Assessment of Multiple Water-Related Hazards under Changing Climate in An Urbanized Sub-Region of Yom River Basin, Thailand

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Abstract

In the Chao Phraya River Basin, Thailand, water-related hazards, particularly river floods, flash floods and droughts, are increasingly causing damages to the local society, economy and environment due to changing climate and urbanization. As its impact, identification of key factors influencing the occurrence and severity of multiple water-related hazards at different temporal and spatial scales is therefore essential to further development of solutions for hazard reduction. The study identified through the analytic hierarchy process several key influence factors to water-related hazards, including precipitation, discharges, natural and green surface areas, and water storage, in the Upper Chao Phraya River basin, Thailand. These factors were then used for the assessments of individual and multiple hazards, as well as potential interventions for hazard reduction. A combination of several research methods was adopted for the hazard assessments, including simulation modelling, multi-criteria decision analysis, and spatial analysis based on both primary and secondary data sources. Eventually, spatial distribution of hazard levels at regional and local scales was mapped out to inform water-related multiple hazards and the potential of selected nature-based solutions to such hazards based on the data of specific years. It was found that increasing vegetation areas and having nature-based reservoirs can effectively improve water management in both wet and dry seasons, contributing to hazard reduction. It is expected that the assessments performed in this study can contribute to awareness-raising of water-related hazards and eventually enhance the preparedness of risk management in the studied areas.

1 Introduction

Historically, natural disasters originate from a variety of hazards throughout the world, such as flood, drought, landslide, rockfall, earthquake, tropical storm, wildfire, causing fatalities, property damage, and socio-environmental disruption in natural and built environments, especially significant in urban and suburban areas (Xu et al., 2016; Gill and Malamud, 2017; Cerè *et al.*, 2017). Countries are exposed to different hazards at different levels, and Thailand is one of the countries that are most exposed to and affected by some major hazards (ADRC, 2019). According to Wallemacq *et al.* (2018), Thailand is even among the top ten countries in the world in terms of absolute losses from natural disasters between 1998 and 2017.

The major types of hazards in Thailand include flood, flash flood, drought, tropical storm, and forest fire (Department of Disaster Prevention and Mitigation, Ministry of Interior, Thailand, 2019). Particularly in the main river basin of the country, the Chao Phraya River Basin (CPRB), river flood, flash flood, and drought are the hazards that have led to the most serious disasters. These types of hazards usually occur at the upstream of the river, or the Upper Chao Phraya River Basin (U-CPRB). In 2011, the historic flood in Thailand resulted in 9.1 percent of the land base flooded in the lower part of northern and central Thailand, and especially Bangkok, with 680 deceased and 13 million affected people, as well as a total of economic losses and damages estimated at approximately USD 46.5 billion (Poaponsakorn et al., 2015). On the other hand, droughts that occurred intermittently between 1989 and 2019 are estimated to have led to a lack of water storage in farmlands and residential areas, causing an accumulated loss at USD

42.1 billion (Department of Disaster Prevention and Mitigation, Ministry of Interior, Thailand, 2019; Hydro and Agro Informatics Institute, 2012).

Base on the observation of historical hazard events, multiple water-related hazards have alternately occurred in the country, posing significant threats to an expansive area. It is therefore of high interest to assess (and further reduce) such multiple hazards. A multiple hazard assessment (and reduction) of a hydrological area involves an overall analysis of water-related hazards in and along the river basin (Zhang et al., 2020). Developing suitable methods/tools is necessary to support the multiple hazard assessment (MHA) process, which can be based on hydrological/hydrodynamic models (HEC-HMS/RAS), Multi-Criteria Decision Analysis (MCDA), and spatial analysis (GIS) (Chen et al., 2015). Meanwhile, natural-based solutions (NBS) such as green areas, wetlands, forests and naturally vegetated lands, are emerging as alternatives or complements to hazard reduction due to a variety of co-benefits they can bring about, which are distinct from the traditional grey solutions (National Infrastructure Commission, 2017; Kalantari et al., 2018; Depietri and McPhearson, 2017). To improve the MHA process and hazard reduction in the U-CPRB, this paper aims at assessing multiple water-related hazards with the key factors hierarchised by local decision-makers and a combination of analytical methods/tools, as well as further identifying potential NBS measures for hazard reduction at different temporal and spatial scales in a selected sub-region of the Yom River Basin (YRB), part of the U-CPRB.

2 Literature Review

2.1 Studies of Water-Related Hazard Characteristics

Hydrological processes play an important role in the global water cycle and seasonal drivers (Trisurat et al., 2019). Spatial and temporal variations in water balance, as well as anthropogenic changes in natural and green surface areas such as land misuse and urbanization, fuelled by climate change, tend to have a significant impact on high-and-low peak streamflow, resulting in extreme events that further affect key resources and processes such as water supply, infrastructure, aquatic habitat, and access (Clifton, 2018). While Komori *et al.*, (2016) claimed that the evidence of a direct relationship between the increased frequency of extreme events and climate change is not clear, an increased probability of urban flooding and flash floods can be observed. The ever-increasing temperature due to global warming also leads to a higher intensity of precipitation and a more frequent occurrence of extreme hydrologic events (Hamlet et al., 2013).

Among all water-related hazards, flooding, flash flooding and drought are the focus of study in this paper. Flooding is the event where water inundates land that is normally dry. It is a natural process which can be caused by different reasons, of which abundant rainfall is a common one. Human activities such as land misuse and urbanization can increase the probability of flooding by deteriorating the vulnerability of our environments to rising water levels. Distinct from the broader sense of flooding, flash flooding is a more extreme event where the ground cannot absorb water as quickly as it falls, usually due to excessive and sudden rainstorms or a dam failure. It is most commonly observed in hilly areas with steep slopes.

Compared to flooding which can sometimes take several months, flash flooding usually happens in a short time, less than 6 hours (Environmental Technology, 2014). At the opposite extreme, drought is the situation of an area that has faced an extended period of unusually dry weather ranging from months to years. Reduction in rainfall and soil moisture would further decrease streamflow and underground water storage, which then result in a hydrological drought. If these drought processes generate social and economic chaos where people and industries fight for their share of water, leading to an overuse of water resources, a social or economic drought may eventually take place. (National geographic society, 2019; Sawatpru and Konyai, 2016).

2.2 Approaches to the Multiple Hazard Assessment

There is an abundance of approaches and methods that can be applied to assess multiple hazards. One of the interesting combinations is the hydrological and hydrodynamic models (HEC-HMS/RAS), the Multi-Criteria Decision Analysis (MCDA), and the spatial analysis, which are successively introduced below.

The Hydrologic Modelling System (HEC-HMS) is a hydrology model, with an advantage of applicable in different environments and under different conditions, developed by the U.S. Army Corps of Engineers (USACE). It is designed to simulate the hydrologic processes of watershed systems and has been widely applied in many geographic areas which used to solve problems relating to river basin water supply, flood hydrology, and watershed runoff, etc. with a function to represent water pathways and the hydrologic cycle. Apart from the HEC-HMS, USACE also introduced a hydrodynamic model for the river analysis system (HEC-RAS). It can be used for one-and-two-dimensional steady flow hydraulic calculation, designed to perform a full network of natural and constructed channels, and therefore is widely adopted in channel flow analysis and floodplain determination (Tate, 1999; Hydraulic Engineer Center, 2019).

The MCDA integrated with the Analytic Hierarchy Process (AHP) method is powerful to analyse the key influence factors among different groups of factors to a given hazard. This method takes into account both natural and anthropogenic factors, while giving different weights to the factors based on decision-makers' pairwise comparison, which will eventually allow for the identification of key influence factors from scoring results. Because of its ability to integrate various criteria and to generate most accurate results from uncertain situations, the AHP method is suitable to be used in the multiple hazard assessment. Upon integration of the spatial analysis based on GIS techniques, the method can then assess the key influence factors to multiple hazards while mapping out the risk areas (Skiludimou et al., 2019; Seejata et al., 2018).

2.3 Nature-Based Solutions for Hazard Reduction

In flood and drought risk management, mitigation measures can be categorised into structural and non-structural solutions. Common examples of non-structural measures include risk management policies and early warning systems, which help to improve the preparedness and awareness of potentially affected people. Meanwhile, structural measures can be further broken down into soft and hard solutions, where the soft-structural (or nature-based) solutions aim at sustainably managing our ecosystems through non-engineering measures like wetland restoration and exploration of natural drainage pathway,

while the hard-structural (or grey) solutions involve the most applied engineering measures such as dams, reservoirs, and drainage systems. With an increased recognition of the role that ecosystems play in providing critical services to reduce and mitigate multiple types of flooding, non-structural and soft-structural (hereinafter referred to as “nature-based”) solutions to flooding hazards are recommended to be prioritised whenever possible (Ilieva et al., 2018; Laforteza et al., 2018; Faivre et al., 2017).

According to European Environmental Agency (2015), nature-based solution (NBS) is defined as “strategically planned network of natural and semi-natural areas that. .. deliver a wide range of ecosystem services”. Examples of applicable NBS to water-related hazards include wetlands, riverine floodplains, natural detentions, etc. The multiple benefits of NBS for water management compared to conventional grey solutions include but not limited to a better management of water supply, moderation of water quality and extreme climate events, as well as a wide range of economic and social co-benefits. (UN Environment-DHI, UN Environment & IUCN, 2018).

Specific to urban areas, NBS can contribute to a number of water supply and wastewater management benefits. Permeable pavements, changing impermeable surfaces into green spaces, tree planting and storage areas for excess runoff, are among the NBS possibilities to reduce sewer system overflows, floods and to relieve the load on the existing flood management infrastructure, while increasing underwater storage to mitigate drought hazards. Some of these measures also have tangible benefits for the society by bringing nature back into the city and providing recreational green spaces. In terms of economic benefits, several studies (Cohen et al., 2012; Horváthová, 2019; Seddon et al., 2020) demonstrate or indicate the cost-effectiveness of NBS relative to grey infrastructure. In summary, NBS can not only maintain the environmental functions in a catchment for water resource management, but also bring about social and economic co-benefits that grey infrastructure can hardly offer.

2.4 Relevant studies in the Chao Phraya River Basin

River flood hazards have been known as the most disastrous phenomena particularly in urban areas (Rubinato et al., 2019). Chuenchooklin et al. (2015) studied the solutions to river flood hazards using Hydrodynamic modeling (HEC-RAS). By properly planning for retention ponds and diversion channels in most paddy fields and some residential areas in Sukhothai Province in the Lower Yom River Basin, Thailand, the authors found that the potentially reduced water levels could have prevented almost all the historical floods that occurred in Sukhothai city. Studies on flash flood hazards in the CPRB have focused on monitoring and warning systems as this hazard can burst out all of a sudden. Kanbua et al., (2009) used Artificial Neural Network (ANN), integrated with the Automatic Weather Stations (AWS), to develop a real-time warning system that can monitor and adjust the network system to reduce the probability of flash flood hazard occurrence in Phrae province, U-CPRB. This is an applicable tool to provide advance notice of potential flash flooding. Upon integration of modeling tools, it can be developed into a virtual planning tool for flash flood management through both engineering and non-engineering measures.

Research on drought hazards typically focus on the influence of insufficient rainfall on drought occurrence and the risk of agricultural droughts covering CPRB and other basins in Thailand.

Rangsiwanichpong et al. (2016) conducted a drought hazard assessment and prediction in CPRB using ANN and Ocean Index Data. They found that performance of ANN to forecasting rainfall can be as earlier as 8 months in advance. Moreover, by comparing the results of ANN with the record of El Nino and La Nina phenomena as well as historical data of floods and droughts in Nakhon Sawan province, the lower and upper bounds of annual rainfall that would lead to a drought or a flood were respectively estimated at less than 899.15 mm and more than 1350.35 mm. Dau et al., (2018) conducted a drought severity assessment in the main agricultural production area of Thailand, Lower Nam Phong River Basin, using the Water Evaluation and Planning (WEAP) model and Standardized Precipitation Index (SPI). The result indicated that the river basin can be considered in a “moderately dry” condition. Meanwhile, high drought risk areas due to water scarcity were identified at a district level to provide useful information for water resources planning and allocation in the basin.

3 Methodology

3.1 Overall Approach and Methods

Figure 1 shows the conceptual framework that there are several natural and man-made factors to the occurrence of major water-related hazards (Gill and Malamud, 2017). While rainfall is a key natural factor, land use change is the main anthropogenic factor, driven by urban expansion, climate change, and economic growth. Pressure of these factors leads to more frequent and extreme multiple hazard events. The multiple hazard assessment of this study takes into account the key influence variables while adding spatial and temporal variations to the analyses to eventually determine the states of multiple hazards in the studied area, and more specifically, their impacts on the environment, human activities and assets. (Liu, 2011; Toosi et al., 2019; Salami et al., 2017; Tiwari, 2019; Kalantari et al., 2018).

Having understood the states and potential impacts of multiple hazards, the study takes a further step to develop adaptive responses to the multiple hazards in the studied area. Instead of conventional grey solutions, the adaptation strategy places emphasis on possible NBS alternatives for water-related hazards reduction and water management planning.

The overall process of this study is divided into nine tasks (see Table 1). Firstly, an analysis of key influence factors to multiple hazards was conducted based on primary and secondary data, collected respectively from interviews, field observations, and official databases. The main analysis methods applied include a simulation modeling through the application of HEC-HMS/RDS models, the MCDA combined with the AHP method and spatial analysis techniques. Additionally, a trend analysis was conducted through Rclimindex software to observe the historical variation of hydrological characteristics such as rainfall, water discharge, and temperature, as well as to predict their future trend and probability of extreme hazard events. Finally, potential NBS as adaptation strategy were tested to identify the appropriate measures for multiple hazards reduction.

Table 1
Operational framework

Inputs	Processes	Analysis methods	Outputs
Results of local decision makers' interviews and literature reviews	Task 1: To analyze the factors that influence the multiple hazard assessment using the MCDA approach	Document analysis, Local decision-makers' judgment and the AHP method	Influence factors to hazards with weighted scores
Digital Elevation Model (DEM), Soil map, Land use map, observed rainfall and discharge, water level, and Geometric data	Task 2: To develop the method for a river flood hazard assessment using HEC-HMS/ RAS modeling with calibration and validation of modeling results	Computation of model simulation, Spatial analysis techniques	River flood hazard assessment
Rainfall data, Soil map, DEM, Geometry data	Task 3: To develop the method for a flash flood hazard assessment using the MCDA approach and spatial analysis techniques	AHP method and Spatial analysis, with weighted overlay techniques	Flash flood hazard assessment
Rainfall data, Soil map, DEM, groundwater, Geometry data	Task 4: To develop the method for a drought hazard assessment using the MCDA approach and spatial analysis techniques	AHP method and Spatial analysis, with weighted overlay techniques	Drought hazard assessment
Results from Task 1–4	Task 5: To develop the method for assessing multiple hazards and potential reductions by integrating MCDA, Spatial analysis and model simulation techniques	AHP method and Spatial analysis, with weighted overlay technique, model simulation	Multiple water-related hazard assessment
Historical rainfall, discharge, and temperature data	Task 6: To analyze temporal and spatial trends of hydrological characteristic based on historical data at different scales	Trend analysis, Climatic indicators	Trend of historical hydrological characteristics, peak and low
Projected rainfall, discharge, and temperature data	Task 7: To analyze temporal and spatial trends of hydrological characteristics based on projection at different scales	Trend analysis, Climatic indicators	Trends of projected hydrological characteristics at peak and low levels

Inputs	Processes	Analysis methods	Outputs
Natural and green surface areas, and natural storage volume	Task 8: To identify NBS alternatives for multiple hazards reduction	Document analysis, Computation of model simulation, Spatial analysis techniques	Hazard reduction potential under NBS scenarios
Results from Task 8	Task 9: To evaluate the identified alternatives for the multiple water-related hazard reductions	Simulation modeling, Spatial analysis techniques	Examples of hazard reduction measures

3.2 Study Area

In a broader sense, the study area locates within the Greater Chao Phraya River Basin (G-CPRB) which covers seven main sub-basins, namely Ping, Wang, Yom, Nan, Sa Kraekrang, Chao Phraya, Tha Chin, and Pasak, shown in Fig. 2(a). While the G-CPRB can be divided into three levels: upper, middle, and lower, the study chose to focus on the Upper Chao Phraya River Basin (U-CPRB), shown in Fig. 2(b), which covers the Yom River Basin (YRB) with a selected sub-regional area located in the lowland of the middle YRB, mostly within the administrative boundary of Sukhothai province, shown in Fig. 2(c). The study further placed its focus on three municipal areas within the province, including Sri Satchanalai municipality and Sawankhalok municipality, Mueang Sukhothai municipality and its vicinity, as well as Old Town municipality and its vicinity.

3.2.1 Sub-regional/Basin Scale

The middle YRB is considered part of the U-CPRB, which covers the provincial areas of lower Phrae, Sukhothai, and some parts of Phitsanulok, Phichit, and Kamphaeng Phet. This identification is based on ecological and sub-watershed aspects. It stretches from latitude 15°50'N to 19°25'N and from longitude 99°16'E to 100°40'E, with a watershed area of 23,616 sq.km. The average annual rainfall is 1,143 mm. and the total average annual runoff at 26,990 MCM. The YRB is the only major basin with no large-scale reservoir that can regulate water flows throughout a year (Hydro and Agro Informatics Institute, 2012).

The major topographic characteristics of this region include highlands alternating with mountainous areas in the lower Phrae province, as well as expansive lowlands in Sukhothai province, where the studied hydrological hazards hotspots are mostly found. This region is a rich ecosystem of wetlands, forests, and various soil types (Department of Disaster Prevention and Mitigation Sukhothai office, 2019; Putthividhya et al., 2016). There are natural wetlands, mainly the Thaphae creek and the Yai swamp, as well as the artificial wetlands Thung Thalaluang, and the reservoirs of Mae Thaphae and Mae Sung. These water resources play an important role in water supply, as well as prevention and mitigation of water-related hazards.

3.2.2 Municipality/Local Scale

At local scale, three municipalities are covered in this study, including; (1) Si Satchanalai and Sawankhalok Municipalities (SSL and SKL), located in the upper part of Sukhothai province, which is an urban area on the highlands, shown in Fig. 3(a); (2) Mueang Sukhothai Municipality and its Vicinity (MSKT), the major hub of economic and community areas on the lowlands in the lower part of Sukhothai province, shown in Fig. 3(b); and (3) Old Town Municipality and its Vicinity (OLT), which is a hilly area where some famous tourist attractions are found, shown in Fig. 3(c). In general, the main economic activities in the studied area include farming, forestry, fishery and local commerce.

3.3 Data Collection and Analysis

3.3.1 Data Collection

This study used both primary and secondary data. The primary data was collected through field observations and interviews with 23 local decision-makers from the organizations involving in natural hazard management and disaster preparedness activities. The secondary data covers historical datasets within the range of 2006 and 2018 on rainfall, river discharge, DEM, soil map, land use map, etc., mainly collected from official sources including Royal Irrigation Department (RID), Land Development Department (LDD) and Thai Meteorological Department (TMD) (see Table 2).

Table 2
Data Collection Items and Sources

Data	Description	Sources	Data characteristics
Rainfall data	Daily unit	Thai Meteorological Department (TMD)	5 stations for Upper Yom River Basin such as 373201, 373301, 378201, 380201 and 386301 during 2007 to 2011
	Daily unit	Royal Irrigation Department (RID)	6 stations including Y.1C, Y.20, 73032, 73082, 73100 and 16092 during 2007 to 2011
Runoff data	Daily and hourly unit	Royal Irrigation Department (RID)	From 2 gauging stations inside Yom River Basin include Y.1C and Y.14 during 2007 to 2011
Temperature	Daily unit	Thai Meteorological Department (TMD)	Degree Celcius
Digital Elevation Model (DEM)	SRTM	USGS	Resolution at 12.5 and 30 m. in 2017
River cross section of Yom River		Royal Irrigation Department (RID)	6 crossections including Y.3A, Y.4, Y.6, Y.14, Y.15 and Y.33 in 2017
Land use map	Resolution 30 m., 12.5 m.	Land Development Department (LDD)	During 2006–2018
Soil map	Resolution 90 m.	Land Development Department (LDD)	In 2017
Influence factors to the multiple hazards		Skilodimou et al., (2019); Palchaudhuri <i>et al.</i> , (2016); Tri et al., (2019); Kazakis et al., (2015) and Stefanidis <i>et al.</i> , (2013)	
Weighted score for influence factors		local decision maker's interview	23 local decision-makers to rank the major influence factors

3.3.2 Analytical methods

Two main research approaches were adopted to carry out different assessments in this study. One is the simulation modeling for the river flood hazard assessment, the other is the MCDA combined with spatial analysis techniques for the flash flood and drought hazard assessments, as well as the assessments of multiple water-related hazards and potential mitigation solutions to them. The details of each assessment are described below.

River Flood Hazard Assessment

The Hydrological Model, or HEC-HMS, plays an important role in the rainfall-runoff modeling of this study. The based maps were created using the HEC-GeoHMS extension and exporting the river network system to the HEC-HMS model. Also, the Hydrodynamic Model, or HEC-RAS, was applied to generate inundation maps from runoff data, which is mainly produced from observed discharge data. The major data in use is rainfall, Digital Elevation Model (DEM), soil maps, and land coverage. The calibration and validation were conducted to increase accuracy by using sensitivity indicators, the observed and simulated runoff data. This result was then reclassified to the flood hazard index at a scale of 1 to 5 and mapped to GIS applications, becoming a river flood hazard assessment map (Scharffenberg, 2018).

Flash Flood and Drought Hazard Assessment

First of all, key influence factors were selected through literature reviews and were weighted based on their importance judged by 23 local decision-makers. Secondly, the AHP method was applied to prioritize the influence factors and calculate weighted scores. This result was then reclassified into a flash flood/drought hazard index at a scale of 1 to 5 and mapped out through GIS applications, becoming a flash flood/drought hazard assessment map (Palchaudhuri et al., 2016; Skilodimou et al., 2019 and Tri et al., 2019),

Multiple Water-Related Hazard and Potential Reduction Assessment

The multiple hazard assessment was carried out by a mix of quantitative methods on the basis of individual hazard assessments mentioned above. Formula (1) shows the calculation of multiple hazard levels, which is an accumulation of individual hazard levels, developed from Skilodimou et al., (2019). GIS software with the Overlay technique and Raster Calculator tool in Model Builder was applied to conduce the assessment and produce the multiple hazard assessment map.

$$\text{MHA} = \text{RF} + \text{FF} + \text{DR} \quad (1)$$

Where,

RF = River flood hazard

FF = Flash flood hazard

DR = Drought hazard

By overlaying individual hazard assessment maps, the multiple hazard assessment map depicted the spatial distribution of multiple hazard levels in different values and colors. The analytical results were presented in three-digit number, signifying different hazards and their corresponding severity in the area (see Table 3). The higher the value is, the higher the hazard is. Eventually, this mapping of multiple hazard assessments allows us to examine the historical and projected hazard occurrence at different temporal and spatial scales

Table 3
Classification of the hazard levels of Multiple Water-Related Hazards

Value	River flood	Value	Flash flood	Value	Drought
1	Very low hazard	10	Very low hazard	100	Very low hazard
2	Low hazard	20	Low hazard	200	Low hazard
3	Medium hazard	30	Medium hazard	300	Medium hazard
4	High hazard	40	High hazard	400	High hazard
5	Very high hazard	50	Very high hazard	500	Very high hazard
Source: adapted from Skilodimou et al., (2019)					

4 Results And Discussions

4.1 Baseline Analysis and Factor Identification of Water-Related Hazards

To understand the baseline trends of hydrological and climate characteristics over time, an analysis based on historical data showed that rainfall has steadily increased between 1988 and 2017, which could have resulted in high discharge rates and more extreme events. In 2006, 2011 and 2016, extreme wet and dry conditions were observed alternately, which could have led to multiple water-related hazards. The situation was observed most significant in 2016. However, it is estimated that rainfall will be limited in the next 30 years, between 2018 and 2050 (Krinner et al., 2013), leading to lower discharge rates. The number of highest accumulated wet days decreases at both sub-regional and local scales, while the number of highest accumulated dry days increases from 2018 to 2050. It implies that drought hazards will be more likely to occur than floods.

In terms of spatial patterns, the cumulative rainfall was high in the middle and lower part of the sub-region, which covers the studied municipalities of MSKT and OLT, whereas the rainfall in the upper part, namely SSL and SKL, was low. As discharge rates are influenced by rainfall, the historical sites within MSKT and OLT can be threatened by additional water volume during wet and dry seasons. However, it is projected that rainfall in the upper and lower part will be higher than in the middle part of the sub-region, and discharge rates will be similar to the historical trend in both seasons. These conditions greatly increase the likelihood of water-related hazard events, augmenting the risk exposure of the studied urban areas.

Having understood the baseline scenario, the influence factors to water-related hazards were identified, weighted and ranked based on their influence over water-related hazards (see Table 4). In general, precipitation is the most influential factor to all water-related hazards studied here, followed by natural and green surface areas. Some other influence factors are more hazard-specific, such as distance from

river and slope for river floods, slope and elevation for flash floods, and existing groundwater and soil type for droughts.

Table 4
Influence Factors to Water-Related Hazards in Sub-Region

Hazards	Main factors	Sub factors	Weighted score	Rank
River flood	Natural	Precipitation	0.334	1
		Slope	0.118	4
		Elevation	0.104	5
		Soil type	0.082	6
	Anthropogenic	Natural and green surface areas	0.215	2
		Distance from river	0.148	3
Flash flood	Natural	Precipitation	0.438	1
		Slope	0.131	3
		Elevation	0.107	4
		Soil type	0.070	5
	Anthropogenic	Natural and green surface areas	0.253	2
	Drought	Natural	Precipitation	0.418
Soil type			0.091	4
Existing groundwater			0.117	3
Anthropogenic		Natural and green surface areas	0.245	2
		Distance from rivers	0.061	6
		Water storage	0.069	5
Source: adapted from the interviews with 23 local decision-makers through the AHP analysis (2020).				

4.2 Individual and Multiple Hazard Assessments

4.2.1 River flood hazard

The HEC-HMS and HEC-RAS models were applied to simulate the process of rainfall to runoff in the basin of the low Yom River, representing the YRB, as well as to simulate inundation and evaluation of river flood hazard levels for flood hazard mapping. The time scale of simulation covers the period between 2016 and 2017, from which the flood inundation maps were generated ever five years including 2006, 2011, and 2016. To ensure model robustness, calibration and validation were also conducted to examine the

indicators of standard sensitivity as mentioned, of which the results were returned with acceptance and fitness for use.

The results suggest that the degrees of river flood hazards at sub-regional scale are generally evaluated as either high or very high from the upper-middle part to the lower-middle part of Sukhothai province, with a concentration of very high degrees of river flood hazards in the middle (see Fig. 4(a)). From dark red to light red, the color degradation represents the degrees of river flood hazard from very high to very low. On a municipal scale, MSKT has the highest concentration of very high degrees of river flood hazards in 2006, 2011, and 2016, and the impacted area covers most of the western part of MSKT (see Fig. 4(b)). Most of the areas along the river were evaluated as high to very high degrees of river flood hazard, as the landforms contain mountains and lowlands.

4.2.2 Flash flood hazard

The flash flood hazard assessment was conducted by the MCDA and GIS techniques, where the influence factors and their weights were pre-determined as shown in Table 7. From dark blue to light blue, the color degradation represents the degrees of flash flood hazard from very high to very low. At sub-regional scale, the degrees of flash flood hazards range in general from high to very high in the upper and western part of the studied area, which is mountainous. However, when taking the temporal factor into account, this area has its degrees of flash flood hazards ranging from high to very high in 2006 (see Fig. 5(a)), while the same indicator dropped to a low degree in 2011 and 2016.

At municipal scale, the degrees of flash flood hazards are in general evaluated as low to zero in the plain and lowland areas including MSKT, SSL and SKL, while a high hazard hotspot was identified in the high terrain area (see Fig. 5(b)) in the west part of the studied area. Similarly, flash flood hazard levels are generally evaluated at a low degree in OLT, except some extreme variations in the hilly area on the bottom left of the map (see Fig. 5(c)). This result suggests that flash flood hazards tend to concentrate in highlands and hilly areas where the slope of hillsides is steep. Therefore, flash flood hazard levels are mostly low in the studied municipalities, and there has been no flash flood in MSKT as it locates in lowlands.

Table 7
Factors and their weights for the Flash Flood Hazard Assessment

Hazards	Main factors	Sub factors	Weighted score	Class	Ratio
Flash flood	Natural	Precipitation (mm.)	0.438	> 110	5
				90–110	4
				60–90	3
				30–60	2
				0–30	1
		Slope (Degree)	0.131	> 20	5
				15–20	4
				10–15	3
				5–10	2
				0–5	1
		Elevation (m.)	0.107	> 800	5
				600–800	4
				400–600	3
				200–400	2
				0–200	1
		Soil type	0.070	Clay loam	5
				Silk clay loam	4
				Sandy clay loam	3
				Loam	2
				Sandy loam	1
	Anthropogenic	Natural and green surface areas	0.253	Vegetation	5
				Soil	3
				Water body	1
Source: Skiludimou <i>et al.</i> , (2019); Kazakis et al., (2015) and Stafanidis <i>et al.</i> , (2013), Modified by researcher					
Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high					

4.2.3 Drought hazard

The drought hazard assessment applies the same method as the flash flood hazard assessment. The pre-determined influence factors to drought hazards and their respective weights can be found in Table 8. Color gradation on the map shows that dark red refers to very high drought hazard to dark blue refers to very low drought hazard. On a sub-regional scale, a very high hazard hotspot was identified in the upper and western sub-region, whereas the degrees of drought hazards were generally low for most of the middle and lower part of Sukhothai province in 2006 (see Fig. 6(a)). At municipal scale, the degrees of drought hazards were generally moderate to high across all the studied municipalities, including MSKT, SSL, SKL, and OLT, based on 2006 and 2016 data (see Fig. 6(b), (c), (d)), while the same indicator shows a moderate degree in 2011 as there was a historical flood that brought heavy rainfall.

Table 8
Factors and their weights for the Drought Hazard Assessment

Hazards	Main factors	Sub factors	Weighted score	Class	Ratio
Drought	Natural	Precipitation (mm.)	0.418	≥ 2.0	1
				1.5 to 1.99	2
				1.0 to 1.49	3
				-0.99 to 0.99	4
				-1.0 to -1.49	5
				-1.5 to -1.99	6
				-2.0 and less	7
		Soil type	0.091	Sandy loam	5
				Loam	4
				Sandy clay loam	3
				Silk clay loam	2
				Clay loam	1
		Existing groundwater (m ³ / hr.)	0.117	< 2	5
				2–10	4
				10–15	3
				15–20	2
				> 20	1
	Anthropogenic	Natural and green surface areas	0.245	Vegetation	1
				Soil	3
				Water body	5
		Distance from rivers (m.)	0.061	> 1000	5
				600–1000	4
				400–600	3
				200–400	2
Source: Palchaudhuri <i>et al.</i> , (2016) and Tri <i>et al.</i> , (2019), Modified by researcher					
Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high					

Hazards	Main factors	Sub factors	Weighted score	Class	Ratio
				0–200	1
		Water storage	0.069	< 4.822	5
		(MCM)		4.822–7.265	4
				7.265–9.144	3
				9.144–11.586	2
				> 11.586	1
Source: Palchaudhuri <i>et al.</i> , (2016) and Tri <i>et al.</i> , (2019), Modified by researcher					
Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high					

4.2.4 Multiple Hazard Assessment

Upon overlaying the results of individual hazard assessments, the multiple hazard assessment allows to understand the severity of multiple hazards at different temporal and spatial scale. From dark blue, green to light yellow, the color gradation on the maps represents the degrees of multiple hazards from very high to very low. At the sub-regional level, multiple hazards have generally occurred in the upper and western part of the sub-region. River flood, flash flood and drought hazards were found, while the degrees of flash flood and drought hazards were evaluated as high and moderate in the upper and western sub-region, where the terrain mostly covers highlands with steep hillsides. Meanwhile, the middle and lower sub-region was mostly characterized by a high degree of river flood hazards and a moderate degree of drought hazards (see Fig. 7(a)).

At the municipal level, the major multiple hazards were found in 2016. In MSKT (see Fig. 7(b)), the degrees of river flood hazards were high while the degrees of drought hazards were moderate to high. In SSL and SKL (see Fig. 7(c)), the degrees of drought hazards were moderate to high, while the degrees of flash flood hazards were very low. And in OLT (see Fig. 7(d)), the degrees of drought hazards were moderate, and the degrees of flash flood hazards were very low. In overall, where the area has a high degree of river flood or flash flood hazards, its degree of drought hazards is then found moderate.

4.3 Potential Nature-based Solutions for Multiple Hazard Reduction

Based on the identification of influence factors, natural and green surface area ranks as the second most influential factors to all water-related hazards, following precipitation. As a result, the study tried to examine how increasing natural and green surface areas can potentially reduce the severity of multiple hazards. Meanwhile, as precipitation is the most influential factor, another NBS evaluated is a nature-based reservoir which is designed to improve water management during wet and dry seasons, such that

the event of extreme high or low precipitation can be mitigated and thus reduce the severity of multiple water-related hazards.

4.3.1 Increase in Natural and Green Surface Areas

To examine the potential of NBS in hazard reduction, natural and green surface areas were analyzed to investigate how it could mitigate the flash flood hazard in the studied area, where hills are mostly found. A simulation modeling was conducted for a scenario analysis between the base case and alternative case, where natural and green surface areas of the studied sub-region increase by 7 percent (from 7,833.95 sq.km in the base case to 8,456.92 sq.km in the alternative case). In comparison between the base and alternative cases on a sub-regional scale, the share of the very-high-hazard surface area relative to total sub-regional area would drop by 6.83 percent, while that of the high-hazard surface area would drop by 7.2 percent. In the meantime, the share of the low-hazard surface area relative to total sub-regional area would increase by 6.67 percent, while that of the very-low-hazard area would rise by 12.19 percent. In terms of the average degree of flash flood hazards at the sub-regional level, the scoring result showed that the degree of such hazards would drop from 2.19 (low hazard) in the based case to 1.65 (very low hazard) in the alternative case (see Fig. 8), suggesting that increasing vegetation areas has the potential to mitigate the severity of flash flood hazards and therefore contribute to hazard reduction.

At municipal scale, the shares of surface areas at different hazard degrees relative to total studied area only vary slightly between the baseline and alternative scenario: the share of the very-high-hazard surface area relative to total studied area in SSL and SKL would drop by 0.96 percent, while that of the high-hazard area would drop by 0.56 percent. Meanwhile, the share of the low-hazard surface area relative to total studied area would increase by 1.9 percent and that of the very-low-hazard surface area would rise by 0.07 percent. In terms of the average degree of flash flood hazards in SSL and SKL, the scoring result only drops from 1.07 in the base case to 1.03 in the alternative case (see Fig. 9). The change in hazard reduction is minor as this area faces only a marginal exposure to flash flood hazards.

In OLT, the degrees of flash flood hazards are in general very low, except in the area where highlands and steep slopes are found. The share of the very-high-hazard surface area relative to total studied area would drop by 9.3 percent, while that of the high-hazard area would drop by 4.07 percent. On the other hand, the share of the low-hazard surface area relative to total studied area would increase by 4.54 percent, and that of the very-low-hazard surface area would increase significantly by 11.37 percent. As for the average level of flash flood hazards, the scoring result only drops from 1.74 in the based case to 1.24 in the alternative case (see Fig. 10).

In summary, an increase of natural and green surface areas at 7 percent tends to reduce the severity of flash flood hazards in the areas facing a high degree of flash flood hazards by 20.69 percent at sub-regional scale, and respectively by 1.97 and 15.91 percent in SSL/SKL and OLT. Such a difference in flash flood hazard reduction is reasonable, as the hilly areas facing a higher degree of flash flood hazards were found in the northwest of the studied sub-region, which do not cover SSL/SKL and OLT. Therefore,

increasing natural and green surface areas tends to contribute more significantly to flash flood hazard reduction at sub-regional scale, while the impact would be relatively limited in the urbanized areas where flash flood hazard is generally low.

4.3.2 Nature-based Reservoir

This measure was only tested at municipal scale, in MSKT specifically, based on 2016 data. This area suffers from severe river floods almost every year, so it is of particular interest to examine the potential of having a nature-based reservoir to hazard reduction. The reservoir was designed as a rectangular with an area of 5,040,304.24 sq.m. (5 sq.km.), 15 m. depth, the capacity of 75 million cubic meters (mcm.). It was assumed to locate in the upper MSKT to protect the city center from river floods. Moreover, to prevent the city (MSKT) from flooding in wet seasons and to support water supply in dry seasons, a piece of natural wetlands is assumed to be restored in Si Samrong district, north of MSKT. (see Fig. 11).

The assessment involves both river flood and drought hazards through simulation modeling. With this nature-based reservoir, the share of the high-hazard surface area relative to total studied area would drop by 26.86 percent, and that of the moderate-hazard surface area would drop by 4.40 percent. In the meantime, the share of the low-hazard surface area relative to total studied area would increase significantly by 31.75 percent. In terms of average scoring results for drought hazards, MSKT faces in general a very low degree of drought hazards, which is 2.91 in the baseline scenario and 2.34 in the alternative scenario. Meanwhile, the surface area prone to inundation slightly decreases (see Fig. 12). The results suggest that by having a nature-based reservoir at the strategic location relative to the urbanized area facing a high degree of river flood and drought hazards, it is likely to significantly reduce hazard occurrence.

4.4 Discussions

The key variables influencing the severity of multiple hazards include precipitation, natural and green surface areas, water storage, and discharge, which is considered as an effect of changing precipitation. Variation of these variables across time and space is also important. They play a major role in both the multiple hazard assessment and identification of hazard reduction measures. Particularly, precipitation is closely related to water discharge. Abnormal rainfall can affect discharge rates, leading to extreme hazard events and increasing the severity of multiples hazards.

According to the baseline analysis of historical trends, rainfall has significantly increased in the studied areas, along with a sustaining high average annual temperature. Extreme events occurred almost every 4–5 years with heavy rainfall in the middle and lower part of the sub-region. In the near future, extreme conditions are expected to be more severe as rainfall is projected to decrease on the upper and lower part of the sub-region between 2018 and 2050, resulting in low discharge rates and low water retention. The average temperature tends to be gently declined, while remaining at a high level which could drive the severity of water-related hazards, especially droughts. In general, rainfall and temperature are expected to vary in the near future in such a way that water-related hazards would continue to be a threat to the studied areas. Comparing the results of this study in CPRB, one of the findings was that the historical and

projection rainfall trend was growing which obtained by Limsakul et al., (2016) with no significant change. As well as historical and projection discharge rate gained from Champathong et al., (2013). The relationship between rainfall and temperature trends implied severe climate change from the past to the near future.

In terms of multiple hazard assessments, river flood hazard and flash flood hazard are more location-specific, where the former tends to be high in the lowlands along the Yom river and the latter is very high on the steep-sloped areas during wet seasons. In the meantime, drought hazard is generally high or very high across the whole sub-regional area in dry seasons. Among the three local-scale studied areas, drought hazard is generally high across all areas, while high degrees of river flood and flash flood hazards are found only in some of the studied areas. Moreover, while some areas face a high degree of river flood and flash flood hazards in wet seasons, it is reduced to a moderate level in dry seasons.

In the development of nature-based solutions for multiple hazard reduction in high-risk areas, the empirical evidence shows that an increase of vegetation surface areas by 7 percent can mitigate flash flood hazards by reducing the share of high-hazard and very-high hazard surface areas while increasing that of low-hazard and very-low-hazard surface areas relative to total sub-regional area. Meanwhile, having a nature-based reservoir with the storage capacity of 50-percent rainfall in the middle and lower part of the sub-region would help to optimize peak and low discharge rates by storing water in wet seasons while increasing discharge rates to maintain the critical water level in dry seasons. In this way, it helps to reduce the severity of hazard events and the share of surface areas prone to river floods and droughts in the studied areas. Comparing the results to Jumrassri et al., (2017) applied different indicators related to our findings with no significant change in terms of reducing the discharge rate, but this study focused on reducing the hazard level and its areas.

5 Conclusions And Recommendations

The main objective of this study is to assess multiple water-related hazards and nature-based solutions for hazard reduction in the Upper Chao Phraya River Basin, one of the most vulnerable areas in Thailand to water-related hazards. To conduct the assessments, the key factors influencing multiple hazard occurrence and reduction were identified and hierarchized by local decision-makers. These factors are interconnected to the occurrence of water-related hazards, influencing the severity of hazard events in different seasons, years, and geographical areas. Precipitation, or rainfall, is the main factor influencing all the water-related hazards included in this study (river floods, flash floods, and droughts). Moreover, excessive precipitation is positively correlated to flash flood hazards. Based on historical data, rainfall has continued to increase, leading to high discharge rates. Sustaining high temperature in the past has also contributed to extreme water-related hazard events, particularly droughts. In the next three decades, rainfall and discharge are expected to be limited, leading to extreme events associated more closely with droughts than river floods and flash floods.

Meanwhile, this study found that increasing natural and green surface areas, as well as having nature-based reservoirs tend to be helpful to multiple hazard reduction. Both measures can moderate the severity of multiple water-related hazards and reduce affected surface areas at sub-regional and local scales, mainly because they can slow down and store water overflows when floods occur in wet seasons. Meanwhile, nature-based reservoirs can also release river discharge to relieve the pressure of drought events in dry seasons. These NBS alternatives can be considered as soft-structural measures, which feature two-sided benefits. On one hand, they can reduce the occurrence and severity of multiple water-related hazards; on the other hand, they can strengthen environmental resilience due to their nature-based quality. As increasing natural and green surface areas was found more effective at sub-regional scale, it is suggested that policy makers could consider implementing it region-wide while planning nature-based reservoirs at selected spots that can strategically alleviate the impacts of water-related hazards on the urbanized communities by improving water resources management and local resilience.

There exist a number of limitations in the study. First of all, the key influence factors to multiple water-related hazards identified are location specific, while some other potential factors such as hydro lithological information, river density, evapotranspiration and humidity are not included due to data inaccessibility. Meanwhile, as the assessments are solely based on historical data, their predictive power of future events is limited to some extent. Finally, the assessment of NBS for hazard reduction, particularly that of increasing natural and green surface areas, is only able to demonstrate the overall potential of hazard reduction at sub-regional scale, without providing more details at local scale. It is therefore recommended that future research could explore other natural, anthropogenic and socio-economic factors for a more comprehensive multiple water-related hazard assessment and development of effective measures for hazard reduction, and could test more details of each NBS measure in different scale. Moreover, using projected input data rather than historical data is to be considered to enhance the predictive power to multiple hazards, as well as to enlarge the scope of study to vulnerability and/or risk exposure. Finally, the research methods developed in this study will require further tests for reliability and applicability if they are to be applied to other areas for other types of hazards.

6 Declarations

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Availability of data and material The datasets and software used to support the study and conclusions of this article are available from relevant public entities identified in the material.

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Figures

Figure 1

Conceptual Framework Source: Adapted from Liu et al., 2016; Salami et al., 2017; Toosi et al., 2019

Figure 2

(a) Boundary of the G-CPRB; (b) Boundary of the U-CPRB; (c) Boundary of the Sub-Regional and Local Studied Areas Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

(a) Boundary of Si Satchanalai and Sawankhalok Municipalities; (b) Mueang Sukhothai Thani Municipality and Vicinity; (c) Boundary of Old Town Municipality and Vicinity Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

(a)

(b)

Figure 4

(a) River Flood Hazard Maps in 2016 at Sub-Regional Scale; (b) River Flood Hazard Maps in 2011 in MSKT Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high Source: RID (2017); LDD (2017) and SRTM DEM (2017), Modified by researcher using HEC-RAS and spatial analysis Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

(a) Flash Flood Hazard Maps in 2006 at Sub-Regional Scale; (b) Flash Flood Maps in 2006 in SSL and SKL; (c) Flash Flood Maps in 2006 in OLT Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high Source: TMD (2017); LDD (2017) and SRTM DEM (2017), Modified by researcher using weighted overlay technique Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

(a)

(b)

(c)

(d)

Figure 6

(a) Drought Map in 2016 at sub-regional scale; (b) Drought Map in 2016 in MSKT; (c) Drought Map in 2016 in SSL and SKL; (d) Drought Map in 2016 in OLT Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high Source: TMD (2017); LDD (2017) and SRTM DEM (2017), Modified by researcher using weighted overlay technique Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning

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Figure 7

(a) Multiple Hazard Assessment Map in 2016 at Sub-Regional Scale; (b) Multiple Hazard Assessment Maps in 2016 in MSKT; (c) Multiple Hazard Assessment Maps in 2016 in SSL and SKL; (c) Multiple Hazard Assessment Maps in 2016 in OLT Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very

high Source: RID (2017); TMD (2017) and LDD (2017), Modified by researcher using weighted overlay technique Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 8

Base Case (a) and Alternative Case (b) with Increasing Natural and Green Surface Area by 7 Percent in the Sub-Region in 2016 Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high Source: TMD (2017); LDD (2017) and SRTM DEM (2017), Modified by researcher using weighted overlay technique Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

(a)

(b)

Figure 9

Base Case (a) and Alternative Case (b) with Increasing Natural and Green Surface Area by 7 Percent of a Local Area Investigating in SSL and SKL in 2016 Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high Source: TMD (2017); LDD (2017) and SRTM DEM (2017), Modified by researcher using weighted overlay technique Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

(a)

(b)

Figure 10

Base Case (a) and Alternative Case (b) with Increasing Natural and Green Surface Area by 7 Percent of a Local Area Investigating in OLT in 2016 Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high Source: TMD (2017); LDD (2017) and SRTM DEM (2017), Modified by researcher using weighted overlay technique Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

(a)

(b)

Figure 12

Base Case (a) and Alternative Case (b) with the nature-based reservoir in MSKL in 2016 for a River Flood Hazard Assessment Note: 1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high Source: TMD (2017); LDD (2017) and SRTM DEM (2017), Modified by researcher using HEC-RAS and spatial analysis Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.