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Assessment of flood mitigation services in Khon Kaen City through integrated modelling and scenario simulations

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Abstract

This study highlighted the identifying remedial measures for flood mitigation under varying rainfall intensity. The MIKE URBAN was coupled with the MIKE 21 within the MIKE FLOOD URBAN model to simulate flood propagation in Khon Kaen City. The reliability of 1D model was proven through calibration and validation, in which the water level observed in Nong Khot Lake was satisfactorily predicted as the values of coefficients of determination (R^2) and Nash-Sutcliffe Efficiency (NSE) are greater than 0.80, Root Mean Square Error (RMSE) is close to zero, and Percent bias (PBIAS) is less than 10%. The MIKE FLOOD URBAN was further calibrated for the rainfall event of 1 September 2019, while the results from a low Relative Error (RE) of 0.14 and a high F-statistics (F_S) of 83.72% indicated a high goodness of fit between UAV-based mapping (0.196 km^2) and MIKE FLOOD URBAN simulated flood extents (0.169 km^2). The MIKE FLOOD URBAN was validated against floodmarks on 25 September 2022, and there was a satisfactory correlation between flood depth reported by news reports and the simulated results. To respond to floods caused by tropical storms Podul and Noru of September 2019 and September 2022, respectively, five flood mitigation scenarios were examined for their effectiveness compared to the baseline. The integration between the drainage improvement project of Maliwan Road and advance depletion of water level in Nong Khot Lake by 3.5 m, was the most promising combination to alleviate flood consequences at repeatedly flooded areas with the maximum decrease in flood depths of 0.77 m. The average flood depth and total flooded areas were decreased by up to 27.66% and 10.66%, respectively, which is an optimistic sign to convince agencies to extend these management actions to include other flood mitigation works for enhancing flood resilience of Khon Kaen City.

Keywords: Floods, Flood mitigation, Model coupling, Flood modelling, MIKE FLOOD URBAN

1. Introduction

It is well documented that flooding can cause significant disruptions to cities, properties, infrastructures, and resulting in negative impacts on social life and well-being [1-3]. Similarly, in the case of Thailand, the incidents of floods, especially in urban areas have become a phenomenon of concern for many cities. This corresponds to the information reported by [4] that Thailand has extremely high exposure to flooding (ranked 9th), including, riverine, flash, and coastal flooding. With the continuing climate change effects, the flooding issue becomes more acute and leads to potentially more severe in dense urban areas [5, 6]. This is in line with [7] who also revealed that the frequency of flooding is likely to rise in urban areas under exacerbating threat of climate change. To tackle the threat of urban flooding, it is worth searching for robust solutions to urban flooding in various case studies. Ferreira et al. [8] added that flood mitigation strategies in urban areas should be tailored through a series of structural and non-structural measures, in which the best mix of options available would be the most optimal as suggested by [9]. Those recommendations reflect the findings of [10] who revealed that for Ayutthaya City in Thailand, the effectiveness of the combination of small-scale Nature-Based Solutions (NBS) (e.g., green roofs, bio-retention, pervious/porous pavements, infiltration trenches, swales, etc.) and local grey infrastructure measures (including alteration/raising of dikes height, construction of gates, amplification of the drainage system and improvement of the pumping strategy, rehabilitation of ancient canals and construction of flood walls along the river) is limited to smaller flood events. However, for coping with larger/extreme events, it is necessary to combine the aforesaid measures with different scales of implementation (i.e., hybrid measures including the construction of Ayutthaya bypass channel and widening of two ponds upstream called the Bang Ban and Thung Ma Kham Yong Ponds). To provide guidance on the effectiveness of different flood mitigation options, the computational models was applied to understand the hydrological dynamics under different management practices. The models also provide the flexibility to adjust a range of assumptions when additional information about flood mitigation is known as addressed by various recent studies

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conducted in Thailand. Mekpruksawong et al. [11] applied the HEC-RAS model for simulating flood situations in the downstream of the Mun River Basin under different flood mitigation alternatives. It was found that the adjustment of bed slope and removing natural complex rock layers seems to be the most effective scheme, but it may not be accepted by the people in Ubon Ratchathani Province. Interestingly, it was recommended that the best alternative scheme would be the combination of adjustment of bed slope and constructing an additional flood storage area, since they would help reduce flood depth and duration significantly and being able to store floodwater for dry season use. Working together with other flood mitigation measures, as claimed by Rather et al. [12], a flood control reservoir is always one of the most frequently used structural approaches for managing flood events. Clearly, the remark was supported by the study of Krue-hom and Kwanyuen [13] who evaluated the efficiency of flood mitigation in Bang Prakong-Prachin Buri River Basin with Huay Sa-Mong Dam and Klong Pra Sathueng Reservoir projects. The InfoWorks ICM model was employed to simulate flood events in 2005, 2006, and 2013. The study revealed the effectiveness of Huay Sa-Mong Dam and Klong Pra Sathueng Reservoirs in mitigating flood damage. However, their effectiveness still largely depends on the characteristics and distribution of rainfall in the basin, in which appropriate flood mitigation measures and preparedness should also be taken into consideration. Wattanaprateep [14] investigated the effectiveness of the floodwater detention area called "Mahachai-Sanamchai Canal Monkey Cheek Project", which stores floodwater in the upper area and releases water into the Gulf of Thailand simultaneously, in relation to the tide levels of the sea. The improvement and construction of regulators and pumping stations in canals within the irrigation project area was also taken into consideration. The obtained findings suggested that the Monkey Cheek Project is an effective measure to alleviate flooding problem as can be seen from the reduction in both flood level and inundation in the areas of Samut Sakhon, Samut Prakan, especially the west of Bangkok. Moreover, there are more relevant studies (for example, [15-18]) that underly the worsening flooding situation in Thailand, along with appropriate flood mitigation solutions applied in those areas. By considering the key points mentioned above, it is worth highlighting the necessity to identify the feasible flood mitigation measures for coping with flooding in Khon Kaen City where rapid economic expansion and unplanned urbanization, improper drainage system, blocking of natural drainage routes through unplanned construction, encroachment on watercourses, etc., are the primary concerns [19]. Eventually, the obtained results from this study can contribute to the provision of initial insights for communicating flood risk and the need for preparedness and mitigation for local authorities and administrators in Khon Kaen City. As well, the lessons drawn from this study can also provide directions for additional research, which can guide researchers to conduct studies related to the assessment of damage incurred by floods and come up with recommendations and mitigation strategies, in case there is no any previous study done in other areas.

2. Materials and methods

2.1 Outline of the methodology

The overall methodology applied in this study, which is graphically presented in Figure 1, presented a systematic approach to identify the possible flood mitigation approaches for reducing the risk of recurrent floods in Khon Kaen City. The first step included gathering two types of information, such as hydrological data and GIS-based spatial layers. Then, the 1D MIKE URBAN and the MIKE FLOOD URBAN models were calibrated and validated with the water level observation data of Nong Khot Lake, and the observed flood extent map, respectively. For scenario analysis, a list of different related alternatives for flood mitigation within Khon Kaen City was proposed. The simulation results obtained herein are maps of flood inundation depth and area for different mitigation scenarios, in which they are compared to each other afterwards. Expectedly, the combination of mitigation scenarios would gear towards the effectiveness of optimal solution for the reduction in frequency and intensity of flood events in Khon Kaen City.

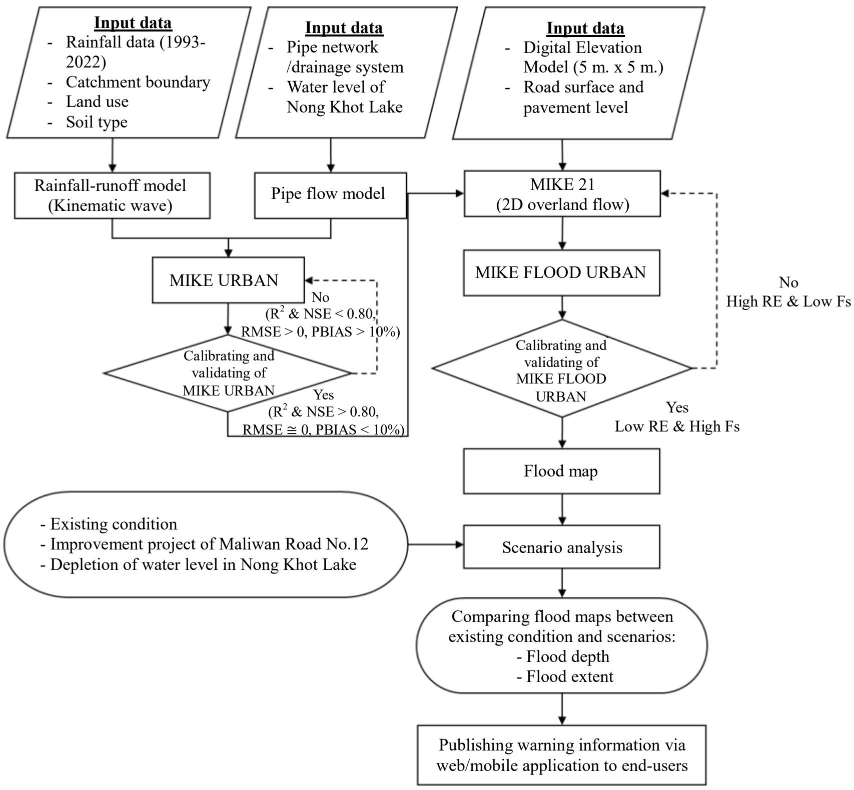

Figure 1 The method for effectiveness assessment of flood mitigation used in this study.

2.2 Description of the study area

The repeatedly flooded areas of 18.70 km^2 situated in the administrative areas of Khon Kaen Municipality and Banped Subdistrict Municipality was selected as the case study site for this research. The area of study included the 12-lane Maliwan Road starting from the front of Khon Kaen University to the intersection of the 8th Infantry Regiment, Siharatdechochai Fort as outlined by the red line indicated in Figure 2. The climate of the study area is characterized by a tropical savanna climate with the mean annual rainfall of 1,234.7 mm. The highest average rainfall occurs in September (246.0 mm) and the lowest is in December (5.7 mm). The average maximum and average minimum temperature are 36.3 °C (in April) and 18.1 °C (in January), respectively, over the 30-year period (1991-2020) [20]. The study area is primarily dominated by peri-urban and agricultural land, while rapid urban development has taken place from 2005 and onwards. Since the natural landscape of the study area is transformed by urban sprawl, its drainage pattern is inevitably disturbed. Some waterways within Khon Kaen City have been artificially landfilled, which could lead to the increased risk of urban waterlogging as the existing drainage pattern is substantially disrupted and weakening the capacity to regulate stormwater runoff. As indicated in the 2023 action plan for flood management in Khon Kaen Municipality prepared by the Division of Public Works, the majority of stormwater that enters Khon Kaen Municipality (with 46 km^2 of drainage area) is originally transferred from the drainage basin of Banped Subdistrict Municipality (with approximately 21 km^2 of drainage area). At present, there is a large flood storage basin called “Nong Khot Lake” located in the southwest part of Khon Kaen City, covering the area of 1.05 km^2 (105 hectares) with estimated drainage area of 10 km^2, and has the average depth of 4.9 m (maximum 10.5 m) [21]. It serves as a stormwater detention area by absorbing rain and holding runoff from its surrounding areas during heavy storms. As informed by the Divisions of Public Works of Khon Kaen Municipality and Banped Subdistrict Municipality, under the existing conditions, the stormwater runoff from Nong Khot Lake is routed eastward through the pumping station located at the outlet of the lake with the capacity to deliver 0.86 m^3/s to an existing open channel, two rows of 1.0 m circular pipes, and a two-cell 2.0 m x 2.0 m box culvert through the residential and open space areas. Then, the stormwater enters a two-cell 2.5 m x 2.5 m box culvert under Srichan Road near Khon Kaen Ram Hospital, and then flows along Srichan Road. The collected stormwater is diverted (a left turn) into the open channel near the railway track next to Central Plaza shopping mall, and it is subsequently conveyed southeast through a 1.8 m x 1.8 m box culvert under 5 Phruetsachika Road. The stormwater flow is then directed into a 1.8 m x 1.8 m box culvert under Ammart Road. The stormwater continues flowing east and discharges into a three-cell 2.5 m x 2.5 m box culvert at Chalermprakiat Road with the capacity of approximately 15 m^3/s. It is eventually transported via Thung Sang Lake and along the open channel, while all stormwater is then released into the Huai Phra Khue River and is delivered into the Chi River afterwards.

In view of flood management, the proposed plan of Khon Kaen Municipality, which is divided into two phases, i.e., pre-disaster stage (prevention, mitigation, and preparedness before the rainy season) and during the disaster stage (emergency response during the rainy season), is formulated to provide guidance for reducing severe injury and loss to individuals and damage to property and infrastructure during flood events. The approaches to flood management such as dredging of drainage channels, removal of trash and debris from stormwater conveyance systems, lowering of water levels in Thung Sang, Kaen Nakhon, Nong Bon, Nong Yai, Nong Waeng, Si Than, and Nong lad Lakes, and Huai Yao Canal, on-site regular inspection, maintenance, and testing of gates and pumping stations, inspection of box culvert structures, and regular review and update of flood emergency response plan, are presently applied before the flood season. During the flood period, the responsible authorities are requested to regularly monitor and follow up flood situations, to collaborate closely with relevant agencies to properly operate drainage pumps, and to collaborate with Banped and Pralub Subdistrict Municipalities on joint water management strategies. Meanwhile, the identified short-, medium-, and long-term holistic engineered solutions for flood management in Banped Subdistrict Municipality are also proposed for ensuring the efficient working of the drainage system within its administrative area. The short-term plan is conducted before the arrival of the rainy season, including drainage improvement, dredging of drainage pipes and channels, extension of drainage pipes and channels, widening and deepening of existing channels, installing temporary pumping stations, and cleaning of drainage facilities for preventing clogging of the drainage system. The medium-term plan is formulated by dredging drainage pipes and channels, and installing a 1-m drainage pipe within the communities. Lastly, the long-term plan is focused on the installation of 0.4-, 0.6-m, and 1.2-m of drainage pipes and manholes within repeated flooding zones, the building of a box culvert under the roads (2.1 m x 1.5 m and 2.1 m x 2.1 m concrete box culverts), and the excavation of Nong Hai retention pond for holding floodwater during times of flooding.

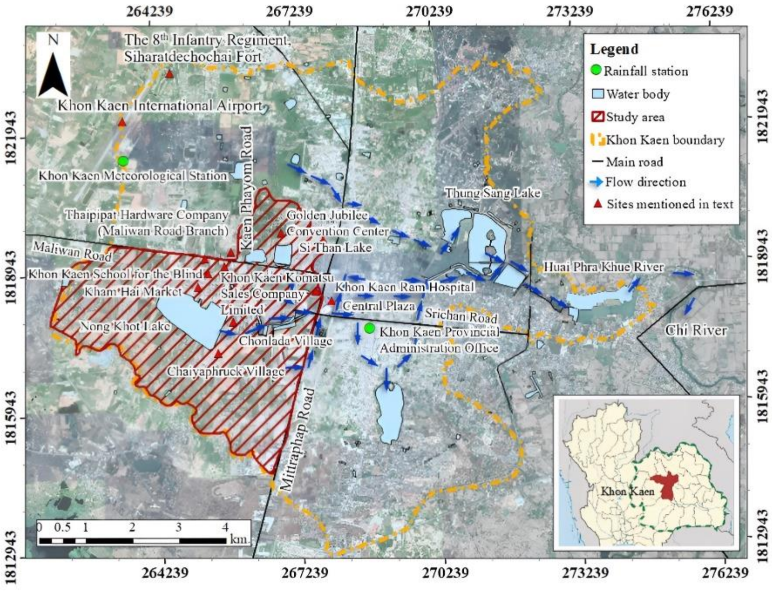

Figure 2 Location of the study area

2.3 Datasets

Various data types such as hydro-meteorological data and spatial information were collected to supplement information for this study. The relevant time series data used included daily rainfall and daily water level measured at Nong Khot Lake. In details, the climate data during 1993-2022 were collected from the Thai Meteorological Department (two stations) including Khon Kaen Meteorological station and Tha Phra Agrometeorological station, and one meteorological station located at Khon Kaen Provincial Administration Office under the responsibility of the Water Resources Regional Office 4, Department of Water Resources (see Figure 2 for their locations, while the location of Tha Phra Agrometeorological station cannot be viewed due to viewing restriction). However, due to lacking data and discontinuous daily in-situ water level records measured at Nong Khot Lake by the Division of Public Works, Banped Subdistrict Municipality, the calibration and validation of the one-dimensional model can only be performed in 2019 and 2022. The description of some physiographic characteristics of the study area, including drainage basin area and shape, drainage lines, drainage pattern, drainage density, stream length, slope, etc., were also required as main inputs of hydrological modelling software to delineate variation in runoff regime. The topographic features of the study area were derived from a 5-m resolution Digital Elevation Model (DEM), while the 2018 land use and soil data with a resolution of 30 m acquired from the Land Development Department (LDD) were also needed as inputs for 2D overland flow modelling. The land use data used in this study was divided into nine major categories, including paddy field, field crop, perennial and orchard, aquaculture, rangeland, marsh and swamp, urban and built-up land, miscellaneous land, and water body.

2.4 Detailed flood modelling and analysis

To ensure that flood characteristics for a range of flood events can be identified, the detailed flood modelling should be undertaken. Thereafter, the key flooding issues can be highlighted, whereas the necessary suite of flood mitigation alternatives can also be identified. In this study, the 1D rainfall-runoff model was internally coupled with the 1D pipe network in MIKE URBAN, in which the rainfall-runoff process and flow routing in drainage pipelines were modeled through the 1D sewer network. Meanwhile, when the drainage capacity of pipe network was exceeded, the flow would spill into the 2D model domain from manholes, and the routing process across the 2D overland surface was then undertaken by MIKE 21.

2.4.1 Modelling of rainfall-runoff processes

The drainage system simulations and computations conducted herein consisted of two different stages, i.e., runoff computations and network simulations. For describing the event-based rainfall-runoff response, there are different hydrological rainfall-runoff models available in MIKE URBAN rainfall-runoff module, i.e., Model A (Time/area Method), Model B (Non-linear Reservoir (kinematic wave) Method), Model C (Linear Reservoir Method), and UHM (Unit Hydrograph Model). The conversion of rainfall into surface runoff to the collection system and river networks was determined through several computations that describe the land and runoff phase of the hydrologic cycle in connection to the hydraulic system. Thereafter, the time series outputs of daily water level from MIKE URBAN rainfall-runoff module were then used as input data in a subsequent MIKE URBAN pipe network module and MIKE 21. In this study, due to the fact that the study area is highly urbanized with high degree of imperviousness, Model B was therefore considered well suited for the simulation task of such urbanized area, and also for calculating hydrograph peak runoff once the heavy rainfall ceases, as suggested by [22, 23], respectively. In MIKE URBAN Model B, the surface runoff was calculated as flow in an open channel, in which gravitational and friction forces were only assumed to dominate the processes. The amount of runoff was dependent upon abstraction of losses (including evaporation, infiltration, and surface storage), the runoff routing by the kinematic wave (Manning) formula and volume continuity, and the size of the runoff producing areas. The shape of runoff hydrograph was dependent on the catchment parameters such as length, topographic slope, and surface roughness. Referring to the rainfall which contributes to the surface runoff, the remaining rainfall after abstraction of losses or "effective rainfall, $I_{eff}(t)$" was firstly computed based on the equations presented below [24].

$$I_{eff}(t) = I(t) - I_E(t) - I_W(t) - I_I(t) - I_S(t) \tag{1}$$

where I(t) refers to the actual rainfall at time t, $I_E(t)$ represents the evaporation loss at time t, $I_W(t)$ stands for the wetting loss at time t, $I_I(t)$ defines the infiltration loss at time t, and $I_S(t)$ denotes the surface storage loss at time t.

In principle, the boundary condition used in MIKE URBAN rainfall-runoff module was spatial-temporal variation of rainfall, while the water level in Nong Khot Lake of 153 m above mean sea level (m+MSL) was set as initial condition. There are 17 sub-basins in total, ranging in size from 0.43 km^2 to 3.30 km^2. As the model input data, the Thiessen polygon method was applied to weigh the rainfall proportion and calculate the areal rainfall for each sub-catchment based on three rain gauges located in the proximity of the study area (Figure 2). The specific procedures and criteria used for calibration and validation of the 1D MIKE URBAN model can briefly be described as follows: (a) the performance of the model was graphically analyzed by plotting the observed and simulated daily water levels throughout the calibration period, (b) the model accuracy was analyzed using the coefficients of determination (R^2) (a value of 1.0 indicates perfect model simulation with no deviation from the observed values), Nash-Sutcliffe Efficiency (NSE) (if the NSE is greater than zero, the simulation output is considered better than the mean of observed values), Root Mean Square Error (RMSE) (the lower the RMSE, the lower the forecast error and the higher the accuracy), and Percent bias (PBIAS) (a value of 0.0 indicates perfect model simulation with no deviation from the observed values), as they are recommended statistics for hydrological calibration and validation [25], and (c) validation was performed afterwards by running the MIKE URBAN model using the calibrated model parameter values. In details, the calibration was carried out during almost 1-month period between August 22 to September 13, 2019, with a time step of 60 seconds, using the manual "trial-and-error" calibration procedure by adjusting the Manning's n values and the percentages of impervious cover for each sub-catchment, within the allowed range until the computed water levels are in good fitness of the observed water levels in Nong Khot Lake. By using the parameters determined during the calibration, the validation was then made during the period July 9 through August 10, 2022.

2.4.2 Modelling of drainage processes

After simulating the hydrological processes, the modeled catchment areas connected to the drainage network were defined by using the computed runoff from the previous rainfall-runoff simulation as a network load to the collection system. The drainage network was modelled in MIKE URBAN pipe network module to simulate the hydrodynamics of the pipe flow, in which all manholes within the study area were coupled to the 2D surface model (MIKE 21) under two specific conditions viz. when manholes are overtopped or when surface runoff reaches a manhole. The computations of the unsteady flow in pipes and manholes with altering free surface and pressured flow conditions, were executed by solving the Saint-Venant equations that were derived from conservation of mass and conservation of momentum equations as expressed by Equations 2 and 3, respectively [26].

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t} = 0 \tag{2}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(\alpha\frac{Q^2}{A}\right)}{\partial x}+gA\frac{\partial y}{\partial x}+gAI_f = gAI_0 \tag{3}$$

where Q denotes the discharge, A defines the flow area, y refers to the flow depth, g represents the acceleration of gravity, x stands for the distance in the flow direction, t represents the time, α is the velocity distribution coefficient, and I_0 and I_f are the bottom and friction slopes, respectively.

The MIKE URBAN pipe network module consisted of 93 nodes that were connected through 105 pipes in total with different shapes and sizes, of which the total length is about 23,124.6 m. At the nodes, the water level was calculated using the previous time step water level and the flow contributions during the time step from each connected pipe and external connected catchment runoff [27]. The amount of surcharged water from the drainage network was calculated based on the principle that the water can spill to the surface from the drainage network, but it cannot re-enter the drainage system. The pipeline Manning's n values, which was considered as the main influencing parameter varying from pipe to pipe, was also adjusted within the same calibration period and time step as the rainfall-runoff module.

2.4.3 Modelling of 2D overland flow

For modelling unsteady two-dimensional free surface flow, the MIKE 21 flow model was employed as it was successfully applied by many research works, including [28-30]. When the terrain data, Manning's n coefficients, and hydrodynamic boundary conditions were entered into the model, the variations in water level and discharge in each grid were simulated. In principle, the following Equations 4 to 6, i.e., the conservation of mass and momentum (x and y directions) integrated over depth, were solved by implicit finite difference methods with the variables defined on a rectangular grid covering the area of interest [31].

$$\frac{\partial \zeta}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y} = \frac{\partial d}{\partial t} \tag{4}$$

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial x}+\frac{gp\sqrt{p^2+q^2}}{C^2\cdot h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx})+\frac{\partial}{\partial y}(h\tau_{xy})\right]-\Omega q-fVV_x+\frac{h}{\rho_w}\frac{\partial}{\partial x}(p_a)=0 \tag{5}$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial y}+\frac{gq\sqrt{p^2+q^2}}{C^2\cdot h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial y}(h\tau_{yy})+\frac{\partial}{\partial x}(h\tau_{xy})\right]+\Omega p-fVV_y+\frac{h}{\rho_w}\frac{\partial}{\partial y}(p_a)=0 \tag{6}$$

where the variables ζ , d, h, p, and q represent surface elevation, time varying water depth, water depth, and flux densities in x- and y-directions, C stands for Chezy resistance, g is the acceleration due to gravity, f(V) refers to the wind friction factor, V, V_x, V_y denote the wind speed and components in the x- and y-directions, Ω defines the Coriolis parameter, P_a represents the atmospheric pressure, ρ_w is the density of water, x, y are the space coordinates, t is time, τ_{xx}, τ_{xy}, τ_{yy} are the components of effective shear stress.

In this study, MIKE URBAN and MIKE 21 models were coupled to form the MIKE FLOOD URBAN model set up for two-dimensional flood inundation simulations in the study area. Clearly, there are several advantages of applying this coupling model including the fact that it contains the benefits from both 1D MIKE URBAN and 2D MIKE 21 models [32]. Under unconfined flow conditions, this coupling can represent more precisely the overland flow and spilling than 1D model based on the integration of floodplains, streets, rivers, sewer/storm water systems, etc. [32, 33]. Even though the accurate and efficient simulation of combined pipe and overland flows can be achieved using this model coupling, there are still some methodological and data-related limitations inherent in the modelling process that might affect the accuracy of assessment findings. First, the parameters used in the coupled model are only applicable to this study area. In addition, as different modelling tools are involved, the consistency between models must then be maintained, while intensive computational requirements (e.g., more time to set up, a large amount of data for model set up, calibration, and validation, more disk space, etc.) and more computing time are also the limitations of the MIKE FLOOD URBAN model [32]. Moreover, the fact that urban flood modelling is somehow complicated as drainage lines and patterns are primarily affected by landscape modification, stormwater networks, buildings, and other facilities. Meanwhile, the parameters controlling flow through drainage networks and river channels such as slope, elevation, direction of slope orientation (aspect), topography, vegetation, soil type, drainage network patterns, land use and land cover, etc., across the study area, are also the most sensitive. Therefore, the adjustment of aforementioned parameters can result in considerable changes in the flood inundation pattern over the area and may also result in inherent uncertainties in flood modelling due to uncertain variables such as topography, hydro-meteorological inputs like precipitation and streamflow, modelling techniques and parameters [34-36]. In this study, the Manning's roughness coefficient of the surface was changed, while the MIKE FLOOD URBAN model was calibrated with a time step of 10 seconds for the rainfall event of 1 September 2019 based on the comparison between the simulated flood extent and the corresponding actual inundated area derived from the Unmanned Aerial Vehicle (UAV) images. The model was further validated against historical watermarks and flood information of flood event on 25 September 2022.

2.5 Model performance evaluation

In this study, the coefficient of determination (R^2), Nash-Sutcliffe Efficiency coefficient (NSE), Root Mean Square Error (RMSE), and Percent bias (PBIAS) were the performance indicators used to evaluate the performance of the 1D MIKE URBAN model. As recommended by Moriasi et al. [25], for daily flow simulations, the model performance can be judged as "satisfactory" if R^2 greater than 0.60, NSE greater than 0.50, RMSE close to zero, and PBIAS less than ±15% for watershed-scale models (the formulas of model performance metrics are given in [25]).

3. Results and discussion

3.1 Modelling of flood propagation

To obtain flood hazard information for specific locations within the study area, the integrated modelling approach was applied based on the hydrological input through rainfall-runoff transformation (MIKE URBAN), integrated with the 2D hydraulic model (MIKE 21) for simulating flood inundation processes in flood-affected areas, as further detailed below.

3.1.1 Simulation results of rainfall-runoff modelling

The modelling of rainfall-runoff processes is considered to be one of the prerequisites of hydrological processes applied to flood inundation modelling. Based on the catchment, drainage network, and meteorological data, the runoff and network simulations of MIKE URBAN were conducted for the monsoon period where severe flooding was reported. At first, it is clear that the success of practical application of modelling of hydrological system at the catchment scale depends highly on the sensitivity analysis and calibration of the model parameters [37, 38]. To better parameterize the model to a given set of actual conditions, the calibration and validation of both rainfall-runoff and pipe flow modules of MIKE URBAN was undertaken during 22 August - 13 September 2019 and 9 July - 10 August 2022), respectively. Based on the preliminary sensitivity analysis, the Manning's roughness coefficient and percent imperviousness, which have the most dramatic affect in adjusting modeled water level in Nong Khot Lake to match observations closely over the entire time series, were varied and adjusted manually. The modelling results revealed that the calibrated Manning's roughness coefficient for different types of pipes in the study area and surfaces assigned by land use categories ranged from 0.012 to 0.033 and from 0.012 to 0.083, respectively, while the percent imperviousness values varied between 13.27% and 100.00%. The green areas with more vegetation around Khon Kaen International Airport and the 8th Infantry Regiment, Siharatdechochai Fort have clearly the least proportion of impervious surface cover with more nature compared to the other areas, whereas the high-density development around Si Than and Nong Khot Lakes, Khon Kaen School for the Blind, and Khon Kaen Ram Hospital was found to be the areas most heavily affected by urbanization characterized by impervious land cover (see Figure 2 for their locations). The graphical and statistical methods were used to evaluate the robust performance of the MIKE URBAN model during calibration and validation periods. The graphical time series plots in Figure 3 denotes that the model simulation is well fitted with the observed water level measurement. Based on the four statistical indices, the values of R^2 and NSE were greater than 0.80, RMSE was close to zero, and PBIAS was less than 10%, the model performance was judged satisfactory and the model was considered highly appropriate for application to this urban catchment case study.

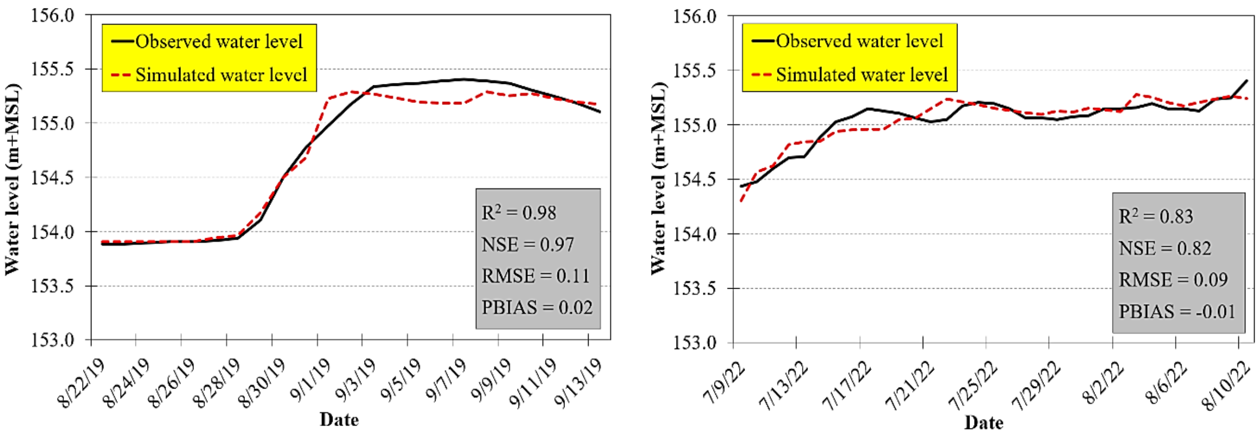

Figure 3 MIKE URBAN calibration (22 August to 13 September 2019) (left) and validation (9 July to 10 August 2022) (right) simulations plotted against measured water level data of Nong Khot Lake

3.1.2 Simulation results of 2D overland flow modelling

To provide physical insight for proper surface water movement, the MIKE FLOOD URBAN model was applied to describe the relationship between the contribution of the upstream area and the volume of the low lying areas. After the calibration on September 1, 2019, the final values of Manning's coefficients for 2D flow areas, which precisely represent the topographic variation, varied from 0.012-0.200. The highest Manning's n value acquired herein was indicated for a dense vegetative cover located near the Golden Jubilee Convention Center and highly dense areas of mainly Chonlada and Chaiyaphruek Villages, and Kham Hai Market, while the bare land around the 8th Infantry Regiment, Siharatdechochai Fort and all roads/pavements were assigned the lowest Manning's n value (see Figure 2 for their locations). The performance of the calibrated MIKE FLOOD URBAN model was evaluated to be reliable for simulating flood propagation and inundation processes based on the acceptable statistical measurements of error, i.e., a low Relative Error (RE) of 0.14 and a high F-statistics (F_S) of 83.72% (see Figure 4). This is strongly supported by recommendations of [39, 40] that the value of RE closer to zero specifies the simulated (0.169 km^2) and observed flood inundations (0.196 km^2) match each other exactly and no overlapping portion was examined, while the high F-statistics indicates the goodness of fit between both flood inundations. Even though there was no observed inundation map available, the MIKE FLOOD URBAN model was still repeatedly validated against historical watermarks and flood information retrieved from several Thai news reports. Three site observations of flood watermarks, i.e., 1) the 12-lane Maliwan Road near Khon Kaen School for the Blind, 2) Khon Kaen School for the Blind and its vicinity areas, and 3) highly dense residential neighborhoods near Northeastern University, were used as benchmark for evaluating the simulated floodwater levels (see Figure 5 for locations of mentioned sites). Based on the total extreme rainfall of 171.8 mm recorded within 24 hours of 25 September 2022 as revealed by the Upper Northeastern Meteorological Center, the simulated flood depths at site 1, which varied from 0.15 to 0.60 m, agreed well with the observed visible flood watermarks ranging between 0.30 and 0.60 m as reported by [41]. At site 2, the simulated flood depths of 0.30 and 1.50 corresponded relatively well with the observed watermarks of 1.00 and 1.50 m as revealed by [42], while the simulated flood depths at site 3 fluctuating from 0.30-1.20 m showed reasonable agreement with the 0.30-0.80 m observed flood watermarks disseminated by [42]. Obviously, both calibration and validation results demonstrated that the model performance of MIKE FLOOD URBAN was highly efficient and can be applied for detecting the flood susceptibility with satisfactory accuracy.

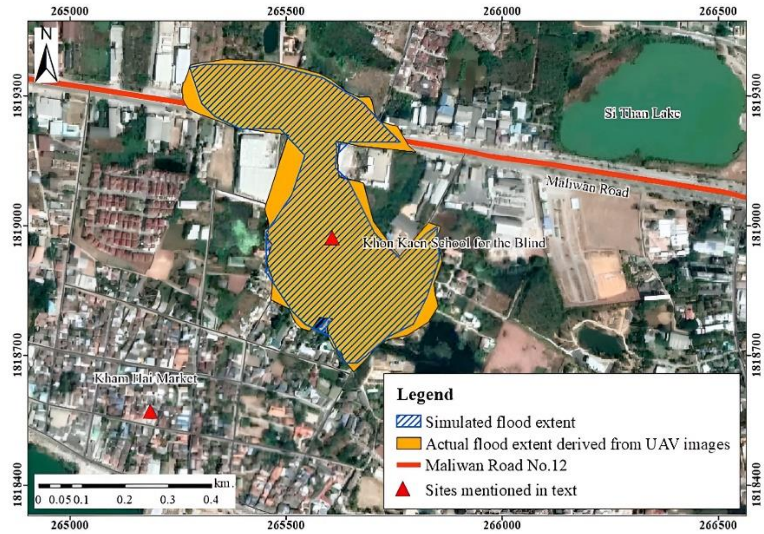

Figure 4 The simulated and actual flood extent derived from UAV images on the flood map during the ***calibration*** (1 September 2019 event)

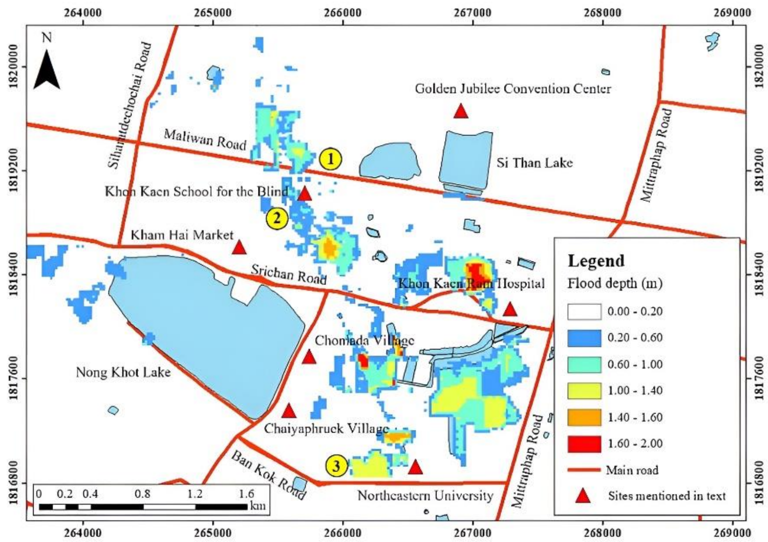

Figure 5 The simulated flood extent on the flood map during the ***validation*** (25 September 2022 event)

3.2 Assessment of mitigation measures for flood risk reduction

After obtaining the reliable and well-suited flood modelling tool that is applicable to flood risk assessment, the MIKE FLOOD URBAN model was then applied to evaluate the efficiency of potential flood mitigation measures in place. Two historical storm events, i.e., 1) 1 September 2019 (the 24-h rainfall with a 40-year return period of 166.2 mm caused by the tropical storm Podul), and 2) 25 September 2022 (the 24-h rainfall with a 50-year return period of 171.8 mm caused by the tropical storm Noru), were simulated to demonstrate how each of the six flood mitigation scenarios used in this study would reduce the flood risk in certain prone areas of Khon Kaen City, as shown the details in Table 1. It should be noted that the 1st storm event (1 September 2019) occurred before the launching of the advance depletion of water level in Nong Khot Lake by 2.5 m (started during April to September 2021 and 2022, and referred to Scenario 2), before the implementation of drainage improvement project for ensuring fast drainage of stormwater to Nong Khot Lake (completed in October 2021 and referred to Scenario 3), and also before the launching of the advance depletion of water level in Nong Khot Lake by 3.5 m (planned to be operated during January to September 2023 and referred to Scenario 4), while the 2nd storm event (25 September 2022) covered specific flood mitigation practices indicated by Scenarios 2 and 3. In fact, the completion of Scenario 3 project and the actual depletion of water level in Nong Khot Lake during April to September 2021 and 2022 of up to 2.5 meters as operated by Banped Subdistrict Municipality are expected to play a vital role in reducing flood losses and ensuring potential residual risks to be avoided. However, both approaches have never been evaluated for their effectiveness at the local level. Therefore, this might be a good chance that this study will lead to guidelines with the systematic identification of flood prone areas that aligns with interventions for integrated resilience and sustainable flood management.

Table 1 Assessed flood mitigation scenarios

Scenario	Name	Description
1	No action (baseline scenario or business as usual)	This scenario looked at what would have happened without the projects in place, i.e., no improvement of Maliwan Road No.12 and its storm sewer system, and no advance depletion of Nong Khot Lake were included in the model simulation. It was used as a basis for comparison of changes resulting from the other proposed scenarios.
2	Advance depletion of water level in Nong Khot Lake by ***2.5 m***	As operated by Banped Subdistrict Municipality, the water level of Nong Khot Lake was set to drop by ***2.5 m*** during April to September to store floodwater.
3	Improvement project of Maliwan Road No.12 and its storm sewer system	To ensure speedy drainage of stormwater to Nong Khot Lake and waterlogging alleviation on Maliwan Road No.12, this project was implemented and completed during 30 March to 25 October 2021 by extending from the north a two-cell 1.2 m x 1.5 m reinforced concrete box culvert from 29 m to 48 m towards the Thaipipat Hardware Company (Maliwan Road Branch) to accommodate the widened road. A 48 m long new two-cell 1.2 m x 1.5 m reinforced concrete box culvert was also constructed from the beginning of Kaen Phayom Road towards the south underneath Maliwan Road. Additionally, a 1.5 km long concrete storm sewer with a diameter enlarging from 1.0 to 1.2 m flowing west from the beginning of Kaen Phayom Road and Khon Kaen Komatsu Sales Company Limited along both sides of Maliwan Road towards the intersection of the 8th Infantry Regiment, Siharatdechochai Fort was also installed (see Figure 2 for aforesaid locations).
4	Advance depletion of water level in Nong Khot Lake by ***3.5 m***	As operated by Banped Subdistrict Municipality, the water level of Nong Khot Lake was set to drop by ***3.5 m*** during January to September to store floodwater.
5	Combination of scenarios ***2*** and ***3***	The combination of Nong Khot Lake management mitigation action by lowering its water level by ***2.5 m***, and the improvement of Maliwan Road No.12 and its storm sewer system, was highlighted.
6	Combination of scenarios ***3*** and ***4***	The combination of the improvement of Maliwan Road No.12 and its storm sewer system, and Nong Khot Lake management mitigation action by lowering its water level by ***3.5 m***, was highlighted.

As presented in Table 2 and compared to Scenario 1, it can be clearly seen that the second storm event (25 September 2022) appeared to be more severe than the earlier storm (1 September 2019) as seen from higher depths of flooding. Therefore, it is important to highlight a wide range of potential implications of climate change on future flood occurrence and its magnitude that would contribute to increases in local flooding within the study area and might spatially and temporally be developed to significant damage to lives and assets. The aforementioned implications emphasize the necessity of a location-specific mix of structural non-structural flood mitigation measures for adapting and reducing/avoiding adverse consequences. The simulated results under the “what-if” scenarios (Scenarios 2 to 6) also revealed a decrease in flood depths under both storm events for all site observations as compared to the baseline scenario or business as usual. However, it seems that the effectiveness of flood depth reduction under Scenario 3 is the lowest among the five what-if scenarios with the smallest reduction in flood depths between 0.04-0.09 m. In details, the combined scenario (identified herein as Scenario 6) accounted for the largest decrease in flood depths at all site observations (ranging from 0.27-0.77 m), followed by Scenario 4 (ranging from 0.22-0.61 m) and Scenario 5 (ranging from 0.13-0.46 m), respectively. Under both storm events, the highest effectiveness of the combined scenario (Scenario 6) was particularly visible in the highly dense residential neighborhoods near Northeastern University with a maximum decrease in flood depth of up to 0.77 m, followed by Scenario 4 at the same location (decrease of up to 0.61 m), and Scenario 3 at the 12-lane Maliwan Road near Khon Kaen School for the Blind (decrease of up to 0.09 m), respectively. Based on the above obtained results, it is obvious that the mitigation options incorporated in Scenarios 3 and 4 can provide a mitigation response to floods throughout critical locations. This is generally a good combination as Scenario 3 can be considered valid and can possibly provide reasonable and realistic benefits in terms of flood risk mitigation as the stormwater will be diverted as complete and as fast as possible from the 12-lane Maliwan Road near Khon Kaen School for the Blind. The lake depletion strategy (Scenarios 2 and 4) is also considered to be valid for the highly dense residential neighborhoods near Northeastern University as the floodwater is stored in the lake for altering the timing and level of peak flows and reducing the flood depth of the abovementioned downstream area. When compared to the validated information reported by news agencies [41, 42] as addressed in section 3.1.2, the simulated results also indicated that the combined scenario provides the highest efficiency in reduction of flood depths for all site observations.

Table 2 Comparison of simulated flood depths between the proposed and baseline scenarios (Scenario 1) under two storm events

Site no. (Storm event)	Flood depth in m for each scenario and changes from Scenario 1 in m										
	Scenario 1	Scenario 2	Change	Scenario 3	Change	Scenario 4	Change	Scenario 5	Change	Scenario 6	Change
1 (Se1)	0.49	0.32	0.17	0.43	0.06	0.24	0.25	0.31	0.18	0.21	0.28
1 (Se2)	0.50	0.35	0.15	0.41	0.09	0.28	0.22	0.32	0.18	0.23	0.27
2 (Se1)	0.78	0.66	0.12	0.73	0.05	0.66	0.29	0.65	0.13	0.37	0.41
2 (Se2)	0.87	0.74	0.13	0.79	0.08	0.43	0.44	0.72	0.15	0.32	0.55
3 (Se1)	0.95	0.78	0.18	0.91	0.04	0.40	0.38	0.69	0.26	0.50	0.45
3 (Se2)	1.29	0.87	0.42	1.22	0.07	0.68	0.61	0.83	0.46	0.52	0.77

Note: Se1 is storm event 1 on 1 September 2019, Se2 is storm event 2 on 25 September 2022

As summarized in Table 3, the majority of flooded areas throughout the entire study were characterized by flood depths ranging from 0.00 to 0.45 m, followed by more than 0.45 m and up to 0.90 m, while the rest were rather small in size of affected areas. Comparing to the baseline (Scenario 1), if the combined scenario (Scenario 6) is deployed, it was found that the average flood depth could be reduced from 0.41 m to 0.31 m or 24.39% under storm event 1 and from 0.47 m to 0.34 m or 27.66% under storm event 2. Meanwhile, the total flooded areas with flood depths under storm events 1 and 2 could potentially be reduced from 32.05 km^2 to 29.59 km^2 or 7.68%, and from 33.57 km^2 to 29.99 km^2 or 10.66%, respectively. It can also be noticed that, when applied individually under both storm events, Scenario 4 is best able to cope with almost all flood depths, except a small flooded area affected by flood depths between 0.90 m and 1.35 m. Importantly, the major benefit of implementing a set of proposed flood mitigation alternatives, i.e., both grey (Scenario 3) and blue (Scenario 4) infrastructures, is the multiplicity of benefits that they could provide in terms of reduction in flood damage to business district of Khon Kaen City. This is due to the synergistic relationship between the proper drainage of stormwater from Maliwan Road to Nong Khot Lake, and the advance depletion of water level in Nong Khot Lake that guarantees more capacity for holding the unexpected inflow into the lake in the flood season and to allow a smaller outflow rate than the inflow rate. Therefore, it can be said that the combination of structural and non-structural measures could be the best scenario for alleviating flood risk, and it is recommended to be adopted by both Khon Kaen Municipality and Banped Subdistrict Municipality for a sustainable flood control and management in Khon Kaen City. However, it seems fair to say that it is not possible to completely eliminate flood risk for affected individuals as each flood mitigation measure to be put in place could reduce the overall risk only up to some degree. That means, besides the proposed mitigation measures, the residual flood risk should likely be managed to acceptable levels that are resilient to continued flood hazard through a judicious mix of structural and non-structural measures based on balanced top-down and bottom-up decision making and a wide involvement of all stakeholders and communities.

Table 3 Comparison of flood inundation areas between five proposed and baseline scenarios under two storm events

Scenario	Flood inundation area in km^2 for each flood depth interval (m)						Average flood depth (m)
	<0.45 m	0.45-0.90 m	0.90-1.35 m	1.35-1.75 m	>1.75 m	Total	
1 (Storm event 1)	29.60	2.04	0.32	0.07	0.02	32.05	0.41
1 (Storm event 2)	30.44	1.53	0.79	0.54	0.26	33.57	0.47
2 (Storm event 1)	29.60	0.93	0.32	0.07	0.02	30.94	0.39
% Change	(0.00)	(-54.41)	(0.00)	(0.00)	(0.00)	(-3.46)	(-4.88)
2 (Storm event 2)	29.36	0.92	0.55	0.14	0.05	31.03	0.37
% Change	(-3.55)	(-39.87)	(-30.38)	(-74.07)	(-80.77)	(-7.57)	(-21.28)
3 (Storm event 1)	29.47	1.03	0.35	0.11	0.02	30.98	0.38
% Change	(-0.44)	(-49.51)	(9.37)	(57.14)	(0.00)	(-3.34)	(-7.32)
3 (Storm event 2)	29.16	0.92	0.32	0.07	0.02	30.49	0.39
% Change	(-4.20)	(-39.87)	(-59.49)	(-87.04)	(-92.31)	(-9.17)	(-17.02)
4 (Storm event 1)	28.98	0.85	0.33	0.07	0.02	30.24	0.37
% Change	(-2.09)	(-58.33)	(3.13)	(0.00)	(0.00)	(-5.65)	(-9.76)
4 (Storm event 2)	29.10	0.98	0.58	0.27	0.05	30.90	0.35
% Change	(-4.40)	(-35.95)	(-26.58)	(-50.00)	(-80.77)	(-7.95)	(-25.53)
5 (Storm event 1)	29.44	0.92	0.47	0.07	0.02	30.91	0.36
% Change	(-0.54)	(-54.90)	(46.88)	(0.00)	(0.00)	(-3.56)	(-12.20)
5 (Storm event 2)	28.87	0.79	0.41	0.17	0.04	30.27	0.35
% Change	(-5.16)	(-48.37)	(-48.10)	(-68.52)	(-84.62)	(-9.83)	(-25.53)
6 (Storm event 1)	28.82	0.48	0.22	0.07	0.01	29.59	0.31
% Change	(-2.64)	(-76.47)	(-31.25)	(0.00)	(-50.00)	(-7.68)	(-24.39)
6 (Storm event 2)	28.49	0.93	0.40	0.14	0.02	29.99	0.34
% Change	(-6.41)	(-39.22)	(-49.37)	(-74.07)	(-92.31)	(-10.66)	(-27.66)

Note: Storm event 1 = 1 September 2019, Storm event 2 = 25 September 2022

4. Conclusion

It should be emphasized that the rapidity of flood occurrence can cause difficulty in capturing the flood propagation after excessive rainfall events in urban area like Khon Kaen City, as there is obviously a lack of analysis of flood prone areas, flood impacts, and potential mitigation and preparedness alternatives, as well as no information regarding socio-economic vulnerability to floods in Khon Kaen City. The flood information and additional data that exist today in Khon Kaen City is still based on collective working experience of responsible agencies, newspapers, and real-life experience and lessons learned from previous floods of individuals, which are sometimes not provided in a timely manner and not accurate enough. Therefore, the assessment of flood impacts at various levels corresponding to different flood scenarios is important and desired, so that more resilient and adaptive flood mitigation services under different hydrometeorological extremes can be recommended that best corresponded to the objective of this research. Based on readily available and sufficiently accurate flood information, the methodology applied herein can also be replicated to other flood affected areas for similar flood damage reduction purpose.

In this study, the hydrological assessment was conducted to estimate the potential flood flow through MIKE URBAN that allows the coupling of a 1D rainfall-runoff model with a 1D pipe network. The interaction between the drainage network and the catchment surface was then investigated by dynamically coupling MIKE URBAN and MIKE 21 2D hydraulic model on the MIKE FLOOD URBAN platform, in which the volume of water that stored and caused inundation in flood hotspot areas, and continued further downstream, and caused the inundation was estimated by MIKE 21. Even though there is a lack of datasets collected regularly for monitoring and management, the frequently used and powerful models including MIKE URBAN and MIKE FLOOD URBAN were still at best calibrated and validated at an acceptable level of statistical accuracy. It can be said that the model results replicated the observed flood behavior through the entire study area quite accurately as confirmed by a comparison to valid observed data (i.e., Nong Khot Lake daily water level between 22 August to 13 September 2019 and 9 July to 10 August 2022, and flood extent from UAV data and flood peak watermarks during the events of 1 September 2019 and 25 September 2022) gathered from relevant agencies and news/websites. As such, the use of a model coupling framework was considered appropriate for flood modelling and mitigation options investigation. The impacts of two separate flood events that caused widespread flooding in Khon Kaen City on September 1st, 2019, and September 25th, 2022, were analyzed including the 40- and 50-year floods, respectively.

Under a "no change" alternative, the findings from the flood scenarios revealed that a major shift in flood depths from the shallow flood depths to considerably deeper values and a larger extent of inundation were observed with the increase in return periods (from 40 to 50 years). To estimate how the proposed scenarios contribute to flood mitigation in Khon Kaen City, the inundation area and depth of flood were determined under six scenarios. A "business-as-usual" scenario with no action taken at all was used as a reference point from which other scenarios can be measured, and the other five scenarios with implemented mitigation efforts for drainage improvement at the 12-lane Maliwan Road near Khon Kaen School for the Blind, and consistently following the depletion schedule of water level in Nong Khot Lake as planned by Banped Subdistrict Municipality for a certain period. As compared to no action (Scenario 1), the integrated flood mitigation measures in the context of combination of drainage improvement for efficient stormwater flow to Nong Khot Lake and waterlogging alleviation on Maliwan Road No.12 (Scenario 3), and advance depletion of water level in Nong Khot Lake by 3.5 m (labeled as Scenario 4) would be the most effective strategy for mitigating floods in Khon Kaen City as it highlighted the highest potential in reducing average flood depths for maximum of up to 0.10 m (24.39%) and 0.13 m (27.66%) under storm events 1 and 2, respectively. Once considered separately, there is no doubt that the 12-lane Maliwan Road near Khon Kaen School for the Blind can gain benefit from drainage improvement for waterlogging areas project (Scenario 3), while the highly dense residential neighborhoods near Northeastern University would benefit from Nong Khot Lake depletion strategy under each lake operation alternative (Scenarios 2 and 4).

Based on the analysis of depth-wise inundation area, most of the flooded areas were those flood depths ranging from 0.00 to 0.45 m. The inundation area with more than 1.75 m flood depth was found to be very small for different flood mitigation scenarios, which perhaps confirmed the effectiveness of proposed measures in dealing with high flood tolerance. However, whilst the combined scenario (Scenario 6) is expected to significantly reduce the flood risk within Khon Kaen City, it cannot completely eliminate the risk as the flooding would still occur although this set of flood mitigation options is still employed. Meanwhile, it is also important to bear in mind that, although the potential of integration of "hard" infrastructure complemented with "soft" infrastructure is recognized, various practical obstacles might still impede its integration into mitigation plans. Therefore, enforcing appropriate land use planning, extensive depletion of storage of Nong Khot Lake of up to 4-5 meters for storing more floodwater than what Banped Subdistrict Municipality does now, and proper design, construction, operation and maintenance of stormwater facilities elsewhere, and other possible alternatives in collaboration with all stakeholders, are also essential and recommended to mitigate the risk from floods to Khon Kaen City. In addition, for further study, the assessment of proposed flood mitigation measures and other possible management activities, which consider both potential benefits and adverse effects, must highlight social and environmental impacts as they are mostly compared based only on the economic criteria. In details, the environmental impact of flood mitigation measures can be minimized by harmonizing future flood mitigation designs with a proper surrounding environment and ecosystem. In respect of social impact perspective, alternative housing and social assistance should be offered to residents living in dwellings at risk as a direct result of flood mitigation efforts. Further, there should also be a paradigm shift towards technically, environmentally, and economically viable flood mitigation alternatives to be well adapted and resilient to the projected and unexpected impacts of climate change at the appropriate point in time in the future.

Finally, as the simulation results agreed well with the actual situation in Khon Kaen City, thereby confirming the applicability and transferability of the proposed modeling framework for risk assessment of other flood prone areas at relevant spatial and temporal scales. In addition, the local government and concerned agencies should also tailor the research findings to provide necessary alternatives and policies to avoid and manage future flood occurrence under climate change conditions in Khon Kaen City.

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