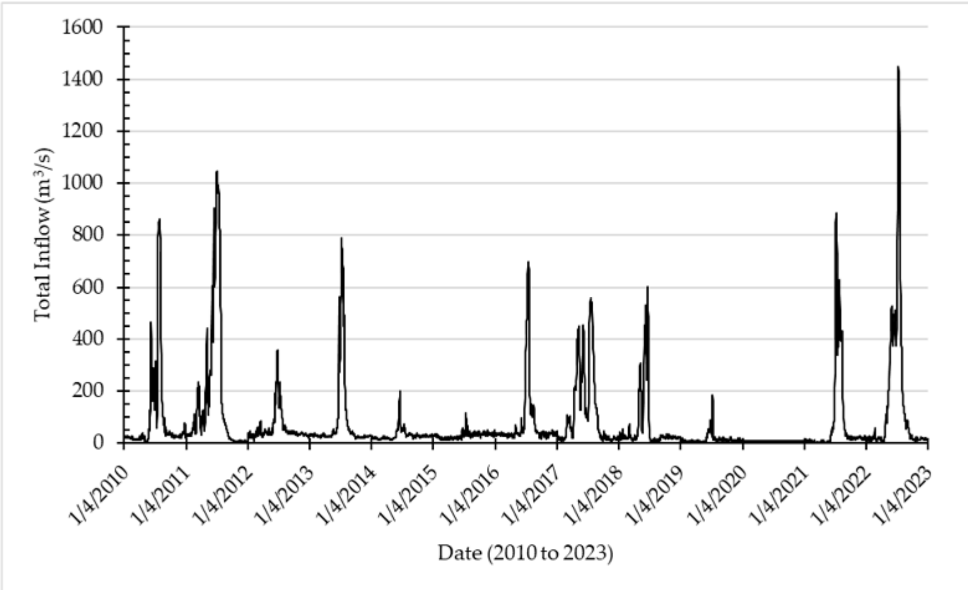

Figure 6. Daily inflow at the upstream boundary to the study area from the Pasak Jolasid Dam and river (2010–2023).

Rainfall and Climate Data: 3 h and daily rainfall data for the Pathum Thani gauge, 2005 to 2022, were obtained from the Thai Meteorological Department (TMD). This period included the benchmarking 2011 Chao Phraya flood event noted above. The climate change scenarios were derived from dynamically downscaled outputs of the CMIP6 General Circulation Models (GCMs) under Representative Concentration Pathways (RCP) 4.5 and 8.5, utilizing data from the CORDEX Southeast Asia domain [55]. Specifically, we used the ACCESS-ESM1-5 model and the IPSL-CM6A-LR model for the rainfall projections. In their assessment of GCM projection performance for monthly mean rainfall, Iqbal et al. [56] found these models to be in the top 5 of 35 CMIP6 models examined for accuracy. Representative Concentration Pathways (RCPs) 4.5 and 8.5 were selected for the climate change scenario assessments as they represent intermediate and worst-case conditions, with a stabilized and maximum radiative forcing. These RCP scenarios were also selected to be consistent with the project partner efforts in Malaysia.

PCSWMM was run in continuous mode using the 3 h rainfall data to provide an initial assessment for current conditions and the build-out scenario at a finer temporal resolution. Subsequently, the model was run at daily time steps for the current conditions, build-out, and climate change scenarios to ensure appropriate temporal comparison, particularly with respect to peak rainfall intensity.

Hydrological and Hydraulic Infrastructure: Data pertaining to canal cross-sections, gate dimensions, pumping station capacities, and drainage pipe networks were obtained from the Royal Irrigation Department (RID), the Pathum Thani Provincial Administrative Organization, Nava Nakorn industrial estate, and field observation (in the case of the moo baan). These data underwent digitization, georeferencing, and were subjected to a thorough cleaning process for topological consistency. Gate operations were initially guided through meetings with RID in which target benchmarks of normal water level, alarm level, and flood level were noted for different parts of the system in consideration of seasonal system inflows and outflows.

Streamflow and Water Level Data: Historical streamflow records for the period 2008 to 2023 were obtained from the RID's telemetry network, which encompasses key flow gauging stations both upstream and downstream of the study area. Hourly water level data (referenced to mean sea level datum) from each khlong and flood-prone intersections were utilized for model calibration and validation.

Geospatial Processing: All spatial datasets were projected to UTM Zone 47N (WGS 84 datum). Preprocessing was conducted using ArcGIS Pro and QGIS. Catchment boundaries, flow directions, impervious surface maps, and slope grids have been created and cross-validated utilizing PCSWMM's GIS toolbox. Attribute consistency and topological correctness have been confirmed through spatial joins, buffering, and topology checks [57,58].

This integrated dataset provided the foundation for developing, calibrating, and validating a high-resolution mixed land use flood model capable of simulating various development and climate change scenarios. Data integration ensured both spatial fidelity and hydrological realism across multiple scales of analysis.

2.4. Model Calibration and Validation

Calibration and validation constitute vital processes for guaranteeing the accuracy and reliability of hydrodynamic models, particularly in intricate and rapidly urbanizing regions such as Rangsit. This study employed a combination of statistical metrics, visual comparisons, and expert judgment to evaluate model performance through the analysis of observed hydrometeorological data across multiple time periods [59].

The PCSWMM model was calibrated for the period 10 October 2021 to 10 October 2022, which represents parts of two wet seasons and an intervening dry season. Bangkok experienced some of the heaviest rainfall in 20 years during August 2022 [60] and upstream Ayutthaya also experienced heavy flooding. By selecting this period of record, we conservatively focus on a potentially more damaging wet period. Indeed, Figure 6 shows that peak flow entering the study area in 2022 was at least 400 m^3/s greater than peak flow for the benchmark 2011 flood. Model validation was performed for the period October 2016 to October 2017. To assess model goodness-of-fit, we used the Nash Sutcliffe Efficiency (NSE) statistic, the Integral Square Error (ISE), and the Pearson Product–Moment Correlation Coefficient (r).

The calibration process emphasized critical hydrological parameters, encompassing infiltration rates (Horton model parameters), surface roughness (Manning's n), depression storage depths, and the percentage of impervious surfaces [61]. Initial estimates for the parameters were informed by PCSWMM modeling previously conducted in the study area and the region [34,48,49,62]. Hydraulic calibration entailed the adjustment of conduit and node parameters, gate opening levels, and channel connectivity. The gate operations, in particular, were challenging to represent, as there are gates at the head and outlet of each of the north–south-running khlongs, as well as on the main east–west khlongs (Figure 3), and based on assessment of the historical water level records, as well as daily field observation of Khlong 4, gates are adjusted through RID interventions from the standard plan, considering incoming flow at the upstream boundary, as well as rainfall forecasts (whereby levels may be lowered in anticipation of a future large event). As such, the timing and extent of gate openings was adjusted through PCSWMM Control Curve scripting as part of the calibration process.

2.5. Scenario Development

In order to evaluate the effects of prospective land use and climate change on urban flood dynamics in Rangsit, four distinct simulation scenarios were formulated. These scenarios are intended to illustrate realistic developmental trajectories, progressing climatic conditions, and strategies for infrastructure adaptation. The objective is to ascertain how urban resilience can be augmented through anticipatory planning and flood mitigation technologies [63,64].

2.5.1. Scenario 1: Baseline Condition (2022)

This scenario delineates the existing condition of land use, infrastructure, and climate. It incorporates land use maps from 2019 to 2022, updated canal geometry, and hydrological parameters that were calibrated based on the period 10 October 2021 to 10 October 2022. The baseline scenario functions as the benchmark for comparison with prospective changes.

2.5.2. Scenario 2: Future Land Use Change (2035)

There is a clear trend towards urban build-out in the study area. To assess the potential impact of this trend on future runoff and flood risk, a plausible build-out scenario was developed based on current planning documents, demographic projections, and previous research [4,5,65]. Runoff and flooding for this build-out scenario is compared to the runoff and flooding results for current conditions. Classification of current land use was guided by Figure 1 and visual interpretation of Google Earth imagery. For the 2015–2020 period, zoning for the study area is primarily residential, indicating anticipation by the regional planning board for continued build-out. The population data for the Khlong Luang district indicates that it has been increasing at a rate of between 1.15 and 1.95% year on year between 2017 and 2021 [66]. These data represent the registered population for Pathum Thani. However, some housing demand also can be attributed to individuals whose official identification is from other provinces but who choose to purchase homes in the BMR due to employment opportunities. This segment of the population is not captured in the official growth statistics. Kamal et al. [4] and Khamchiangta and Dhakal [5] to the period 2016 are generally consistent and represent about a 45% loss of green space from the early 1990s, while Likitswat and Sahavacharin [65] indicated green space loss for the study area might be around 59%. Based on these development trends, we estimate that build-out would represent a maximum of 65% of the area over a 10-year planning horizon. It seems likely that most development would continue to focus along Khlong Luang and Nakon Nayok Roads, with more infilling particularly on Khlongs 3 and 4, as well as some gap areas on Khlongs 1 and 2. Furthermore, construction of an additional ring road is planned and would cross-sect an area in Khlongs 8–10 (https://www.thailandplus.tv/archives/751227, accessed on 24 December 2024). We have noted that land preparation for future development is evident particularly in Khlongs 8–10, and these localized development patches were also included in our infilling scenario. To operationalize the infill scenario, we increased per cent imperviousness in these build-out areas to 70%, which accounts for the current 30% pervious land guidance for residential development permits. We expect much of the development will be townhouse and single residence moo baan designs. It is recognized that more sophisticated techniques are now being employed to project urban development, particularly the combination of GIS and AI modeling [67,68], but it was beyond the scope of this project to implement such approaches. Instead, we have used a more brute force approach that reflects past land use studies, Pathum Thani population demographics, and our own field observations in development trends over the past five years.

2.5.3. Scenario 3: Climate Change (RCP4.5 and RCP8.5)

To isolate the effects of climate variability, synthetic rainfall inputs were generated for mid-century and end-of-century conditions based on Representative Concentration Pathways (RCPs) 4.5 and 8.5. These inputs were derived from dynamically downscaled projections under the CORDEX Southeast Asia domain utilizing regional climate models (RCMs) [69]. RCP4.5 is an intermediate climate change scenario that represents a stabilization in radiative forcing at 4.5 W/m^2 post-2100 in which CO2 emissions would decline from 2045 [70] to reach approximately half of the levels of 2050 by 2100. Under this scenario, temperature would increase globally by 1.8 °C (range 1.1–2.6 °C). RCP8.5 is considered a worst-case climate change scenario with an increase in radiative forcing to 8.5 W/m^2 by 2100, under which technological change and energy intensity improvements are minimal, resulting in high energy demand and GHG emissions [71]. Globally, the temperature is projected to increase by 3.7 °C (range 2.6–4.8 °C) under this scenario.

The mean annual rainfall in Pathum Thani province for the period 1976–2005 was 1301 mm. It was reported [72] that for the period 1955–2014, TMD gauge stations in central Thailand (including Pathum Thani) exhibited significant decreasing trends in annual total precipitation, while the annual number of days when precipitation was ≥20 mm (an indicator of rainfall intensity) was greater in some areas of the Central Plain and less in others. Maichandee et al. [73] noted that average rainfall intensity on a rainy day for Pathum Thani should decrease in the range of 1% for the period 2020–2029. Tangang et al. [74] concluded that the central area of Thailand may become wetter by as much as 12% compared to recent historical periods by mid-century, but may be drier by the end of the century under RCP4.5 and RCP8.5. De Oliveira-Junior et al. [17] found that the maximum number of dry days would increase with both climate change scenarios, while consecutive wet days and maximum number of consecutive wet days would increase by 2.5% and 0.92%, respectively. Finally, Thanvisitthpon et al. [75] examined the R20 (number of days when precipitation ≥ 20 mm) and R10 (number of days when precipitation ≥ 10 mm) trends for RCP4.5 and RCP8.5 between 2022 and 2099, indicating that R20 would decrease under both climate change scenarios while trends in R10 were inconclusive; consecutive wet days were expected to increase. In general, the literature suggests we may expect a greater average annual rainfall in Pathum Thani under climate change scenarios, while the extent of increasingly intense rainfall is more uncertain.

2.5.4. Scenario 4: Combined Land Use and Climate Change

This integrative scenario examines the combined effects of urbanization in 2035 and projected rainfall patterns under RCP4.5 and RCP8.5. The general workflow for the study is summarized in Figure 7, including the consideration of the land use and climate change scenarios.

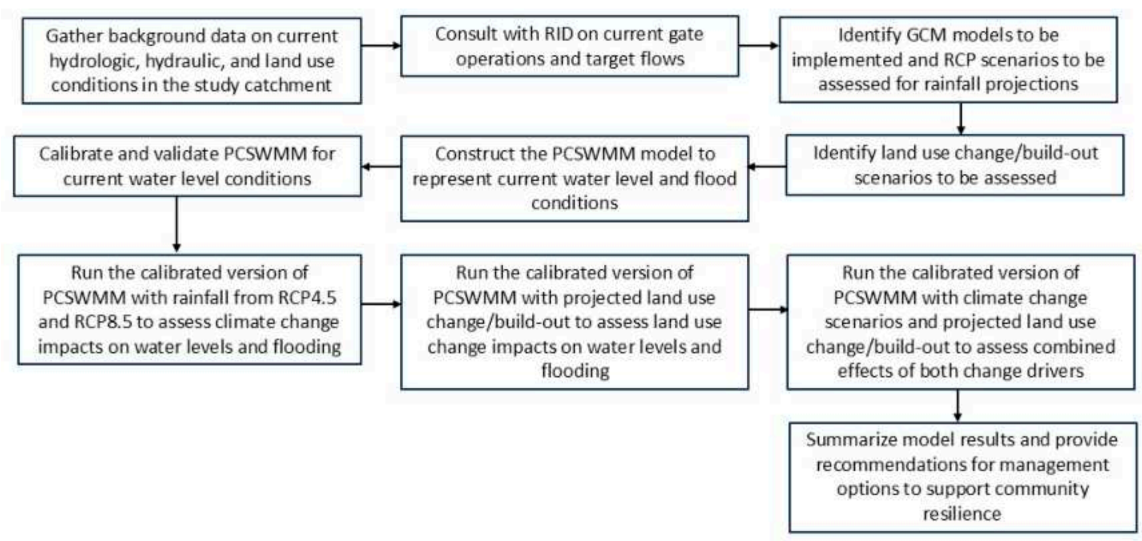

Figure 7. Workflow for the study.

3. Results

3.1. Calibration and Validation Results

The calibration results for 10 October 2021 to 10 October 2022 are presented in Figure 8 and the goodness-of-fit statistics are summarized in Table 1. The calibration results indicate that PCSWMM is able to accurately reflect the dynamics of the water levels within the system. Shamsi and Koran [76] suggested that NSE values in the range 0.5–1.0 represent excellent calibration results whereby the model could be used with confidence for planning, preliminary designs, and final designs. Furthermore, NSE values of 0.4 to 0.49 were considered very good and could be used for planning, preliminary design, and final design; NSE values of 0.3 to 0.39 were considered good and could be used for planning and preliminary design; while values of 0.2 to 0.29 are fair and should be used for planning only [76]. Shamsi and Koran [76] also suggested that ISE classifications of model calibration in the Very Good (ISE values of 3.1–6) and Excellent (ISE values of 0–3) categories could be used for planning, preliminary designs, and final designs. The NSE value for Khlong 3 is lower than we might like, although the r and ISE values are reasonable. The modeled results for Khlongs 2, 3, and 4 may represent a more rapid response during storm events due to the representation of the urbanization in the area, while late October 2022 low water levels are slightly underestimated. Given the overall complexity of the system hydraulics, however, the model provides us with reasonable certainty that it can capture system dynamics (Table 1, Figure 8).

Table 1. Goodness-of-fit statistics for PCSWMM calibration from 10 Oct 2021 to 10 Oct 2022.

	K2	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**
ISE rating	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
ISE	1.03	1.29	0.867	0.776	0.937	0.783	0.93	0.986
NSE	0.538	0.292	0.695	0.77	0.682	0.792	0.726	0.706
r	0.795	0.836	0.878	0.944	0.926	0.896	0.86	0.871

The ranges of subcatchment parameter values for the calibrated model are presented in Table 2. As noted above, initial selection of parameter values in Table 2 were guided by PCSWMM modeling previously conducted in the study area and the region [35,48,50,62]. Irvine et al. [62] reported that for subcatchments in Singapore, PCSWMM estimates of peak flow were most sensitive to percent imperviousness, width of overland flow, Manning's n for impervious surfaces, and slope, while estimates of event volume were most sensitive to the Horton infiltration parameters and width of overland flow. Width of overland flow is defined as subcatchment area/length of overland flow and reflects both subcatchment shape (e.g., longitudinal vs. circular) and time of concentration, where a more longitudinal subcatchment geometry will have a greater time of concentration. While the theoretical basis for width of overland flow is strongly grounded in the subcatchment physical characteristics, it is more difficult to precisely determine a representative value, compared, for example, to slope, percent imperviousness, or infiltration. The hydrologic and hydraulic representations in this watershed were more complex than those reported in [62]. As such, while the model results were impacted by the traditional parameters reported in [62], the greater impacts in this study were associated with the large and dynamic surface storage depths of the rice paddies, the variability of the upstream flows coming into the study area, and the hydraulics of the gate operations.

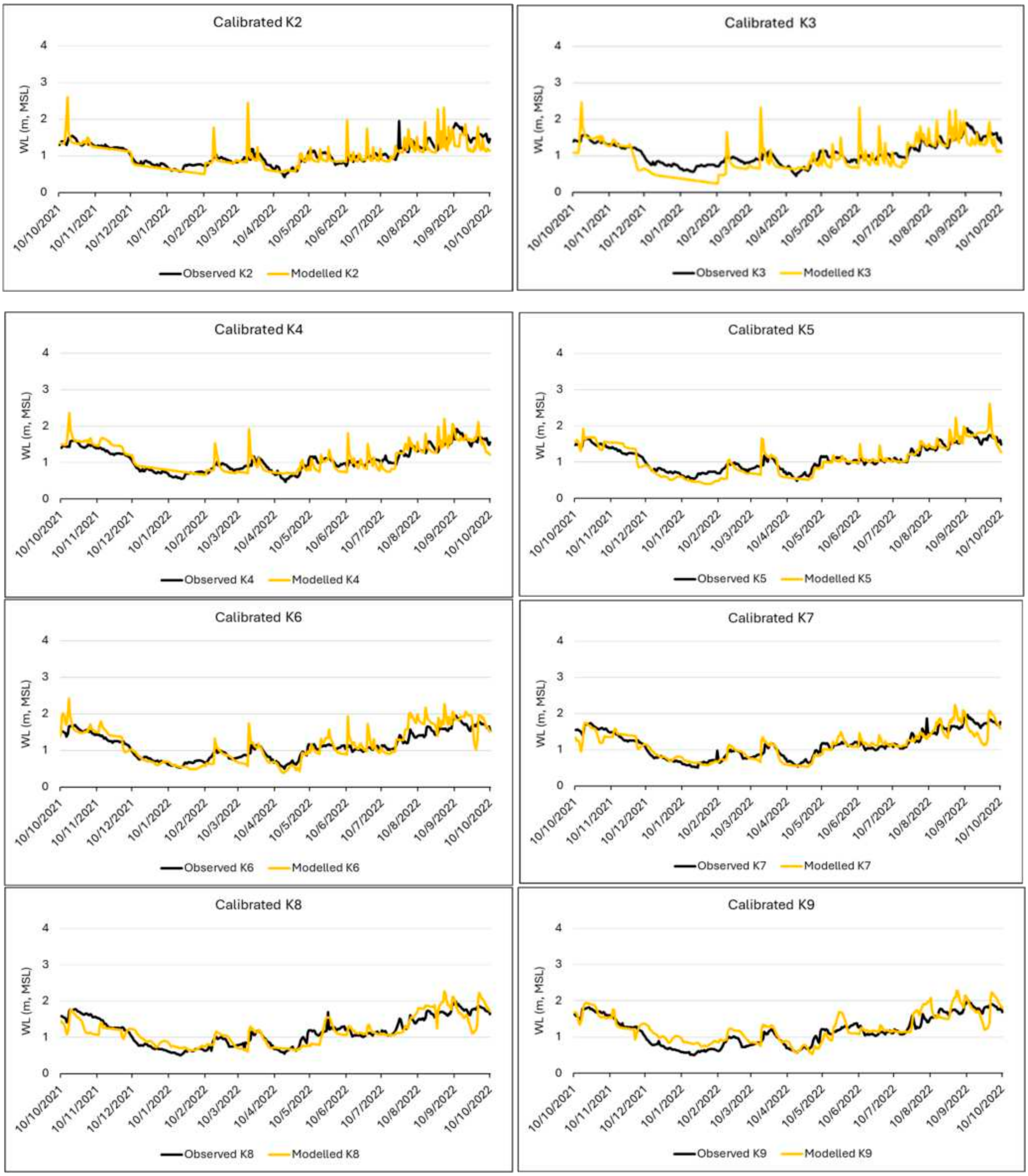

Figure 8. Comparison of simulated and observed water levels for PCSWMM calibration.

Table 2. Ranges of subcatchment parameter values used for the calibrated PCSWMM.

Subcatchment Variables	Urban	Non-Urban
Impervious Surface (%)	>=40	<40
Number of Subcatchments (n)	470	624
Slope (%)	0.5–5.2	0.5–4.57
N Imperv	0.06–0.08	0.024–0.08
N Perv	0.15	0.15
Dstore Imperv (mm)	1.27	1.27
Dstore Perv (mm)	3.81, 450	3.81, 450
Infiltration Method	Horton	Horton
Max. Infil. Rate (mm/h)	50.8	50.8
Min. Infil. Rate (mm/h)	1.27	1.27
Decay Constant (1/h)	4.14	4.14
Average Width of Overland Flow (m) and Range (in brackets)	497 (1.8–3701)	1728 (24–10,576)

Because of the variable gate operations throughout the year that are strongly influenced by the incoming flow at the upstream boundary to the system, it is a challenge to establish a set of standard gate operation procedures that reflects current practice. As such, the gate operations used in the calibration for the wet period of 10 October 2021 to 10 October 2022 are not expected to provide a highly accurate reflection of system conditions under a drier period. Nonetheless, we explored this dynamic system situation as part of a validation exercise using the period October 2016 to October 2017, encompassing both pre-monsoon and post-monsoon events. This period was considerably drier than the 2021–2022 calibration period, with peak flow being about half of the wetter calibration period. Example validation results for this period are shown in Figure 9. The validation run approximated the general temporal trend for the period but, as expected, the peak depths are less accurately captured due to the system dynamics. However, because we are comparing relative changes in runoff patterns with different land use and climate change scenarios in this study, it is an acceptable compromise to use the calibrated gate operations for a particularly wet period.

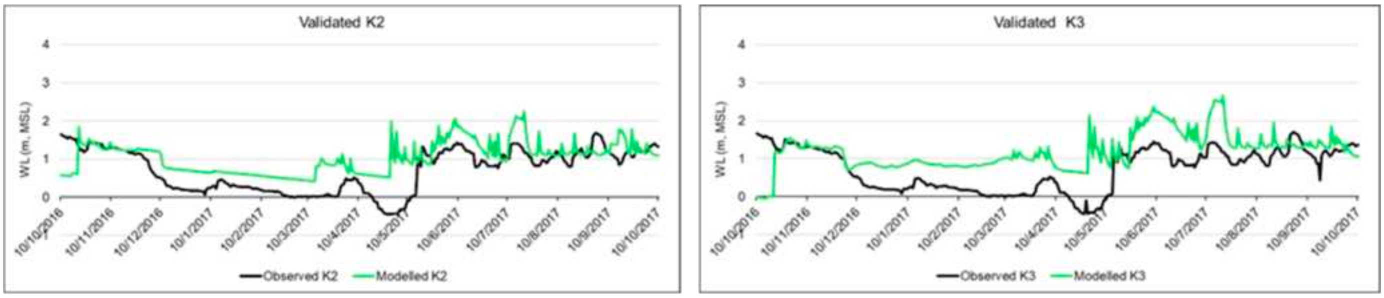

Figure 9. Comparison of simulated and observed water levels for PCSWMM validation.

Based on meetings with the local RID office, a concern was expressed regarding the impact of future residential build-out on runoff volumes entering the khlongs within the study area. The total contributing area for the study site is 77,881 ha, of which 80% is currently open space and agriculture. The non-urban land use space (here conservatively defined as <40% impervious) is 4.5 times bigger than the urban land use space for the calibration run period. This urban land use represents only 18% of the total catchment area but contributes 73% for the total runoff volume (Table 3). Table 3 also illustrates that the mean runoff coefficient, C, is considerably greater for the urban subcatchments compared to the non-urban subcatchments. Subcatchments with 0 or near 0 runoff coefficients were the paddy fields where surface storage was set to 450 mm (Figure 5).

Table 3. Runoff characteristics for current land use conditions and build-out scenario.

		Total Area (ha)	Total Impervious Area (ha)	Runoff Volume (m^3)	Mean Runoff Coefficient	Min. Runoff Coefficient	Max. Runoff Coefficient
Current Land Use	Non-Urban	63,910	4324	$53{,}575 \times 10^3$	0.08	0	0.48
	Urban Area	13,971	9799	$147{,}370 \times 10^3$	0.67	0.26	0.81
Build-out Scenario	Non-Urban	18,593	5679	$59{,}316 \times 10^3$	0.19	0	0.46
	Urban Area	59,289	43,676	$488{,}148 \times 10^3$	0.55	0.17	0.81

Potential flooding conditions under the future build-out scenario were modeled using the same rainfall time series as was used for the calibration results, from 10 October 2021 to 10 October 2022. The proportion of non-urban areas decreased to 24% under the future build-out scenario. Model results for the future build-out scenario are summarized in Table 3. The future build-out scenario produced a total runoff volume that was 2.7 times higher than under the current land use scenario. This extra runoff produced a 78% increase in flood volume as well as an increase in the spatial extent of flooding under the future build-out scenario (Figure 10). While there are uncertainties associated with this future build-out model scenario (e.g., exact change in land use, gate operations), in general, we see that the increased urbanization produces a greater risk of more widespread flooding, particularly in the Khlong 2-Khlong 8 central region (Figure 10). Under this future build-out scenario, additional flood management measures may be required, including increasing the hydraulic capacity of the canal system through dredging, increasing the minimum height of new development landfill, and expanding implementation of Nature-based Solution/green infrastructure features (e.g., raingardens, constructed wetlands/ponds). Real-time flood forecasting to enhance flood warning for better flood preparation would also help to improve local flood resilience, as discussed in the next section.

3.2. Climate Change and Future Land Use Scenarios

The current condition calibration/validation and build-out scenario runs discussed in the previous section were performed using 3 h rainfall data to ensure better model accuracy. However, the climate change scenario rainfall data were only available on a daily time step. Rainfall data with shorter time steps tend to capture peak intensities more accurately, while daily data may smooth out short-term extremes. For appropriate comparative purposes, all scenarios discussed in this section were therefore run using daily rainfall. Furthermore, in the interest of computational time, the climate change scenarios were run for the October through October annual period, 2061/2062 and 2091/2092, covering parts of two rainy seasons that can be compared to current conditions in 2021/2022. This comparison enabled us to divide the climate change scenario into thirds, under which we can examine mid- and end-century conditions.

Results of the modeled runoff for the different scenarios are summarized in Table 4, along with the annual rainfall data for the modeled time period. As shown in Table 4, total annual rainfall was higher under the RCP8.5 scenario compared to RCP4.5. Notably, both climate scenarios show increasing precipitation between 2062 and 2092. Interestingly, total rainfall in the calibrated year 2022 was comparable to that of the RCP8.5 scenario in 2092. By calibrating current conditions using a wet year, we effectively incorporated the uncertainty associated with projected increases in rainfall due to climate change into our baseline scenario.

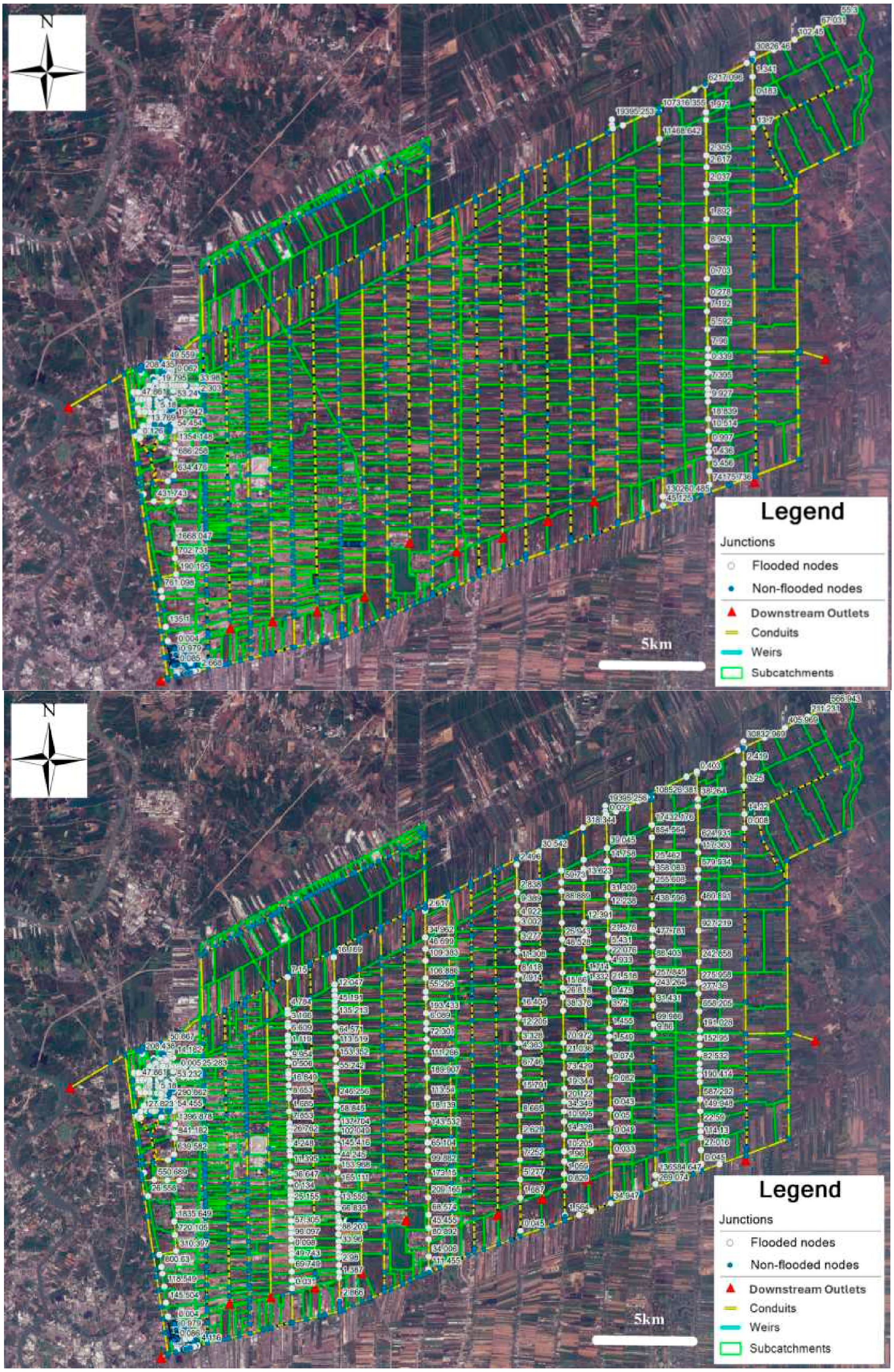

Figure 10. Flooding maps. Top shows the model nodes flooding under current conditions for the calibration year 10 October 2021 to 10 October 2022; bottom shows model nodes flooding under the build-out scenario for the same period. The flooded node volumes are megaliters.

Table 4. Comparison of runoff volume under current and future climate and scenarios.

Scenario	Total Rainfall mm	Runoff (m^3)	
		Current Land Use	Future
Calibrated Year (2022)	1724	159,305 × 10^3	463,808 × 10^3
SSP2-4.5 (2062)	1129	41,899 × 10^3	145,479 × 10^3
SSP5-8.5 (2062)	1607	63,993 × 10^3	224,748 × 10^3
SSP2-4.5 (2092)	1496	56,400 × 10^3	198,163 × 10^3
SSP5-8.5 (2092)	1718	79,810 × 10^3	276,475 × 10^3

Despite the similar total annual rainfall, runoff in 2022 exceeded that of the RCP8.5 scenario for 2092. This difference is attributed primarily to the higher rainfall intensities observed in 2022, whereas the climate projections represented lower intensities—an assumption consistent with previous findings [75].

As illustrated in Table 4, land use changes driven by ongoing and anticipated urban development may exert a stronger influence on runoff than climate change alone. For instance, under the RCP8.5 scenario, the combined effects of future build-out and climate change produce runoff levels 3.4 times greater than those under current land use with climate change. This underscores the important role of urban expansion in shaping future flood risk, aligning with prior analyses that highlighted the impact of development in Pathum Thani based on historical flood mapping between 2010 and 2019 [75].

In addition to the runoff dynamics generated by the entire study area, we also examined the flooding conditions for the three existing developed areas where the drainage systems were modeled in greater detail. The results are presented in Table 5. The moo baan is a new housing development, with Phase III only being completed in 2022. Field investigation confirms that the drainage system of the site is developed to Thai code, and the site has been infilled (per routine Thai practice) so that it is elevated above the surrounding agricultural and green space areas. Irvine et al. [40] noted that no flooding was observed at this location for a 3.5-year rainfall event that occurred on 16 October 2021, with a 24 h total depth of 63.8 mm depth and a peak intensity of 89 mm/h. Furthermore, no flooding at the site has been observed between 2020 and 2025. As such, model results in Table 5 are consistent with field observation for the moo baan site. Teang et al. [49] showed that flooding in Nava Nakorn could be expected in association with a 2-year design storm (72 mm for 24 h) and that a rainfall of 39–43 mm in 2–3 h was observed to produce pluvial flooding. Future build-out and climate change scenarios would have relatively lesser impact on Nava Nakorn because of the well-developed internal drainage system combined with updated pumps to evacuate onsite water, as well as flood walls that were reinforced after the historical 2011 flood in Thailand [28,29]. Ratanakosin is an older urban development at the downstream end of the khlong system. Unlike Nava Nakorn, it is not protected by floodwalls, and a study by Chaosakul et al. [77] indicated that localized flooding would be expected with a design storm of 93 mm and peak intensity of 113.2 mm/h. Consistent with the larger study area, future build-out conditions would exacerbate flooding in Ratanakosin Village to a greater extent than climate change. In particular, the increased flow in the main east–west Rangsit Canal (khlong) would produce greater risk for Ratanakosin Village, as was witnessed during the 2011 flood when the khlong overtopped its banks, resulting in flooding throughout the village.

Table 5. Flood volumes associated with selected urbanized areas under current and future scenarios.

Scenario	Rainfall (mm)	Nava Nakorn Flood Volume (m^3)		Ratanakosin, Flood Volume (m^3)		Moo Baan, Flood Volume (m^3)	
		Current Land Use	Future Build-Out	Current Land Use	Future Build-Out	Current Land Use	Future Build-Out
Calibrated Year (2022)	1724	8611×10^3	$11{,}475 \times 10^3$	632×10^3	3394×10^3	0	9×10^3
SSP2-4.5 (2062)	1129	2919×10^3	3363×10^3	160×10^3	182×10^3	0	0
SSP5-8.5 (2062)	1607	4145×10^3	4895×10^3	247×10^3	262×10^3	0	0
SSP2-4.5 (2092)	1496	3787×10^3	4399×10^3	220×10^3	233×10^3	0	0
SSP5-8.5 (2092)	1718	5029×10^3	6056×10^3	307×10^3	348×10^3	0	0

4. Discussion

The Rangsit study area, Pathum Thani province, currently experiences both pluvial and fluvial flood risk that would be exacerbated under climate change scenarios, and to an even greater extent, by future build-out scenarios in this rapidly developing peri-urban region north of Bangkok. We concur with Thanvisitthpon et al. [75] that "To mitigate the impacts of future climate-induced rainfall and repetitive floods, the provincial government of Pathumthani needs to implement non-structural anti-flood policies and measures (i.e., flood adaptation strategies), in addition to existing structural anti-flood measures, e.g., flood embankments, floodwater pumping. Examples of the non-structural anti-flood strategies include early flood warning systems, community awareness and education, and community-based flood adaptation programs. A sustainable anti-flood strategy requires integration of structural measures with non-structural strategies to better cope with climate-induced future floods..." More specifically, structural options may include emergency measures, such as sandbags and pumping; traditional engineering solutions, such as flood walls, for example, those protecting Nava Nakorn, and higher offset floor levels; but also should include NbS/green infrastructure solutions. Chaosakul et al. [77] showed that a combination of rain barrels and bioretention cells could reduce combined sewer overflow volume to Rangsit Canal by 41%, associated pollutant loads by 34–40%, and virtually eliminate surface flooding, compared to current conditions in Ratanakosin Village, Rangsit. Based on community surveys, Irvine et al. [29] found that flood insurance was not widely used as a form of resilience to flood conditions in this area, and explored other NbS/green infrastructure options at different spatial scales to improve resilience. Options included the "retreat adapt and defend" concept that advocated for the accommodation of floodwater through temporary storage on agricultural fields as well as with enhanced naturalization and pond storage areas (retreat). Farmers would need to be reimbursed for their loss under this scenario as part of a payment for ecosystem services policy. Other areas would have structural adaptation to floods (e.g., traditional stilted houses or amphibious designs (i.e., adapt)). A combination of NbS/green infrastructure and hard engineering (e.g., flood walls) could protect more sensitive development areas. Other development options such as establishing eco-villages that accommodate fluctuating floodwater levels, increased use of NbS/green infrastructure features such as eco-corridors, connected wetlands, and expansion of the traditional "monkey cheeks" approach along the riparian zone of waterways (i.e., maintaining wetland capacity to absorb and slowly release floodwater) might also be considered [78].

Li and Burian [79] explored the use of real-time control methods to improve the irrigation and drainage system operation of local agricultural fields to reduce flooding, and this reflects the importance of mathematical modeling as a scenario evaluation and decision-making tool to enhance flood resilience. The modeling outcomes derived from this study underscore the intricate interactions among land use change, climate-driven rainfall changes, and flood risk within rapidly urbanizing lowland regions, such as Rangsit. The results accentuate the pressing necessity for the adoption of integrated flood management approaches that amalgamate physically based simulation with adaptive infrastructure planning and stakeholder engagement. Physically based hydrodynamic models, such as PCSWMM, offer substantial advantages over empirical or lumped models, particularly in urban environments characterized by complex hydraulic networks. The capacity to simulate both surface and subsurface interactions, dynamically routed through detailed canal networks and structural controls, enables a more comprehensive understanding of flood propagation. This is of particular importance in areas like Rangsit, where drainage heavily relies on manually controlled gates and non-uniform infrastructure configurations. The calibration of PCSWMM demonstrated high spatial and temporal accuracy, thereby confirming the model's reliability as a planning instrument. This paper represents the start of a modeling development process. The larger project will progress to include development of a real-time platform that manages a rainfall forecasting model with weather radar and rain gauge data to automatically drive and update PCSWMM flood forecasts. This type of system already has been demonstrated within the city of Bangkok [79] and will be developed for the Rangsit area. The implementation of real-time floodgate control provides the potential to mitigate flood severity, even under high-stress conditions. Ruangapan et al. [34] in their modeling study showed that real-time control could be effective in reducing water level in khlongs for a small subsection of our study area, compared to the system without real-time control. Preemptive gate operations may result in reduced peak water levels and decreased duration of inundation, effectively flattening the hydrograph and delaying flood wave propagation. This form of adaptive infrastructure is particularly valuable in peri-urban settings, where rapid urban growth often exceeds large-scale capital investments in drainage capacity. However, the success of such systems is contingent not only upon technological capabilities but also on institutional readiness. Automated control systems must be supported by reliable hydrometeorological forecasting, clear operational protocols, and coordination among multiple administrative jurisdictions. The Rangsit case study exemplifies the importance of aligning technological innovation with governance capacity and local stakeholder engagement.

There can be considerable uncertainty in projecting rainfall characteristics under climate change modeling. Hosseinzadehtalaei et al. [80] suggested that the greatest uncertainty in rainfall projection was associated with the choice of GCM (up to 65%), followed by GCM initial conditions and RCPs (38 and 23%, respectively); the method of downscaling also will have an impact [81]. Certainly, as noted in Section 2.5.3., there are differences in rainfall projections for Thailand. It has generally been reported that there is greater uncertainty associated with the GCM and climate change modeling than with the hydrologic models that translate the climate change rainfall scenarios into runoff [82,83]. The uncertainty in GCM projections of rainfall is often addressed using an ensemble modeling approach [84]. It was beyond the scope and focus of this particular study to investigate the uncertainties associated with projected rainfall under climate change and coupling with the hydrologic/hydraulic modeling. Moving forward, this type of uncertainty analysis should be undertaken (see [85] for possible directions). The greatest uncertainties in the hydrologic modeling for this study were associated with upstream inflow dynamics, gate operations, and surface storage dynamics (particularly in the rice paddy areas). Furthermore, the observed rainfall data were only available for one gauge site and therefore were not able to capture the impact of rainfall spatial variability on runoff [62]. It is possible to script gate timing and extent of opening to produce accurate representation of gate operations and hydraulic response, if the details of operations are provided [37]. It was possible to calibrate PCSWMM with sufficient accuracy in the study area to provide planning level estimates of khlong water level. However, the gate operations are actually influenced by the target or ideal levels identified by the Royal Irrigation Department and the inflow from upstream (which in part is also affected by reservoir releases further upstream and outside of the jurisdiction of the RID office with whom we coordinated). We have observed that water levels in some khlongs are proactively lowered when a typhon event is predicted. We believe this is why real-time control and better definition of user intervention rules would be helpful but would require further study. In addition, future work should include 1D inundation or full 2D modeling to examine the spatial extent of flooding and map flood risk. We explored the 1D inundation option in this study, but the area is a flat floodplain with limited relief, and the available DEM did not have sufficient vertical resolution to accurately distribute flow. As such, for this study we can only identify flooded nodes and flood volume. The focus on an observed extreme wet year for calibration helps to accommodate the uncertainty for the climate change scenarios in developing planning level water management options.

5. Conclusions

This study presents a comprehensive assessment of urban flood risks in Rangsit, Pathum Thani, Thailand, utilizing a physically based hydrodynamic modeling framework under varying land use and climate change scenarios. By employing PCSWMM, the research integrates spatial data and dynamic infrastructure simulations to elucidate the drivers of flooding and assess resilience strategies for future conditions. The simulation results demonstrate that both urban expansion and changing rainfall attributable to climate change are likely to increase flood magnitudes, durations, and impacted areas, although in this rapidly developing peri-urban area, land use change was the most important driver. Indirectly, we were able to accommodate flood considerations from climate change by focusing on an extremely wet year (2022) for model calibration.

The outcomes of this study have direct implications for flood risk management policy and urban development planning. Firstly, land use planning practices and zoning regulations must be strictly applied and enforced to prevent development in high-risk floodplain areas. Such practices are well-established in Global North countries [86–89] and have been recommended for countries of Southeast Asia [90–92]. Secondly, urban infrastructure investments should prioritize green and blue infrastructure such as retention ponds, bioswales, constructed wetlands, and conservation of existing pervious space concurrently with conventional drainage enhancements [51,93–96]. Green and blue infrastructure can provide additional ecosystem service benefits, such as water quality improvement, urban heat island mitigation, carbon sequestering, increased biodiversity, and enhanced community wellbeing [40]. Thirdly, integrated urban water management frameworks ought to incorporate scenario-based modeling into the decision-making processes, as has been demonstrated for a province in Thailand by Phinyoyang and Ongsomwang [97], but, as argued by Marks [98], should also consider "...the embedded nature of the socio-political and physical geographies shaping flood governance.", or the socio-hydrology of the system. This ensures that future developments are not only economically viable, but also hydrologically sustainable. The application of modeling as a participatory tool, particularly within stakeholder workshops (as implemented in our broader project), has proven effective in fostering local awareness and institutional commitment. Lastly, this research underscores the necessity for dynamic, cross-sectoral adaptation strategies. Achieving flood resilience cannot be realized solely through engineering interventions; it necessitates coordinated land management, environmental conservation, real-time data integration, and inclusive governance. The Rangsit study offers a scalable framework that is adaptable to other rapidly developing flood-prone regions in Southeast Asia and beyond.

Author Contributions: Conceptualization, K.N.I., D.C., F.L. and A.S.; methodology, D.C., L.H.C.C., F.L. and A.S.; software, L.T.; validation, R.C. and L.T.; formal analysis, D.C. and L.T.; investigation, D.C., K.N.I., F.L. and A.S.; writing—original draft preparation, D.C. and K.N.I.; writing—review and editing, K.N.I. and L.T.; visualization, L.H.C.C., F.L. and A.S.; supervision, K.N.I. and L.H.C.C.; project administration, K.N.I.; funding acquisition, K.N.I. and L.H.C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Asia-Pacific Network for Global Change Research (APN), CRRP2022-07MY-Basri.

Data Availability Statement: The data presented in this study are available upon reasonable request from the corresponding author.

Acknowledgments: The authors gratefully acknowledge the support from the Royal Irrigation Department (RID), Thailand Meteorological Department (TMD), Thammasat University, Kasetsart University and community members who participated in stakeholder workshops. We would like to thank the three reviewers for their thoughtful and constructive comments that helped to improve the quality of the manuscript.

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

Abbreviations

The following abbreviations are used in this manuscript:

PCSWMM	Personal Computer Storm Water Management Model
RCP	Representative Concentration Pathway
SSPs	Shared Socio-economic Pathways

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