Flood Modelling Group Report

The GCRF-OSIRIS Project

Optimal Investment Strategies to Minimize Flood Impact on Road Infrastructure in Vietnam

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1. Introduction

Urban flooding is a serious hazard posing multiple challenges due to its force and its rapid impact. Many cities in developing countries in Southeast Asia face challenges posed by urban flooding, as a result of changing rainfall patterns combined with rapid urban growth, which is often associated with poor drainage infrastructure (Mark et al., 2004). Urban flooding has become more prevalent in recent decades due to land use change and climate change (Chang et al., 2010). The social and financial costs of urban flooding are raising the concern of relevant stakeholders. Predictions of the extent of flood inundation are now greatly improved, by advances in numerical modelling techniques, radar and optical remote sensing, and GIS modelling.

Many studies of urban flooding have been carried out using a combination of physical modelling and GIS approaches (e.g. Sarhadi et al., 2012, Zhang et al., 2014). Some have applied the Storm Water Management Model (SWMM) which is a typical urban storm/flooding hydrologic model to address urban inundation (e.g. Lin et al., 2004, Zhang et al., 2013) while others employ hydro-dynamic models (e.g. Mark et al., 2004, and Chang et al., 2010).

In Vietnam, the number of studies on urban flooding has been limited. Some have applied a numerical modelling approach to simulate flood situations. Of these, most employ MIKE software developed by the Danish Hydraulic Institute (DHI). The packages used for inundation research in Vietnam are primarily MIKE 11, MIKE 21 and MIKE URBAN. For example, Thang et al. (2009) used MIKE 11 and NAM modules for inundation caused by heavy rain and sea level rise in the city of Da Nang. Results showed that the flooded area and inundation depth in Da Nang are both increasing under trends linked to climate change, intensive rainfall, and inadequate sewage systems. Pham et al. (2015) applied the MIKE Flood model which combines the MIKE URBAN module with MIKE 21, to simulate historical rainfall events of 2008 and 2013 for Hanoi. Results showed that urban flooding was caused by the excess of rain water to drainage capacity of the old sewage system. Dai (2015) conducted research on urban flooding in Ninh Kieu District in the city of Can Tho, using a MIKE package including MIKE NAM, MIKE 11 and MIKE Open. The research utilized climate scenarios published in 2012 by Vietnam's Ministry of Natural Resources and Environment for future climate projections. Results of this study were consistent with the findings of Huynh and Pathirana (2013) about the causes and magnitude of inundation in Can Tho.

Nguyen et al. (2013) developed a flood map for the extreme rainfall event in Hanoi in 2008, and assessed vulnerability. Their study collected Aster and SPOT or Landsat satellite image data from different periods, and analyzed them using ILWIS software to identify inundated areas. These were used with DEM created from topographic maps, to calculate the inundation depths. Next, the authors used remote sensing image processing combined with geomorphologic data, to separate low ranges and riverbeds. Finally, the data were combined to create a flood map of Hanoi. The results showed that inundated areas are increasing from the northern to the southern area of the city, and from east to west.

Kefi et al. (2018) applied spatial analysis to assess tangible future flood damage in To Lich urban area of Hanoi. Results revealed that the impacts of climate change will increase total flood damage by 26%. The findings also indicated that climate change combined with the expansion of built-up areas increases the vulnerability of urban areas to flooding and economic damage. Lou et al. (2018) set up a flood inundation model for Hanoi using a Flo-2D model, to analyze water depth and the inundation area under four historical, extreme rainfall types, and to identify sustainable approaches to urban flood management under present conditions and under climate change conditions. Referenced photographs were used to calibrate flood simulation results in Hanoi's central area in 2008. The water depth at the different locations was simulated under the four extreme rainfall types: the historical rainfall of 2008; the historical maximum two-day rainfall; probable precipitation in a return period of 200 years; and probable maximum precipitation. The flood inundation under the 'probable maximum precipitation' presented the highest risk in terms of water depth and inundation area. However, care should be taken since this study only considered the dimensions of the river channel based on elevation, due to a lack of cross-section data.

Few studies have applied the Storm Water Management Model (SWMM) which is a typical urban storm-flooding hydrologic model for simulation of urban flooding (Lin et al. 2004). This model considers precipitation and runoff mechanisms in urban locations to simulate rainfall-runoff, especially from a single storm or successive rainfall runoff in urban areas (Zhang et al. 2014). A study by Huynh and Pathirana (2013) used a 1-D/2-D coupled urban-drainage/flooding model (SWMM-Brezo) to simulate storm-sewage surcharge and surface inundation, to establish the increase in flood hazard resulting from a change in parameters. The results showed that under the combined scenario of significant change in river water levels (due to climate-driven sea level rise and increase of flow in the Mekong) and 'business as usual' urbanization, the flooding of Can Tho could increase significantly.

Overall, although urban flooding in some of Vietnam's major cities has been studied, the number of studies is still small. In general, the MIKE modelling package from DHI is the prevailing tool for research. Challenges for these studies include the difficulties in obtaining data on topography, sewage and pipeline networks due to data unavailability and/or fragmental data storage in different government departments or agencies.

This study aims to simulate the urban flooding of Hanoi (including 8 old districts, with focus on one hotspot, Dong Da District), for the historical flooding event of 2008, and to generate flood maps under different climate change scenarios, and to consider various mitigation measures which have been carried out to improve Hanoi's drainage capacity.

2. Methodology and Computation using MIKE URBAN

2.1. General introduction to MIKE URBAN

MIKE URBAN is a software that simulates urban drainage system and is capable of integrating with GIS systems. It is able to calculate and simulate a whole city water network including the water supply system and rainwater and wastewater drainage systems, within combined or separate sewage system.

MIKE URBAN is based on the development platform of ESRI Arcobjects, meaning it shares the same data storage and processing protocols as other ArcGIS tools. MIKE URBAN data is stored in a Geodatabase format to facilitate utilization of the ArcGIS toolbox of ESRI. MIKE URBAN supports development of both water supply and drainage systems in a single set of integrated GIS data. MIKE URBAN has the following features:

- GIS integrated environment
- Supported by GIS tools from ESRI, the latest version with a standard simulation technology

- Open data model
- Comprehensive, no additional GIS or copyrighted software required
- Includes all necessary tools for floodwater system analysis and water diversion system in one software package.
- Links with GIS, CAD and acts as a management model.

2.2. Main Components of MIKE URBAN

The Collection System (CS) is based on two simulation algorithms: MOUSE-HD and SWMM5, which include these minor modules:

- CS – Rainfall-Runoff: simulates rainfall-runoff for each time period by region, dynamic wave, and linear reservoir.
- CS – PipeFlow: simulates unstable flow in pipes and channels.
- CS – Control: capable of implementing time operating of dykes, pumps etc. Supports description of control devices' activities, and gives logical explanations of the operations procedures of control devices.
- CS – Pollution Transport: simulates spread and amplification of pollutants, including muds; including building models of water quality upon building amplification model of pollutants from surface water to wastewater system.
- CS – Biological Processes: simulates chemical and biological process(es) of polluted and compound systems.

Water Distribution (WD): The components of the WD system are based on the advanced extension of DHI with the calculation core EPANET and the slow flow modulation core WH of DHI. Basic components of WD include:

- Stable runoff simulation
- Extension period simulation
- Water quality simulation by time periods.

MOUSE is the main module of MIKE URBAN. It includes the following:

- Runoff modelling with MOUSE: used to calculate the flow from rainfall data and flow data as input, from the calculation of one-dimensional flow (1D) in the system.
- Hydraulic Network Modelling with MOUSE: used to calculate the one-dimensional flow in the system. The Runoff module's calculation is taken as input for this module.
- 2D Overland Flow: used to calculate the overland flow in an area, the input for this model being the results from the Network module. The result of this module is used as the basis for developing inundation maps and the system's drainage status.
- MOUSE drainage pipe design model
- MOUSE water quality model
- MOUSE hydraulic network model

The MOUSE Flow module is the main module and unstable flow simulation tool in the alternative pipes in free surface with pressured flow condition. Calculation is based on some 1-D methods and the Saint-Venant method. The algorithms provide suitable and accurate solutions in the module that is connected with the calculation network. MOUSE Flow calculations are applied in the flows running along the pipes, urban drainage collection nodes, drainage areas, pressured drainage pipes, and outlets with different water levels. Calculations also simulate hydraulic factors of open prismatic channels. Flow calculation is implemented by narrow slot and extended to the length of the pipe via different cross-sections of the closed channel. At that time, surface flow (with no pressure) and the pressured flow simulated in the basic algorithms, ensure a smooth and stable transition between two flows. A non-linear flow equation can be applied in edge conditions (Q~H, H~t) or automatically taken into the conditions of calculation. In the pipe flow model, calculations allow description of factors within a drainage system such as the pipe system, operation feature system and flow system.

The components of Flow MOUSE are:

- Link: through standard pipe and transverse section.
- Nodes: manholes, basin, storage, outlets.
- Equation: overflow weirs, orifices, pumps, non-return valves, flow regulators.
- Controllable structures: modulation of factor activities based on time and real time.

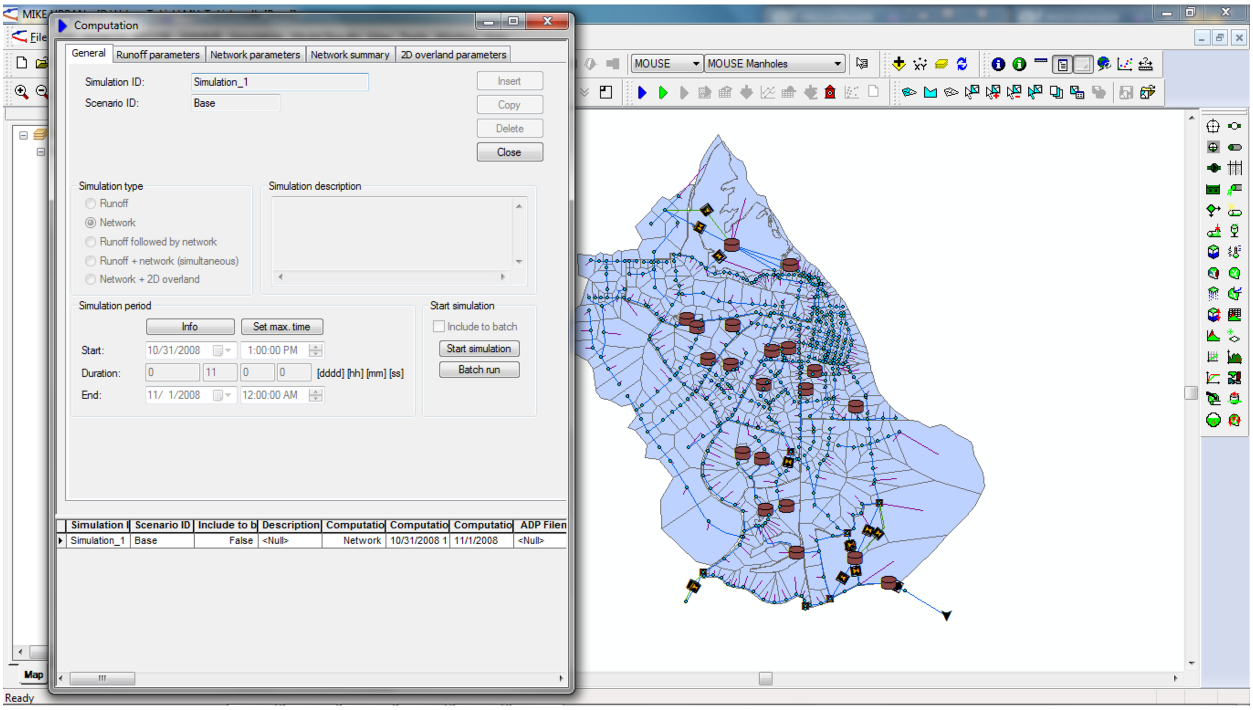

Figure 1: Interface of MIKE URBAN MOUSE

Flows in nodes and function area calculated using basic hydraulic formulas. Uneven flows in links are described using the Saint-Venant equation and solved using a differential algorithm.

2.3. Saint-Venant Function

Models applied for cases of hydraulic waves solving of equations along the length of the pipe, based on the following assumptions:

- The water cannot be compressed and uniform, so change in the density is very small.
- Bed Slope is small, thus the cosine of the angle with the length can be considered as equal to 1.
- Vertical acceleration can be overlooked.
- Supercritical flows area also modelized in MOUSE, but in a more limited condition.

Continuity equation is as follows:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \qquad (1)$$

Dynamic equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial(\boldsymbol{\alpha}\frac{Q^2}{A})}{\partial x} + gA\frac{\partial y}{\partial x} + gAI_f = gAI_0 \qquad (2)$$

In which:

Q – Flow rate (m^3/s)
A – Cross-sectional area of the flow (m^2)
y – Cross-sectional flow depth (m)
g – Gravitational acceleration (m/s^2)
x – Distance in the flow direction (m)

t – Time (s)
α – Velocity of partition coefficient
I_0 – Bed slope
I_f – Slope friction

Flow equations, in general, are non-linear and are a hydraulic component of differential equations. Equations identify flow conditions (water pressure and flow discharge) in one pipe or channel in the baseline condition and edge condition.

2.4. Rainfall Runoff Model in MOUSE

MOUSE provides a toolbox and flexible models to simulate urban surface runoff and infiltration. A rainfall-runoff model helps develop simulation at a different detail level, and the result of this model can be taken as input to model the water collection system. Calculation of direct runoff into the system from rainwater is divided into two steps in the rainfall flow model, as illustrated opposite.

Step 1: Flow is calculated based on the water collection catchment, the links to the system, the parameters of the hydrological models, temperature, rainfall, and evaporation parameters.

Step 2: The results are used as input for the hydraulic system and dividing flow into the system.

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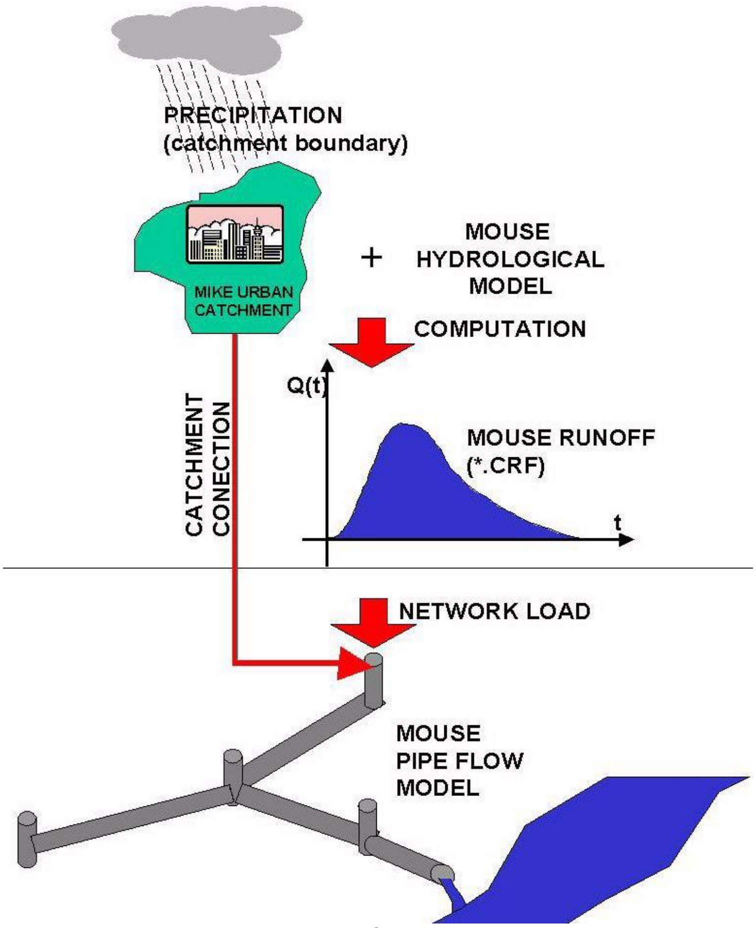

Figure 2: Illustration of Transitional Steps in Rainfall-Runoff Model

There are two types of hydraulic model: the surface runoff model (surface runoff calculation is disrupted between raining intervals) and the continuous hydrology model (simulation model of precipitation flows from continuous rain. The result of flow modelling is the sum of surface runoff and other sub-surface runoff). The surface runoff model is suitable for urban areas with large and fast flows, while the continuous flow model is suitable for suburban areas with no fast simulation of surface with small percolation like urban areas.

2.5.Flow in Pipeline System

In a rainfall event, part of the rain water will infiltrate into the ground surface (only the permeable area) while the remainder will form the runoff and subsequently concentrate to the manhole, flowing through the pipeline to the outlet of a drainage system (often a pumping station). When rainfall amount exceeds the pipeline capacity, a portion of the water is temporarily stored in regulating reservoirs/ponds (described as BASIN in the MIKE-URBAN model). If the regulating ponds are full, then flooding occurs (the water overflows at the manhole). As the water level in the pipeline drops, the water flows from the regulating ponds to the pipeline.

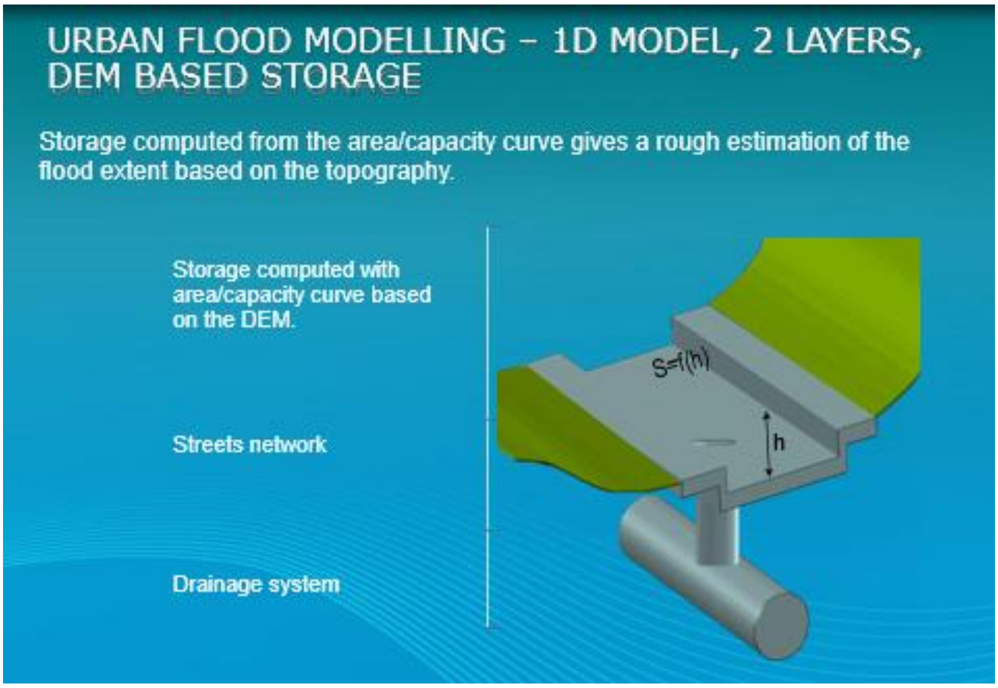

Figure 3: *1D model in MIKE URBAN*

3. Data and Materials

3.1. Collection of Data on Topographic, Drainage System and Inundation

In this study, the following data were collected and processed for the generation of flood maps:

- A topographic map for 8 urban districts (DEM with resolution of 30m)
- A map of land use in 2012 with a scale of 1/25,000
- A map of current infrastructure
- Documentation of the current drainage and irrigation systems (sewer, canals, reservoirs, regulating lakes, pumping stations).

- The modelling group also measured parameters of 20 sewer pipelines in Dong Da District with size 0.4-1m for 40 node points, and updated bottom elevation parameters, and topography of drainage sewers for the 8 urban districts.

3.2. Hydro-Meteorological Data

3.2.1. Rainfall Data

Results of the hourly rainfall simulations with spatial resolution of 1km x 1km simulated from the WRF model were provided by the GCRF-OSIRIS Project's Rainfall Modelling Group. Rainfall data from the flood events of 2008, 2012 and 2013 were extracted from a meteorological model in a 1km grid cell, and calibrated and validated with rainfall data measured at meteorological stations surrounding Hanoi, (see report prepared by the Climate Modelling Group for further information).

Hourly rainfall data derived from the event of 17-18 August 2012 were used for model calibration, and data from 8-9 August 2013 were used for model validation. Figure 4, below, shows the spatial domain, in grid cells, for rainfall used in this study.

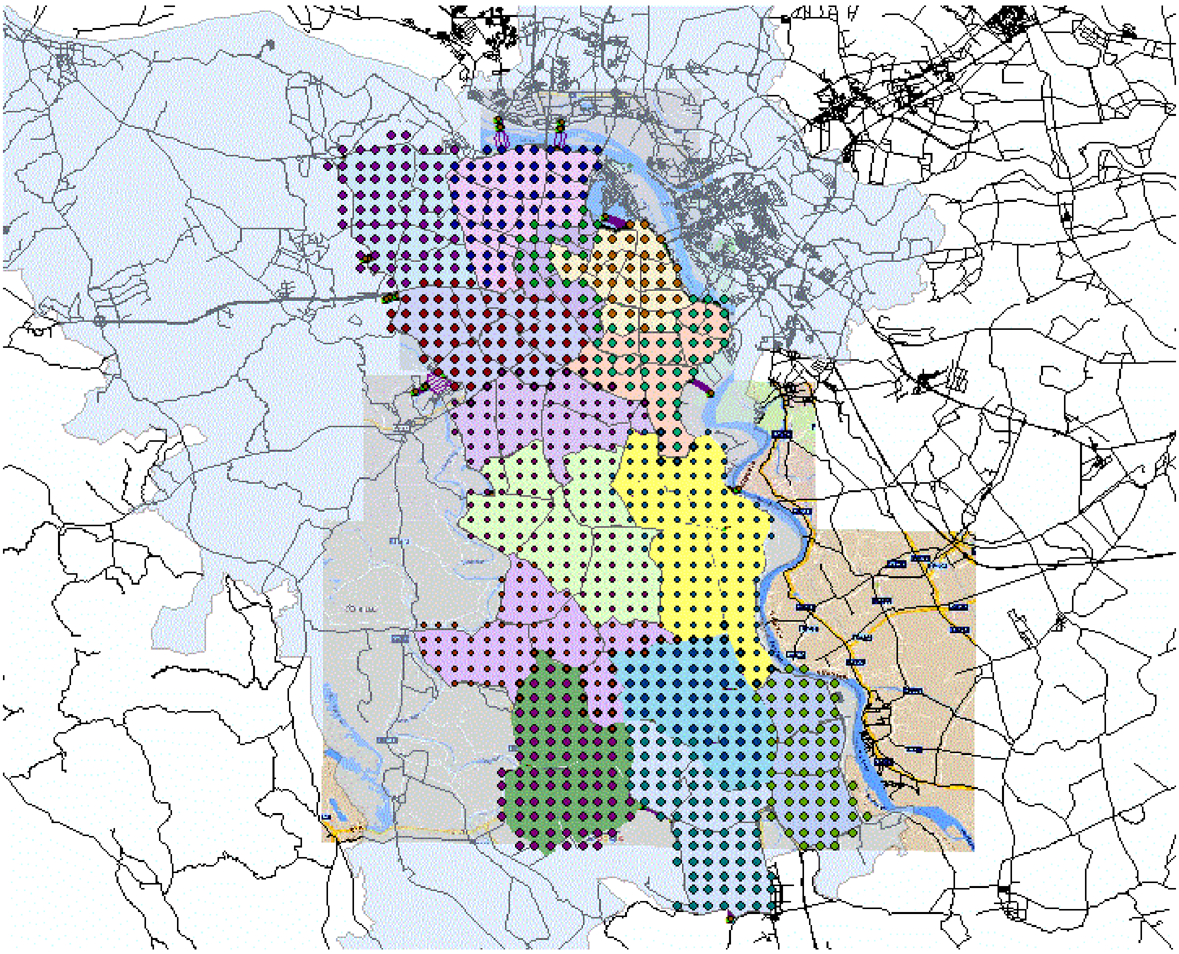

Figure 4: Gridded Rainfall Data used in MIKE URBAN

Information on water levels in reservoirs, lakes and irrigation system were collected from Hanoi Drainage One Member Co., Ltd. and Hanoi Irrigation Department.

3.2.2. Floodwater Depth

Data on urban flood events caused by heavy rains in the past, were collected for this study. These are flooded marks distributed in eight districts including Dong Da District, obtained from the Hanoi Drainage One Member Co. Ltd., and the Hanoi Irrigation Department. Details of these data include:

- Data for the flood event in 2008 with 37 flood marks
- Data for the flood event in 2012 with 138 flood marks
- Data for the flood in 2013 event with 65 flood marks.

In addition to the above-mentioned data, the flood modelling group gathered measurements of water depths at locations in Dong Da District during the rainfall events of July 2018.

3.2.3. Precipitation Probability

To calculate flooding under different rainfall distribution probabilities (1% and 5%), the 1-day maximum annual rainfall of 36 years (from 1982 to 2017) at Lang meteorological station was used. The highest value for 1-day rainfall during this period is 142.2 mm. The characteristics of the distribution curve (Pearson III) are Cv = 0.53 and Cs = 2.39. From this frequency curve, the largest 1-day rainfalls corresponding to the frequencies of 1% and 5% were defined as 428.97mm and 293.61mm respectively. The representative year corresponding to 1% frequency was 1984, with the highest daily rainfall of 394.9mm, and the year corresponding to 5% frequency was 1989, with the highest daily rainfall of 220.6mm. However, since 1984 and 1989 were many years ago, real time series of hourly data are not available, and therefore data from 2008, with the largest one-day rainfall of 347mm, was used instead, to generate frequencies of 1% and 5%.

4. Setting up MIKE URBAN for Simulation of Flooding in Hanoi

The MIKE URBAN model was applied to simulate the rainfall-runoff process on the surface 1-dimensional flow in drainage systems and holes. The results derived from the model were subsequently combined with a DEM map to generate the flood map of the study area.

4.1. Networking and Setting Input

A detailed set up (with additional information and data on the drainage network) was made for Dong Da District, the hotspot in this study, including a network of computing nodes, sewers, canals, manholes, regulating lakes, pumping stations, and a less dense drainage network, was prepared using MIKE URBAN, for 8 urban districts, with the following:

- 848 computed nodes: 818 manholes, 21 regulating lakes (basin) and 9 outlets
- 6 pumping stations with 29 units and 6 damper valves.
- 939 sewers (link) including rectangular ones and circular ones.

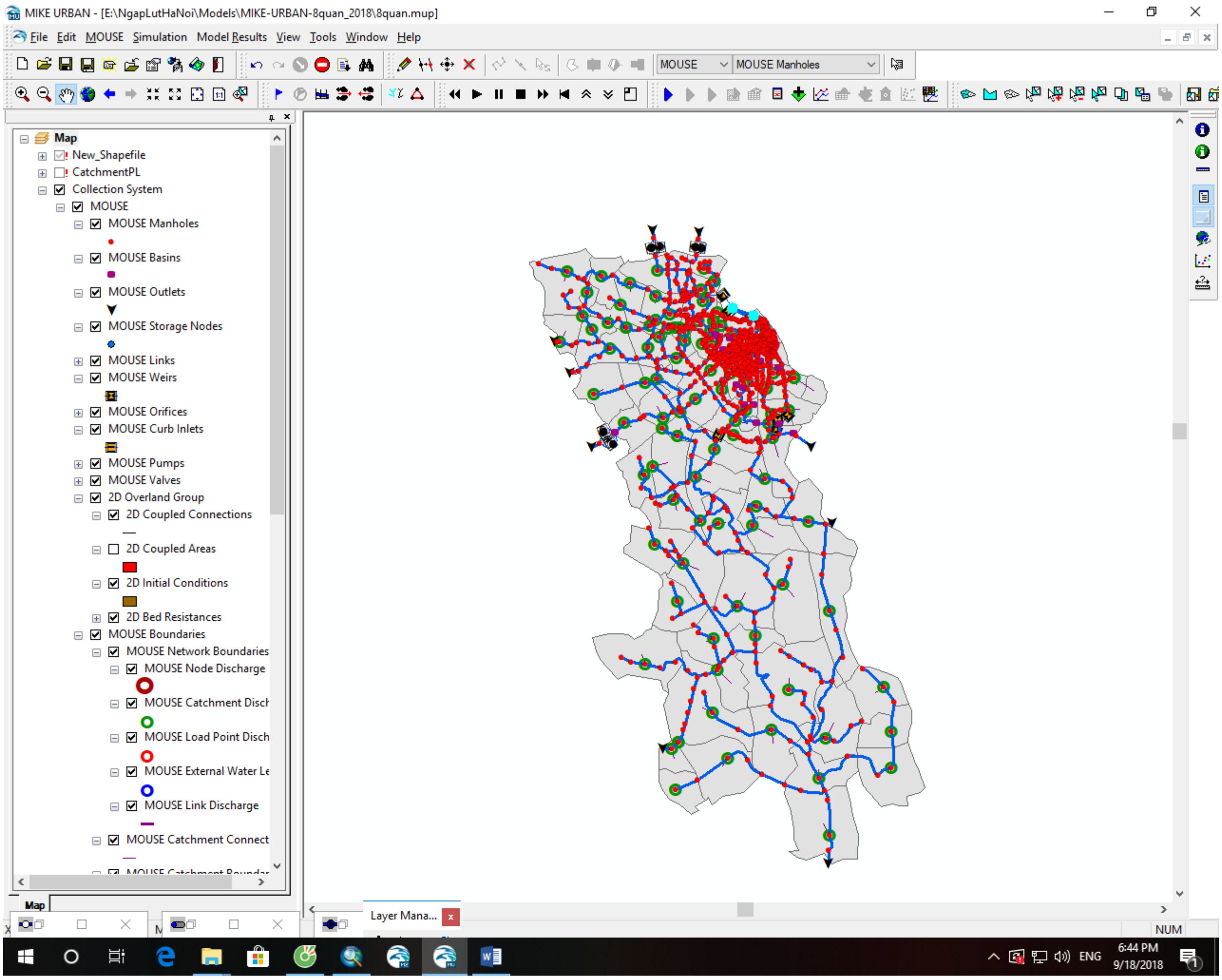

Figure 5: Research Area and its Drainage System set up in MIKE URBAN

Nodes [Base]

Node ID *	Node type *	Bottom lev	Ground lev	Diameter	Critical leve	ID	Use loc
831	Manhole	3.76	7.26	4.0000	<Null>	MOUSE Clas	F
832	Manhole	3.26	6.76	4.0000	<Null>	MOUSE Clas	F
833	Manhole	0.93	5.93	2.0000	<Null>	MOUSE Clas	F
834	Manhole	3.16	7.16	5.0000	<Null>	MOUSE Clas	F
835	Manhole	0.70	7.70	5.0000	<Null>	MOUSE Clas	F
836	Manhole	0.70	7.70	5.0000	<Null>	MOUSE Clas	F
837	Manhole	7.00	16.00	2.0000	<Null>	MOUSE Clas	F
838	Outlet	7.00	10.00	25.0000	<Null>	Weighted Inle	T
84	Manhole	1.20	1.64	4.5000	<Null>	MOUSE Clas	F
840	Manhole	3.00	14.51	1.0000	<Null>	MOUSE Clas	F
841	Manhole	7.00	16.00	1.0000	<Null>	MOUSE Clas	F
842	Outlet	7.00	11.00	1.0000	<Null>	Weighted Inle	T
843	Manhole	7.30	16.70	2.0000	<Null>	MOUSE Clas	F
844	Outlet	3.30	7.03	2.0000	<Null>	Weighted Inle	T
845	Manhole	5.30	14.70	2.0000	<Null>	MOUSE Clas	F
846	Outlet	3.30	7.02	25.0000	<Null>	Weighted Inle	T
847	Manhole	3.10	12.50	10.0000	<Null>	MOUSE Clas	F
848	Outlet	3.10	6.82	1.0000	<Null>	Weighted Inle	T
85	Manhole	0.99	3.72	2.0000	<Null>	MOUSE Clas	F
86	Manhole	0.73	2.57	2.0000	<Null>	MOUSE Clas	F
87	Manhole	0.57	2.57	2.0000	<Null>	MOUSE Clas	F
88	Manhole	0.19	5.03	2.0000	<Null>	MOUSE Clas	F
89	Manhole	0.17	1.78	4.5000	<Null>	MOUSE Clas	F

Pipes and Canals [Base]

Link ID *	Shape *	UpLevel	DwLevel	Length	Slope
898	Rectangular	3.30	3.20	434.730	
899	Rectangular	3.20	3.10	1018.783	
9	Rectangular	3.40	3.38	228.425	
900	Rectangular	7.30	3.30	138.219	
908	Rectangular	2.80	2.50	1168.563	
909	Rectangular	2.50	3.40	1548.271	-
910	Rectangular	3.40	3.29	1033.657	
911	Rectangular	5.30	3.30	221.283	
917	Rectangular	0.20	-1.00	670.620	
918	Rectangular	-1.00	-1.00	913.272	
919	Rectangular	-1.00	2.23	1732.249	-
920	Rectangular	2.23	-1.00	372.951	
921	Rectangular	-1.00	-1.00	1343.541	
922	Rectangular	-1.00	-1.00	1164.952	
923	Circular	3.10	3.10	683.332	
93	Rectangular	3.29	3.25	190.560	
938	Rectangular	4.01	2.90	479.442	
939	Rectangular	0.00	2.50	404.465	-
94	Rectangular	3.25	3.22	91.134	
95	Rectangular	3.22	3.07	77.871	
96	Rectangular	3.07	3.03	353.932	

Figure 6: Parameters of nodes, pipeline and canals set up in MIKE URBAN

Based on 2018 traffic and topographic maps, the study area was divided into 105 sub-basins/catchments.

Catchments [Base]

MUID *	Drainage ar	User X coo	User Y coor	Total area	X coordinat	Y coordinat	Max. level
Catchment_18_3	<Null>	576669.757	2326418.80	0.096	576669.757	2326418.80	<Null>
Catchment_19_2	<Null>	578392.323	2324777.71	766.328	578392.323	2324777.71	<Null>
Catchment_20_2	<Null>	579057.942	2326989.11	0.300	579057.942	2326989.11	<Null>
Catchment_21_1	<Null>	577788.465	2326919.62	269.973	577788.465	2326919.62	<Null>
Catchment_22_1	<Null>	579535.839	2326489.47	63.704	579535.839	2326489.47	<Null>
Catchment_22_2	<Null>	579390.230	2325922.66	68.214	579390.230	2325922.66	<Null>
Catchment_25_2	<Null>	583266.524	2331471.66	475.545	583266.524	2331471.66	<Null>
Catchment_25_3	<Null>	584069.598	2330251.47	0.011	584069.598	2330251.47	<Null>
Catchment_25_4	<Null>	584338.803	2329970.17	0.000	584338.803	2329970.17	<Null>
Catchment_26_2	<Null>	582737.358	2329971.73	333.721	582737.358	2329971.73	<Null>
Catchment_28_2	<Null>	582675.125	2328373.61	491.800	582675.125	2328373.61	<Null>
Catchment_30_2	<Null>	587994.880	2326312.17	340.981	587994.880	2326312.17	<Null>
Catchment_32_1	<Null>	588531.722	2324272.95	444.105	588531.722	2324272.95	<Null>
Catchment_33_2	<Null>	588956.565	2322649.77	404.503	588956.565	2322649.77	<Null>
Catchment_36_1	<Null>	585617.941	2326069.68	509.987	585617.941	2326069.68	<Null>

Figure 7: Parameters of Sub-Catchments

4.2. Calibration and Verification of the MIKE URBAN Model

In most conditions, calibration is a prerequisite for successful application of the model in a catchment (Cullman et al, 2011). In this study, the parameters of the MIKE URBAN model were calibrated against the observed flood event of 2012, and validated by the 2013 flood event, to identify the optimal model parameter set, using trial and error methods.

4.2.1. Model Calibration

The rainfall event of 17-18 August 2012 was used for model calibration. Tables 1 & 2 show modelled water depth and measured water depth for eight districts, and details for Dong Da District, respectively. It is clearly shown in the table that the difference between simulated and measured water depth is in the range of ΔH = 0.03 - 0.22 m, showing a reasonably good fit between simulated and measured water depth for the model calibration. The flood maps were generated using the simulated water depths as input data.

No	Location	Modelled water depth (m)	Measured water depth (m)	ΔH(m)
1	Tường nhà cô Mơ, Hoàng Quốc Việt, Cầu Giấy	1.38	1.33	-0.05
2	Tường nhà chị Lan Anh, Xuân La, Tây Hồ	1.32	1.29	-0.03
3	33 Tường nhà chị Minh, Phạm Ngọc Thạch, Đống Đa	1.33	1.28	-0.05
4	Tường nhà anh Kim, Nguyễn Khánh Toàn, Cầu Giấy	1.22	1.19	-0.03
5	20 Công ty thiết bị phụ tùng Hòa Phát, Yên Sở, Hoàng Mai	1.22	1.19	-0.03
6	Tường nhà anh Văn, Trần Đăng Ninh, Cầu Giấy	1.2	1.17	-0.03
7	Tường nhà ânh Hải, Thanh Nhàn, Hai Bà Trưng	1.19	1.12	-0.07
8	31 Tường nhà anh Minh, Trương Định, Hoàng Mai	1.15	1.11	-0.04
9	Tường nhà chị Châu, Đại Kim, Hoàng Mai	1.12	1.07	-0.05
10	32 Tường nhà cô Kê, Nguyễn Tam Trinh, Hoàng Mai	1.05	1.01	-0.04
11	Tường nhà chị Thúy, Thịnh Liệt, Hoàng Mai	0.97	0.94	-0.03
12	4 Tường nhà số 32D1B, ngõ 231, Tân Mai, Hoàng Mai	0.93	0.9	-0.03

Table 1: Modelled and measured water depth at locations in eight districts in 2012 (calibration)

No	Location	District	Measured water depth (m)	Modelled water depth (m)	ΔH(m)
1	Nguyễn Khuyến	Đống Đa	0.3	0.486	0.186
2	Phạm Ngọc Thạch	Đống Đa	0.4	0.3	-0.1
3	Khâm Thiên (ngõ Toàn Thắng)	Đống Đa	0.3	0.25	-0.05
4	Thái Thịnh	Đống Đa	0.3	0.39	0.1
5	Nguyễn Lương Bằng (BV Đống Đa)	Đống Đa	0.4	0.57	0.17
6	Trường Chinh (số 510- Ngã Tư Sở)	Đống Đa	0.5	0.56	0.06
7	31 Nguyễn Chí Thanh	Đống Đa	0.2	0.31	0.11
8	Thái Hà (ngõ 161)	Đống Đa	0.2	0.26	0.06
9	Cát Linh	Đống Đa	0.25	0.13	-0.12
10	Lê Duẩn (cửa ga)	Đống Đa	0.5	0.72	0.22
11	33 Tường nhà chị Minh, Phạm Ngọc Thạch	Đống Đa	1.28	1.1	-0.18
12	Số 5, Thái Hà	Đống Đa	0.35	0.27	-0.08
13	Thái Thịnh	Đống Đa	0.15	0.29	0.14
14	Trường Chinh	Đống Đa	0.31	0.56	0.25

Table 2: Modelled and measured water depth at locations in Dong Da District in 2012 (calibration)

Figures 8 and 9 show the flood maps corresponding to modelled water depths in 2012 for eight districts and Dong Da District respectively.

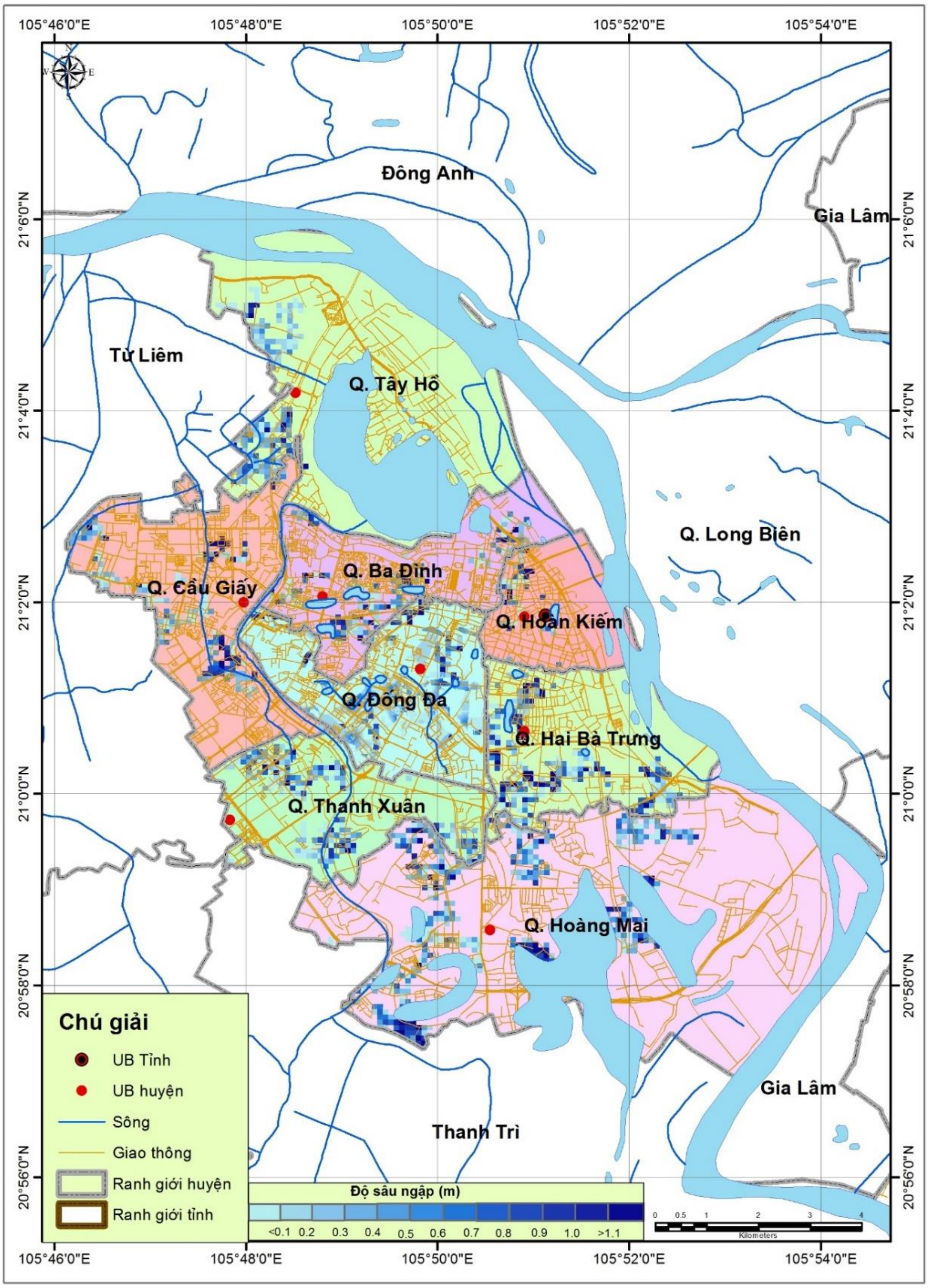

Figure 8: Flood map for eight districts in the flood event 16-17 August 2012

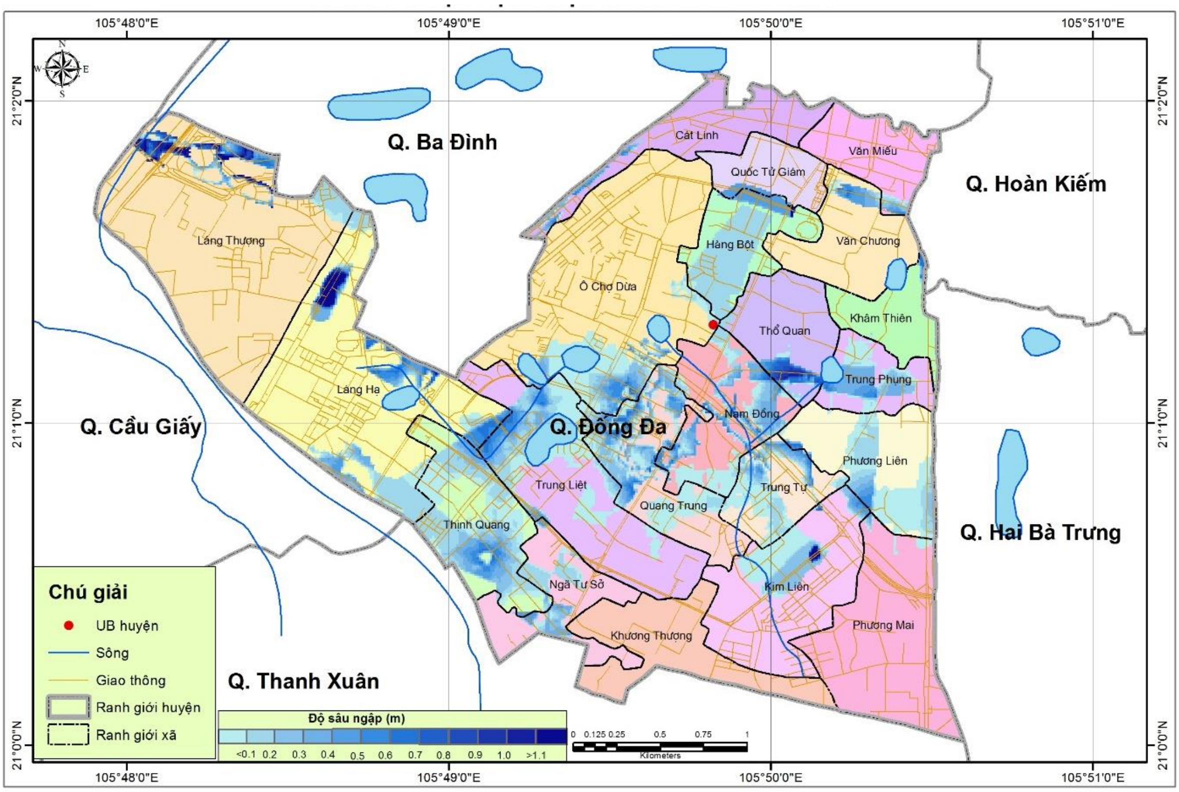

Figure 9: Flood map for Dong Da District in the flood event 16-17 August, 2012

4.2.2. Model Validation

For the model validation, the flood event caused by rainfall during 8-9 August 2013 was used to verify the model's parameters. Tables 3 and 4 show modelled water depth and measured water depth for eight districts and for Dong Da District respectively. Similarly, it is clearly shown in the table that the difference between simulated and measured water depth is in the range of ΔH = -0.09 to 0.23 m, showing a reasonably good fit between simulated and measured water depths, for the model validation. The flood maps were generated using the simulated water depths as input data.

No	Location	Measured water depth (m)	Modelled water depth (m)	ΔH (m)
1	Tường trường PTTH Chu Văn An	0.5	0.71	0.21
2	Cột điện đối diện TT Phụ nữ và phát triển	0.55	0.67	0.12
3	Cột điện cạnh tường sau nhà khách Bộ QP	0.59	0.78	0.19
4	Cột điện cạnh số 13 Đường Thành đối diện 50 Bát Đàn	0.7	0.84	0.14
5	Cột điện trước cửa nhà số 25 Hai Bà Trưng	0.41	0.61	0.2
6	Cột đèn trước số nhà 98 Bà Triệu	0.6	0.84	0.24
7	Trụ tụ điện hạ thế trước số nhà 8A (Điện Biên Phủ)	0.66	0.78	0.12
8	Tủ điện biến áp Lý Thường Kiệt	0.86	0.9	0.04
9	Cột điện đèn trước nhà số 14 Nguyễn Gia Thiều	0.77	0.93	0.16
10	Trên cột bê tông trạm biến áp Nguyễn Trường Tộ 2	0.88	0.96	0.08
11	Góc tường rào nhà tư lệnh cảnh vệ	0.72	0.84	0.12
12	Cột đèn trước nhà 209 Đội Cấn (cạnh ngõ 209)	0.66	0.84	0.18
13	Cột điện trước nhà 343 Đội Cấn	0.38	0.51	0.13
14	Cột đèn đối diện trước cửa số nhà 28 Điện Biên Phủ	0.49	0.67	0.18
15	Cột điện ngã 3 Núi Trúc đối diện số nhà 53 Núi Trúc	0.15	0.35	0.2
16	Cột điện trước số nhà 158 Ngọc Khánh	0.71	0.89	0.18
17	Trên cột đèn điện trước cổng công viên Thống Nhất	0.29	0.51	0.22
18	Cột điện đôi trước nhà 30A (Hàng Chuối)	0.59	0.8	0.21
19	Cột điện trước số nhà 124 phố Lạc trung	0.46	0.61	0.15
20	Cột bê tông cạnh đường vào công ty bánh kẹo Hải Châu sát số nhà 11	0.32	0.48	0.16
21	Thành tường nhà cạnh cổng tổng công ty lương thực miền Bắc số 780	0.61	0.84	0.23
22	Trên cột điện trước cửa nhà Bia hơi Minh béo số H7	0.57	0.48	-0.09
23	Trên tường nhà số 48 ngay đầu đường Thi Sách - Hòa Mã	0.61	0.72	0.11
24	Cột điện trước số nhà 118 Định Công	0.3	0.51	0.21

Table 3: Modelled and Measured Water Levels at Locations in Eight Districts in 2013 (validation)

No	Location	District	Measured water depth (m)	Modelled water depth (m)	ΔH(m)
1	106A Phạm Ngọc Thạch	Đống Đa	0.81	0.91	0.10
2	115 Nguyễn Lương Bằng	Đống Đa	0.91	0.71	-0.20
3	29 Huỳnh Thúc Kháng	Đống Đa	0.96	0.73	-0.23
4	số 5 Thái Hà	Đống Đa	0.88	0.55	-0.33
5	198 Hồ Đắc Di, Nam Đồng	Đống Đa	0.8	0.73	-0.07
6	Trên cột tường hàng rào công ty Sprodex hà Nội- đường Láng Hạ	Đống Đa	0.3	0.29	-0.01
7	Cột điện trước nhà 167 Thái hà	Đống Đa	0.71	0.64	-0.07
8	Cột điện trước cửa nhà số 152 phố Chùa Bộc	Đống Đa	0.24	0.29	0.05
9	Cột điện trước Ki ot 24 tòa nhà B4 Phạm Ngọc Thạch	Đống Đa	0.43	0.36	-0.07
10	Cột đèn HBTT/5-1 trước đình Kim Liên	Đống Đa	0.57	0.34	-0.23
11	Cột điện B4 Ki/15 sát tường lưu niệm CTHCM đường Hoàng Tích Trí	Đống Đa	0.23	0.21	-0.02
12	Cột điện trên đường Quốc Tử Giám, sát bờ tường vườn hoa	Đống Đa	0.64	0.49	-0.15
13	Cột điện đối diện trường tiểu học Lý Thường Kiệt, sát bệnh viện da liễu HN	Đống Đa	0.95	0.72	-0.23
14	Cột đèn đường gần ngõ 117 Nguyễn Lương Bằng, cạnh công ty xe máy Cường Ngân	Đống Đa	0.21	0.32	0.11

Table 4: Modelled and Measured Water Levels at Locations in Dong Da District in 2013 (validation)

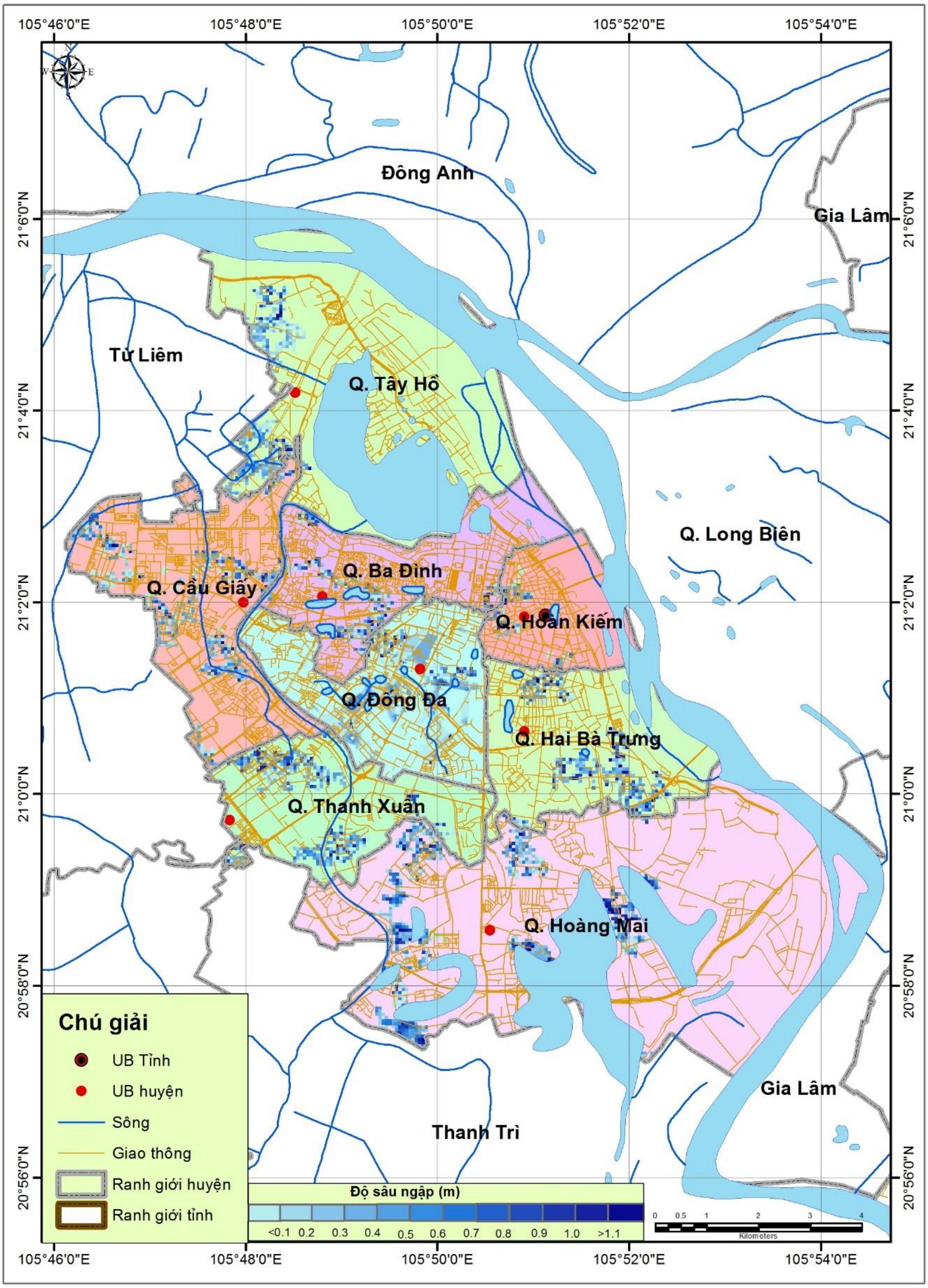

Figure 10. Flood Map for Eight Districts in the Flood Event 8-9 August 2013

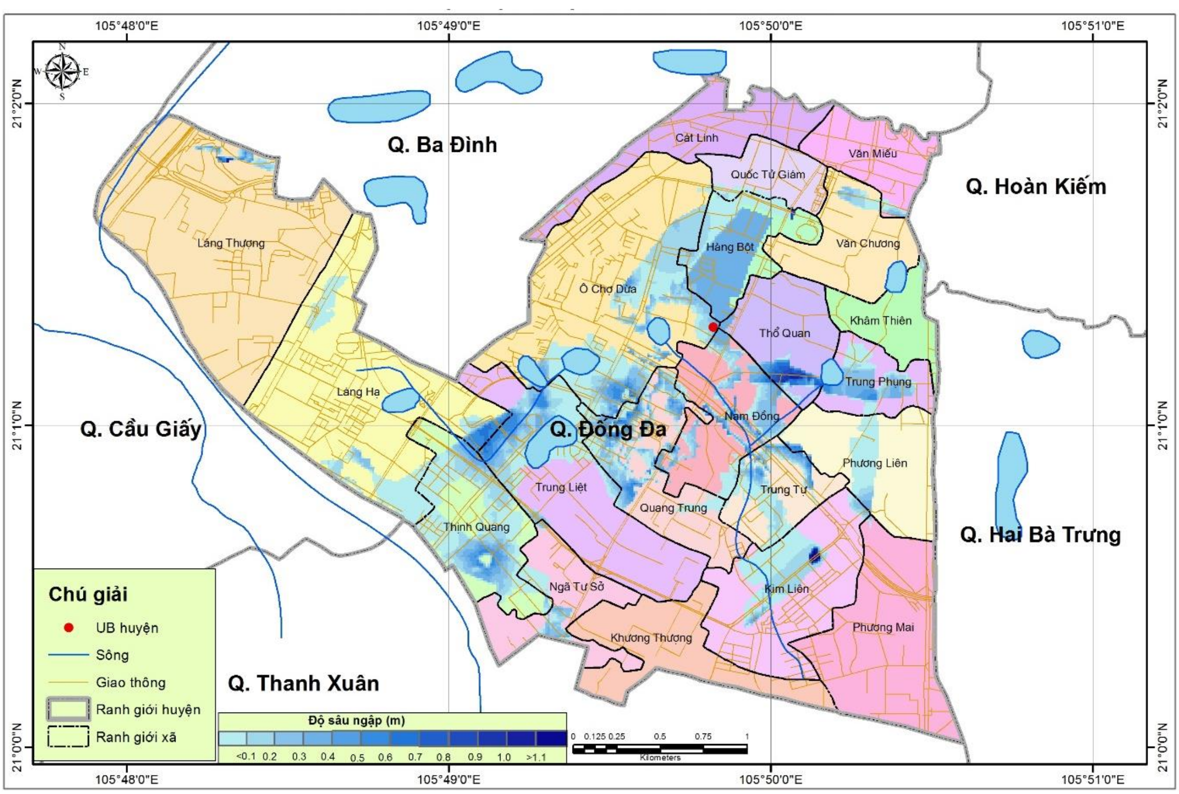

Figure 11. Flood Map for Dong Da District in the Flood Event 8-9 August, 2013

4.2.3. Discussion

Results of model calibration and validation show that there is agreement between measured and simulated water levels, indicating the model reasonably reproduces flood water depths for both eight districts in general and for Dong Da District in particular. The differences between modelled and measured water depths for model calibration and validation are relatively small, ranging between -0.38 to 0.24 m. Therefore the model can be realiably applied to simulate water depths under different future rainfall scenarios. The results of this study are comparable with findings from other studies in this area (e.g. Lou et al 2018, Kefi et al, 2018). The calibrated model can be applied for generating flood maps of historical events and future periods, using climate change scenarios, and applying various mitigation measures for improvements in the drainage network.

5. Results and Discussion

5.1. Flood Maps

This section shows the flood maps derived from the rainfall event of year 2008 for eight districts of Hanoi, and in more detail for Dong Da District. Flood maps for the time slice 2016-2035 with probabilities of rainfall of 1% and 5% for Hanoi and Dong Da District specifically are also presented.

BẢN ĐỒ NGẬP LỤT 8 QUẬN NỘI THÀNH HÀ NỘI NĂM 2008

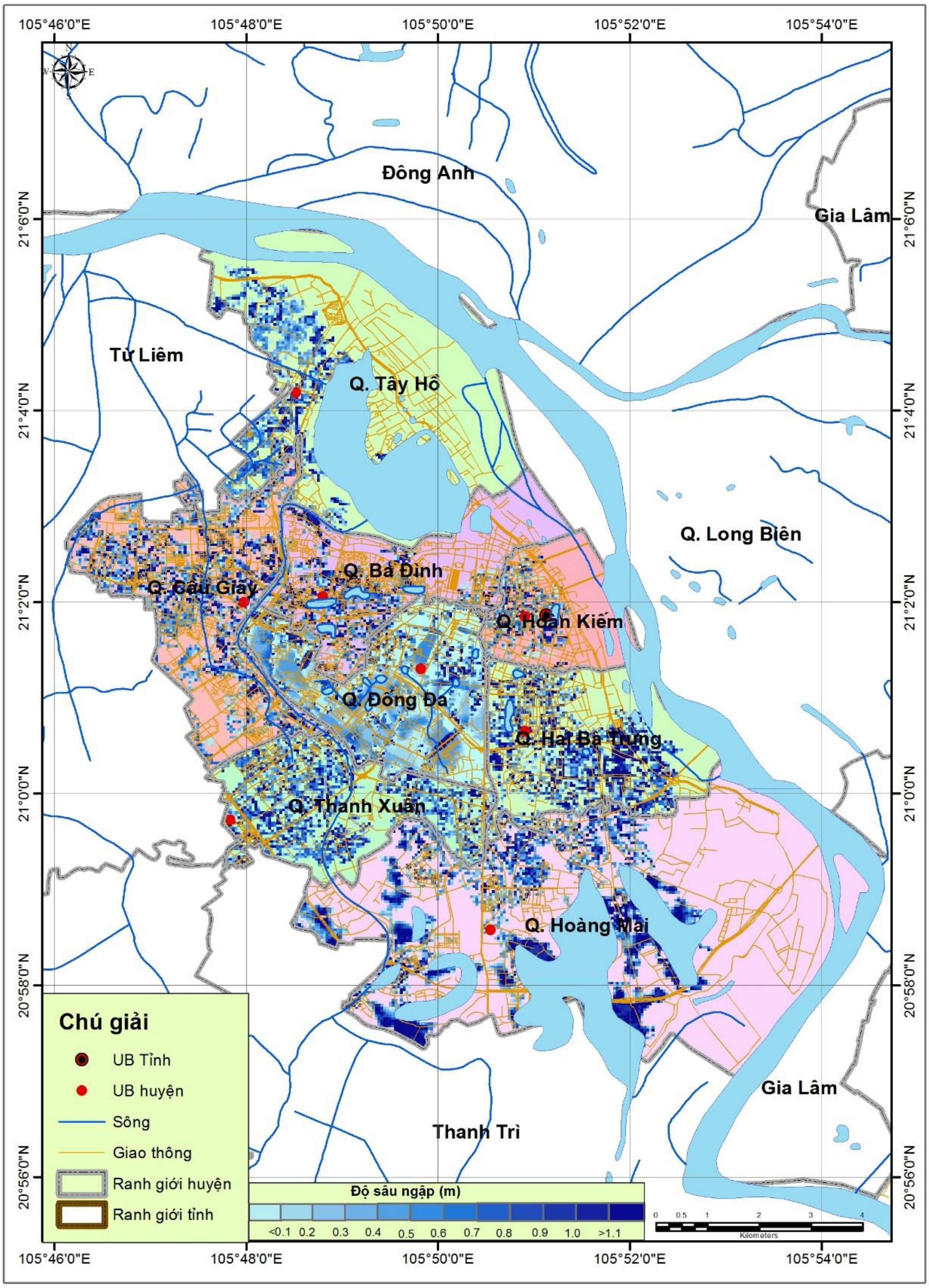

Figure 12. Flood Map of Hanoi for the Flood Event 2008

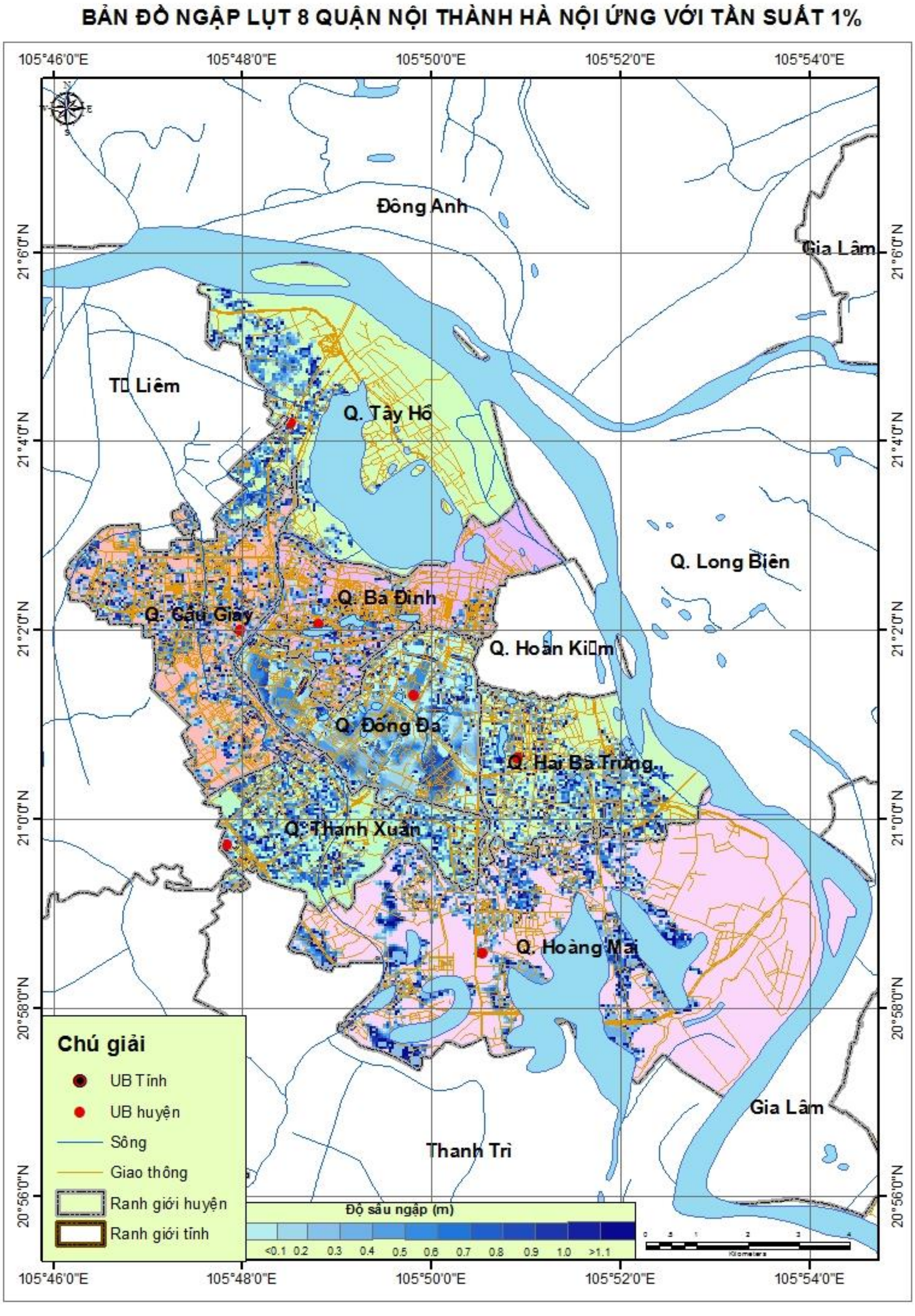

Figure 13. Flood Map for Hanoi with Probability of 1%

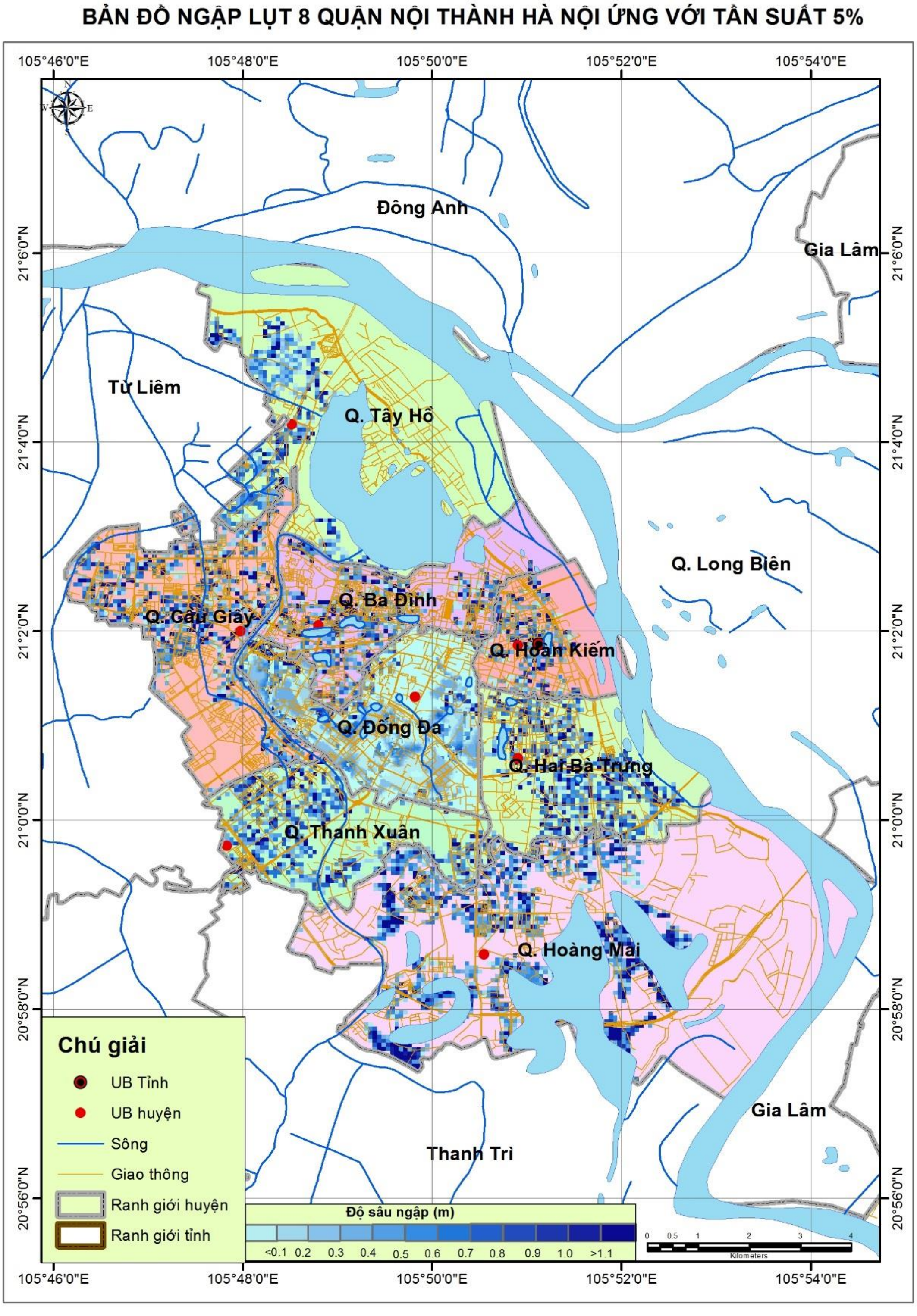

Figure 14. Flood Map for Hanoi with Probability of 5%

BẢN ĐỒ NGẬP LỤT QUẬN ĐỐNG ĐA NĂM 2008

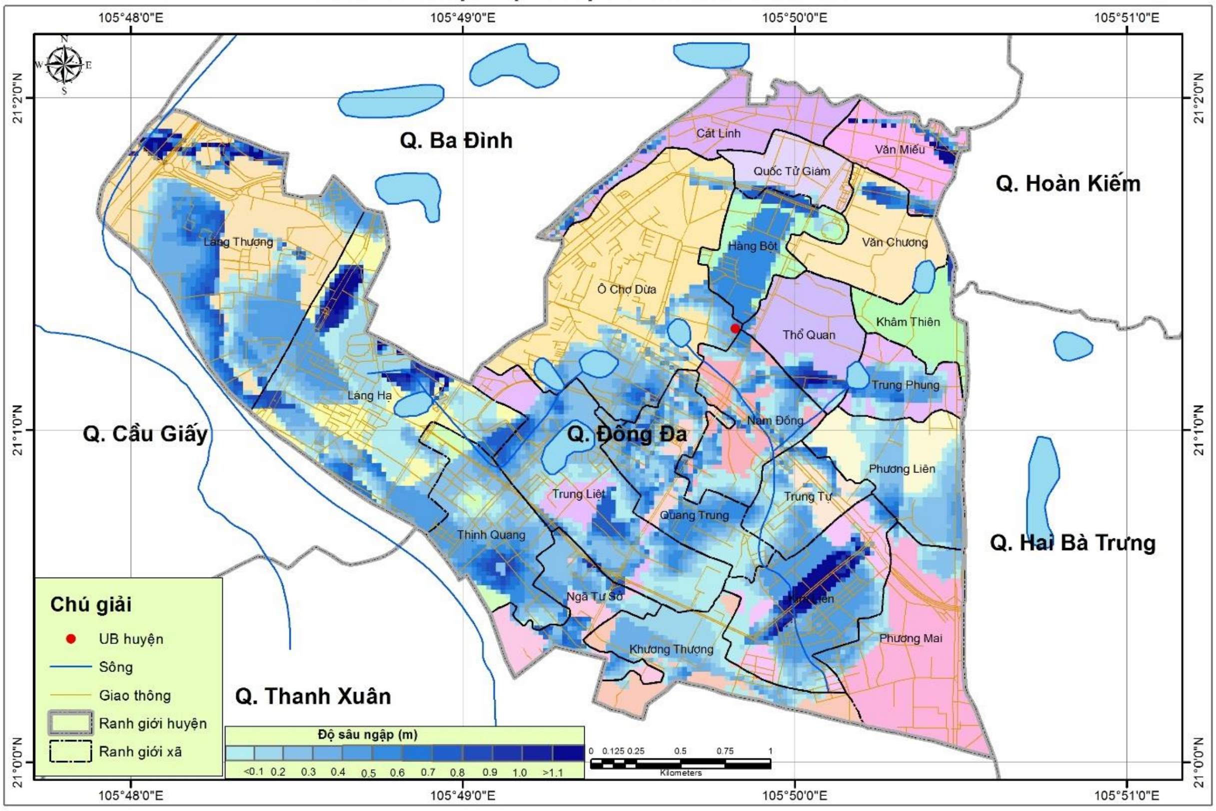

Figure 15. Flood Map of Dong Da District for the Flood Event 2008

BẢN ĐỒ NGẬP LỤT QUẬN ĐỐNG ĐA ỨNG VỚI TẦN SUẤT 1%

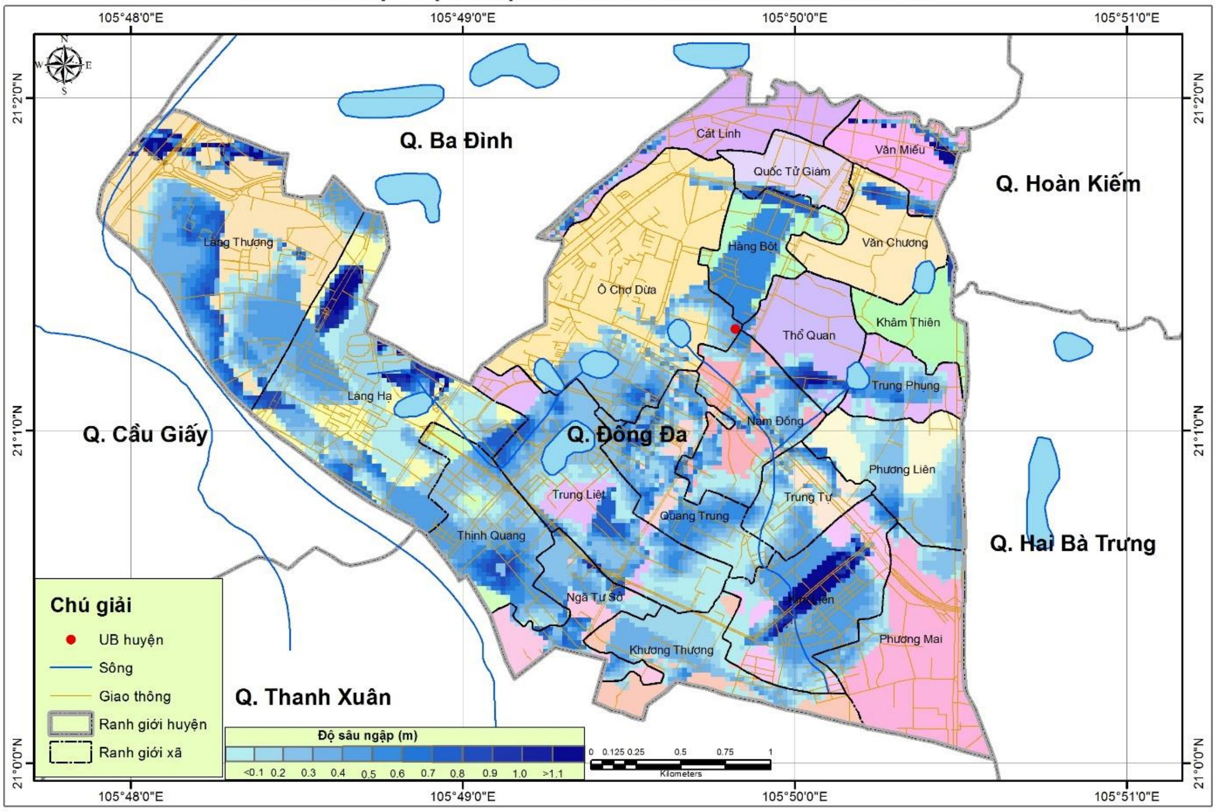

Figure 16. Flood Map for Dong Da District with Probability of 1%

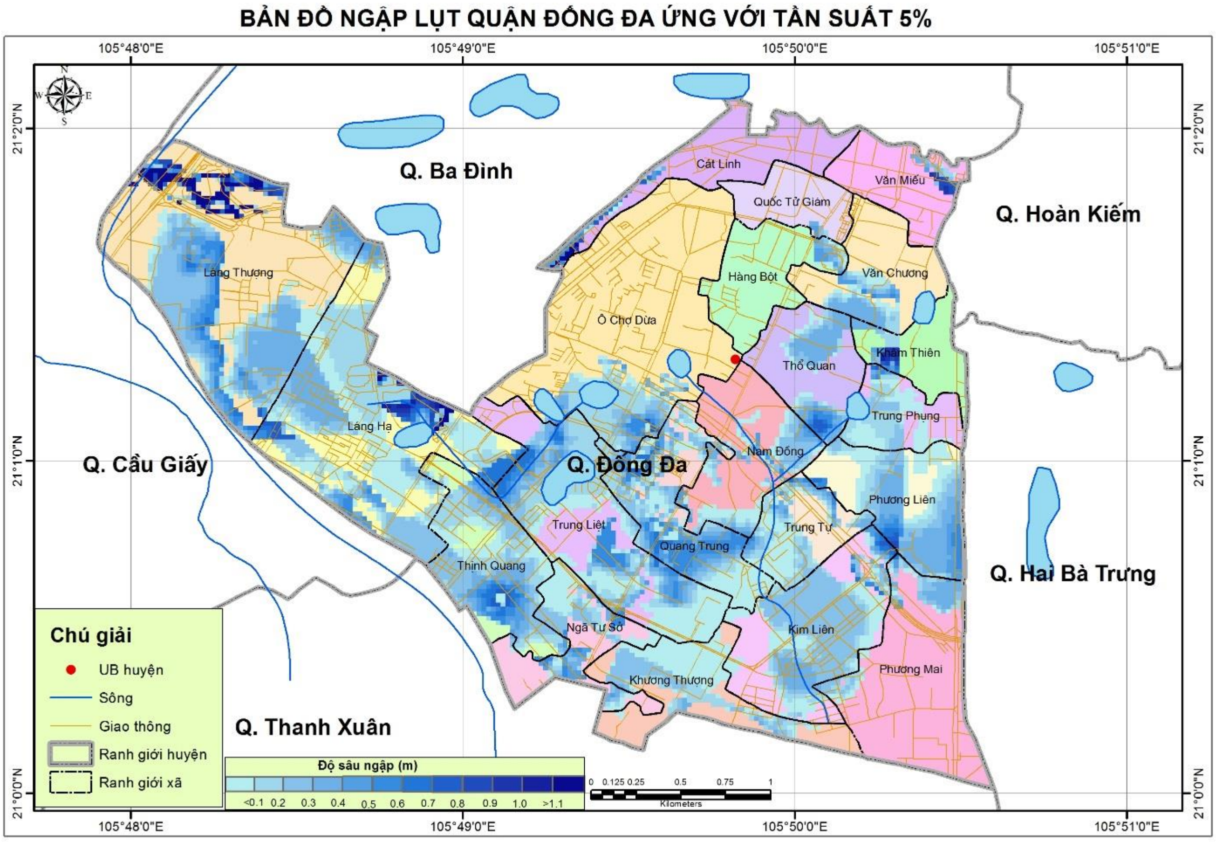

Figure 17. Flood Map for Dong Da District with Probability of 5%

As can be seen in the Figures above, most roads in the middle of Hanoi, that is, in Dong Da District, Ba Dinh District, Ring Road 3, and roads in Linh Nam, Vinh Hung and Nam Du Wards of Hoang Mai District, are inundated. With a rainfall of 1% frequency, many roads in Dong Da District are completely submerged.

5.2. Flood Maps After Implementing Mitigation Measures

This section describes the development of urban flood maps for the whole of Hanoi, using rainfall scenarios as input for the MIKE URBAN hydrological model, and considering the implementation of different interventions such as renovating lakes, culverts, manholes and pumping stations to improve the city's drainage capacity. In total, three groups of mitigation measures were considered: Group 1 consisting of 7 projects, and Groups 2 and 3 each consisting of 9 projects making a total of 25 projects. Finally, the model was simulated and flood maps generated, with all 25 projects. The 25 projects include mitigation measures throughout Hanoi. Details of the 25 projects are shown in Table 5 below. Then, Figures 18 to 22 show flood maps of Hanoi under different probabilities of rainfall, with the three Groups of mitigation measures taken into account.

Project	Project ID	Catchment	Category	Status	Group
1	10	Catchment_38_2	lake		1
2	9	Catchment_38_2	lake		2
3	36	Catchment_38_2	culvert		3
4	17	Catchment_36_1	culvert		1
5	34	Catchment_36_1	culvert		2
6	4	Catchment_36_1	Culvert Joint culvert manholes		3
7	18	Catchment_25_2	lake		1
8	20	Catchment_25_2	lake		2
9	22	Catchment_25_2	lake		3
10	38	Catchment_47_2	lake		1
11	47	Catchment_30_2	culvert, manholes culvert reservoirs	under consideration	2
12	90	Catchment_49_2	lake		1
13	91	Catchment_49_2	lake		2
14	89	Catchment_49_2	culvert		3
15	60	Catchment_58_2	lake		2
16	61	Catchment_58_2	lake	finished	3
17	72	Catchment_54_1	lake		2
18	73	Catchment_55_2	lake		2
19	66	Catchment_55_2	lake		3
20	65	Catchment_62_2	pump station	finished	1
		Catchment_55_2 Catchment_54_1 Catchment_56_2 Catchment_52_1	drainage canals		
		Catchment_62_2	waste water treatment station		
		Catchment_55_2 Catchment_54_1 Catchment_56_2 Catchment_52_1	culvert		
21	1	Catchment 38-1	manholes culverts		3
22	52	Catchment_33_2	lake		3
23	56	Catchment_66_1	pump stations reservoir reservoir Drainage canal underground sewer	finished	1
24	88	Catchment_42_1	Culvert Ditches Culvert Manholes catch holes	finished	3
25	64	Catchment_52_1	culverts ditch Manholes Dredging of ponds and lakes		2

Table 5: Mitigation Projects in Three Groups

5.2.1 Flood Maps After Implementing Group 1 Projects

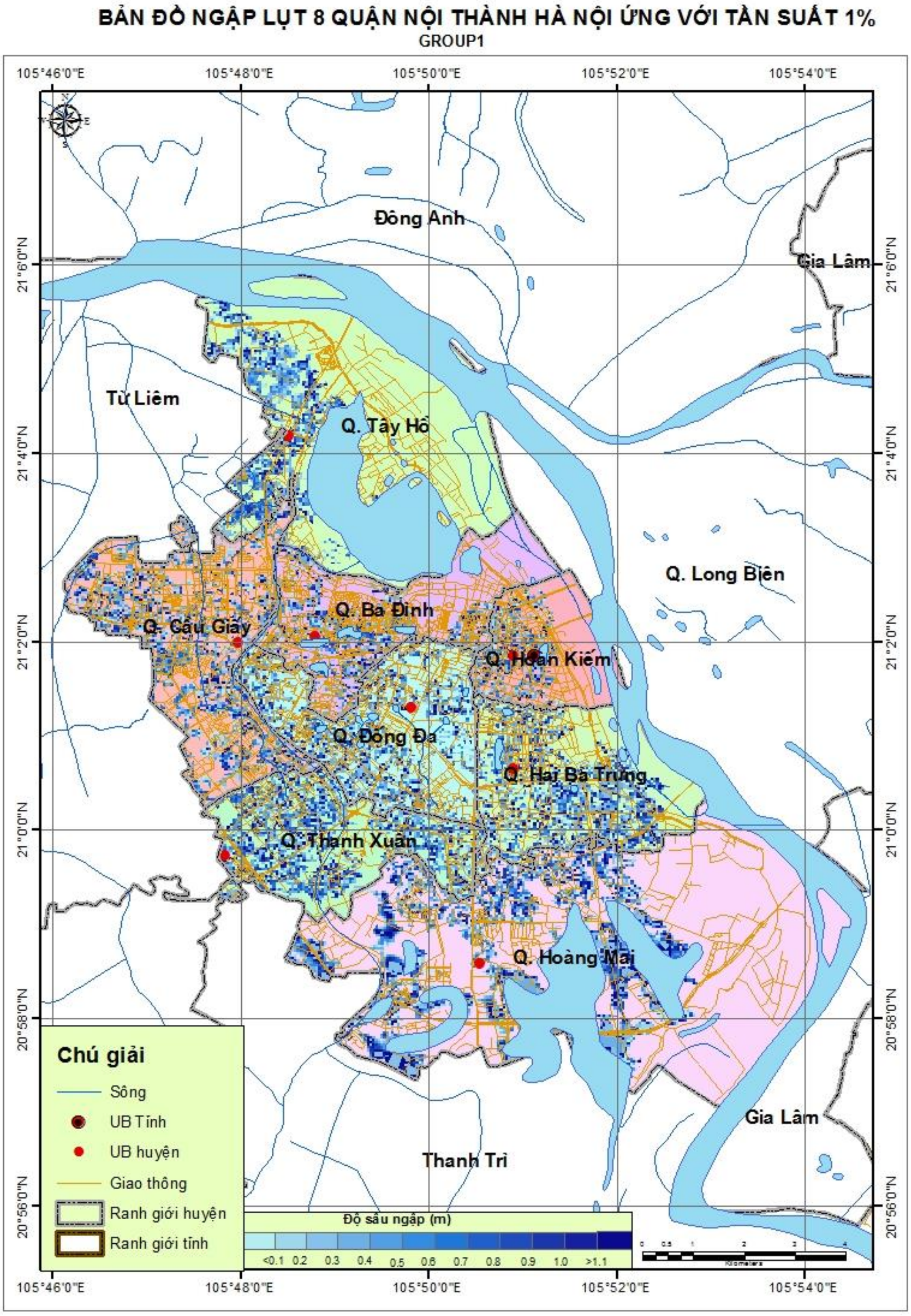

Figure 18. Flood Map for Hanoi for Period 2016 – 2035 with Probability of 1% Considering Group 1 Projects

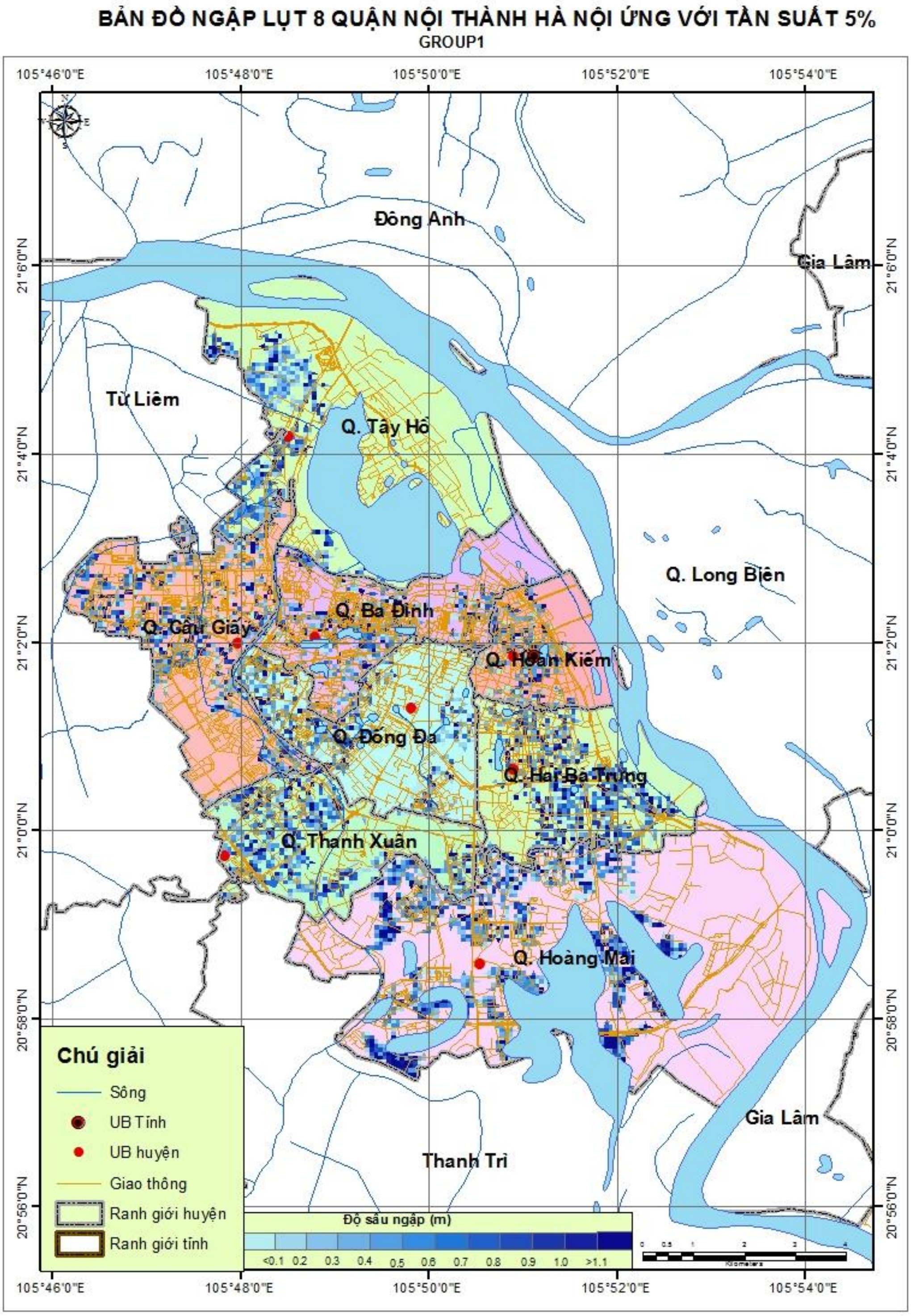

Figure 19. Flood Map for Hanoi for 2016-2035, with Probability of 5%, Considering Group 1 Projects

5.2.2 Flood Maps After Implementing Group 2 Projects

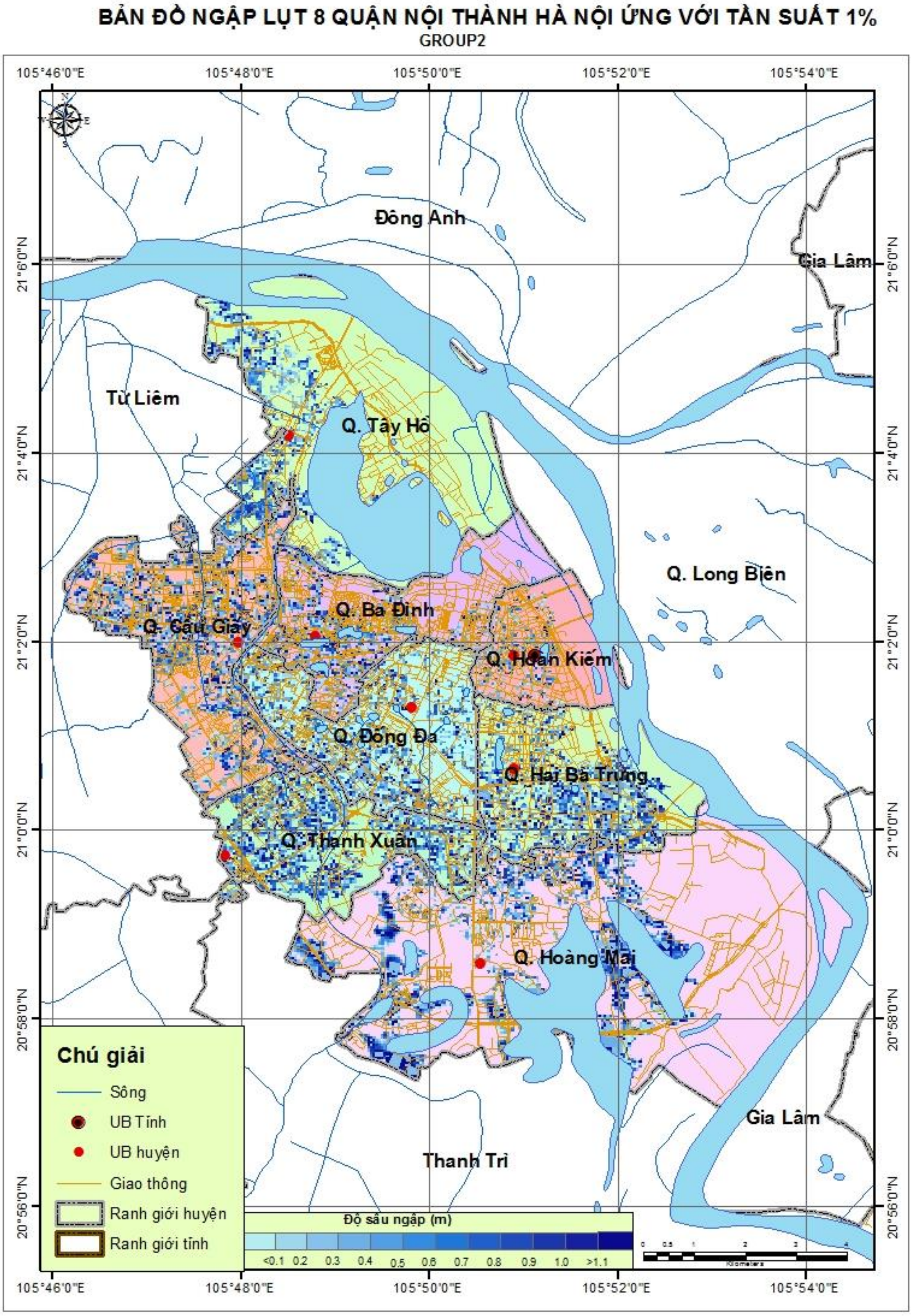

Figure 20. Flood Map for Hanoi for period 2016 – 2035 with Probability of 1% Considering Group 2 Projects

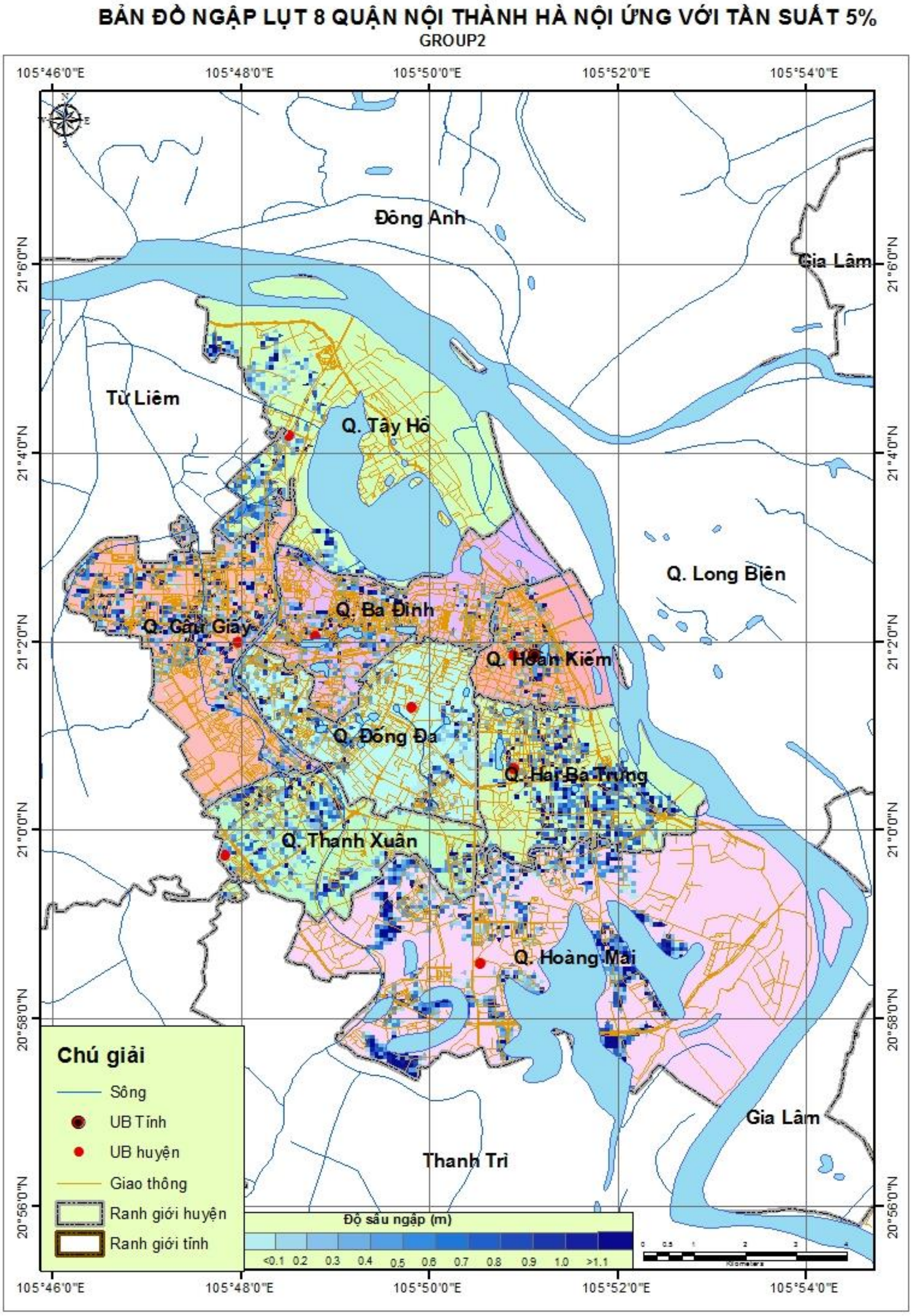

Figure 21. Flood Map for Hanoi for Period 2016 – 2035 with Probability of 5% Considering Group 2 Projects

5.2.3 Flood Maps After Implementing Group 3 projects

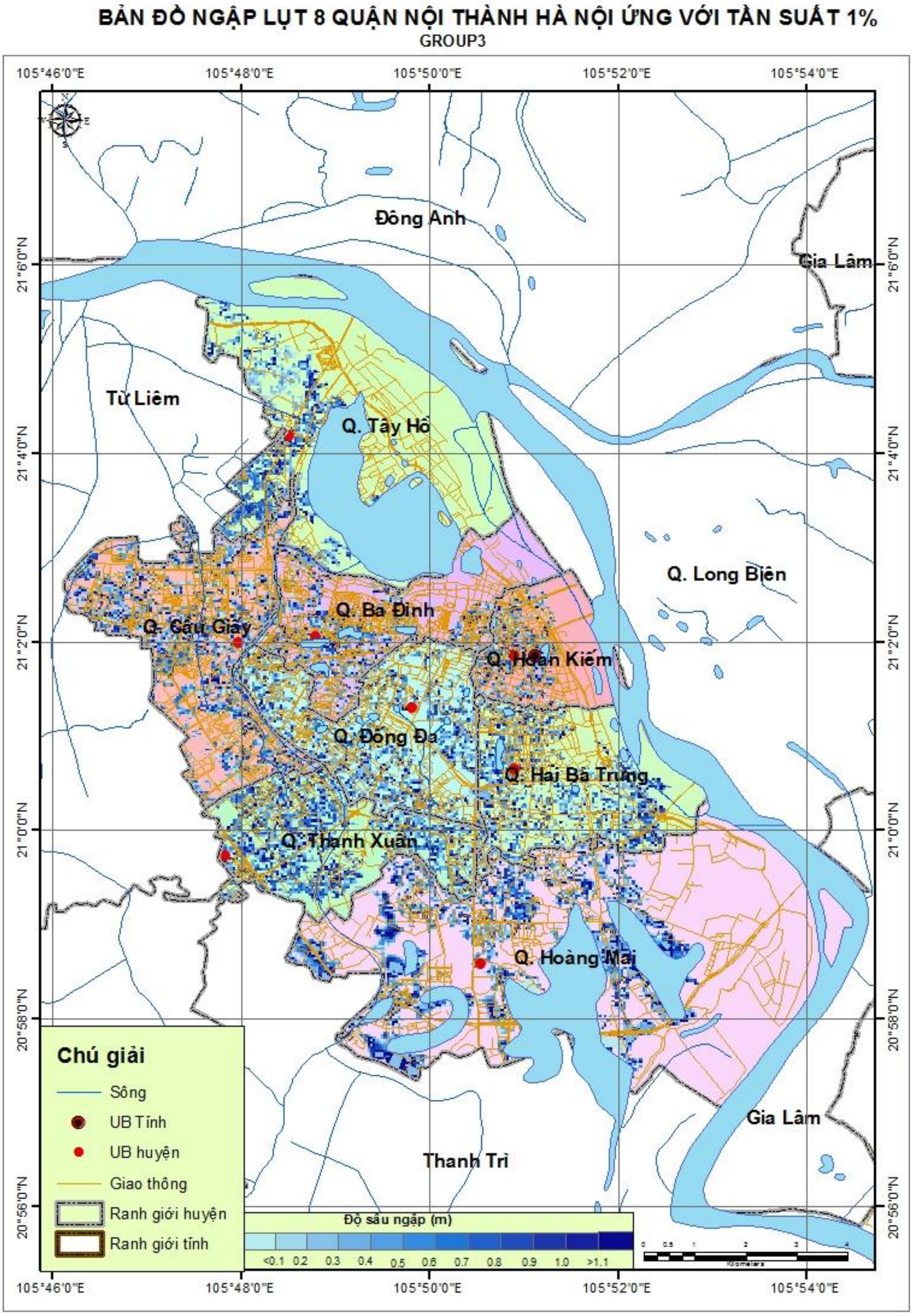

Figure 22. Flood Map for Hanoi for Period 2016 – 2035 with Probability of 1% Considering Group 3 Projects

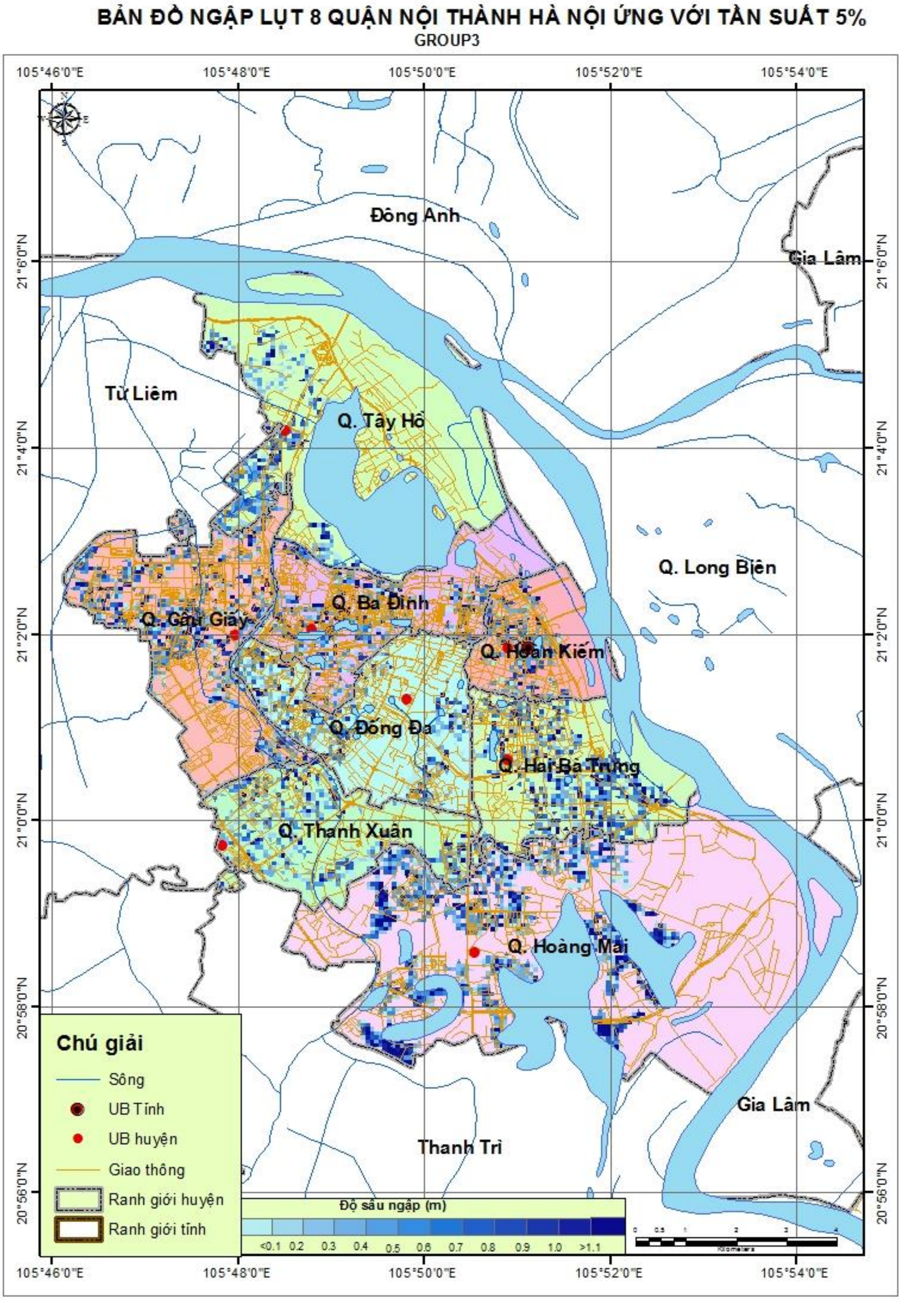

Figure 23. Flood Map for Hanoi for Period 2016 – 2035 with Probability of 5% Considering Group 3 Projects

5.2.4 Changes of Flood Depth

This section shows the change of flood depth after taking into account the implementation of mitigation measures for Hanoi compared to baseline scenarios. Tables 6-11 show the reduction of flood depth with different water levels for the three Groups of projects, under different probability of rainfall, 1% and 5%.

Table 6: Reduction of flooded depth between baseline and implementation of mitigation measures in Group 1 with probability of 1%

ID	Quận	District area (km2)	Depth (m)											
			<0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	>1.1
0	Ba Đình	9.39	0.38	0.43	0.45	0.30	0.22	0.22	0.19	0.16	0.13	0.12	0.11	0.08
1	Cầu Giấy	12.40	0.78	0.85	0.87	0.71	0.62	0.57	0.47	0.42	0.35	0.30	0.25	0.16
2	Đống Đa	9.94	0.50	0.55	0.58	0.40	0.30	0.23	0.22	0.18	0.17	0.11	0.10	0.06
3	Hai Bà Trưng	10.48	0.17	0.23	0.24	0.16	0.12	0.11	0.10	0.08	0.09	0.08	0.07	0.04
4	Hoàn Kiếm	5.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Hoàng Mai	39.35	0.17	0.27	0.30	0.17	0.11	0.10	0.09	0.06	0.07	0.07	0.07	0.05
6	Tây Hồ	24.01	0.32	0.38	0.38	0.26	0.19	0.16	0.13	0.11	0.08	0.08	0.05	0.04
7	Thanh Xuân	8.84	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
	Total	119.91	2.32	2.73	2.82	2.01	1.57	1.40	1.20	1.02	0.89	0.77	0.66	0.43

Table 7: Reduction of flooded depth between baseline and implementation of mitigation measures in Group 1 with probability of 5%

ID	Quận	District area (km2)	Depth (m)											
			<0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	>1.1
0	Ba Đình	9.39	0.41	0.41	0.50	0.44	0.32	0.21	0.18	0.21	0.21	0.14	0.10	0.07
1	Cầu Giấy	12.40	0.47	0.43	0.35	0.38	0.37	0.38	0.30	0.25	0.19	0.19	0.19	0.19
2	Đống Đa	9.94	0.32	0.23	0.32	0.32	0.29	0.18	0.16	0.13	0.09	0.11	0.10	0.11
3	Hai Bà Trưng	10.48	0.12	0.13	0.13	0.11	0.09	0.07	0.07	0.06	0.05	0.04	0.04	0.03
4	Hoàn Kiếm	5.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Hoàng Mai	39.35	0.13	0.14	0.17	0.18	0.15	0.12	0.12	0.09	0.08	0.09	0.10	0.10
6	Tây Hồ	24.01	0.14	0.15	0.14	0.12	0.10	0.06	0.05	0.06	0.07	0.04	0.03	0.02
7	Thanh Xuân	8.84	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	119.91	1.59	1.49	1.61	1.57	1.32	1.03	0.89	0.80	0.67	0.62	0.56	0.52

Table 8: Reduction of flooded depth between baseline and implementation of mitigation measures in Group 2 with probability of 1%

ID	District	District area (km2)	Depth (m)											
			<0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	>1.1
0	Ba Đình	9.39	0.29	0.32	0.38	0.29	0.27	0.25	0.21	0.16	0.14	0.12	0.11	0.08
1	Cầu Giấy	12.40	0.20	0.22	0.21	0.23	0.23	0.22	0.18	0.11	0.06	0.03	0.02	0.01
2	Đống Đa	9.94	0.78	0.97	1.04	0.75	0.55	0.50	0.46	0.37	0.30	0.26	0.22	0.17
3	Hai Bà Trưng	10.48	0.40	0.46	0.43	0.33	0.28	0.28	0.24	0.16	0.16	0.14	0.13	0.07
4	Hoàn Kiếm	5.51	0.60	0.60	0.61	0.49	0.44	0.38	0.31	0.25	0.20	0.17	0.14	0.09
5	Hoàng Mai	39.35	1.12	1.41	1.47	1.17	0.98	0.88	0.71	0.55	0.44	0.41	0.32	0.21
6	Tây Hồ	24.01	0.68	0.76	0.75	0.64	0.55	0.48	0.40	0.37	0.28	0.21	0.15	0.09
7	Thanh Xuân	8.84	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.01	0.00
	Total	119.91	4.11	4.78	4.93	3.90	3.31	3.01	2.52	1.98	1.60	1.34	1.09	0.73

Table 9: Reduction of flooded depth between baseline and implementation of mitigation measures in Group 2 with probability of 5%

ID	District	District area	Depth (m)											
			<0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	>1.1
0	Ba Đình	9.39	0.69	0.60	0.65	0.64	0.52	0.45	0.37	0.34	0.26	0.19	0.13	0.16
1	Cầu Giấy	12.40	0.21	0.23	0.26	0.30	0.31	0.28	0.20	0.16	0.12	0.08	0.05	0.02
2	Đống Đa	9.94	0.63	0.61	0.74	0.75	0.69	0.54	0.48	0.36	0.28	0.25	0.22	0.20
3	Hai Bà Trưng	10.48	0.10	0.12	0.14	0.16	0.13	0.12	0.12	0.14	0.11	0.09	0.04	0.03
4	Hoàn Kiếm	5.51	0.35	0.32	0.36	0.39	0.33	0.24	0.17	0.16	0.13	0.10	0.08	0.08
5	Hoàng Mai	39.35	1.22	1.27	1.39	1.33	1.13	0.82	0.70	0.57	0.49	0.41	0.33	0.28
6	Tây Hồ	24.01	0.73	0.67	0.67	0.50	0.43	0.36	0.34	0.23	0.19	0.14	0.10	0.10
7	Thanh Xuân	8.84	0.51	0.59	0.63	0.64	0.61	0.52	0.40	0.25	0.18	0.16	0.14	0.11
	Total	119.91	4.45	4.41	4.83	4.71	4.15	3.34	2.78	2.21	1.75	1.41	1.09	0.97

Table 10: Reduction of flooded depth between baseline and implementation of mitigation measures in Group 3 with probability of 1%

ID	District	District area	Depth (m)											
			<0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	>1.1
0	Ba Đình	9.39	0.15	0.24	0.29	0.20	0.16	0.18	0.18	0.13	0.11	0.08	0.08	0.09
1	Cầu Giấy	12.40	0.45	0.53	0.59	0.43	0.36	0.34	0.29	0.25	0.20	0.18	0.14	0.12
2	Đống Đa	9.94	0.43	0.62	0.66	0.43	0.33	0.32	0.30	0.22	0.19	0.17	0.15	0.14
3	Hai Bà Trưng	10.48	0.77	0.97	1.00	0.67	0.43	0.41	0.41	0.35	0.31	0.27	0.27	0.17
4	Hoàn Kiếm	5.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Hoàng Mai	39.35	1.03	1.38	1.41	0.95	0.65	0.61	0.51	0.45	0.41	0.38	0.37	0.24
6	Tây Hồ	24.01	0.53	0.54	0.59	0.56	0.49	0.35	0.25	0.18	0.12	0.09	0.08	0.07
7	Thanh Xuân	8.84	0.00	0.00	0.00	0.01	0.01	0.03	0.03	0.01	0.00	0.00	0.00	0.00
	Total	119.91	3.37	4.28	4.54	3.24	2.43	2.23	1.96	1.61	1.35	1.18	1.09	0.82

Table 11: Reduction of flooded depth between baseline and implementation of mitigation measures in Group 3 with probability of 5%

ID	District	District area	Depth (m)											
			<0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	>1.1
0	Ba Đình	9.39	0.27	0.24	0.35	0.40	0.30	0.18	0.16	0.15	0.13	0.09	0.05	0.06
1	Cầu Giấy	12.40	0.51	0.44	0.33	0.34	0.29	0.28	0.30	0.25	0.21	0.16	0.15	0.11
2	Đống Đa	9.94	0.48	0.32	0.39	0.53	0.44	0.33	0.29	0.22	0.19	0.14	0.15	0.14
3	Hai Bà Trưng	10.48	0.36	0.30	0.34	0.53	0.56	0.37	0.23	0.22	0.19	0.18	0.20	0.17
4	Hoàn Kiếm	5.51	0.06	0.03	0.02	0.02	0.03	0.02	0.00	0.00	0.00	0.01	0.01	0.00
5	Hoàng Mai	39.35	0.33	0.34	0.46	0.66	0.57	0.28	0.22	0.22	0.25	0.22	0.17	0.19
6	Tây Hồ	24.01	0.58	0.58	0.55	0.41	0.35	0.31	0.24	0.14	0.10	0.10	0.07	0.09
7	Thanh Xuân	8.84	0.72	0.79	0.86	0.85	0.79	0.69	0.57	0.45	0.31	0.27	0.20	0.17
	Total	119.91	3.30	3.04	3.32	3.73	3.33	2.46	2.01	1.66	1.39	1.15	0.99	0.93

5.2.5 Inundation Maps After Implementation of 25 projects

Tables 12 and 13 show flooded areas in eight urban districts in Hanoi. As shown, the flooded areas in these eight districts with flood depth ranging from 0.1-0.3m is 35-45 km², is concentrated in the central area of Dong Da, Cau Giay, Thanh Xuan and Hoang Mai Districts. In the Hoang Mai District, are many areas growing agricultural crops, and drainage systems are still under construction, so the flood area is very large, especially in Linh Nam and Tran Phu Wards, Thanh Tri, Vinh Tuy and Phuong Mai. Many areas are submerged with a flood depth of up to 1.0m - 1.2m. These are primarily grassland areas where land use has shifted from agricultural to residential. Tay Ho District is also flooded, particularly the large floodplain in Phu Thuong Ward. The flood depth, flooded area, and affected length of roads in all catchments, are all shown in the Annex.

Table 12: Flooded Area of District with Rainfall Probability of 1% Considering all 25 projects

District	District Area km²	Flood Depth (m)											
		<0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	>1.1
Ba Đình	9.39	2.94	2.57	2.34	1.86	1.52	1.29	1.07	0.87	0.71	0.54	0.40	0.31
Cầu Giấy	12.40	6.16	5.49	4.93	3.99	3.27	2.71	2.12	1.66	1.21	0.89	0.62	0.44
Đống Đa	9.94	4.28	3.76	3.33	2.62	2.11	1.74	1.40	1.09	0.83	0.64	0.45	0.31
Hai Bà Trưng	10.48	4.87	4.35	4.02	3.10	2.45	2.07	1.76	1.42	1.11	0.82	0.62	0.45
Hoàn Kiếm	5.51	1.47	1.29	1.10	0.86	0.68	0.54	0.41	0.31	0.25	0.16	0.12	0.10
Hoàng Mai	39.35	11.68	10.78	9.94	7.61	6.38	5.49	4.58	3.72	3.02	2.43	1.83	1.28
Tây Hồ	24.01	2.64	2.27	1.97	1.67	1.38	1.07	0.84	0.57	0.39	0.26	0.16	0.13
Thanh Xuân	8.84	5.09	4.68	4.31	3.44	2.92	2.39	1.91	1.48	1.10	0.81	0.59	0.39

Table 13: Flooded Area of District with Rainfall Probability of 5% Considering all 25 projects

District	District Area km²	Flood Depth (m)											
		<0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	>1.1
Ba Đình	9.39	2.93	2.55	2.20	1.89	1.61	1.28	1.00	0.81	0.67	0.56	0.43	0.34
Cầu Giấy	12.40	4.61	4.11	3.60	3.11	2.70	2.20	1.77	1.36	1.12	0.85	0.63	0.42
Đống Đa	9.94	2.74	2.29	1.99	1.77	1.47	1.20	0.92	0.71	0.57	0.44	0.33	0.23
Hai Bà Trưng	10.48	3.50	3.25	2.94	2.51	2.14	1.75	1.47	1.10	0.94	0.71	0.51	0.36
Hoàn Kiếm	5.51	1.32	1.11	0.95	0.79	0.68	0.51	0.40	0.32	0.27	0.22	0.16	0.10
Hoàng Mai	39.35	8.16	7.34	6.50	5.61	4.77	4.00	3.25	2.70	2.30	1.87	1.55	1.18
Tây Hồ	24.01	2.32	1.98	1.72	1.44	1.10	0.83	0.66	0.45	0.34	0.26	0.21	0.13
Thanh Xuân	8.84	3.42	2.87	2.48	2.17	1.82	1.42	1.17	0.92	0.71	0.56	0.42	0.34

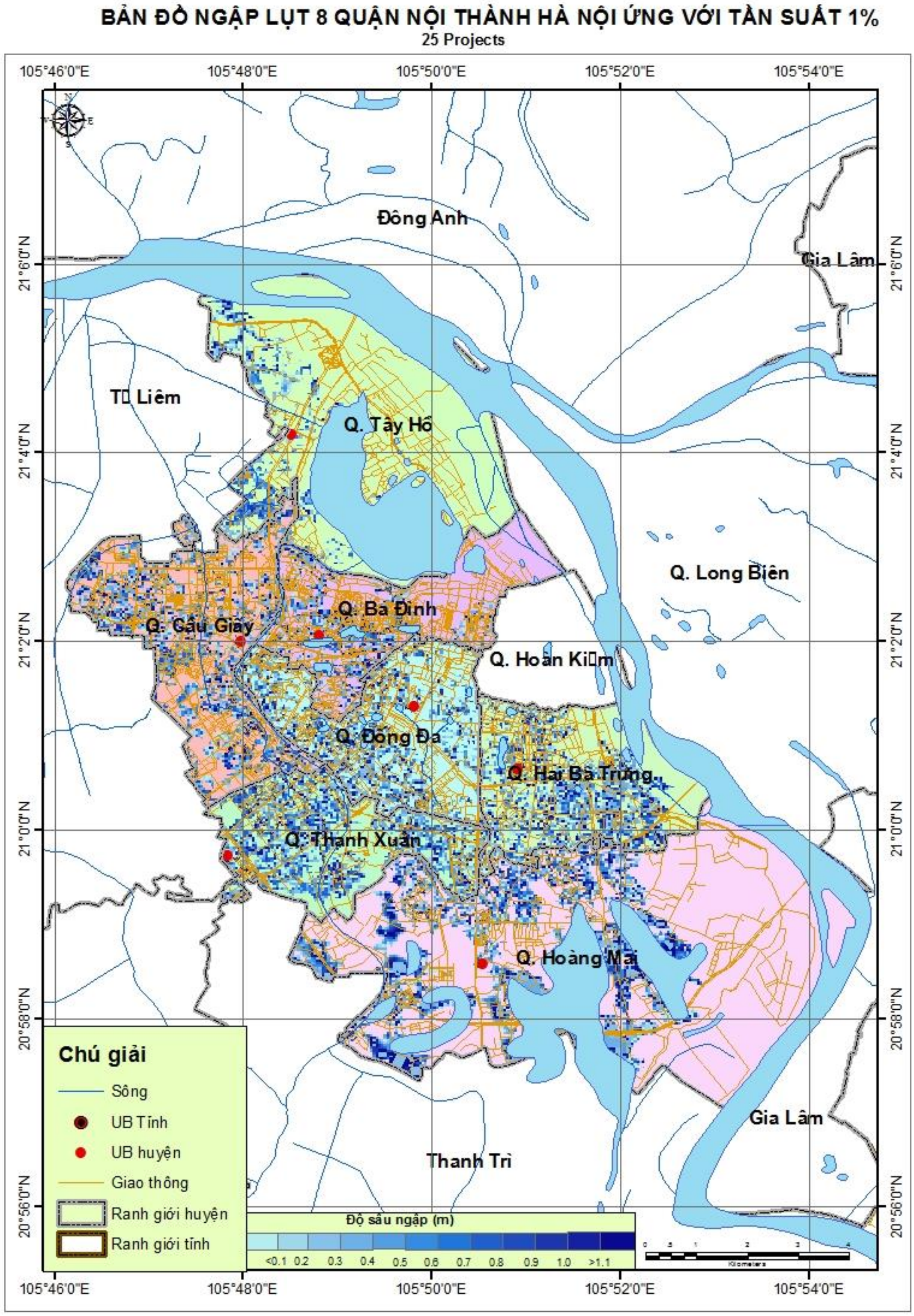

Figure 24. Flood Map for Hanoi for Period 2016 – 2035 with Probability of 1% Considering all 25 Projects

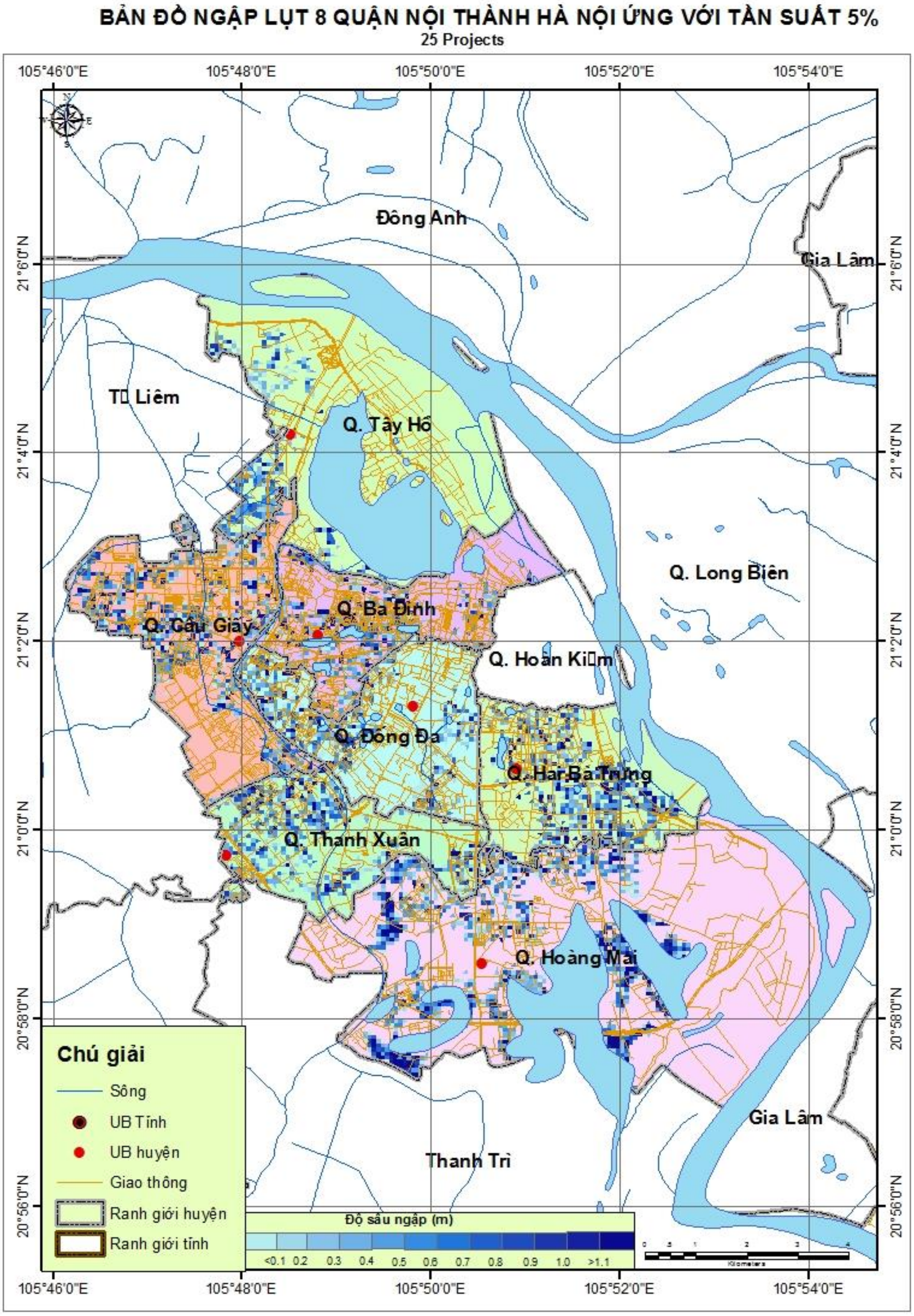

Figure 25. Flood map for Hanoi for Period 2016 – 2035 with Probability of 5% Considering all 25 projects

5.2.6 Discussion

Results show that after implementing different mitigation measures the flood depths are reduced, resulting in the shrinking of flooded area in nearly all districts of Hanoi. It can be seen that the flooded areas with probability of 1% are larger than those of probability of 5% in the three Groups being considered, with most flood water levels. However, the magnitude of reduction strongly depends on the locations of the flood areas and the mitigation measures. Among eight districts, a significant reduction of flood water in Hoang Mai can be observed in Groups 2 and 3. This could be due to the mitigation measures in these two Groups implemented in Hoang Mai District play an important role in improving flood conditions as a whole. Flood maps considering all 25 projects show the smallest flooded area under both rainfall probabilities of 1% and 5%. This could be due to the effectiveness of mitigation measures implemented in the 25 projects.

6. Conclusion

This study applied the MIKE URBAN package to simulate urban flooding for Hanoi using climate data with resolution of 1km derived from Weather Research and Forecasting model. Flood maps were generated under different rainfall distribution probabilities and considered various mitigation measures for improving the flood situation. Comparison between flood maps generated with and without the implementation of mitigation measures was carried out, to assess the effectiveness of investment projects in reducing flood impacts. The study concludes as follows.

- Urban flooding is a serious problem facing Hanoi. Great efforts are being made to reduce the impacts of flooding.
- The MIKE URBAN package can reliably simulate the flooding caused by rainfall events in Hanoi's tropical monsoon climate.
- After implementing different mitigation measures, flood depths are reduced, resulting in shrinking of the flooded area in nearly all districts of Hanoi.
- The magnitude of reduction of the flooded area strongly depends on the flooded area's location, and the particular mitigation measures.
- Regarding different groups of projects, the flood maps which considered all 25 projects produced the smallest flooded area.
- The unavailability of data, especially for the drainage system, limits the possibility to generate flood maps in great detail.

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